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Foot-ankle injury prevention in adolescent athletes

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(3) Fourchet F, Girard O, Kelly L, Horobeanu C, Millet G.P. (2011). Changes in leg spring behaviour, plantar loading and foot mobility magnitude induced by a treadmill exhaustive run in adolescent middle-distance runners. Gait & Posture (submitted).

(4) Fourchet F, Kuitunen S, Girard O, Millet G.P. (2007). Comparison of foot plantar distribution between training and spikes shoes in young sprinters. Science & Sports, 22(3-4) 176-178.

(5) Fourchet F, Kelly L, Horobeanu C, Loepelt H, Taiar R, Millet G.P. (2011). Comparison of plantar pressure distribution in adolescent runners at low vs. high running velocity. Gait & Posture (in press).

(6) Fourchet F, Horobeanu C, Loepelt H, Taiar R, Millet G.P. (2011). Foot-ankle injuries and maturation in young Track and Field athletes. International Journal of Athletic Therapy & Training, 16(3), 19-23.

(7) Fourchet F, Materne O, Horobeanu C, Hudacek T, Buchheit M. (2012). Reliability of a novel procedure to monitor lower limb muscle groups flexibility in highly-trained adolescent athletes. Physical Therapy in Sport, doi:10.1016/j.ptsp.2012.02.004.

(8) Guex K, Fourchet F, Loepelt H, Millet G.P. (2011). Passive Knee Extension Test to Measure Hamstring Tightness: Influence of Gravity Correction. Journal of Sport Rehabilitation, doi 2010-0091.

(9) Fourchet F, Kilgallon M, Loepelt H, Millet G.P. (2009). Plantar muscles electro-stimulation and navicular drop. Science & Sports, 24:5:262-264.

(10) Fourchet F, Kuitunen S, Girard O, Beard A.J, Millet G.P. (2011). Effects of combined foot-ankle electromyostimulation and resistance training on the in-shoe plantar pressure patterns during sprint in young athletes. Journal of Sports Science and Medicine, 10, 292-300.

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(12) 6th Congress of the European Interdisciplinary Society for Clinical and Sports Application (EISCSA) – St- Etienne, France (20th & 21st May 2010) – Oral presentation. “Effects of intense running to exhaustion on ankle plantar and dorsal flexors isokinetic resistance to fatigue in young distance runners” – Isokinetics and Exercise Science, 18(2), 85-86 – Fourchet F, Horobeanu C, Loepelt H, Millet G.P.

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Publications

(15) Materne O, Fourchet F, Hudacek T, & Buchheit, M. (2012). A novel method to monitor lower limb muscles flexibility in young elite athletes: is it examiner-dependent? Proceedings of Science and Football VII (in press).

(16) Edouard P, Chatard J-C, Fourchet F, Collado H, Degache F, Leclair A, Rimauda D, Calmels P. (2011). Invertor and Evertor Strength in Track and Field Athletes with Functional Ankle Instability. Isokinetics and Exercise Science, 19, 91-96.

(17) Girard O, Eicher F, Fourchet F, Micallef J.P, Millet G.P. (2007). Effects of the playing surface on plantar pressures and potential injuries in tennis. Br J Sports Med, 41(11), 733-738.

(18) Girard O, Eicher F, Fourchet F, Micallef J-P & Millet G.P. (2007) Effects of the playing surface on in-shoe foot loading patterns during tennis-specific movements. Tennis Science and Technology III (Edited by S. Miller & J. Capel-Davies), London: ITF, p.p. 199-206. (Book chapter).

Presentations

(19) 7th World Congress on Science & Football – Nagoya, Japan (26th to 30th of May 2011) – Oral presentation. “A novel method to monitor lower limb muscles flexibility in young elite athletes” – Materne O, Fourchet F, Hudacek T, Buchheit M.

(20). 3ème congrès de la Société Suisse des Sciences du Sport (4S): Les sciences du sport : usages et utilité – Lausanne, Switzerland (11th and 12th February 2011) – Poster presentation. ‘’Passive Knee Extension Test to Measure Hamstring Tightness: Influence of Gravity Correction’’ – Guex K, Fourchet F, Loepelt H, & Millet G.P.

(21) NZ Sports Medicine and Science Conference – Wellington, New Zealand (18th to 20th of November 2010) – Oral presentation. “Muscle flexibility as a risk factor for muscle injury in elite adolescent soccer players” – Paoloni J, Fourchet F, Materne O, Sailly M, Hamilton B, Chalabi H.

(22) Annual medical conference of the French Athletics Federation – Paris, France (1st to 3rd of October 2010) – Oral presentation. “Innovative method for measuring muscle flexibility in adolescent athletes” –Fourchet F, Horobeanu C.

(23) 12th biennial ESM (Emed Scientific Meeting) – Providence Rhode Island, USA (14th to 17th August 2010) – Poster presentation. “Effects of intense running to exhaustion on the in-shoe plantar pressure patterns in young middle-distance athletes” – Fourchet F, Kelly L, Horobeanu C, Millet G.P.

(24) French Society of Sports Medicine and Sports Traumatology – Biarritz, France (29th to 31st of October 2009) – Oral presentation. “Epidemiology of foot-ankle injuries in young Track and Field athletes and relationships to maturity status” - Fourchet F & Millet G.P.

(25) 3rd World Congress of Science & Technology in Tennis – London, UK (10th to 12th of September 2007) – Oral presentation. “Effects of the playing surface on in-shoe foot loading patterns during tennis-specific movements” – Girard O, Eicher F, Fourchet F, Micallef J-P, Millet G.P.

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Glossary

Cyclogram	Joint angle–angle diagram.
Flexible flat foot	Foot with an arch that is high when unloaded but flattens with standing, but weight bearing does not cause calcaneal eversion.
Foot mobility magnitude	Composite value of vertical and medial-lateral mobility of the midfoot (taking into account navicular drop and drift), proposed by Mc Poil and Cornwall in 2007.
Leg stiffness	In the spring mass model paradigm, the stiffness of the leg spring represents the average overall stiffness of the integrated musculoskeletal system during the ground-contact phase.
Medial (longitudinal) arch	Complex made up of the calcaneus, the talus, the navicular, the cuneiforms and the first three metatarsal bones and their related ligamentous and muscular structures.
Muscle tuning	The strategy of changing the coupling between the soft and rigid structures of the runners' leg.
Navicular drop	Difference in height of the most prominent aspect of the navicular tuberosity when the subtalar joint is placed in "neutral" as compared with when the foot is positioned in a relaxed standing foot posture.

Peak height velocity	Somatic biological maturity indicator which records the moment of maximum velocity of growth during adolescence
Pes cavus	This is an umbrella term encompassing several high arch conditions; Common descriptions of this deformity frequently include inversion of the calcaneus, inversion of the midfoot, adduction of the forefoot and plantar flexion of the first metatarsal.
Pes planus (flat foot)	Anomaly which is characterized by the decreasing or disappearing of the height of medial arch of the foot.
Planting action	Action of plantar flexing the ankle during the propulsion part of the stance phase.
Poulaine	Name of the ankle-knee cyclogram shape, proving from a French word defining a Middle-age shoe.
Procrustes	In Greek mythology, Procrustes was a legendary highwayman from Attica who offered hospitality to passing strangers. He tied them to an iron bed, stretching them if they were too short and chopping off their legs if they were too tall. This name was given to a method designed to allow quantitative analyses of biological shapes using geometric morphometrics.
Pronation	Movement allowing a downward rotation of the medial border of the foot and hallux towards the ground.

Roll-over	Process of the foot plantar surface rolling on the ground during the stance phase.
Supination	Movement bringing the lateral border of the foot into more direct plantigrade contact
Spring mass model	This paradigm considers running as a typical human movement where the musculo-tendinous structures of the lower limb alternately store and return elastic energy during the stretch-shortening cycle and where the lower limbs can be considered as springs loaded by the weight and inertia of the body mass.
Toe-in	Forefoot adduction
Vertical stiffness	In the spring mass model paradigm, the vertical stiffness is defined as the ratio of the maximal force to the vertical downward maximal displacement of the centre of mass as it reaches its lowest point, i.e. at the middle of the stance phase. It is used to model the vertical motion of the centre of mass during contact.

List of abbreviations

AE	Athlete-exposure
AIMS	Athletic injury monitoring system
APHV	Age at peak height velocity
CISIR	Canadian Intercollegiate Sport Injury Registry
CM	Centre of mass
CNS	Central nervous system
COM	Centre of mass
DF	Dorsi-flexor
DIP	Distal interphalangeal
EMG	Electromyography
Fp	Frontal plane
FMM	Foot mobility magnitude
GP	Greulich-Pyle
IAAF	International Association of Athletics Federations
IEMG	Integrated electromyographic signal
IOC	International Olympic Committee
ISAK	International Society for the Advancement of Kinanthropometry
ISS	Injury surveillance system
K	Stiffness
MLA	Medial longitudinal arch
MTP	Metatarsal phalangeal

MVC	Maximal voluntary contraction
MVC-CON	Maximal voluntary concentric contraction
MVC-ISO	Maximal voluntary isometric contraction
NAIRS	National athletic injury / illness reporting system
NCAA	National Collegiate Athletic Association
NCHSAIS	North Carolina High School Athletic Injury Study
NMES	Neuromuscular electromyostimulation
OCD	Osteochondritis dissecans
PF	Plantar-flexor
PIP	Proximal interphalangeal
PHV	Peak height velocity
RIO	Reporting information online
RL	Relative load
RMS	Root mean square
RPE	Rating of perceived exertion
RT	Resistance training
SSC	Stretch-shortening cycle
SMDCS	Sport medicine diagnostic coding system
SMM	Spring-mass model
SF	Step frequency
SL	Step length
Sp	Sagittal plane
Tc	Time contact

Tf	Time flight
Tp	Transverse plane
TRIPP	Translating research into injury prevention practice
TW	Tanner-Whitehouse
V	Velocity

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Part 1. General introduction

Today, participation in children and youth sports is increasingly popular[47] and it is encouraged by the medical community in order to promote public health.[229] Engaging in sports activities at a young age has however numerous health benefits but also involves risk of injury. Indeed the rationale for implementing efficient injury prevention strategies in children and adolescent athletes is of course the protection of this vulnerable population, followed by the reduction of the health costs. For a couple of decades, injury prevention field tended to be more and more evidence-based and numerous researchers explored this topic.[87-89, 91, 95, 238-241, 243, 244, 349, 352]

It is worth noting that a considerable amount of the publications dealing with injury prevention in young athletes focused on contact / traumatic injuries,[86, 90, 92-94, 223, 265] including the subsequent injury prevention recommendations in terms of rules adaptation and body protection. It has been however reported recently that overuse or repetitive trauma injuries represented approximately 50% of all paediatric sport-related injuries.[349] Despite this high prevalence, overuse and micro traumatic injuries and their prevention countermeasures in adolescent athletes are dramatically underreported in the scientific literature, especially if focusing only on the track and field events. In 2005, Zemper[376] carried out a literature review on "*injuries to youth in track and field or athletics*" and he collected only nine prospective or retrospective studies that either stated an injury rate or provided enough information to allow some estimation of an injury rate. These scarce data revealed anyway some relevant findings such as:

- the high prevalence of injuries affecting the foot-ankle region in young track and field athletes,
- the lack of consideration for the growth-related injuries in the existing sport epidemiological studies,
- the lack of available data regarding the relationships between injuries and maturation in track and field
- and the lack of considerations for the risk factors that are closely related to the "field" or the training (but not measurable in the medical department at the beginning of the season), such as the effects of fatigue and the influence of shoe type or training running pace.

As it was already speculated that more than half of the overuse injuries may be preventable with simple approaches,[349] it appears of interest to examine some undervalued and field-related risk factors in order to propose useful injury prevention strategies.

The present thesis was therefore structured in four parts:

1. a general review of the existing literature,
2. a general description of the material and methods used in the experimentations,
3. a "personal contributions" part including articles whether those were published, accepted or submitted,
4. a general synthesis, where the main results, the practical applications and the main interests of these experiments were discussed. Some perspectives are also mentioned at the end of the document.

The general purpose of this work was to examine the foot-ankle injury prevention in adolescent athletes through three approaches: the running-related foot-ankle injury risk factors, the epidemiology of foot-ankle injuries and the implementation of prevention strategies (Figure 1.1).

The approach dealing with the running-related foot-ankle injury risk factors aimed to determine:

- How running-related fatigue may affect the force and the fatigability of the ankle plantar and dorsal flexor muscles, the foot plantar pressure distribution, the running mechanics and the medial arch stiffness of adolescent athletes,
- How the shoe wear (spikes or running shoes) may affect the plantar load distribution in adolescent athletes while sprinting,
- How running velocity may alter the plantar load distribution.

The approach related to the epidemiology of foot-ankle injuries aimed at collecting and analysing, over three seasons, the foot-ankle injuries sustained by highly-trained adolescent athletes of the Aspire Academy, Qatar, and their potential relations with the maturity status of these athletes.

The approach presenting the implementation of prevention strategies aimed to design and validate a convenient and reliable flexibility measurement method. The second purpose of this approach was to assess the effects of a neuromuscular electromyostimulation strengthening protocol on the foot medial arch stiffness and the effects of a combined foot-ankle strengthening training on the foot plantar pressure distribution and the performance of young athletes while sprinting.

The literature review and the general discussion of this thesis have been built using references articles found in “Pubmed” and/or “Sportdiscuss”. Some other resources have been necessary such as books or reports (e.g. the recommendations of the International Association of Athletics Federations or the retrospective study published in Luxembourg).

Introduction générale

De nos jours, l'engouement des enfants et des adolescents pour le sport est grandissant[1] et est encouragé par la communauté médicale afin de promouvoir la santé publique.[2]

Pratiquer des activités sportives au plus jeune âge présente effectivement de nombreux avantages mais peut également induire un risque accru de blessures. Il apparait donc logique de mettre en place des stratégies efficaces de prévention des blessures chez les jeunes sportifs en vue de protéger cette population vulnérable et de réduire les dépenses de santé. Depuis plus de vingt ans, l'approche dans le domaine de la prévention des blessures est devenue de plus en plus scientifique et de nombreux chercheurs ont exploré cette thématique.[3-15] Il est important de signaler qu'un nombre considérable de publications traitant de la prévention des blessures se sont concentrées exclusivement sur les pathologies traumatiques,[16-22] proposant des conseils de prévention lies à l'adaptation des règles de jeu et au port de protections notamment. Il fut néanmoins rapporte récemment que les pathologies micro traumatiques dites « de surmenage » représenteraient environ 50% de l'ensemble des blessures liées au sport chez les enfants.[15] Malgré ce taux élevé, les pathologies micro traumatiques et leur prévention sont très largement sous-estimées chez les jeunes sportifs dans la littérature scientifique, particulièrement si seul l'athlétisme est pris en compte. En 2005, Zemper[23] a mené une revue de littérature intitulée « Les blessures chez le jeune en athlétisme » et n'a pu rassembler que neuf études (prospectives ou rétrospectives) fournissant un taux de blessures ou, à défaut, donnant suffisamment d'informations pour calculer ce taux. Ces données, bien que limitées, ont toutefois révélé quelques résultats intéressants :

- La prépondérance des blessures touchant le complexe pied-cheville chez les jeunes athlètes.
- Le manque de considération pour les blessures liées à la croissance dans les études épidémiologiques existantes.
- Le manque de données disponibles à propos des relations potentielles entre la survenue de blessures et la maturation en athlétisme.

- Le manque de considération pour les facteurs de risque de blessures qui sont étroitement liés au « terrain » ou à l'entrainement (mais non mesurables dans le cabinet médical en début de saison lors de la visite d'aptitude), comme les effets de la fatigue, l'influence du type de chaussage ou l'allure de course à l'entrainement.

Comme il a déjà été démontré que plus de la moitié des blessures de surmenage pouvaient entre évitées avec des mesures simples, [15] il semble pertinent d'examiner certains facteurs de risque, souvent sous-estimés, en vue de proposer des stratégies de prévention adaptées.
La présente thèse fut donc structurée en quatre parties :

1. Une revue générale de la littérature existante.
2. Une description générale des matériels et méthodes utilisés au cours des expérimentations.
3. Une partie intitulée « contributions personnelles » regroupant les articles soutenant la thèse, que ceux-ci aient été publiés, acceptés ou soumis.
4. Une synthèse générale dans laquelle les principaux résultats, les applications pratiques et les enseignements majeurs de ces expérimentations ont été discutés.

Certaines perspectives et futurs projets ont également été évoqués en fin de document.

L'objectif principal de ce travail était d'examiner la prévention des blessures du pied et de la cheville chez les jeunes athlètes au travers de trois approches : les facteurs de risques de blessures au niveau du complexe pied-cheville qui sont liés à la course à pied, l'épidémiologie des blessures du pied et de la cheville chez les adolescents en athlétisme et enfin la mise en œuvre de stratégies de prévention (Figure 1.1).

L'approche examinant les facteurs de risques de blessures liés à la course à pied et intéressant le complexe pied-cheville avait pour but de déterminer :

- Comment la fatigue induite par la course à pied pouvait affecter la force et la fatigabilité des muscles fléchisseurs plantaires et dorsaux de la cheville, la répartition des pressions plantaires, la mécanique de la course et la raideur de l'arche médiale du pied chez les jeunes athlètes.

- Comment le chaussage (chaussures d'entrainement type « training » ou bien chaussures à pointes) pouvait affecter la répartition des pressions plantaires chez les jeunes athlètes en sprint.
- Comment l'allure de course pouvait influencer la répartition de pressions plantaires.

L'approche relative à l'épidémiologie des blessures du pied et de la cheville chez les adolescents en athlétisme avait pour but de rapporter et d'analyser sur trois saisons, les blessures du pied et de la cheville contractées par de jeunes athlètes de haut-niveau de l'Académie ASPIRE (Doha – Qatar) et leurs possibles relations avec le niveau de maturité de ces athlètes.

L'approche présentant la mise en œuvre des stratégies de prévention avait pour premier objectif de concevoir et de valider une méthode fiable et pratique de mesure de la souplesse. Le second objectif de cette approche était d'évaluer les effets d'un protocole de renforcement musculaire par électrostimulation sur la raideur de l'arche médiale du pied, puis les effets d'un programme combiné de renforcement du pied et de la cheville sur la répartition des pressions plantaires et la performance en sprint chez de jeunes athlètes.

La revue de littérature et la discussion générale de cette thèse ont été rédigées en utilisant des références d'articles trouvées dans « Pubmed » et/ou « Sportdiscus ». D'autres ressources furent parfois nécessaires comme certains ouvrages ou rapports (par exemple les recommandations de l'Association Internationale des Fédérations d'Athlétisme ou l'étude rétrospective publiée au Luxembourg).

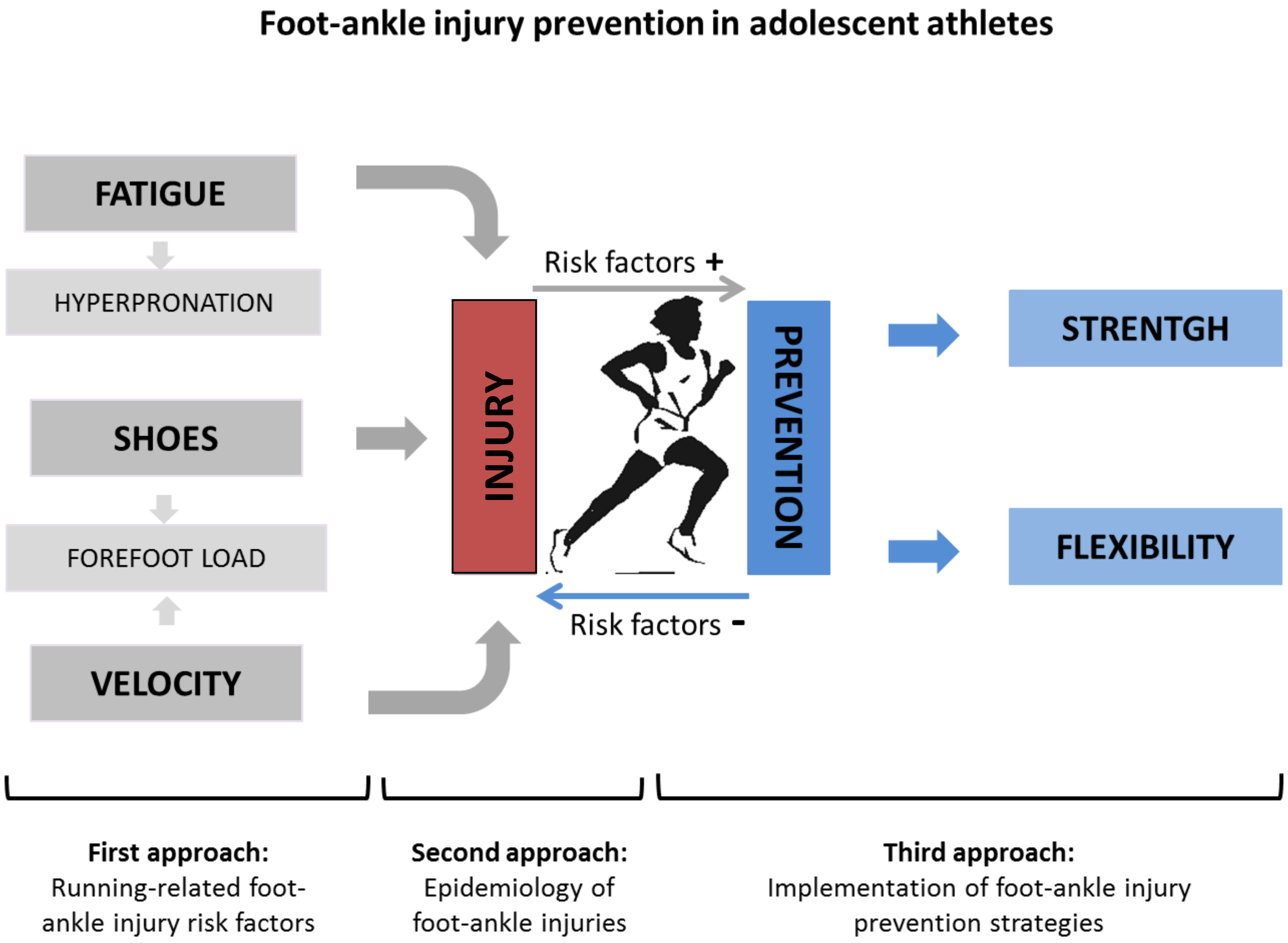


Figure 1.1: The three approaches for foot-ankle injury prevention in adolescent athletes.

Part 2. Review of the literature

2.1 Anatomy and movements of the foot-ankle region and overview of the running biomechanics

For clarity, the foot and the ankle regions will be described separately in the “anatomy”section. Following this, the two components will be considered together in most of the next chapters – as the “foot-ankle region”.

2.1.1 Anatomy of the foot

The foot contains 26 bones, 2 sesamoid bones, 33 joints, 19 muscles and 107 ligaments (Figure 2.1).

<u>The rearfoot (or hindfoot)</u>

The rearfoot consists of two bones: The talus and calcaneus. The tibia articulates with the dome of the talus and thereby transmits the forces of the leg to the ankle. The talus also articulates with the fibula. The talus articulates with the calcaneus, the main weight-bearing (and the largest) bone of the foot by way of the subtalar joint which has three surfaces of articulation with three separate facet joints. A great deal of the movement in the ankle occurs in this joint - the rest of the movement occurs at the tibialtalar joint.

<u>The midfoot</u>

The midfoot consists of five bones with numerous articular surfaces.

- navicular
- cuboid
- three cuneiform bones: medial, middle and lateral.

Distally, the fourth and fifth metatarsals articulate with the cuboid bone. The first, second and third metatarsals articulate with each of their respective cuneiform bones. Each of these has an individual joint capsule but all are wrapped in one big capsule to form the tarso-metatarsal joint (the “Lisfranc joint”).

Proximally, the talonavicular and calcaneocuboid joints, together form the combined articulation of the midtarsal joint (“Chopart joint”).

The forefoot

The forefoot consists of five metatarsals starting with the first to the fifth; and five toes, each of which consists of three bones (except for the big toe which consists of two). The bones of each toe are the proximal phalanx, the middle phalanx and the distal phalanx (except the big toe which has only proximal and distal). Between each of these bones is a joint which allows for the movement necessary to each section of the foot.
The joints in the forefoot are:

- MTP joint - metatarsal phalangeal joint - between the metatarsal and the proximal phalanx of the adjacent toe.

- PIP joint - proximal interphalangeal joint - between the proximal phalanx and the middle phalanx of each toe.

- DIP joint - distal interphalangeal joint - between the middle phalanx and the distal phalanx of each toe.

- The big (“great”) toe has only one joint between its two phalanges and therefore this joint is called the great (or “big”) toe interphalangeal joint.

- Metatarsal head is the end of the metatarsals, which articulates with the proximal phalanx of the adjacent toe.

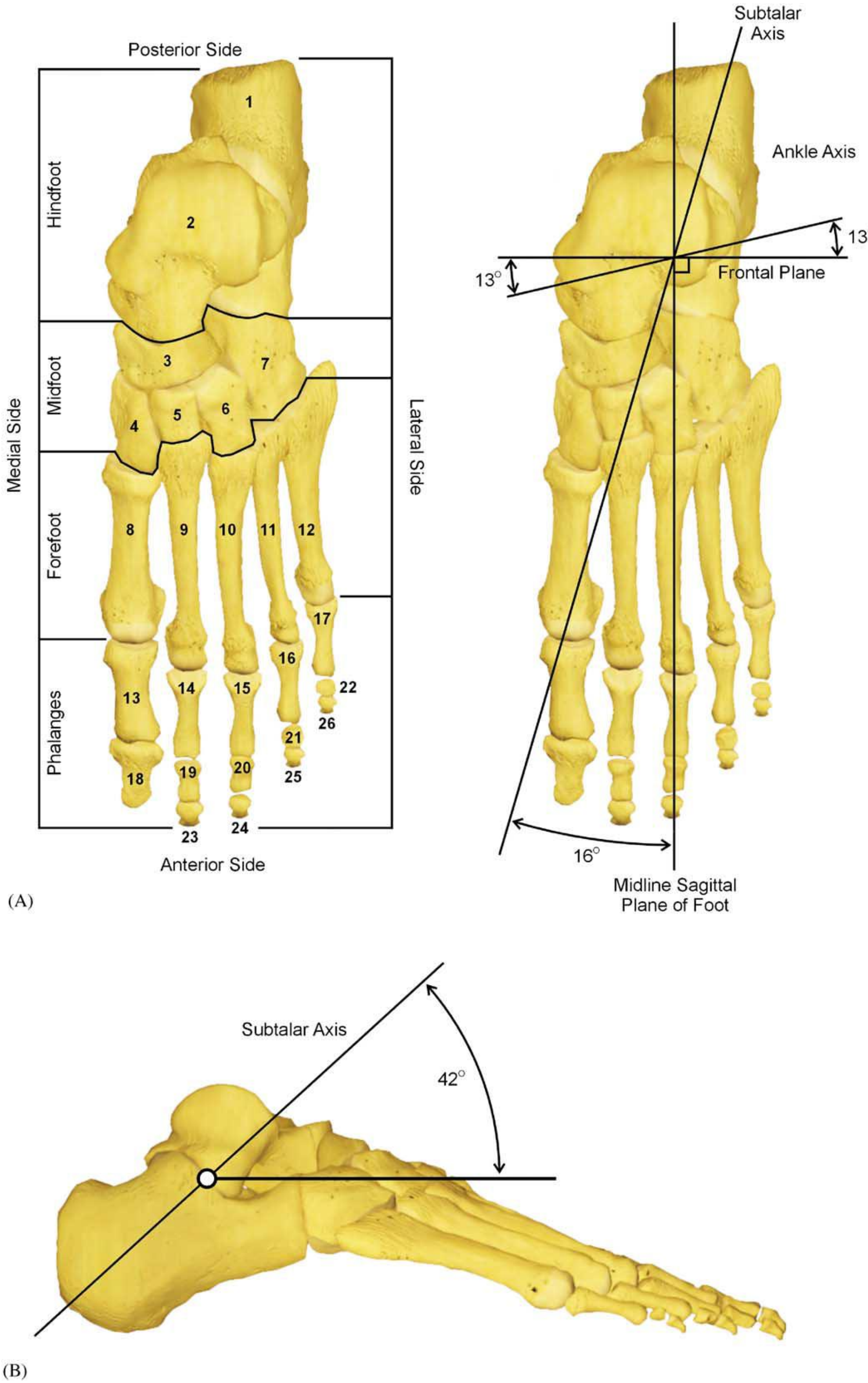
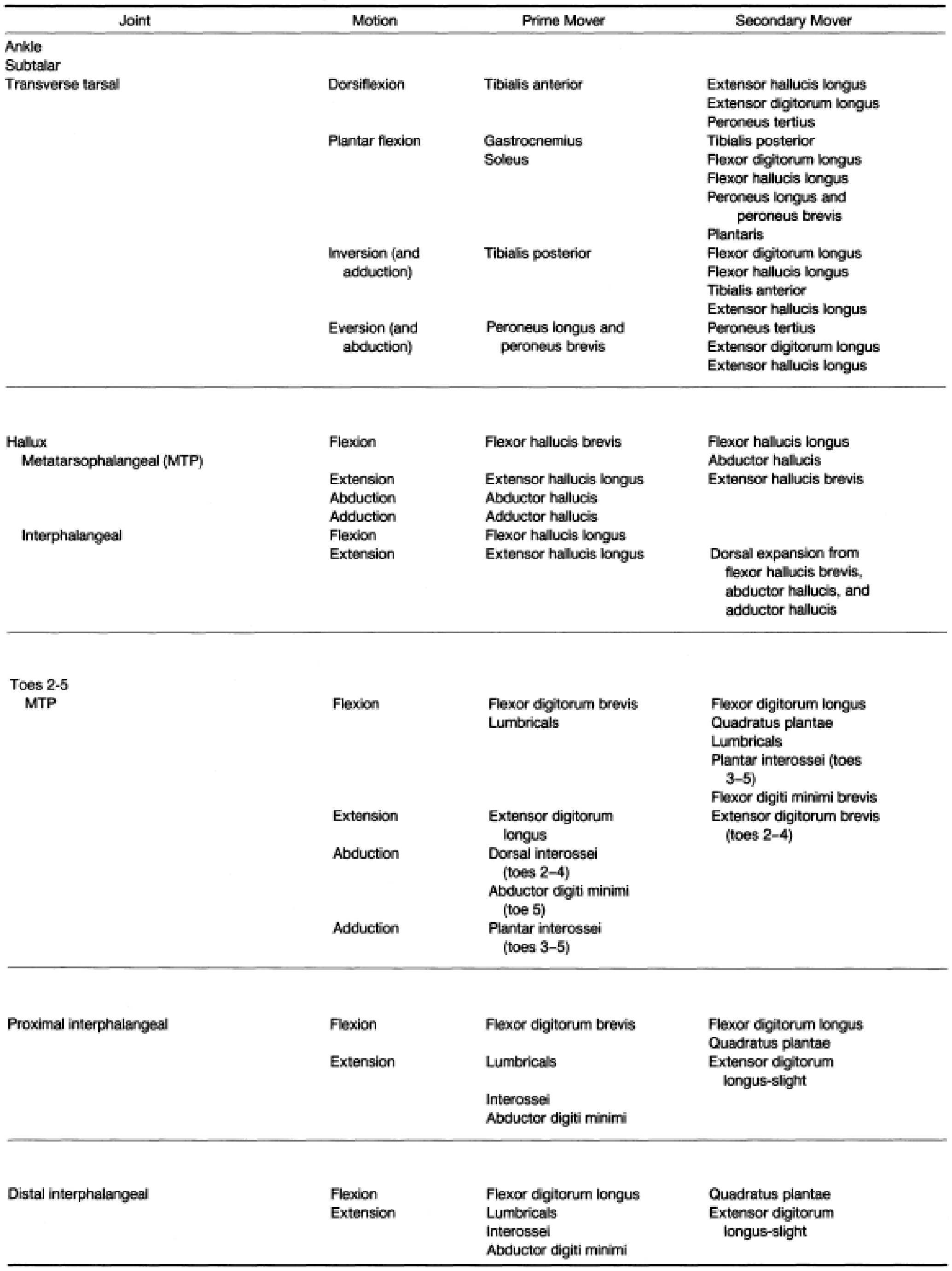


Figure 2.1: Foot structure: (A) four segments: rearfoot (1: calcaneaus, 2: talus),midfoot (3: navicular, 4: medial cuneiforme, 5: intermediate cuneiform, 6: lateral cuneiform, 7: cuboid), forefoot (8-12: first to fifth metatarsals), phalanges (13-26), (B) main ankle and subtalar axes.(Abboud, 2002)

The muscles of the foot aim to maintain the shape of the functional foot. Main actions of the foot and ankle muscles are displayed in Table 2.1.1. They can be divided into extrinsic muscles arising from the lower leg and intrinsic muscles arising within the foot itself. These can in turn be divided into dorsal and plantar groups.

Table 2.1.1: Ankle and foot joints and muscles performing associated motions. (Riegger, 1988)[307]



Joint	Motion	Prime Mover	Secondary Mover
Ankle Subtalar Transverse tarsal	Dorsiflexion	Tibialis anterior	Extensor hallucis longus Extensor digitorum longus Peroneus tertius
	Plantar flexion	Gastrocnemius Soleus	Tibialis posterior Flexor digitorum longus Flexor hallucis longus Peroneus longus and peroneus brevis Plantaris
	Inversion (and adduction)	Tibialis posterior	Flexor digitorum longus Flexor hallucis longus Tibialis anterior Extensor hallucis longus
	Eversion (and abduction)	Peroneus longus and peroneus brevis	Peroneus tertius Extensor digitorum longus Extensor hallucis longus
Hallux Metatarsophalangeal (MTP)	Flexion	Flexor hallucis brevis	Flexor hallucis longus Abductor hallucis
	Extension	Extensor hallucis longus	Extensor hallucis brevis
	Abduction	Abductor hallucis	
	Adduction	Adductor hallucis	
Interphalangeal	Flexion	Flexor hallucis longus	
	Extension	Extensor hallucis longus	Dorsal expansion from flexor hallucis brevis, abductor hallucis, and adductor hallucis
Toes 2-5 MTP	Flexion	Flexor digitorum brevis Lumbricals	Flexor digitorum longus Quadratus plantae Lumbricals Plantar interossei (toes 3–5) Flexor digiti minimi brevis
	Extension	Extensor digitorum longus	Extensor digitorum brevis (toes 2–4)
	Abduction	Dorsal interossei (toes 2–4) Abductor digiti minimi (toe 5)	
	Adduction	Plantar interossei (toes 3–5)	
Proximal interphalangeal	Flexion	Flexor digitorum brevis	Flexor digitorum longus Quadratus plantae
	Extension	Lumbricals Interossei Abductor digiti minimi	Extensor digitorum longus-slight
Distal interphalangeal	Flexion	Flexor digitorum longus	Quadratus plantae
	Extension	Lumbricals Interossei Abductor digiti minimi	Extensor digitorum longus-slight

Specificities regarding children and adolescents

As described by Scheuer et Black,[319] fusion of the centres of ossification starts in the distal phalanges, followed by the middle phalanges; i.e. between 11 and 12 years of age in females and between 14 and 15 years in males (Figure 2.1.2). Then the heads of metatarsals 2 to 5 fuse to the diaphyses at approximately 11-13 years in females and 14 and 16 years in males, while the proximal phalanges and the base of the first metatarsal are a little later at 13-15 years in females and 16-18 years in males.[319] Around 75% of all females will have completed foot epiphyseal fusion by 15 years of age and 75% of all males by 17 years of age.

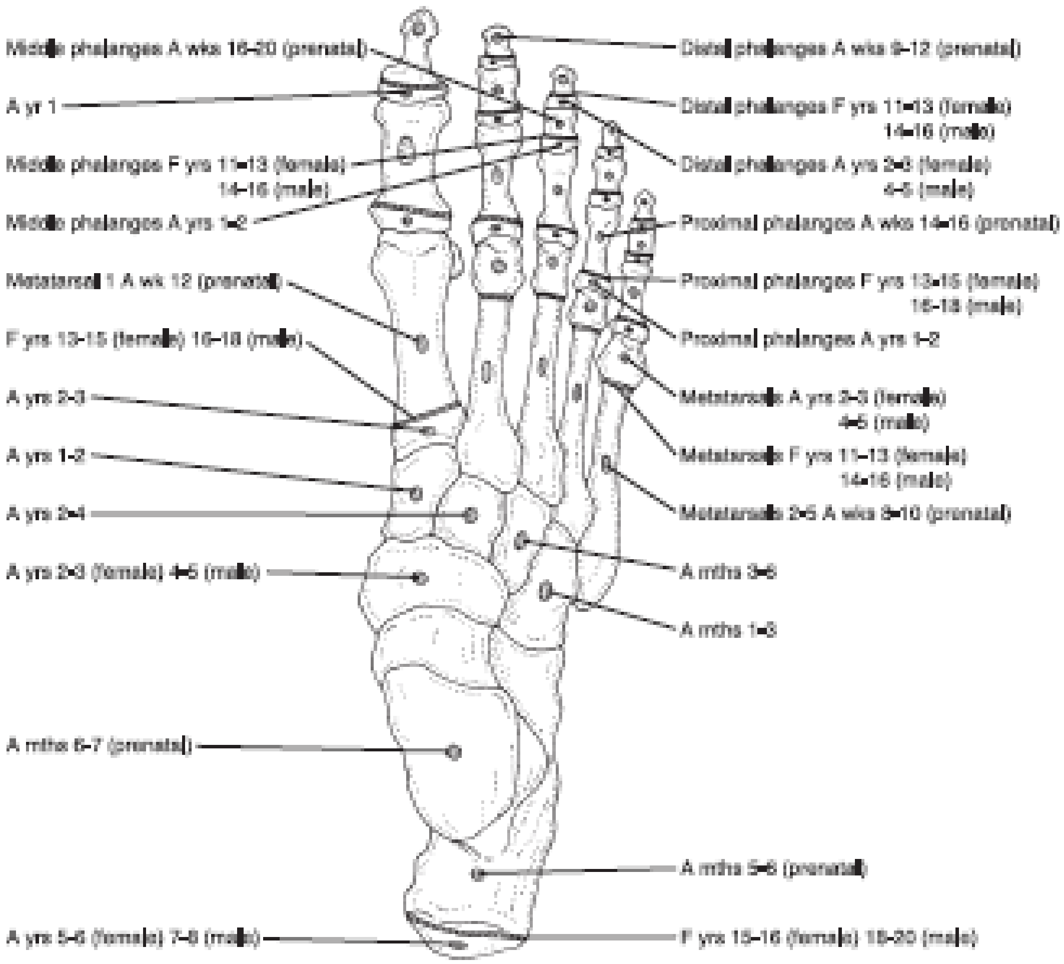


Figure 2.2: Appearance (A) and fusion (F) times of the ossification centres of the foot. (Scheuer and Black, 2004)

Compared to other body regions, the development of the foot is completed before other regions. Indeed, 95% of mature length is achieved by 12-13 years in females and 15 years in males. Mature length is generally achieved by 14 years in females and 16 years in males.This will protect the foot from future insults (whether they may be nutritional, mechanical, metabolic…), so that even if growth in stature is interrupted, there is little effect on foot size.[319]

Finally, there are several apophyses of interest at the foot level, in accordance with the subsequent growth-related injuries that may be sustained, e.g. the calcaneal epiphysis (Figure 2.3), the navicular tubercle, the base of the fifth metatarsal bone.This topic will be further detailed in the injury-related section.

Figure 2.3: Lateral x-ray view of young athlete with calcaneal apophysitis. (www.e-radiography.net, 2012)

2.1.2 Anatomy of the ankle

The ankle joint consists of a bony fit between the talus and the tibia proximally and medially and the talus and the fibula laterally (Figures 2.4 and 2.5). The dorsal and the medial surface of the talus contact reciprocally shaped areas of the tibia. The lateral aspect of the talus articulates with the articular surface of the distal fibula. This joint adds critical stability to the ankle joint.[307] Functionally, the ankle joint also includes the proximal tibiofibular joint, located at the posterior inferior and lateral region of the knee.

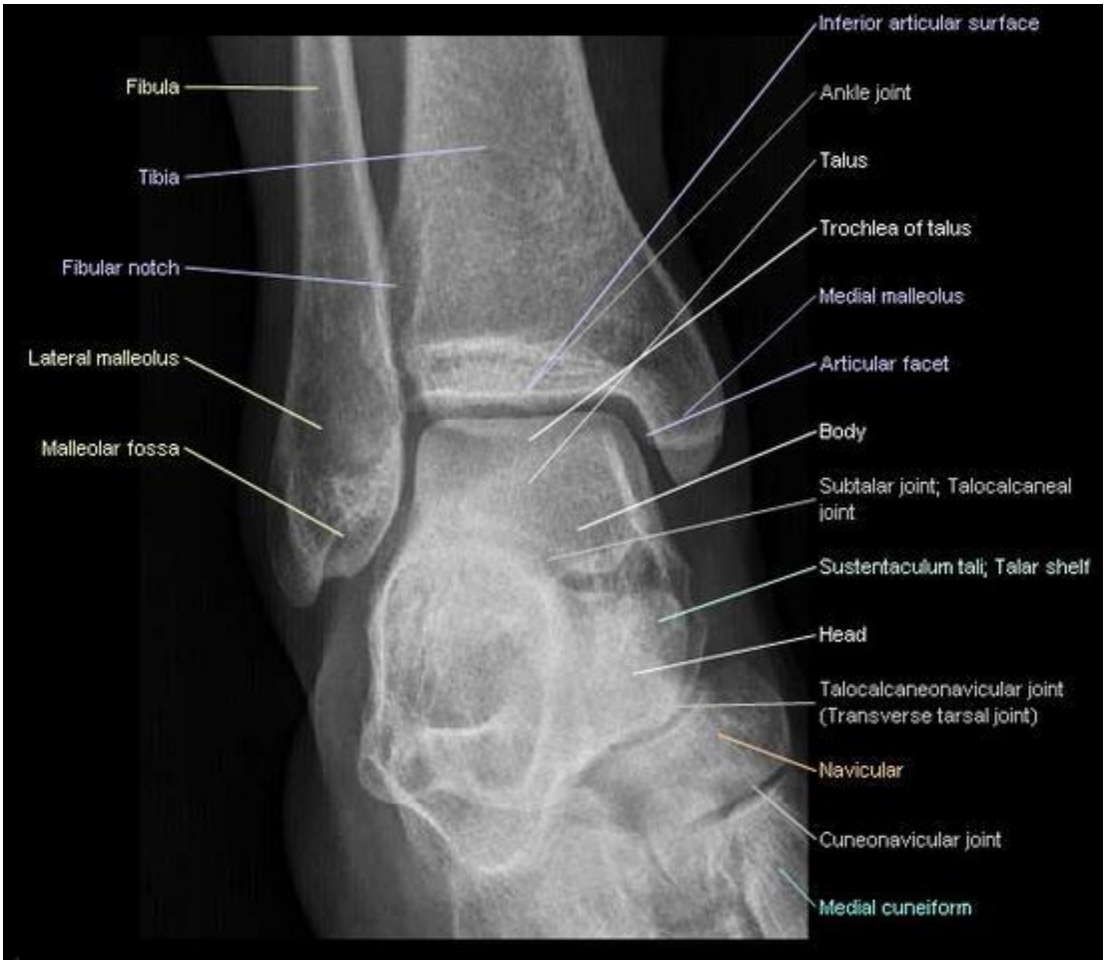


Figure 2.4: Radiographic antero-posterior view of the ankle joint. (www.e-radiography.net, 2012)

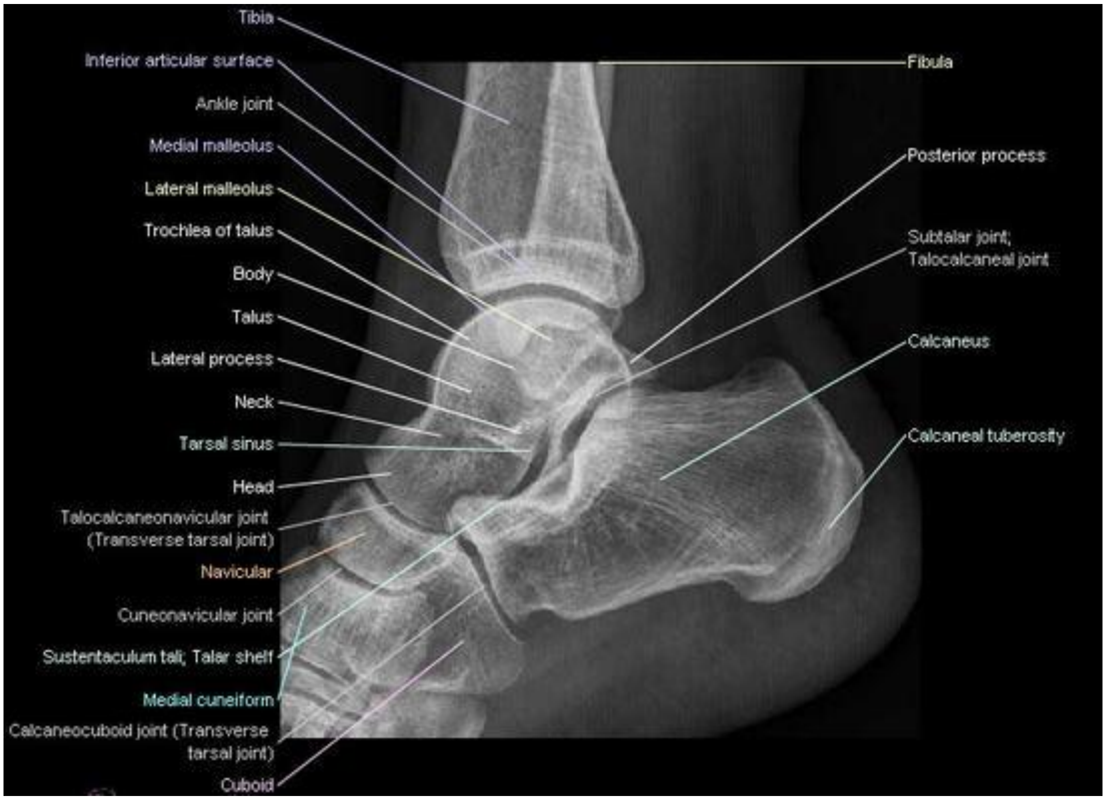


Figure 2.5: Radiographic medial view of the ankle joint. (www.e-radiography.net, 2012)

2.1.3 Foot and ankle movements

The joints of the foot are controlled by extrinsic and intrinsic muscles of the lower limb (Table 2.1.1). As with all joints, motion occurs by rotation about an axis in a plane of motion.[1] The three planes of motion in the foot are: sagittal plane (Sp), frontal plane (Fp) and transverse plane (Tp). The foot (or any part of the foot) is considereed as being:

- adducted when its distal aspect is angulated towards the midline of the body in the Tp,
- abducted when the distal aspect is angulated away from the midline (Figure 2.6 A),
- plantar flexed when the distal aspect is angulated downwards in the Sp away from the tibia,
- dorsiflexed when the distal aspect is angulated towards the tibia in the Sp (Figure 2.6 B),

- inverted when it is tilted in the Fp, with its plantar face towards the midline of the body,
- everted when its plantar faces away from the midline of the body (Figure 2.6 C),
- supinated when it is simultaneously adducted, inverted and plantar flexed,
- pronated when it is abducted, everted and dorsi flexed (Figure 2.6 D).

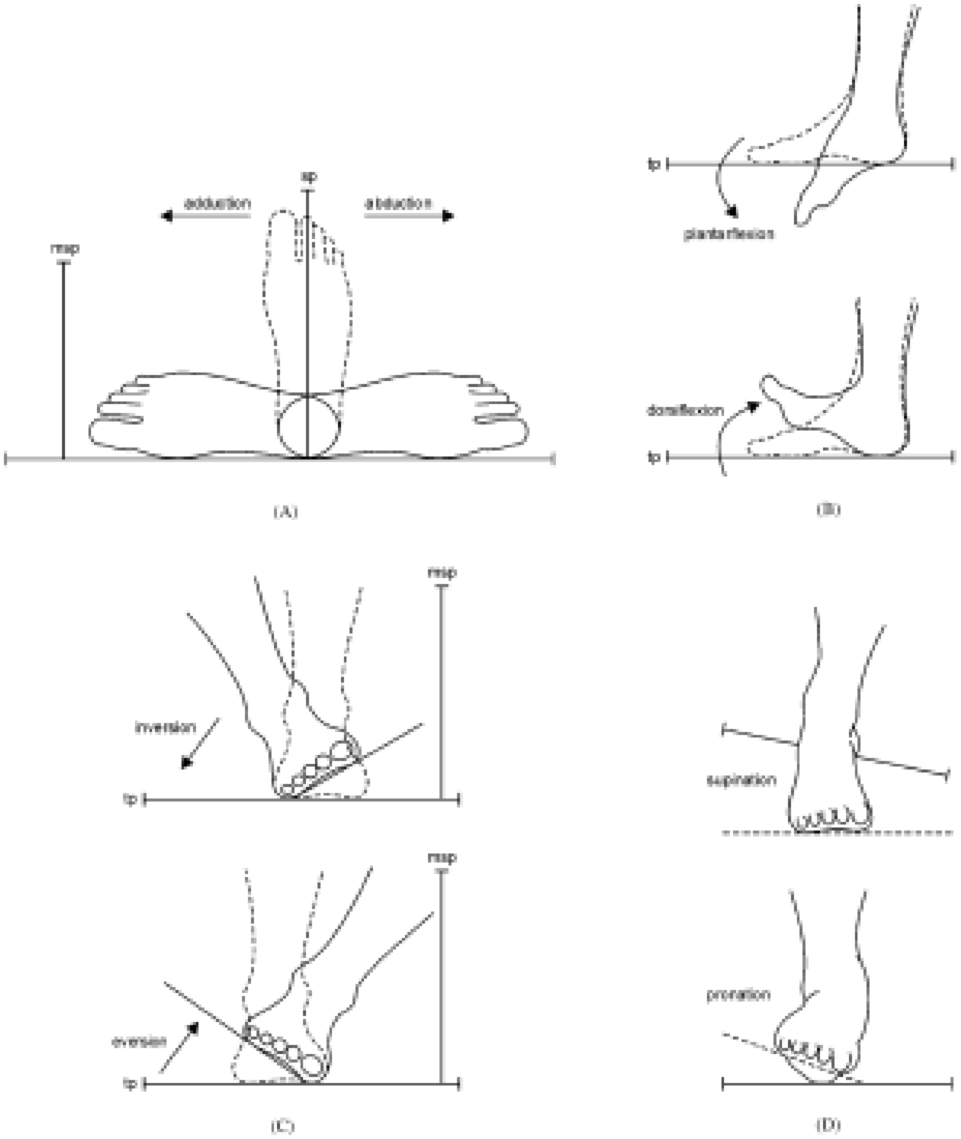


Figure 2.6: The movements of the foot-ankle region. (A) adduction-abduction, (B) plantar flexion-dorsi flexion, (C) inversion-eversion, (D) supination-pronation. (Abboud, 2002)

The subtalar joint encompasses the talocalcaneal joint and the talocalcaneal part of the talocalcaneonavicular joint. Its axis of motion passes through the subtalar joint obliquely and is called Henke's axis (Figure 2.1 B). The normal actions at this joint are supination and pronation. The talonavicular and the calcaneocuboid joints together form the midtarsal joint. This joint has two axes of motion, an oblique and a longitudinal axis, resulting in the supination/pronation movements of the forefoot. At the interfaces between the metatarsal bones and the lesser tarsus, only the joint between the first metatarsal bone and the medial cuneiform displays considerable movement. At the MTP joints, up to 90^o of extension is possible, but only a few degrees of flexion. All of the interphalangeal joints allow extension and flexion.

The ankle joint is the articulation between the distal part of the tibia and the body of the talus, allowing dorsiflexion and plantar flexion of the foot (Figure 2.6 B). The ankle joint also has slight movement in the Tp during plantar flexion, causing instability of the joint in this position.[1, 309]

All the definitions proposed above are the most frequently used. In the section "*Other factors altering the foot-ankle mechanics*", some additional details will be provided about nuances when describing foot-ankle movements, positions or types.

2.1.4 Anatomy and biomechanics of the medial longitudinal arch

The medial longitudinal arch (MLA) is made up of the calcaneus, the talus, the navicular, the cuneiforms and the first three metatarsal bones. These bony structures, specifically the stability of the navicular, serves as a primary support structure for the MLA.[113, 154] Numerous ligaments maintain the structural integrity of the MLA, including the spring ligament,[36, 72, 113, 154] the plantar fascia[58, 154, 164, 321] and the deltoid ligament.[154, 194, 195] The role of the muscles which support the arch is still unclear but recent research provided valuable contributions. Extrinsic muscles, including the *tibialis posterior*,[154, 192, 347] *tibialis anterior*,[154, 282, 321] *peroneous longus*[154, 282, 321, 347] and *peroneous tertius*[154, 282] muscles have all been shown to provide dynamic support of the MLA. Studies of the plantar intrinsic foot muscles such as the *abductor hallucis*, *flexor hallucis brevis*, *flexor digitorum brevis*, *abductor digiti minimi* and *dorsal interossei* muscles have shown electromyographic (EMG) activity during gait[154, 220] and also in static stance.[183] Dysfunction of any of these intrinsic muscles supporting the MLA appears to predispose individuals to hyperpronation.[111, 154]

From a biomechanical point of view, two models exist to describe the MLA: the beam model and the truss model.[277, 318] The beam model presents the MLA as a curved beam made up of interconnecting joints. Tensile forces are produced at the inferior surface of the beam and compressive forces are concentrated at the superior surface of the beam (Figure 2.7).[277]

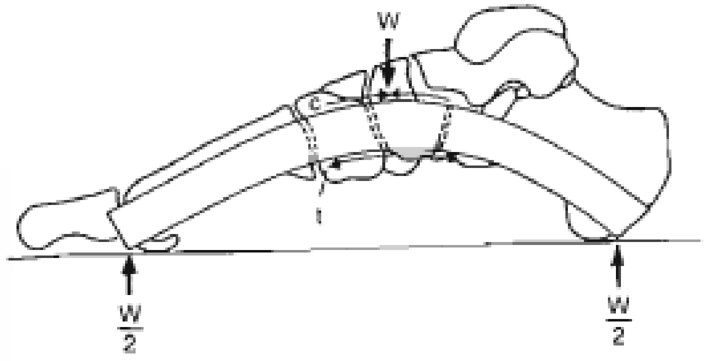


Figure 2.7: The beam model of the medial longitudinal arch. (Nordin and Frankel, 1989)

The truss model states that the MLA has a triangular structure with two struts connected at the base by a tie rod: the struts being under compression and the tie rod being under tension (Figure 2.8). Both models have validity and can be demonstrated clinically.[277]

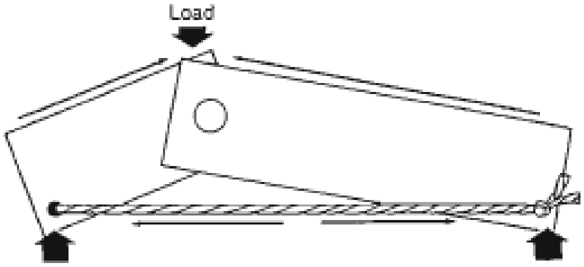


Figure 2.8: The truss model of the medial longitudinal arch. (Nordin and Frankel, 1989)

In the truss model, the hypotenuse (horizontal line) represents the plantar fascia (= the tie rod). The orientation of the vertical and ground reaction forces would cause a collapse of the truss; however, increased plantarfascia tension in response to these forces maintains the truss's integrity (Figure 2.9).

Figure 2.9: The truss model: X-ray view. The triangle shows the truss formed by the calcaneus, midtarsal joint and metatarsals. (Bolgla and Malone, 2005)[30]

As the plantar fascia originates on the medial tuberosity of the calcaneus and inserts on the metatarsophalangeal plantar plates and collateral ligaments as well as the hallucal sesamoids, dorsi flexion of the metatarsophalangeal joints places traction on the plantar fascia and causes elevation of the arch. This occurs through a mechanism known as the "windlass effect" (Figure 2.10).[307,277]

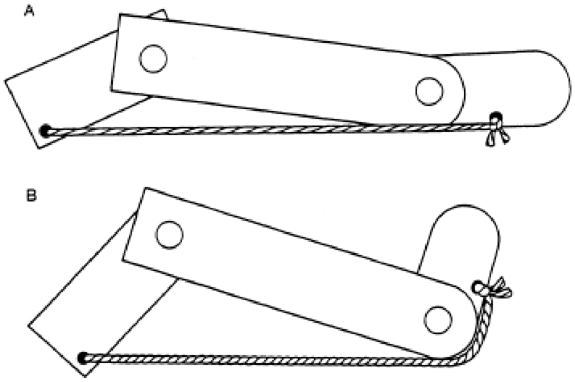


Figure 2.10: Functional role of the plantar aponeurosis. Raising arch of foot while locking the joints and making a single unit from multiple individual bones and joints. (Riegger, 1988)

While walking or running, during toe-off, the toes are dorsi flexed passively, the plantar fascia tightens and acts to shorten the distance between the heel and the metatarsal heads. This mechanism results in MLA elevation and increases the midfoot rigidity (Figure 2.11).[277,80]

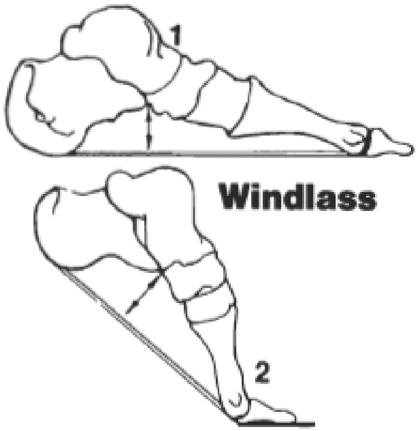


Figure 2.11: Windlass effect of toe dorsi flexion. 1, Plantar aponeurosis in a slack position with the foot in neutral. 2, increased tension of the plantar aponeurosis as the toes extend, raising the medial arch and facilitating supination. (Donatelli, 1985)

2.1.5 Overview of running biomechanics

2.1.5.1 Running kinematics

Kinematics are a description of movement without considering the forces that cause that movement. Running is a cyclic activity: one running stride follows another in a continuous pattern. A running stride is defined as being from touchdown of one foot to the next touchdown of the same foot, or from toe-off to toe-off. In opposition to walking gait, running can be divided into a support phase (i.e. one foot is on the ground) and a swing phase (i.e. both feet are off the ground).[277] The start of the stance phase is the touchdown (or foot strike) and its end is the toe-off (Figure 2.12). The swing phase (or aerial phase, or recovery phase) starts at toe-off and ends at touchdown; this stage aims to prepare the leg for the next touchdown. In slow running or jogging, the swing phase will be very short; it will then increase with running speed. The hip and knee patterns are displayed on the figure 2.12, but will not be detailed in the text.

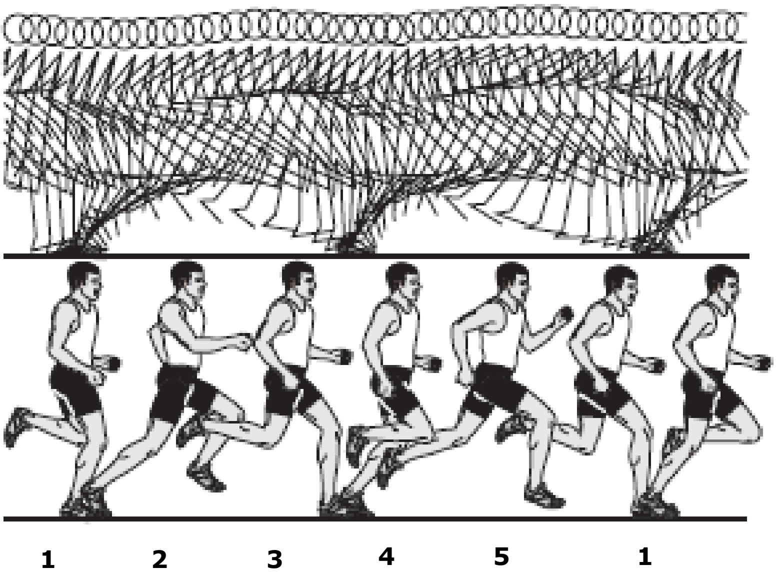


Figure 2.12: Kinogramm displaying the running stride. 1. Stance phase absorption. 2. Stance phase generation. 3. Swing phase generation. 4. Swing phase reversal. 5. Swing phase absorption. (Adapted from Leboeuf et al.[206], 2006 and Novacheck, 1998)

In order to assess gait patterns, especially at the ankle, a common procedure is to normalize strides both in time and magnitude.[74] The stride duration is usually normalized to a time percentage before averaging curves. The Procrustes method describes curve shape in a mathematical and statistical framework, independently of time and size factors. This method, which combines quantitative and visual features, was applied to the shape of the ankle cyclograms.[74] As shown in figure 2.13, cyclograms may provide accurate information about the relative position of ankles at a given time of the running cycle.

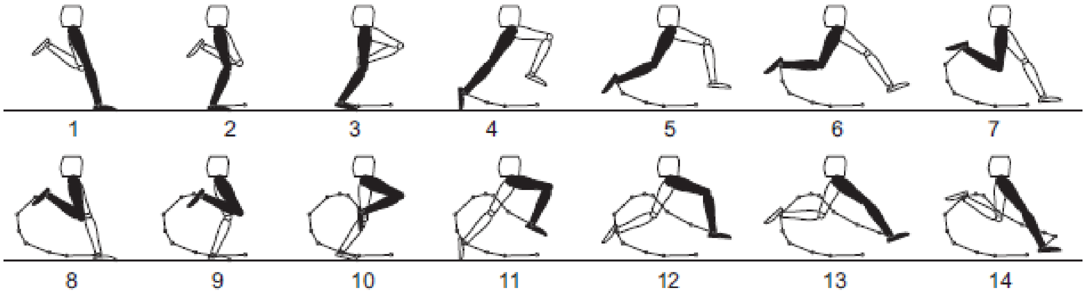


Figure 2.13: Reference frames of the running cycle corresponding to the 14 equivalent spatiotemporal landmarks on ankle cyclograms. (Decker et al., 2007)

From the frames of the running cycle, poulaine-shaped cyclogram can be built by a combination of significant kinematic features in the successive phases of the running cycle (Figure 2.14).[74]

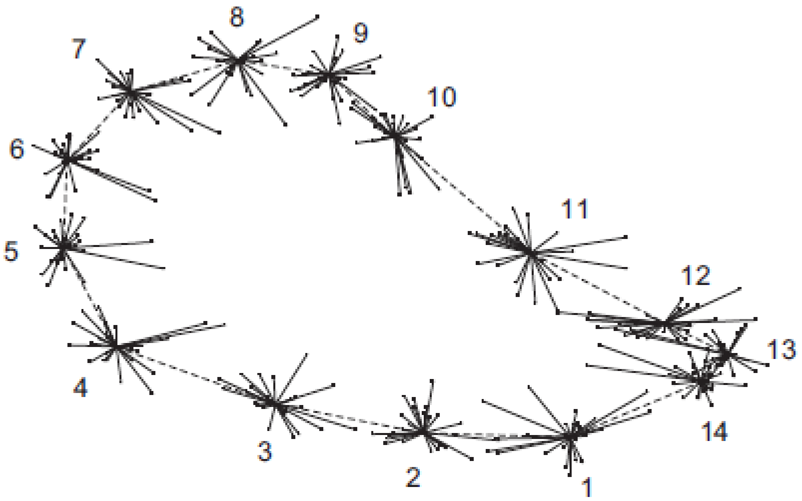


Figure 2.14: Procrustes superimposition of several ankle cyclograms in sagittal view. The numbers identify the ‘‘isodynamic’’ landmarks according to the scheme of Figure 2.13. (Decker et al., 2007)

The tracking of the ankle axis (or the foot centre of mass), during the lower limb cycles, constitutes then a poulaine-shape, which characterises the style or technique of each runner (e.g. anterior or posterior cycle, as shown in the figure 2.15)[74, 206]

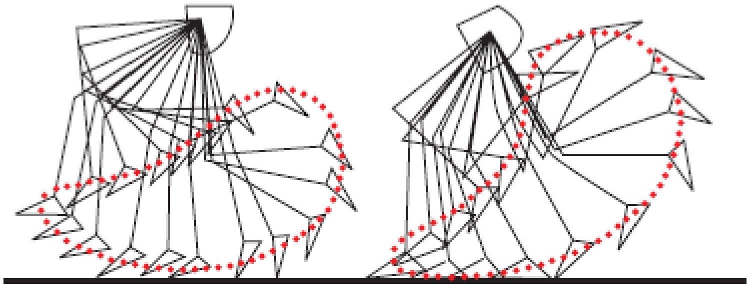


Figure 2.15: Representation of the poulaine-shaped cyclogram for anterior running cycle (left) and posterior running cycle (right). (Leboeuf et al., 2006)

While running, the ankle movements vary depending on whether the runner lands on the midfoot/forefoot or rear foot (Figure 2.16). The ankle is essentially in a neutral position at touchdown. For a rear foot striker, the ankle then plantar flexes slightly until the whole foot is on the ground; dorsiflexion then occurs until mid-stance. The ankle plantar flexes from mid-stance until toe-off, as the whole support leg lengthens. The ankle then dorsiflexes to a neutral position in the swing phase and plantar flexes slightly just before touchdown. For a midfoot striker, the initial plantar flexion does not occur, as by definition, almost the whole foot sole is in contact with the ground at touchdown.

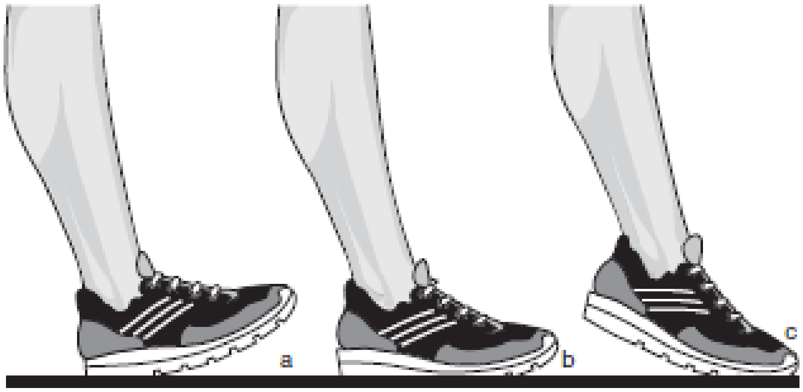


Figure 2.16: The three foot-strike patterns. a: heel-strike, b: midfoot strike, c: forefoot strike. (Leboeuf et al., 2006)

Regardless of the foot-strike patterns, the support phase while running is divided into two sub-phases: the breaking phase and the propulsion phase. These two consecutive sequences were well described by Novacheck in his review of the running biomechanics (Figure 2.17):[280] *"At initial contact, the hindfoot is typically inverted. Pronation then occurs as the limb is loaded during the absorption phase. Pronation 'unlocks' the transverse tarsal joint increasing the flexibility of the foot allowing it to function more effectively as a shock absorber. Peak pronation normally occurs at 40% of stance phase. The foot then begins to supinate and reaches a neutral position at 70% of stance. The transverse tarsal joint is then 'locked'. The generation* [propulsion] *phase has been reached and the foot is now more rigid allowing it to act more effectively as a lever for push-off."* It appears then of primary interest to accurately assess the foot plantar pressure distribution "in vivo" during running activities.

Pedobarography is today the preferred technology in this regard. The figure 2.18 displays how the foot sole can be divided in several regions or “mask” in order to explore the plantar pressure parameters under different anatomical sites of the foot.[133]

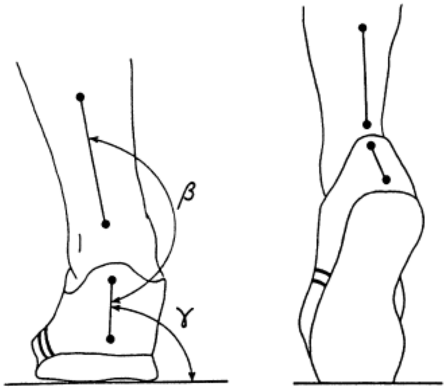


Figure 2.17: Successive pronation and supination of the foot-ankle at the absorption and propulsion phases of the running stance. (Nocacheck, 1998)

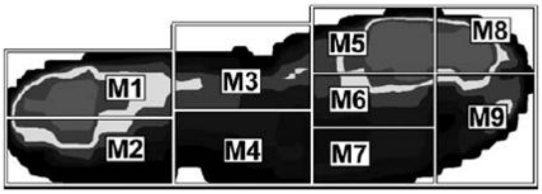


Figure 2.18: Regions of interest at the foot were masked to the size of the Pedar insole (Groupmask Evaluation, Novel GmbH, Munich, Germany). The regions consisted of the following: M1 medial heel, M2 lateral heel, M3 medial midfoot, M4 lateral midfoot, M5 medial forefoot, M6 central forefoot, M7 lateral forefoot, M8 hallux and M9 lesser toes. (Girard et al., 2007)

2.1.5.2 Ankle muscles activity during running cycle

It is shown in the literature that EMG is an accurate method for describing the activity of the main lower limb muscles during running (Figure 2.19 A).[147, 206, 280, 283, 305] This description of the muscles levels of activation encompasses several criteria:[147]

- The period of activation (to locate the muscular activity in the stride cycle),
- The duration of activation (in milliseconds or in % of the gait cycle),
- The level of activation (in % of the maximal activity level),
- The mode of contractions used during the different stride phases.

Using EMG, the bursts (i.e. the visible signal obtained for each muscle contraction) analysis allows assessing these criteria regarding the activity of each muscle during the running cycle. It has been stated that a variable number of bursts of activity occurred for the different lower limb muscles (Figure 2.19 B).[124, 147, 283, 305]

- One burst: *gastrocnemius, vastus lateralis* and *gluteus maximus*
- Two bursts: *rectus* and *biceps femoris*
- More than two bursts: *tibialis anterior*

Regarding the level of activation of ankle-related muscles especially, it is worth noting some differences with (Figure 2.19 B):[124, 147, 283, 305]

- *Gastrocnemius* being a highly activated muscle
- *Tibialis anterior* being a muscle activated during a long period

In general, muscles are more active in anticipation of and just after initial contact for the preparation for and the act of leaving the ground, as displayed in the figure 2.19.

Ankle plantar flexors:

The *gastrocnemius* and *soleus* have important eccentric and concentric functions in running gait. These posterior muscles therefore show a peak in activity during the midstance phase, as the centre of gravity passes over the ankle joint, as opposed to terminal stance as previously thought: they do not provide power for push off,[147, 221, 280, 305] this task being accomplished by the reuse of the elastic energy previously stored during the first part of the stance phase. All four calf muscles (*soleus, gastrocnemii medialis* and *lateralis* and *peroneus longus*) display an EMG single peak starting shortly before stance and ending before toe-off (Figure 2.19). Gazendam and Hof reported in addition that the amplitudes of *soleus* and *peroneus longus* activation remained about constant, while *gastrocnemii* increased some 40%, when increasing the running velocity from 2.25 to 4.5 m.s^{-1}.[124] It was stated that in higher running velocity, stance duration is so short that no additional activity is necessary.[124]

Ankle dorsi flexor (i.e. *tibialis anterior*):

Tibialis anterior activity extended almost over the complete swing phase, starting immediately after toe-off and ending lately after heel contact, with a minor activity during the first half of stance. When running at slow velocity, activity of the *tibialis anterior* starts at toe off and ends around foot contact, but there is no prominent peak. At higher jogging speeds *tibialis anterior* activity always corresponds with toe-off but it starts earlier. *Tibialis anterior* activity is needed to keep the foot in the neutral position against gravity and passive triceps surae elasticity. The final peak at terminal swing is a co-contraction against *triceps surae*.[124] In other words, the *anterior tibialis* dorsiflexes the ankle in concentric mode to (i) provide clearance in swing phase and to allow ground contact with the hindfoot initially for the rearfoot strikers and (ii) control the lowering of the forefoot to the ground during the first part of stance (eccentric).[280] The *tibialis anterior* muscle has a much different firing pattern than the other muscles in the leg. It has a higher sustained level of activity, which makes it more susceptible to fatigue and related injuries. These findings would suggest that endurance training of this muscle may prevent many of these problems.[305] This result will be discussed in the fatigue-related part of this work, as it may be an important injury risk factor at the foot-ankle and lower leg level.[62, 305]

Tibialis posterior and *peroneus brevis*:

Interestingly, it has been suggested that the *tibialis posterior* muscle had higher activity than the *peroneus brevis* muscle during the early stance phase due to its action for controlling the normal pronation forces during the early stance phase. Reber et al. proposed that increasing the strength of the *tibialis posterior* muscle may help to avoid excessive pronation early in the stance phase;[305] this assumption will be discussed in the injury prevention part of this thesis. Among the ankle-related muscles, the *peroneus brevis* muscle appears to display the most dramatic increase in activity when the running velocity increases. As proposed by Reber et al., the initial ground contact point tends to move forward on the plantar surface of the foot when the velocity increases.[305]. As a consequence, the subtalar joint is unloaded and diminishes its stabilizing task.

Without anatomic stability, the *peroneus muscles* are consequently forced to contract more forcefully to stabilize the foot.

In the end, all ankle-related muscles showed increased activity when the pace of running increased. As EMG data indicate that many of the commonly seen running injuries are related to muscle fatigue or overuse of improperly trained muscles,[305] there is a need to proposing programs in order to strengthen specific muscles for preventing injuries.

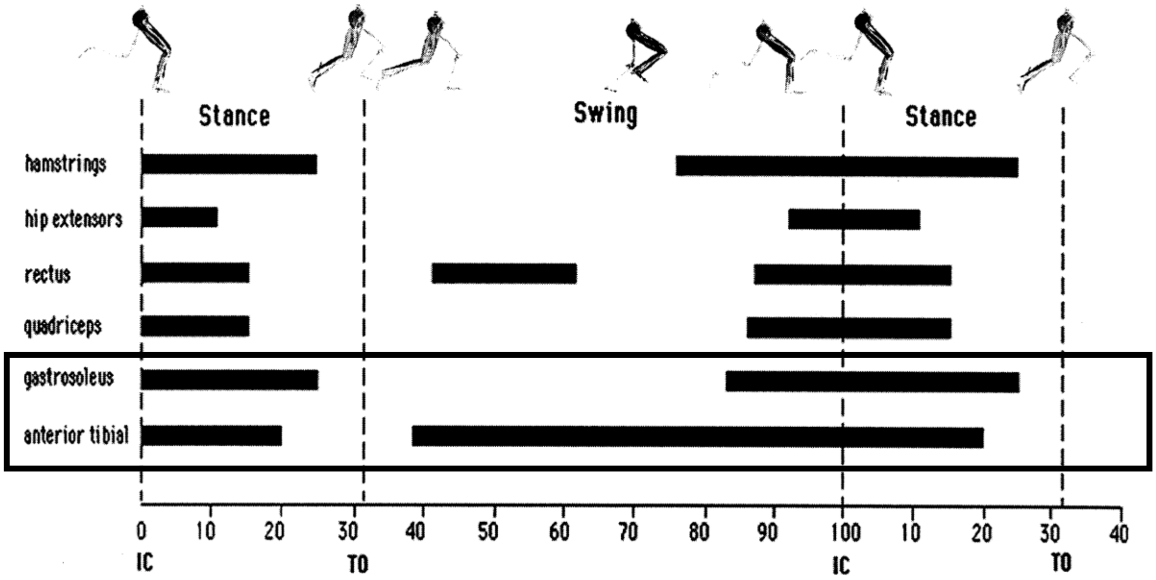


Figure 2.19 A: EMG activity of the main lower limb muscles during running. Ankle-related muscles are framed. Note the greater number of active muscle groups around the time of initial contact (IC) and the lack of muscle activation at the time of toe off (TO). (Adapted from Novacheck, 1998)

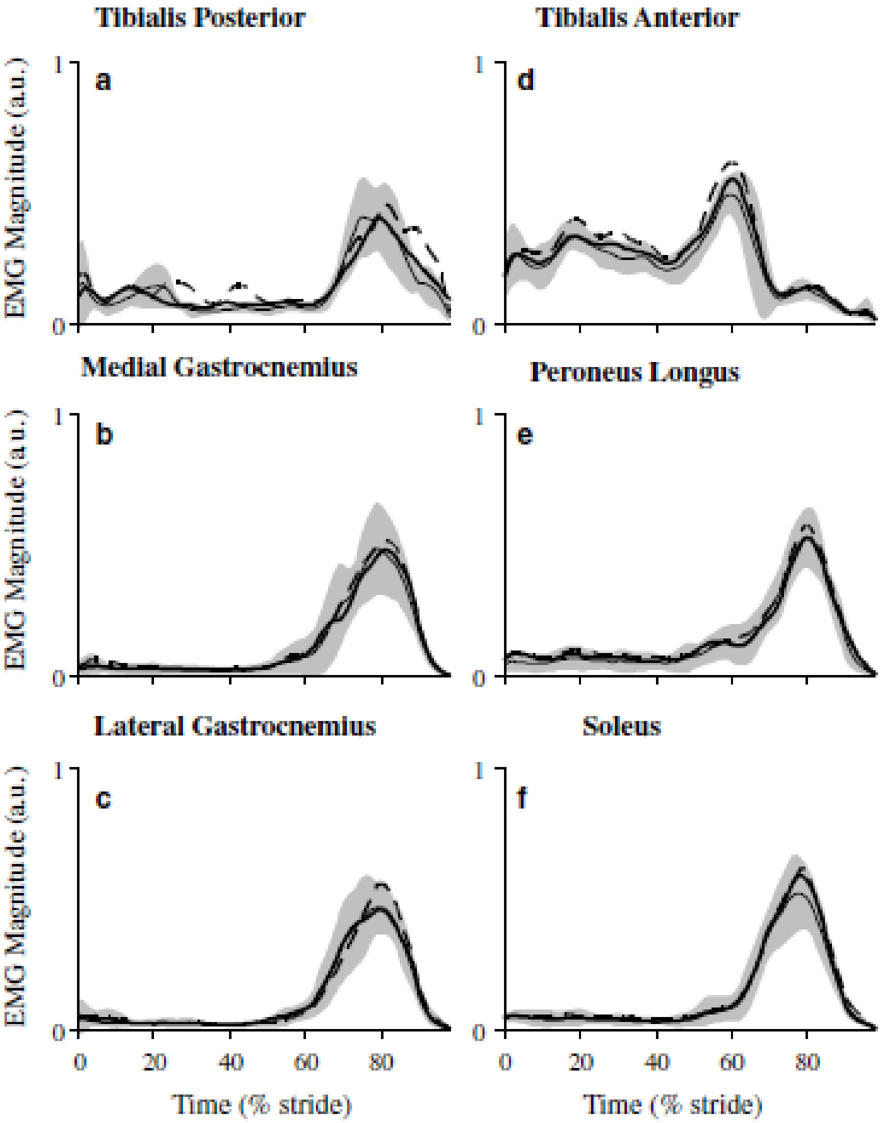


Figure 2.19 B: EMG activity of the main lower limb muscles during running while treadmill running at 13 km.h^{-1}. Time is reported from right toe off to the next right toe-off. Right heel contact occurs at around 65% of the stride. The shaded area represents ±1 SD from the neutral condition (The dashed line represents a varus condition, the thin line represents the neutral condition and the thick line represents a valgus condition). (Adapted from O'Connor, 2006).[283]

Take home message

- ✓ The foot is divided into three parts: rearfoot, midfoot and forefoot.
- ✓ The ankle contains the talocrural joint and superior and inferior tibiofibular joints.
- ✓ Children and adolescents anatomical specificities exist, such as immature epiphyses and apophyses.
- ✓ The foot-ankle movements are complex and combined in the three planes of motion.
- ✓ The medial longitudinal arch (MLA) is made up of the calcaneus, the talus, the navicular, the cuneiforms and the first three metatarsal bones.
- ✓ Numerous ligaments and extrinsic and intrinsic muscles maintain the structural integrity of the MLA.
- ✓ From a biomechanical point of view, two models exist to describe the MLA: the beam model and the truss model.
- ✓ A kinematic model is used for representing the ankle movements during the lower limb cycles: the poulaine-shape cyclogram.
- ✓ Three types of runners are described, in accordance with their touchdown technique: forefoot, midfoot and rearfoot strikers.
- ✓ The posterior lower leg muscles show a peak in EMG activity during the midstance phase, as the centre of gravity passes over the ankle joint.
- ✓ During the running cycle, the *tibialis anterior* muscle shows the highest rate of sustained activity of all lower leg muscles.

Ce qu’il faut retenir

- ✓ Le pied est divisé en trois parties : l’arrière-pied, le médio-pied et l’avant-pied.
- ✓ La cheville contient l’articulation talo-crurale et les articulations tibio-fibulaires supérieure et inférieure.
- ✓ Il existe des spécificités anatomiques chez les enfants et les adolescents comme les épiphyses et les apophyses immatures.
- ✓ Les mouvements de l’ensemble pied-cheville sont complexes et combinés dans les trois plans de l’espace.
- ✓ L’arche médiale du pied est formée par le calcaneus, le talus, le naviculaire, les cunéiformes et les trois premiers métatarsiens.
- ✓ De nombreux ligaments et muscles intrinsèques et extrinsèques assurent l’intégrité structurelle de l’arche médiale du pied.
- ✓ D’un point de vue biomécanique, deux modèles existent pour décrire la structure de l’arche médiale du pied : la poutre et la ferme.
- ✓ Un modèle cinématique est utilisé pour représenter les mouvements de la cheville pendant le cycle du membre inférieur en course à pied : la poulaine.
- ✓ Trois types de coureurs sont décrits en rapport avec leur technique d’attaque du sol : ceux qui attaquent avec l’avant-pied, ceux qui attaquent avec le médio-pied et ceux qui attaquent avec l’arrière-pied.
- ✓ Les muscles de la loge postérieure de la jambe ont un pic d’activité EMG pendant la phase intermédiaire de l’appui au sol, au moment où le centre de gravité passe à l’aplomb de l’articulation de la cheville.
- ✓ Pendant le cycle de course, c’est le muscle *tibialis anterior* qui montre le taux d’activité le plus élevé parmi tous les muscles de la jambe.

2.2 Factors altering the foot-ankle mechanics

2.2.1 The fatigue-related mechanisms at the foot-ankle region

2.2.1.1 Introduction about fatigue

Previously, fatigue was defined as an exercise-induced reduction in the ability of muscle to produce force or power whether or not the task can be sustained.[26, 328] More recently, Enoka and Duchateau[99] noticed that a critical feature of this definition was the distinction between muscle fatigue and the ability to continue the task. Accordingly, muscle fatigue is not the point of task failure or the moment when the muscles become exhausted. Rather, muscle fatigue is a decrease in the maximal force or power that the involved muscles can produce and it develops gradually soon after the onset of the sustained physical activity.[99] A common protocol used to quantify the development of muscle fatigue is to interrupt the fatiguing exercise with brief maximal contractions (voluntary or electrically evoked) to estimate the decline in the maximal force capacity.[24, 166, 247, 328] The amount of muscle fatigue caused by an intervention can be quantified as the decline in the maximal force or power measured immediately after the fatiguing contraction.[166, 207, 234, 343]

The location of fatigue, divided into peripheral and central levels, dictates the influence it will have on motor tasks (Figure 2.20).[186] Peripheral fatigue was defined as the decrease in force caused by a decrease in muscle fibre contractility induced predominantly by metabolic events within the muscle.[137] It reduces the muscles' ability to produce torque by impairing the system at and distal to the neuromuscular junction.[100] Specific mechanisms of peripheral fatigue include the reduction of the action potential propagation across the neuromuscular junction and along the muscle fibres,[323] as well as changes in the excitation–contraction coupling mechanisms within the muscle fibres.[26, 278] Central fatigue was defined as an exercise-induced decrease of muscle force caused by a reduction in recruitment.[137] This occurs proximal to the neuromuscular junction and progressively impairs the CNS's capacity to fully activate a muscle.[122] This impairment may be due to physiologic and/or cognitive factors (Figure 2.20). Identifying central and peripheral fatigue is complicated by the fact that (i) both supraspinal (i.e. changes in neurotransmitter concentrations and flux) and (ii) spinal (i.e. inhibition of motoneuron excitability) mechanisms are involved and that spinal fatigue involves both positive and negative influences of afferent sensory feedbacks (Figure 2.20).[137]

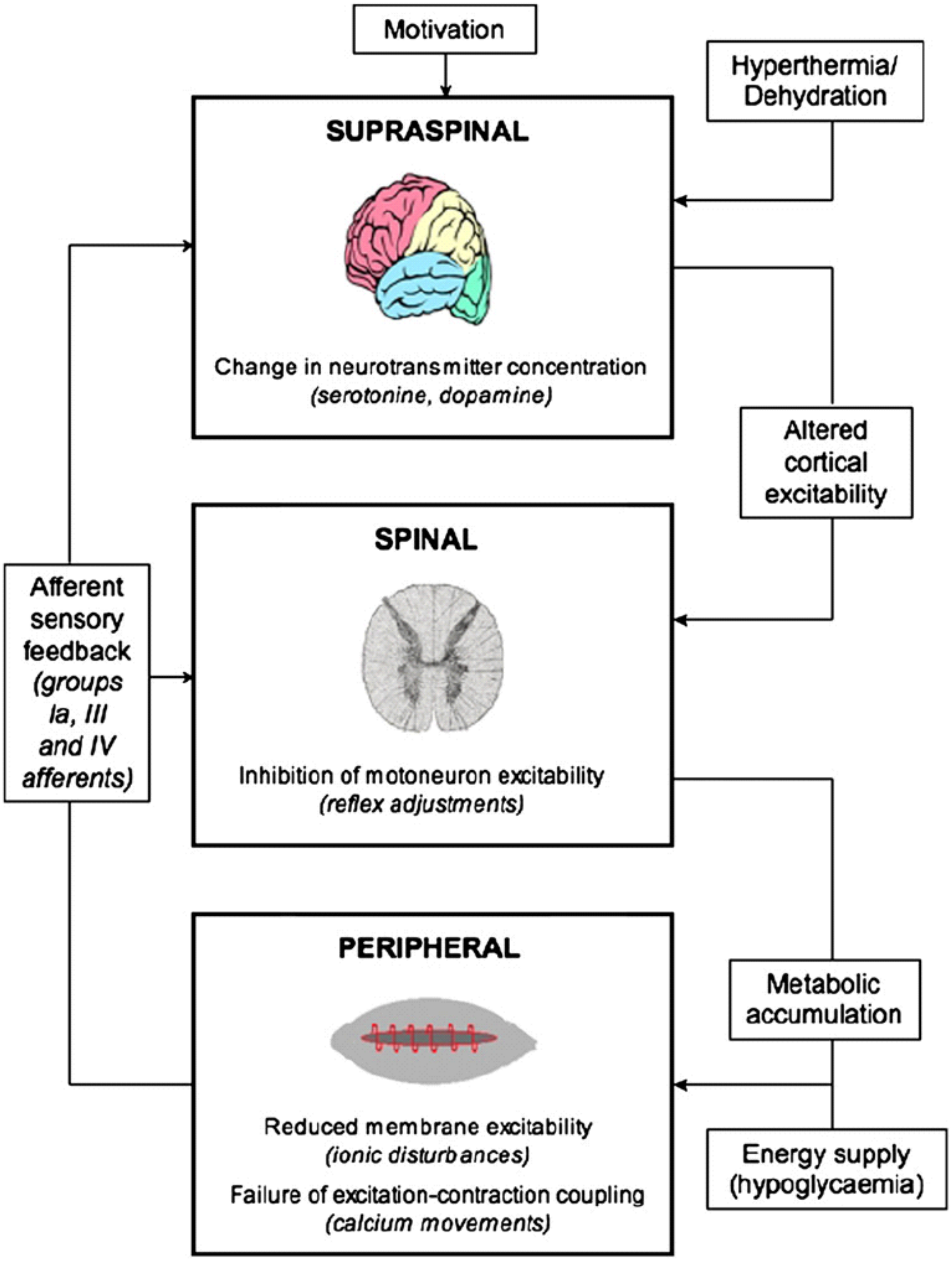


Figure 2.20: Potential mechanisms underlying neuromuscular fatigue. (Girard and Millet, 2008)

Fatigue has been hypothesized to alter biomechanical and neuromuscular function, i.e. reaction time,[146] movement coordination and motor control precision, muscle force generation capacity and running performance.[181, 256] It was hypothesized that changes resulting from localized muscle fatigue may lead to abnormal loading and in turn, altered stress distribution on musculoskeletal structures.[302] Localized muscle fatigue may also have negative effects on performance.[181]

After describing how running can induce fatigue, the following sections will describe the main effects of fatigue on plantar pressure distribution and running patterns.

2.2.1.2 Running exercise induces fatigue at foot-ankle muscle level

It is possible that fatigue at lower leg muscles is induced by running. It is of interest to review the literature for assessing if this potential running-induced fatigue may affect preferentially the ankle plantar-flexor (PF) or the ankle dorsi-flexor (DF). In addition, as a sizeable amount of training/competitions today include uphill and downhill running, it may be interesting to scrutinize whether the fatigue affects lower legs muscles in the same extent in these two conditions.

Running-related fatigue following repeated sprints, middle distance or long running trials has been described in the literature.[9, 48, 81, 134-136, 138, 139, 165, 254, 259-263, 301, 324] Numerous authors reported running-related fatigue to be predominant at the PF level (e.g. including sometimes the *flexor digitorum longus*),[320] due to the major activity of these muscles during the stance phase.[364] Weist et al.[364] showed that the EMG activity significantly decreased in the fatigued calf muscles following an exhausting running trial at 14.8 km.h^{-1} on treadmill in adults, which was in accordance with the results reported in previous investigations.[125, 256] The studies of Saldanha et al.,[317] Petersen et al.,[298] Perrey et al.[297] and Finni et al.[110] also displayed results emphasizing PF central and/or peripheral fatigue (using EMG or pre- and post MVC measurements) following repeated sprints, middle distance or long running trials. Kennedy et al.[185] provided some more detailed findings about the type of fatigue in the study examining the fatigue produced in the ankle plantar and dorsiflexors during intermittent, isometric contractions and monitoring the post-fatigue recovery process in 14 healthy adult subjects. The authors found that while PF and DF torque production capacity may be reduced to approximately the same level, the mechanisms responsible for this decrease may be quite different between these two muscle groups. The results suggested that central fatigue played an important role in the decreased PF torque production capacity, while peripheral fatigue appeared more important in DF. The resistance of the PF to peripheral fatigue may be due to the histological composition of the predominantly slow twitch *soleus* muscle[140, 173] and/or the fact that PF can produce force through three muscles: both *gastrocnemii* and the *soleus*. DF torque is primarily produced by the *tibialis anterior* which is normally responsible for rapid ankle contractions.[264] Interestingly, Kawakami et al.[180] assessed the fatigue responses of human triceps surae muscles during repetitive contractions in nine healthy men who completed 100 repetitive maximal isometric contractions of the ankle plantar flexor muscles in two knee positions of full extension and flexion at 90° (i.e. positions that varied the contribution of the *gastrocnemii*). Their findings confirmed that the decrease in plantar flexion torque during these repetitive maximal isometric contractions was attributable to both central and peripheral fatigue. Additionally, they reported a greater decrease in torque with the knee extended than flexed, which may suggest a greater fatigability of the *gastrocnemius* than the *soleus*. This suggestion will be of interest when choosing the best testing position in order to assess ankle plantar and dorsiflexor muscles fatigability.

Some studies revealed that running activity induced significant fatigue at the DF level,[305, 311] despite this muscle group being predominantly active at the swing phase. Ross et al. reported a 16.7% decrease in *tibialis anterior* MVC force following prolonged (>2 h) running. This may be explained by the long duration of the *tibialis anterior* contraction during the gait cycle (i.e. more than 20% of MVC during 85% of the gait cycle).[305] The consequences of the ankle dorsiflexors fatigue will be detailed in the section 2.2.1.4.3 of this chapter.

It appears clearly that fatigue in DF and PF can be induced by running, in accordance with duration, repetitions or intensity. Another factor to influence fatigue, especially in long distance running, is the terrain.[17, 40, 141, 257] It has been reported that downhill running induces more foot/ankle/lower leg injuries than level running,[40, 141, 257] due to the greater eccentric muscle contractions imposed in downhill running. Conversely, the major locomotor muscles shorten while exerting force during uphill running, in which they consume more energy, resulting in higher metabolic fatigue.[141] Some authors speculated that *tibialis anterior* tendonitis/tenosynovitis in runners might be due to an increase in training distance, particularly with uphill and downhill running.[17, 27, 101] However, to date, the effects of a long distance run including uphill and downhill running on PF and DF fatigue have not been reported.

2.2.1.3 Roll-over phase and landing strategy changes due to running-induced fatigue

As mentioned by Weist et al.,[364] with decreased activity during fatigue, the supinatory action of the triceps surae is diminished and the pronation may be more pronounced. This causes an increased loading under the medial midfoot and forefoot and will therefore affect the push-off force by modifying the roll-over process. This mechanism would also reduce the shock-absorbing effect of the muscles during the loading response with an increased loading of the second and third metatarsal and the medial midfoot. Similarly, Nagel et al.,[267] Karagounis et al.[179] and Willson et al.[370] found that the plantar load was transferred from the toes to the metatarsal heads (especially at the medial and central regions), probably due to local muscle fatigue after middle distance or long race, on a treadmill or over ground (Figures 2.21 and 2.22). Conversely, Girard et al.[135] did not report any substantial alterations in plantar pressure patterns following repeated sprinting on natural grass with players wearing soccer boots, although their leg-spring behavior (vertical stiffness) was altered.

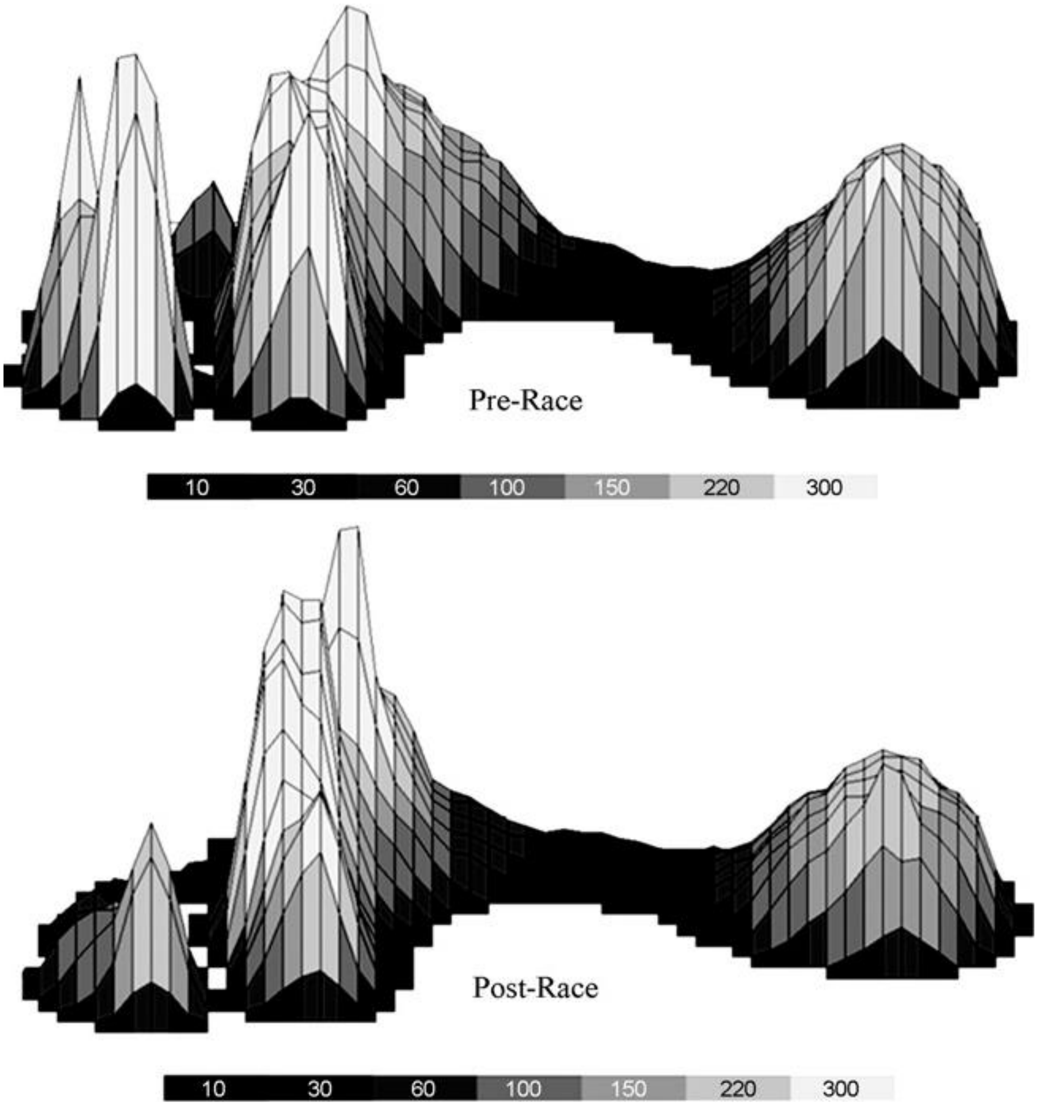


Figure 2.21: Plantar pressure distribution before and after marathon race. (Nagel and Rosenbaum, 2009)

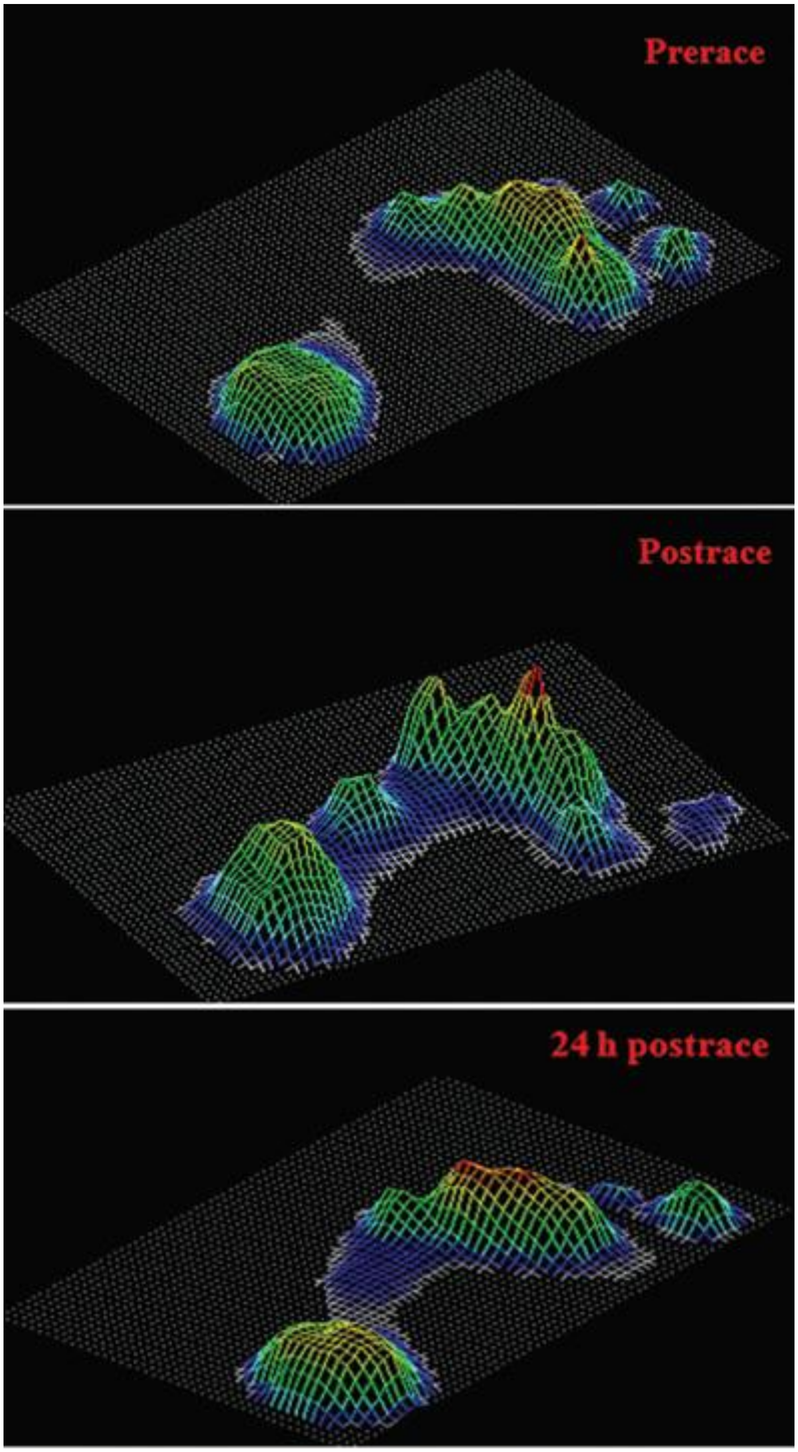


Figure 2.22: Plantar pressure distribution before and after an ultra-marathon race. (Karagounis et al., 2009)

Nigg reported that runners who tended to land with a midfoot landing strategy,[271] produce a dorsiflexion moment that is counteracted by the much larger and stronger muscles located at the posterior side of the lower leg. Therefore, overloading the anterior muscles of the lower leg can be avoided by changing the landing pattern from a heel-toe to midfoot landing strategy. In the aforementioned studies, where running-related fatigue induced a load increase under the medial midfoot and forefoot, it may be suggested that the subjects have engaged a midfoot landing strategy in an attempt to unload the fatigued anterior muscles of the lower leg from their previous heel-toe running pattern. A second theory was proposed by Willson and Kernozek[370] suggesting that increased first ray loading may be a characteristic of greater pronation. Muscles such as the *tibialis posterior*, that supinate the foot and support the medial longitudinal arch, may have fatigued to the point where they can no longer maintain the rigid bony architecture necessary for propulsion. Therefore, during the fatigued condition, the foot may fall into pronation to a greater degree or for a longer time during midstance.

Nevertheless, the midfoot and forefoot areas appear not to be the sole regions affected by fatigue-related changes.[350] A few researchers have studied the influence of excessive fatigue on rearfoot kinematics in a frontal plane. Bruggeman et al. observed extremely uncontrolled and unstable mid- and rearfoot motions at the finish phase of a marathon or 15 km run.[38] They demonstrated that maximal pronation and rate of pronation increase with fatigue. Bruggeman et al. observed an increase in rearfoot angle at touchdown and a later occurrence of its maximal value after subjects ran 15 min on a treadmill, indicating a significant disturbance in the planting action of the foot.[37] Then Vangheluwe and Madsen concluded that running to exhaustion resulted in significant increase of maximal heel eversion and its velocity and significant increase of subtalar pronation and its velocity.[350]

2.2.1.4 Protective and absorbing role of the muscles and effects of fatigue

2.2.1.4.1 Protective and absorbing role of the lower leg muscles during running

In 1997, i.e. 10 years after his first theory about the "*midfoot landing strategy*", Nigg proposed a new paradigm for impact forces during running.[272] Theoretical, experimental and epidemiological evidence on impact forces showed that one cannot conclude that impact forces are important factors in the development of chronic and/or acute running-related injuries.[272, 273] He proposed that impact forces are input signals that produce muscle tuning (i.e. the change of the coupling between the soft and rigid structures of the runners' leg) shortly before the next contact with the ground to minimize soft tissue vibration and/or reduce joint and tendon loading. The proposed muscle tuning reaction affects the muscle activation before ground contact, i.e. foot-ankle muscles would be pre-activated in order to create a damped mechanical system at foot-ground impact. This model supposed that pre-activation increased the stiffness of the muscle-tendon complex, which subsequently induced an impact force absorption and a decrease in vibrations, but also a higher load imposed to the Achilles tendon.[272, 273] This latter effect will be further discussed in the *injury prevention* section. This theory appeared to be similar to previous authors regarding the protective and absorbing role of the foot-ankle/lower leg muscles during the stance phase of running. These authors reported that muscles lower the bending stress on bone and attenuate the peak dynamic loads that can damage musculoskeletal tissues.[170, 302, 354] Similarly, Mizrahi et al.[256] reported that muscles have an important role in bone loading, particularly bending and since bone is weaker in tension than compression, it should be of interest to protect the bone from excessive tensile stresses. Mizrahi et al.[256] cited that co-contraction of antagonistic muscles help in providing that protection by (i) compound bending, i.e. converting non-axial bending stresses into more axial and compressive stresses, therefore lowering the tensile stresses on the bone; (ii) stabilizing the lower leg at heel strike while loading occurs; (iii) serving as effective shock absorbers to lessen the impact on the shank due to the initial heel contact.

2.2.1.4.2 How fatigue affects the bone protection role of the muscles

Recently, Friesenbichler et al.[115] investigated whether the damping and frequency of these soft-tissue vibrations were affected by fatigue (i.e. time into an exhaustive exercise). They reported that this vibration damping mechanism of muscle tuning may be reduced by fatigue.[115] These findings confirmed the assumptions of former authors: Verbitski et al. noted a clear association between fatigue and increased heel strike-induced shock waves.[354] Nyland et al.[281] suggested that one of the consequences of running while fatigued was a diminished stabilizing capacity of the runner's muscles. The loads (delivered to the feet) while running must be absorbed by inert internal tissues such as ligaments, cartilage and bones, instead of the muscles.[370] While assessing the fatigue-induced changes sustained during the stance phase by subjects running 30 min at their anaerobic thresholds, Mizrahi et al.[256] found that when imbalance between the muscles develops, it results in a decrease in the protection abilities of the muscles (Figure 2.23). They concluded that fatigue in long-distance running at a speed exceeding the anaerobic threshold involves a gradually increasing impact loading on the shank and an imbalance in contractions of the muscles acting on the shank. The combination of these two conditions may hamper the loading balance on the tibia since the bone becomes exposed to higher bending stresses.[256]

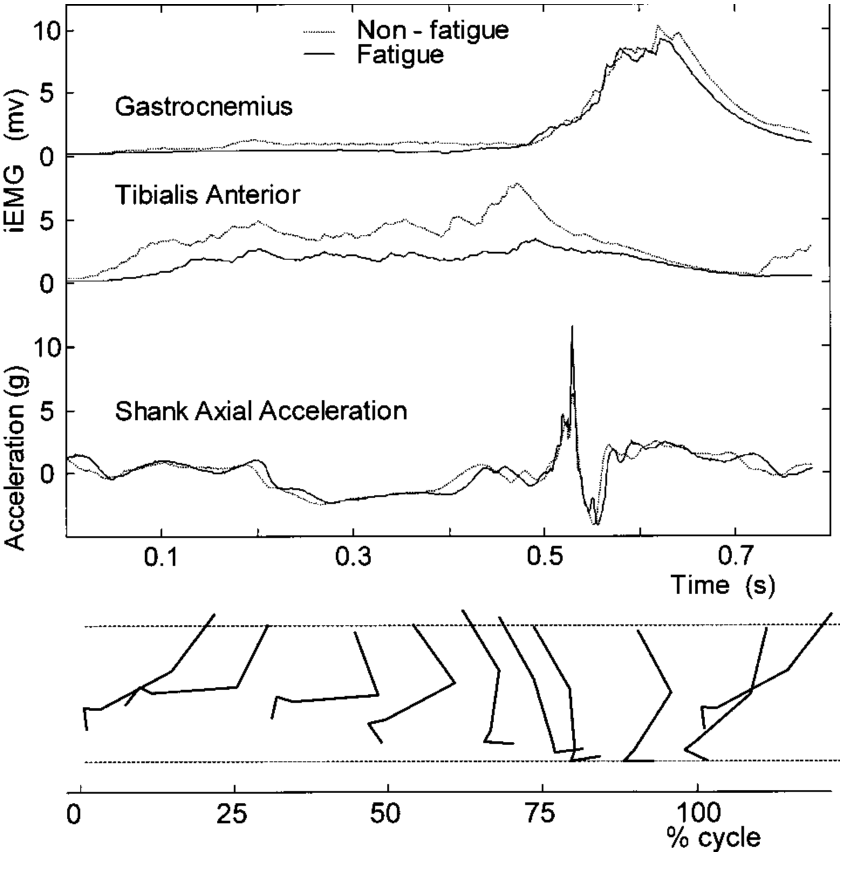


Figure 2.23: Typical one-stride output for one subject of the shank axial acceleration and of the iEMG of the *gastrocnemius* and the *tibialis anterior*. The 1st min (nonfatigue, dotted line) and in the 30th min (fatigue, solid line) of running. A stick diagram of the leg is presented in the lower part of the figure, showing one running cycle of the right leg. (Mizrahi et al., 2000)

2.2.1.4.3 Consequences of ankle dorsiflexors fatigue on heel-strike phase

Kellis and Liassou reported that exercise-induced ankle muscle fatigue caused a decrease in dorsiflexion angle during the initial impact phase, when testing 15 females running at 3.61 m.s^{-1} on a treadmill prior to and following an isokinetic ankle plantar flexion/dorsiflexion fatigue protocol.[181] These findings were in agreement with those of Christina et al.[62] who examined the changes in vertical ground reaction force and ankle joint motion during the first 50% of the stance phase following fatiguing exercise of the dorsiflexors in female runners. They found that the ankle angle at heel contact was 3.2° less dorsi-flexed when running under fatigue (Figure 2.24). A decreased dorsiflexion angle position results in a greater portion of the heel making contact with the ground at impact, enabling a greater attenuation of the impact force.[126, 181] This might also explain the increased loading rate, which was observed in this study after localized fatigue of the dorsiflexors.

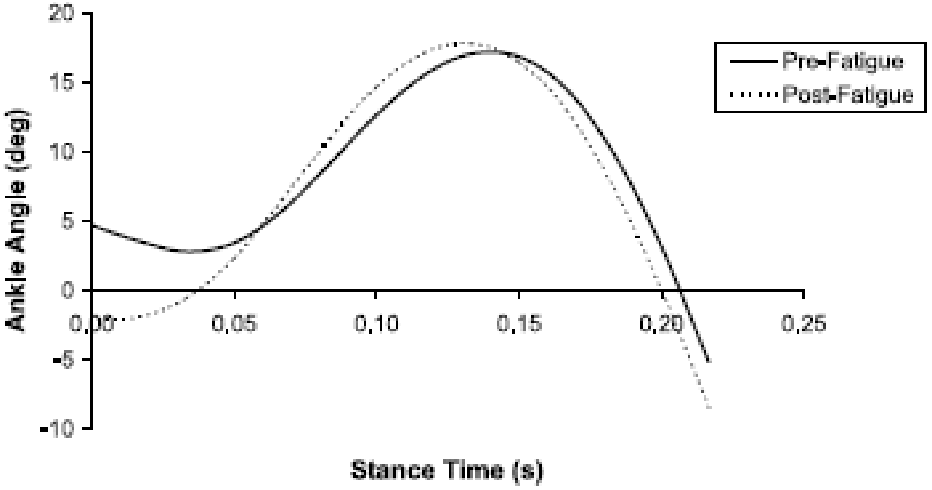


Figure 2.24: Ankle plantar/dorsiflexion curves prior to and following fatiguing exercise of the dorsiflexors. Each curve represents the average of five right steps. Dorsiflexion angles are positive; plantar flexion angles are negative (T=0 was defined to be 10% of body weight). (Christina et al., 2001)

These outcomes seem to confirm that increased shank acceleration during fatigued running is the result of muscular imbalances between the dorsiflexor and plantar flexor muscles,[256] as the activation of the plantar flexors remains constant, while the activation of the dorsiflexor muscles decreases when running to exhaustion.

2.2.1.5 Non running-induced foot muscles (medial arch intrinsic muscles) fatigue

Despite the role played by the medial arch intrinsic muscles, in foot stability,[154, 220, 270, 313] only a few authors examined the effects of fatigue of this muscle group.[111, 154] Headlee et al.[154] assessed the effect of foot intrinsic muscle fatigue on pronation, comparing pre- and post navicular drop measure, during static stance. They demonstrated that fatigue of the plantar intrinsic muscles of the foot leads to an increase in foot pronation in static stance. These results reinforced the findings of Fiolkowski et al.,[111] who ablated the activity of intrinsic muscles via a tibial nerve block in 10 healthy young adults and observed a large decrease in muscle activity, as measured by EMG of abductor hallucis which corresponded to a significant increase in navicular drop. They concluded that the intrinsic foot muscles provide substantial support to the MLA in static stance.[111] While their results provided evidence of the important contribution of the intrinsic foot muscles to controlling pronation during static stance, both authors suggested that further research would be necessary to address the impact of impaired plantar foot intrinsic muscle function on pronation during walking/running gait.[111, 154]

Take home message

- Muscle fatigue is a decrease in the maximal force or power that the muscles can produce and it develops gradually soon after the onset of the sustained physical activity.
- There are two types of fatigue: central and peripheral.
- Running-related fatigue affects ankle plantar and dorsiflexors, but it predominates at the plantar flexors.
- Running-related fatigue increases loading under the medial midfoot and forefoot modifies the rollover process.
- Fatigue-related imbalance between the lower leg muscles results in a decrease in the protection of the foot-ankle-lower leg bony structures.
- Even though the contribution of intrinsic foot muscles to controlling pronation during stance is well established, further researches are needed to address the role of these muscles while running.

Ce qu’il faut retenir

- La fatigue musculaire est une diminution de la force ou de la puissance maximale que le muscle peut produire et elle se développe progressivement aussitôt après le début de l’activité physique considérée.
- Il y a deux types de fatigue : centrale et périphérique.
- La fatigue liée à la course à pied touche les fléchisseurs plantaires et dorsaux de la cheville, mais elle prédomine au niveau des fléchisseurs plantaires.
- La fatigue liée à la course à pied augmente la charge sous la partie médiale du médio-pied et de l’avant-pied et modifie le processus de déroulé du pied.
- Le déséquilibre entre les différents muscles de la jambe qui est induit par la fatigue a pour effet de diminuer la protection des structures osseuses du pied, de la cheville et de la jambe.
- Même si la contribution des muscles intrinsèques du pied dans le contrôle de la pronation en station debout est désormais bien établie, d’autres recherches sont nécessaires afin d’établir le rôle de ces muscles pendant la course.

2.2.2 The relationships between fatigue and running patterns

Running-related fatigue has been hypothesized to alter biomechanical and neuromuscular function,[181] such as reaction time,[146] movement coordination and motor control precision,[331] muscle force generation capacity[203] and running performance.[256] Several mechanical variables encompass numerous neuromuscular and mechanical phenomena simultaneously characterizing the running system:[103, 261, 262] stride length and frequency, contact and flight time, vertical peak force, centre of mass displacement or stiffness. Examining these parameters is of primary interest when studying how fatigue may affect running mechanics during distance running. In order to better address this topic, it is proposed to remind the elastic mechanisms related to running activity in the following sections.

2.2.2.1 Elastic mechanisms related to running activity

In human running, elastic mechanisms are used in two main ways.[4] Firstly, elastic mechanisms reduce the work that the muscles have to do and then save energy (Figure 2.25). While running, an athlete rises and falls, gaining and losing gravitational potential energy. Also the centre of mass of the body accelerates and decelerates, so the athlete alternately gains and loses external kinetic energy. Almost 50 years ago, Cavagna et al.[52] showed that decreases of (potential and kinetic) energy were not all being affected by degradation of mechanical energy into heat. Some of the energy was stored as elastic strain energy and later recovered in elastic recoil (figure 2.25).[4] Secondly, elastic structures serve as suspension springs. The elastic properties of some lower limb structures (mainly the foot) moderate the impact force, similar to the springs of a car that prevent the driver getting a severe shock, when driving over a bump. This second mechanism prevents quick deceleration of the foot and potential anatomical damages during the landing phase of the stride. It is constituted by the heel fatty pad and compliant soles or shoes (Figure 2.25).[4] This second category of elastic structures is not detailed here as the present section aims to focus on energy store/recoil mechanisms.

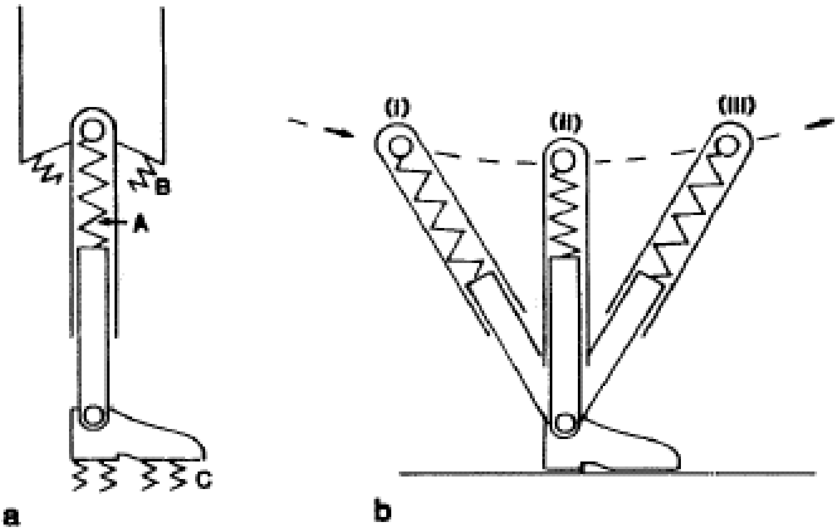


Figure 2.25: a, Diagram of a leg with springs. The springs would serve the functions described in the text (section 2.2.2.1); b, Diagram showing how spring A can store and return external energy during the stance phase of running. (Alexander, 1988)

Muscle and tendon are the materials usually considered as strain energy stores in running. Alexander and Bennet-Clark[5] pointed out that a muscle and its tendon transmit equal forces but that larger elastic strains were likely to occur in the tendon. In case of short muscle fibres and long tendon (e.g. triceps surae), the tendon would store most of the strain energy.[4] Three main storing/reusing "springs" energy have been described in the literature, at three lower limb levels, from proximal to distal (Figure 2.26).[4,187]

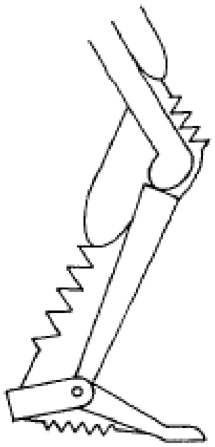


Figure 2.26: The structures that store strain energy during the stance phase. (Alexander, 1988)

The most proximal of these three springs represents the elastic properties of the quadriceps muscle and its tendons, as shown in Figure 2.26. The second spring represents the elastic properties of the triceps surae and its proximal and distal (i.e. Achilles) tendons. The most distal spring represents the structures of the medial arch of the foot (ligaments, plantar fascia, intrinsic muscles).[111, 154,4] As described by Alexander[4] and confirmed by Novacheck in a literature review about the biomechanics of running,[280] the total energy turnover in each stance phase of a 70 kg man is 100 J when running at 4.5 $m.s^{-1}$. It was estimated that 35 J is stored as strain energy in the heel cord and 17 J in the arch of the foot. The remaining energy must be stored in the stretch of the quadriceps and its tendons. These findings and those of Farley et al.[104, 106] established the idea that the body's system of muscle, tendon (and ligament) springs behaves like a single linear spring ("leg spring").

As our region of interest is the foot-ankle, it is worth examining the figure 2.27. The forces displayed in this figure load the foot in three-point bending, tending to flatten the medial longitudinal arch.[4] It is already known that severe flattening occurs at mid stance: the ankle joint is forced about 10 mm nearer the sole than in the unloaded foot.[4]

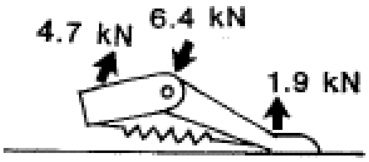


Figure 2.27: External forces that act on the foot at the stance phase. (Alexander, 1988)

Interestingly, while simulating the pattern of force that is applied in running, Ker et al. reported that the foot deformed and recoiled elastically with reasonably low energy dissipations; i.e. around 22% (Figure 2.28). Twenty-five years ago, these authors mentioned that the plantar aponeurosis, the long and short plantar ligaments and the spring ligament were responsible of the MLA stiffness. Nevertheless, in the last two decades, several authors also reported the role of the foot intrinsic (plantar) muscles in this process.[111, 121, 154, 183]

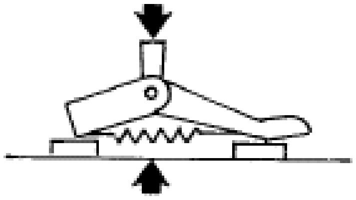


Figure 2.28: Experiment of Ker at al. regarding the medial longitudinal arch stiffness. (Alexander, 1988)

2.2.2.2 The spring mass model

From a mechanical point of view, running is a typical human movement where the musculo-tendinous structures of the lower limb alternately store and return elastic energy during the stretch-shortening cycle.[29, 197, 231, 232, 260] Accordingly, the lower limbs can be considered as springs loaded by the weight and inertia of the body mass. This paradigm refers to the "spring-mass model" (SMM) and has been used increasingly in recent years to describe the behavior (stiffness regulation) of the lower limb musculoskeletal system during bouncing and running gaits.[29, 70, 102-104, 108, 153, 231, 232, 260] In this model, the stiffness of the leg spring represents the average overall stiffness of the integrated musculoskeletal system during the ground-contact phase (referred to as ‘‘leg stiffness’’)[105] and is defined as the ratio of the maximal force to the maximum leg compression at the middle of the stance phase.[104, 260] Moreover, the vertical stiffness is used to model the vertical motion of the centre of mass (COM) during contact[104, 231, 260] and is defined as the ratio of the maximal force to the vertical downward maximal displacement of the COM as it reaches its lowest point, (i.e. at the middle of the stance phase). During running, the leg spring is compressed during the first half of the ground-contact phase and lengthens during the second half of the ground-contact phase (Figure 2.29).

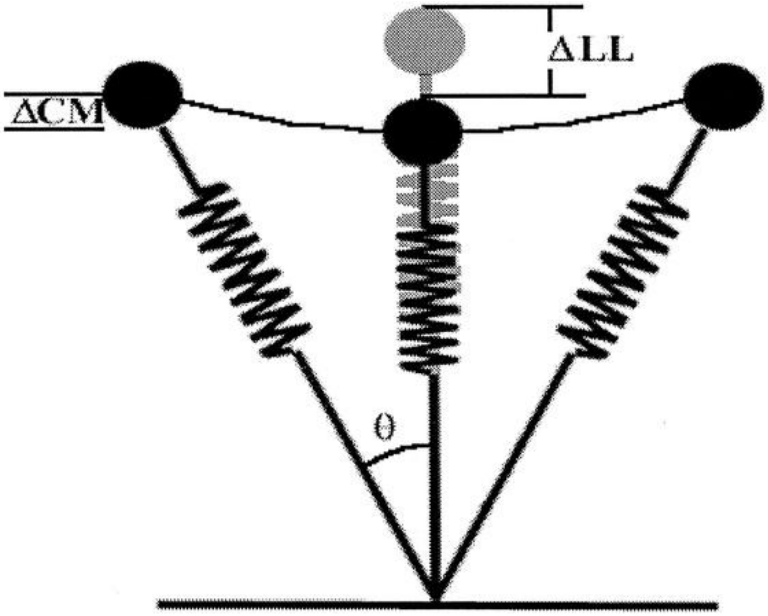


Figure 2.29: Representation of the leg (described as a spring) during the stance phase of running based on the spring mass model. In this figure, the system is moving from left to right. The middle figure depicts mid-stance and theta (θ) depicts half of the angle swept by the leg spring during stance; ΔCM is the displacement of the centre of mass and ΔLL is the change in leg length. (Dutto and Smith, 2002)

Since the article by McMahon in 1985,[230] more than 60 papers (including several reviews) have been published about the SMM behaviour while running. Some of these studies explored the effects of fatigue on SMM parameters.

2.2.2.3 Effects of fatigue on spring mass model parameters

Recently, the SMM has been used in several studies to describe the behaviour (stiffness regulation) of the lower limb musculoskeletal system during fatiguing runs.[9, 48, 81, 134-136, 138, 139, 165, 254, 259-263, 301, 324] Some of these studies examined the SMM parameters over ultra-long distance events and reported increased leg and or vertical stiffness and step frequency with fatigue,[252, 259, 263] while other authors examined sprint running repetitions and reported, conversely, a constant peak vertical force and constant or decreased stride frequency and vertical stiffness in fatigued state.[135, 138, 139, 260, 263] In the middle between these extremes, experimentations about SMM characteristics during middle-distance running bouts have showed contrasting results.[9, 48, 81, 165, 301, 324] On an athletic track, Slawinski et al. observed no changes in the main SMM parameters with fatigue, however their measures were obtained at slow velocities before and after a 2000 m maximal running test of approximately seven minutes duration.[324] However, as the running bout was self-paced in this experimentation, subjects could adapt individually their velocity and running patterns (especially at race end) and it may have influenced the outcomes. Other authors have explored SMM changes during constant pace exhaustive runs.[9, 48, 81, 165, 301] Two studies confirmed lower stride frequency and vertical stiffness while running under fatigue on a treadmill, but only at relatively low pace (i.e. ~80% of the velocity associated with the maximal oxygen uptake).[81, 165] To the best of our knowledge, only Rabita et al. examined the SMM parameters variations at severe constant velocity (i.e. 95% of the velocity associated with the maximal oxygen uptake).[301] Their results, obtained on a track, confirmed the peak vertical force decrease with fatigue reported by Slawinski et al.[324] but showed also higher stride frequency, constant vertical stiffness but decreased leg stiffness in fatigued state (Figure 2.30). These latter finding contradicts former studies and might be specific to high intensity running speed.

It is worth noting that no studies have looked at fatigue induced alterations of SMM characteristics in adolescent runners. Only Ratel et al. reported the influence of fatiguing intermittent running on stride parameters in adults and children.[303] They observed a lower decline in step frequency with fatigue in children, but the underlying mechanisms remained unclear.

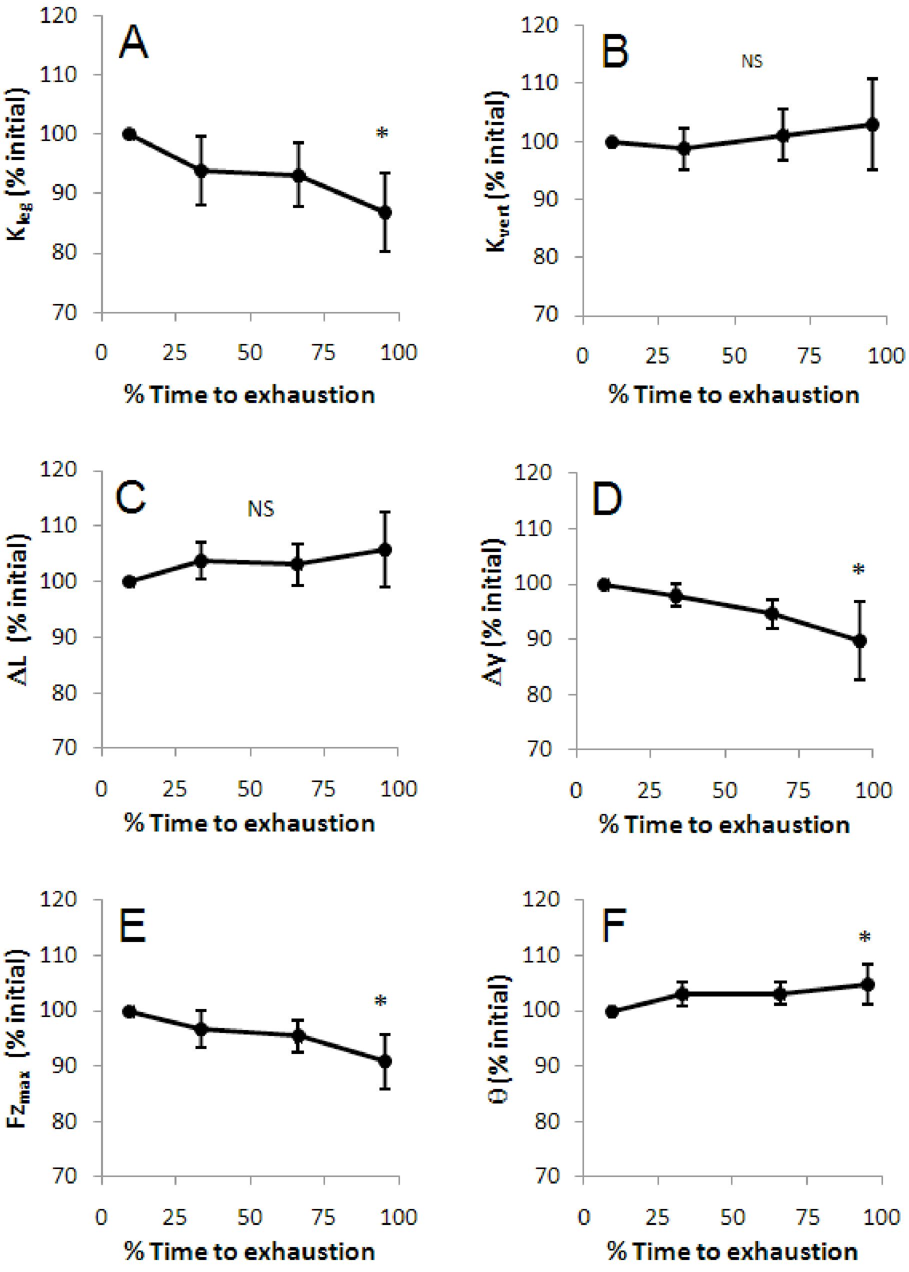


Figure 2.30: Evolution of the mean normalized value (+/- SD) in A) Leg stiffness (Kleg), B) vertical stiffness (Kvert), C) leg compression (ΔL), D) vertical displacement of the COM (Δy), E) vertical component of reaction force (F_{max}) and F) angle of spring leg at touch down (θ). Data were normalized and express as percent of the values obtained at 10% of the time to exhaustion. * denotes significant difference at $P<0.05$. (Rabita et al., 2011)

Take home message

- ✓ In human running, elastic mechanisms reduce the work that the muscles have to do and then save energy and they serve as suspension springs.
- ✓ The three main storing/reusing springs are the quadriceps muscle and its tendons, the triceps surae and its tendons and the structures of the medial arch of the foot.
- ✓ The lower limbs can be represented as springs loaded by the weight and inertia of the body mass. This is the “spring-mass model” (SMM) paradigm.
- ✓ The peak vertical force seems to decrease due to middle distance running – related fatigue, while higher stride frequency, constant vertical stiffness and decreased leg stiffness in fatigued state have been described.
- ✓ There is lack of data regarding the SMM parameters behaviour under fatigue in adolescent athletes.

Ce qu’il faut retenir

- ✓ En course à pied, les mécanismes élastiques réduisent le travail que les muscles doivent produire et économisent ainsi de l’énergie, en même temps qu’ils servent de ressorts de suspension.
- ✓ Les trois principaux ressorts de stockage/restitution sont le quadriceps et ses tendons, le triceps sural et ses tendons et l’arche médiale du pied.
- ✓ Les membres inferieurs peuvent être représentés comme des ressorts comprimés par le poids et l’inertie de la masse corporelle. Il s’agit du « modèle masse-ressort ».
- ✓ La force de réaction verticale du sol semble diminuer sous l’effet de la fatigue en course de demi-fond, tandis que la fréquence de la foulée augmente, la raideur verticale stagne et la raideur du membre inferieur diminue.
- ✓ Il existe une carence de données concernant les variations des paramètres du modèle masse-ressort chez les jeunes athlètes en état de fatigue.

2.2.3 Other factors altering the foot-ankle mechanics

2.2.3.1 Running velocity

While the biomechanical differences between running and sprinting activities have been widely described in the literature in the past two decades,[84, 221, 280, 338] much less data is available regarding the changes between slow and fast jogging or between jogging and running. Kernozek and Zimmer[188] or researchers from the Taiwan Sports Medicine University published results on this topic in the last decade. They[188] examined how in-shoe loading parameters change with increasing running speed from 2.24 $m.s^{-1}$ to 3.13 $m.s^{-1}$ in 17 college-age students and noted that peak pressure and maximum force increased significantly under the whole foot when the speed increased. Ho et al.[162] assessed the plantar pressure parameters of twenty young female adults while jogging at a slope of 0% with different speeds of 1.5, 2.0 and 2.5 $m{\cdot}s^{-1}$ (Figure 2.31). They reported that faster speeds resulted in higher peak plantar pressures and greater maximum force in all regions. Ho et al. also observed an increased foot inversion during stance phase when jogging faster and concluded that subjects increased their inversion of the ankle/foot at faster speed.[162] Nevertheless, these conclusions appear rather speculative and controversial as the differences in the relative load for each region between different running velocities was not measured in this study.

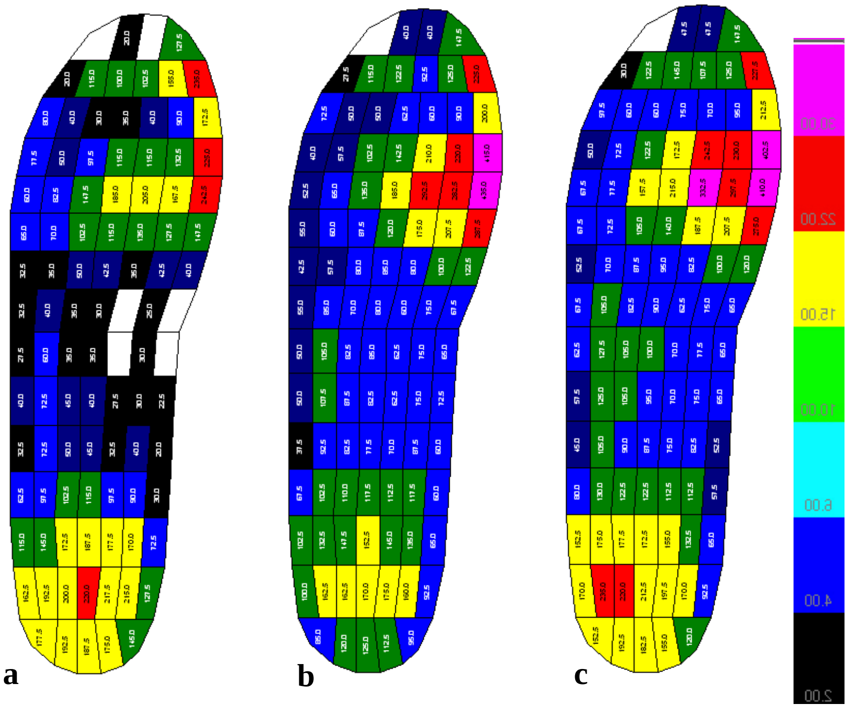


Figure 2.31: The peak pressure at same slope 0% with different speeds (a) 1.5 m·s^{-1} (b) 2.0 m·s^{-1} (c) 2.5 m·s^{-1} with the increasing speed, the value of the peak pressure would become larger. (Ho et al., 2010)

Guo et al. investigated the lower extremity movement in 18 young healthy males during jogging at different speeds (i.e. 2.0, 2.5, 3.0 and 3.5 m.s^{-1} at 0% slope) using a high speed three-dimensional motion analysis system.[145] Interestingly, they reported that the lower extremity changed its movement pattern in the transverse plane, with the foot showing increased toe-in at terminal stance when jogging faster. It was then suggested that increased foot toe-in is accompanied with subtalar inversion for providing a stable lever for push off as required for increasing propulsion force at increased speed.[145] This finding highlights the need for a rigid foot lever in order to ensure efficient force transmission at the push-off phase. This point will be discussed in section 2.3.11.4.2, as it appears that other strategies may achieve the same target but without increasing the foot toe-in.

2.2.3.2 Increased foot pronation or supination

2.2.3.2.1 Introduction and terminology

There is unfortunately a great deal of confusion in the terminology of foot movement and posture. It is important to distinguish between the description of a movement of a specific joint and the movement of the entire foot-ankle complex.[321] In order to understand properly the effects of pronation and supination processes on foot mechanics during running, it is critical to clarify some terms, even if there is no full consensus. Stovitz and Coetzee[340] stated that foot pronation and supination are active processes that must be distinguished from pes planus and pes cavus, which are terms describing a static foot.[340] Gray's anatomy uses the analogy of a "*twisted plate*" when applied to the forefoot.[360] If the heel is abducted on a level surface the mid- and forefoot "*untwist*" (supinate) and the medial longitudinal arch is lowered. A similar untwisting or supination occurs if the heel is perpendicular to the ground and the forefoot is placed on a wedge based medially (Figure 2.32). If the heel is adducted, the forefoot/midfoot is pronated to maintain a level forefoot and the medial longitudinal arch is raised. Pronation and supination of the forefoot in this manner occur around the axis of the least mobile second metatarsal. Pronation allows a downward rotation of the medial border of the foot and hallux towards the ground. Supination brings the lateral border into more direct plantigrade contact.[321]

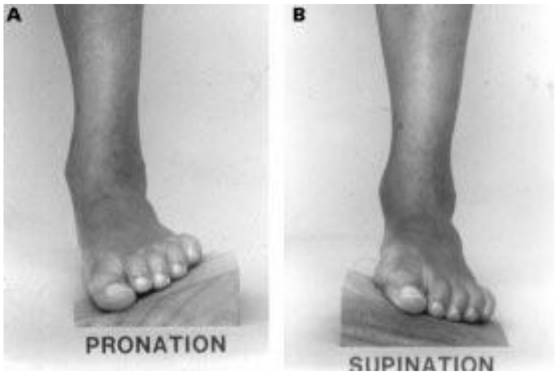


Figure 2.32: Pronation or supination (Heel is perpendicular to the ground and the forefoot is placed on a wedge). (Sherman, 1999)

Clinically Alexander has described supination of the foot-ankle complex as a combination of adduction of the foot, inversion of the subtalar joint and plantar flexion and pronation as the converse (abduction, eversion and dorsiflexion respectively).[3]

Razeghi and Batt,[304] and Stovitz and Coetzee[340] proposed an even more comprehensive and synthetic definition of foot pronation; i.e. calcaneal eversion (frontal plane), combined with medial deviation (transverse plane) and reduced vertical height (sagittal plane) of the navicular (Razeghi and Batt, 2002) and then forefoot abduction and dorsiflexion.[340]

Finally, it is worth noting that terms pronation and supination are applied when the foot is load-bearing (Figures 2.33, 2.34 and 2.35) and that pronation is not synonymous with pes planus.[321] Indeed, pes planus signifies a flatfoot and pes cavus denotes a hollow foot. While pes planus is typically described from visual observation alone, the actual definition depends on the metatarsal bones losing their normal longitudinal arch.[340] Additionally, the term "flexible flatfoot" describes an arch that is high when unloaded but flattens with standing if weight bearing does not cause calcaneal eversion.[340] The bottom of a "fixed" flatfoot remains flat whether the patient is sitting or standing.[340] Stovitz and Coetzee named “hyperpronation” a calcaneal eversion caused by weight bearing, in which case the static property of the foot cannot be clinically specified.[340] Nevertheless, there is also here an unclear consensus about the definition. Beckett et al.[16] considered as hyperpronated, any foot with a navicular drop > 10 mm, while Stolwijk et al. associated the hyperpronation with lowering and insufficiency of the foot arch and decrease weight bearing capacity of the first ray, from a more holistic and pathophysiological point of view.[339] Khamis and Yizhar[189] summarized that excessive pronation or hyperpronation occurred as a result of abnormal function of the subtalar joint. This was defined as an excessive and prolonged rearfoot pronation causing the foot to remain in maximum pronation to late or never resupinate in terminal stance for push off. Flat foot, flexible flat foot and low arch are considered as factors inducing excessive pronation or hyperpronation.[326]

For clarity, this latter concept will considered as “hyperpronation” in the following chapters, in order to encompass globally the consequences of excessive calcaneal eversion and decreased arch stiffness (or increased arch compliance) in functional weight bearing conditions and regardless of the hyperpronation causes. It is worth noting that this concept may also encompass an excessive moment of eversion occurring at stance phase, during the absorption process. McClay and Manal[225] studied the lower-extremity mechanics of runners with excessive rearfoot eversion. They defined “excessive” as having a peak two-dimensional eversion greater than 18° (based upon rearfoot mechanics previously collected on 100 normal runners whose mean rearfoot angle was 12°).

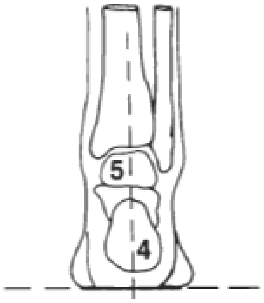


Figure 2.33: Neutral position of the subtalar joint. 5, Talus; 4, calcaneus. (Donatelli, 1985)

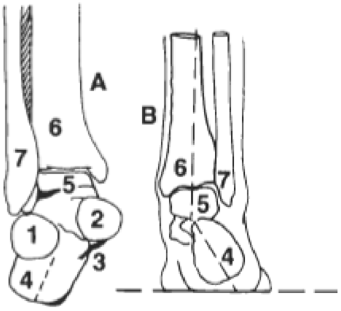


Figure 2.34: Closed kinetic chain pronation. A, Anterior view of the subtalar joint and the talocrual joint; B, posterior view of the subtalar joint and the talocural joint. 1, Calcaneal/cuboid articulation; 2, talo/navicular articulation; 3, sustentaculum tali; 4, calcaneus; 5, talus; 6, tibia; 7, fibula. (Donatelli, 1985)

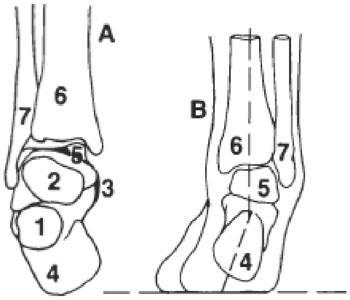


Figure 2.35: Closed kinetic chain supination. A, Anterior view of the subtalar joint and the talwrural joint; 8, posterior view of the subtalar joint and the talocrural joint. 1, Calcaneal/cuboid articulation; 2, talo/navicular articulation; 3, sustentaculum tali; 4, calcaneous; 5, talus; 6, tibia; 7, fibula. (Donatelli, 1985)

2.2.3.2.2 How pronation / hyperpronation may alter foot-ankle region mechanics

While reviewing the running biomechanics related literature in 1998, Novacheck[280] emphasized that excessive pronation may dramatically alter the running foot mechanics (Figure 2.36). This author mentioned that the time to maximum pronation is delayed beyond 40% of stance. Likewise, the period of pronation is prolonged delaying the onset of supination. In this case, the "hyper pronating" runner would not start supinating or reaching a neutral position until later (i.e. well after propulsion phase was to have begun). Accordingly, the foot is not an effective lever.[280]

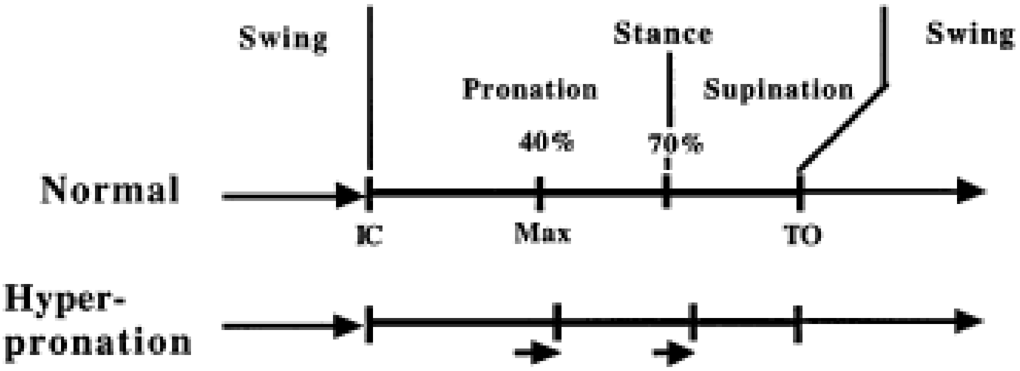


Figure 2.36: Abnormal excessive pronation or hyperpronation. This schematic illustrates the difference between normal foot mechanics and that of the hypermobile, 'pronated' foot. (Novacheck, 1998)

Several researchers have investigated the question of the relationships between the pronation, as a subjects' characteristic and the related foot-ankle running parameter.[63, 273, 325, 364] Chuckpaiwong et al. investigated the differences in plantar pressure between 50 healthy active adults with a normal and a low arch foot while running with running shoes.[63] They reported that, in the low arch foot when compared to the normal foot, the contact area and maximum force in the medial midfoot were significantly greater, while the peak pressure and maximum force in the lateral forefoot were significantly decreased.[63] Examining the plantar pressure patterns of 24 athletes running barefoot and divided in pes planus, pes cavus and pes rectus sub-groups, Sneyers et al.[325] reported that the plantar heel load was distributed more toward the anterior part of the calcaneus in the pes planus group compared with the normal group. Interestingly, the relative load under the midfoot region was lower in the pes cavus group compared with the other foot types, while the relative load of the forefoot was higher in the pes cavus group and lower in the pes planus group.[325] It has been confirmed by other authors that a flat foot or a more pronounced pronation causes a higher loading of the medial longitudinal arch, whereas a high arch foot transfers the load to the lateral edge of the foot.[198, 273, 364]

It is worth digressing briefly here about equipment. Today, a lot of running shoes are designed in the view to counteract hyperpronation.[44, 45, 57, 59, 314] This topic will be further detailed in the *injury prevention* section. It means conversely that some shoes may induce more hyperpronation than others. This is what Queen et al.[300] and Wiegerinck et al.[367] suggested after their experiments comparing racing flats and cushioned running shoes, that racing flats may not control properly the hyperpronation while training shoes may achieve this control, due to their better cushioning and rearfoot motion control. Some types of shoes may then be considered as allowing (or even facilitating) the hyperpronation. Interestingly, very small body of literature is available regarding spikes shoes,[335] even though it is well known in the track and field community that this type of very soft shoes does not prevent at all the runner from hyperpronation.

Even the relationship between pronation/hyperpronation and foot plantar patterns appear to be quite clear, the causes of the pronation/hyperpronation must still be identified (except fatigue and foot morphology, which have been dealt separately).

Hintermann and Nigg suggested that compensatory hyperpronation may occur for anatomical reasons, such as a tibia vara of 10° or more, forefoot varus, leg length discrepancy, ligamentous laxity, or because of muscular weakness or tightness in the *gastrocnemius* and *soleus* muscles,[161, 276] which was confirmed by Snook.[326] Biomechanical theory suggests a two-way relationship between plantar flexors weakness and hyperpronation, as excessive pronation makes the foot less rigid as the midfoot remains "unlocked" and therefore, generates less torque. In addition, with excessive pronation, the angle of pull of the Achilles tendon and the plantar flexors would be less than ideal such that some of the force generated by the muscles would pull medially as well as upward (Figure 2.37).[129, 326]

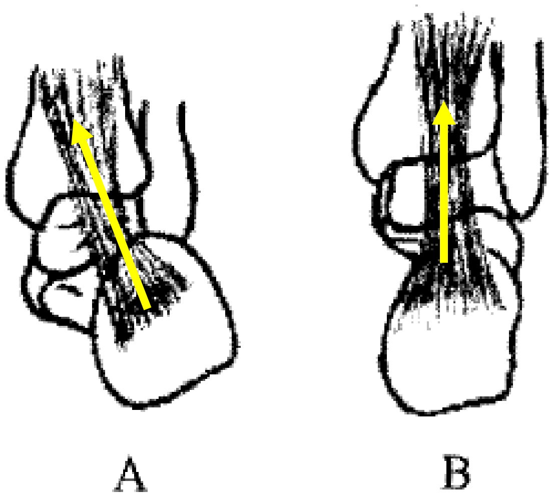


Figure 2.37: Triceps surae and pronation. A, Effect of pronation on the pull of triceps surae; B, pull of the triceps surae in subtalar neutral. Adapted from Snook (2001)

It has been well established in literature that there is also a two-way biomechanical relationship between foot hyperpronation and upper pelvis/lower limbs segments:[189] the foot hyperpronation being a potential cause or consequence inside the chain reaction with the upper segments (Figures 2.46 and 2.49).

2.2.3.2.3 How excessive supination may alter foot-ankle region mechanics

For clarity, supination of the foot-ankle complex will be defined here as the combination of adduction of the foot, inversion of the subtalar joint and plantar flexion, as proposed by Alexander.[3] Therefore, supination brings the lateral border into more direct plantigrade contact.[321]

During stance phase, the foot must perform three main tasks: adapt to the ground surface, aid in shock absorption and make its transition to a rigid lever to ensure an optimal push off.[66, 269] In midstance, the normal foot achieves maximum pronation, unlocking the midtarsal joint. The foot therefore becomes more flexible for adjusting to the underlying surface and absorbing shocks. The midtarsal joint locks again afterwards in supination to maximize foot stability and to provide a rigid lever for push off.[66, 269] Although the normal foot effectively makes the transition between pronation and supination during the stance phase, an excessively supinated foot (characterized by a high arch and "hypomobile" midfoot) may not properly accomplish this task. These abnormal mechanics are illustrated by the findings of various researchers who reported that high arch subjects had higher pressure-time integral under their rearfoot and forefoot, smaller contact area in the midfoot, higher peak pressure in the rearfoot region, higher peak pressure and relative loads in forefoot and shorter contact times than normal arch counterparts.[42, 43, 268, 325, 369]

In addition, an excessive lateral roll-over process is characterized by a poor midfoot pronation process.[128] This consequently increases the force along the lateral border of the foot as well as the demand on the foot lateral musculoskeletal structures.[66, 69, 113, 128, 351]

Take home message

- ✓ The transition from jogging to running pace is characterized by increased peak pressure and maximum force under the whole foot.
- ✓ Hyperpronation or excessive supination alters the foot-ankle running mechanics during both absorption and propulsion phases.
- ✓ Racing flats may not control properly the hyperpronation while training shoes may achieve this control, due to their better cushioning and rearfoot motion control.

Ce qu'il faut retenir

- ✓ La transition d'une allure de jogging à une allure de course soutenue est caractérisée par une augmentation des pics de pression et de le force maximale sous l'ensemble du pied.
- ✓ L'hyperpronation ou la supination excessive affectent la mécanique du complexe pied-cheville en course à pied, pendant les phases d'absorption et de propulsion.
- ✓ Les chaussures de course légères ne contrôlent probablement pas correctement l'hyperpronation contrairement aux chaussures de course plus lourdes et plus classiques qui peuvent mieux satisfaire à cette exigence en raison d'un meilleur amorti et d'un meilleur contrôle de l'arrière-pied.

2.3 Injuries and injury prevention

2.3.1 The rational for recording and reporting sport-related injuries in adolescents

Children and adolescents take part today in more and more sports activities.[47] Many of the youngsters undertake year-round training and specialization in their sports at a very early age. This is probably due to the 'catch them young' philosophy and the belief that, to achieve international standing in later sporting life, intensive training should be started before puberty.[212] It is not uncommon today, for example, for teens to train 20 or more hours each week in tennis or gymnastics or to compete in triathlons.

Engaging in sports activities at a young age can have numerous health benefits but also involves risk of injury. Indeed, the young athlete may be particularly vulnerable to sport injury due to the physical and physiological processes of growth. Injury risk factors that are unique to the young athlete include susceptibility to growth plate injury, nonlinear growth, limited thermoregulatory capacity.[47, 346] Although problems do not ordinarily arise at normal levels of activity, the more frequent and intense training and competition of young athletes today may create conditions under which this susceptibility becomes apparent.[47] Interestingly, the literature reflects a unique dichotomy: a recognition that excessive efforts to train athletes from a young age to competition can result in injury and current literature citations concerning how best to achieve optimal performance from these athletes.[222] As children and adolescents train harder and participate in sports year-round, injury patterns are changing and an increasing number of children with fatigue and overuse injuries is reported.[222]

Pressure from others - especially adults - may play a role in the development of overuse injury. Parents and coaches who promote excessive intensity or who encourage a "*no pain, no gain*" or win-at-all-costs attitude may well contribute to injury.[78] Coaches should be aware that training programs designed for adults are not appropriate for young athletes. In fact, because of the great variation in physical and emotional maturity among children and adolescents, individualization of training schedules must be encouraged. Coaches should be educated regarding training errors that may have occurred, the importance of scheduled rest periods and the need to avoid excessive training volumes, especially during the adolescent growth spurt.[78,266]

Approximately 38% of high school children and 34% of middle school children sustain a physical activity related injury that will be treated by a doctor or nurse yearly in the US.[151] It is estimated that approximately 50% of these injuries can be attributed to overuse-type mechanisms.[71, 349] The cost and long-term health risks associated with overuse injuries in children warrants developing tools or strategies that can be used to prevent and treat these injuries.[151]

With this growing popularity in sports, it becomes increasingly apparent that additional consideration must be given to the injury problem associated with sport. Reducing the incidence of these injuries may be achieved by identifying factors that may predispose a child to injury and through proper training, technique and fitness.[151, 243, 349] Efforts to reduce these injuries are warranted both to ensure the long-term health of children and to reduce medical costs.[176] Given that an understanding of causes and risks are prerequisites for injury prevention, standardised assessment of sports injuries provides not only important epidemiological information, but also directions for injury prevention and the opportunity for monitoring long-term changes in the frequency and circumstances of injury.[109, 118, 169, 176, 241, 352] In addition, Finch et al.[109] stated that injury surveillance during sporting events should be a part of the duty of care to the participants to help make future events safer.

Take home message

- ✓ Engaging in sports activities at a young age can have numerous health benefits but also involves risk of injury.
- ✓ Approximately 38% of high school children and 34% of middle school children sustain a physical activity related injury that will be treated by a doctor or nurse yearly in the US.
- ✓ Efforts to reduce these injuries are warranted to ensure the long-term health of children.

Ce qu'il faut retenir

- ✓ Pratiquer très jeune des activités sportives présente de très nombreux avantages en terme de santé mais implique également des risques de blessures.
- ✓ Chaque année aux Etats-Unis, environ 38% des lycéens et 34% des collégiens contractent une blessure liée à la pratique sportive et nécessitant un traitement par une infirmière ou un médecin.
- ✓ Les efforts visant à réduire ces blessures permettront d'assurer une bonne santé à long terme pour ces jeunes.

2.3.2 History of sports injury recording systems

Before 2007-08, the lack of consensus in study methodologies and inconsistencies in definition of a reportable injury provided major hindrances for making comparisons or combining data across studies. In addition, most studies did not differentiate between running and field events or between adolescents and adults. Much of the available literature dealing with children's track and field injuries were case reports, case series and opinion pieces, which did not allow analysis of injury rates or etiological factors.[376]

The number of prospective and retrospective studies was small and studies providing data on the number of exposures to injury for the calculation of rates were rarer still. For example, Zemper[376] found only nine prospective or retrospective studies dealing with track and field injuries in youth that either included injury rate data or provided enough information for estimating an injury rate (Table 2.3.6).[11, 19, 68, 290, 306, 361, 371, 375]

The need for agreement on the definition and standards to be used in sports injury epidemiology has been expressed[21, 174, 241] and consensus statements for certain sports, such as football and rugby have been published.[119, 120] These consensus statements provide detailed approaches for injury surveillance studies within specific sports, but they may not be appropriate for all individual sports or when several diverse sports are being compared. In terms of epidemiological research in track and field, the turning point appeared to be the paper published in 2008 by Junge et al.:[176] "*Injury surveillance in multi-sport events: the International Olympic Committee approach.*" The aims of this statement was to present standards for injury surveillance during major single- (e.g. track and field and swimming) and multi-sports tournaments (football and ice hockey) and specifically to provide the methodology that will be applied during the 2008 Olympic Games in Beijing. This system proved feasible for team sports during the 2004 Olympics and for individual sports during the IAAF World Championships 2007.[176]

The most important principles and advantages of the system reported were:

- The comprehensive and broad definition of injury allowing assessment of the effect of the full spectrum of injuries from mild contusions to fractures,
- The injury report completed by a qualified physician or physiotherapist responsible for the athlete, to ensure valid information on the characteristics of the injury and a comparable standard of data,
- A single-page report of all injuries,
- A daily report irrespective of whether or not an injury occurred.

Despite the fact that this injury surveillance system was accepted by an experienced team of physicians and accredited by the IOC and the main international sports federations, it contained some major weaknesses:

- The "*multiple-choice questionnaire*" format of this system, with only a very limited amount of terms available (Figures 2.40 and 2.41); in comparison to an injury report made in an editorial way and including a comprehensive description of injury circumstances or diagnosis.
- For similar reasons, the absence of a proper diagnosis which was replaced by the superimposition of the injury type and site (chosen in a non-exhaustive list, with no precise difference between sprain or strain grades, for instance).
- The estimation of the expected duration of the subsequent absence instead of retrospectively recording the real duration of absence.
- The lack of consideration towards specific adolescent injuries (osteochondrosis, apophysitis…) which makes this system effective mainly for adults.

However, most of the aforementioned criticisms are related to the initial target of the IOC injury surveillance system; i.e. to record and report injuries occurring during elite competitive events. This probably explains the limited amount of available injury types and site choices or the approximated estimation of the absence duration for that system, in order to deal with thousands of injuries in only few days.

Moreover, this system was described as a progressive one, as mentioned by the author in her conclusion: “*The system can be modified to address the specific objectives of a certain sport or research question; however, a standardised use of injury definition, report forms and methodology will ensure the comparability of results.*”[176]

There are some other existing reports or systems attempting to improve this general lack of adequate athletic injury data collection:

- The NCAA (National Collegiate Athletic Association) Injury Surveillance System (ISS), designed and implemented by Eric D. Zemper in USA, (and most recently the Athletic Injury Monitoring System (AIMS), also designed and implemented by Zemper, University of Oregon).[77, 229, 376] In 1982, the NCAA began its own sports injury data collection system (ISS), similar in many ways to NAIRS (National Athletic Injury/Illness Reporting System) but using only two basic data collection forms and with a representative national sample of NCAA member schools.[229] However, ISS covered only selected NCAA sponsored sports at member schools and there has been no broad dissemination of results. AIMS started in 1986 with the intent of covering a wider variety of sports at all levels of participation.[229,77]
- The North Carolina High School Athletic Injury Study (NCHSAIS) report[266] based on NCAA ISS, where the data collection instruments were developed and refined with consideration from many sources; i.e. NCHSAIS Advisory board, NCHSAA personnel, Rules Books (published by the National Federation of State High School Associations), Sports Injuries in Youths: Surveillance Strategies, NCAA reporting forms, previous and on-going sports injury research and experts in athletic training.
- High School RIO™ (Reporting Information Online), an Internet-based sports injury surveillance system.

The strength of these systems or reports was the good level of consensus about the definitions, the severity and the rate of injuries, as well as the sample population size. Nevertheless, because the ISS, the North Carolina High School Athletic Injury Study report and the RIO are (or are derived from) surveillance systems, with more variability than a smaller well-controlled research study, they may lack the sensitivity to monitor the effects of some policy changes on injury rates. In particular, these systems collect a sample of data from a larger population, rather than acting as a registry, in which every occurrence of a particular event is reported. Therefore, rare but high-profile events, such as deaths or a well-publicized injury to a star player may not be included in this database if the school associated with the event was not part of the sample. However, the consistency and longevity of these systems including stable basic system definitions and recording methods provide a general foundation of collegiate sport injury risk across multiple sports that is an unmatched resource anywhere in the sports medicine literature. These data are the foundation for informed decision making, policy development and injury prevention strategies set-up at both the individual institution and national governing body and sport committee level.[376]

It is worth noting that the Luxembourg government requested a retrospective report about injury incidence in young elite athletes in Luxembourg, which was developed by Theisen et al. in 2007.[346] This report was of high interest because it focused on the overuse injuries of young elite athletes in Europe. Unfortunately, the retrospective methodology and the small number of subjects by sports have probably affected the accuracy of this work; the authors concluding that a prospective approach should be developed allowing the long-term follow-up of the young athletes.

Finally none of the aforementioned systems or reports appeared to be 100% satisfying for recording accurately and specifically the injuries occurring in youth track and field. If the consensus regarding the main criteria definitions seems to be closer now, the main weakness remains the poor consideration of specific adolescent and growth-related injuries or complaints in the existing systems. Nevertheless, it should be noted that one coding system was created more than 20 years ago and took into account these adolescent specificities: the Sport Medicine Diagnostic Coding System (SMDCS) which was first developed in 1990 for clinical research at the University of Calgary Sport Medicine Centre. Then in 1991, it was used as a tool in the epidemiologic study of sport injuries with the development of the Canadian Intercollegiate Sport Injury Registry (CISIR).[242] The SMDCS has been designed to be flexible and permit easy retrieval, defining an injury by one pair of letters followed by two pairs of digits (Figure 2.38; Tables 2.3.1, 2.3.2 and 2.3.3). It follows a systematic anatomical design, first listing the region (pair of letters), then structure (first pair of digits) and then the type of injury (final pair of digits).

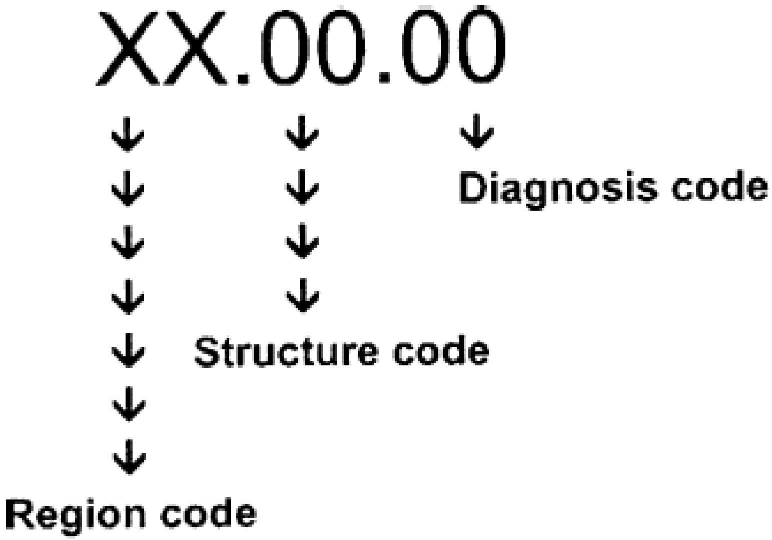
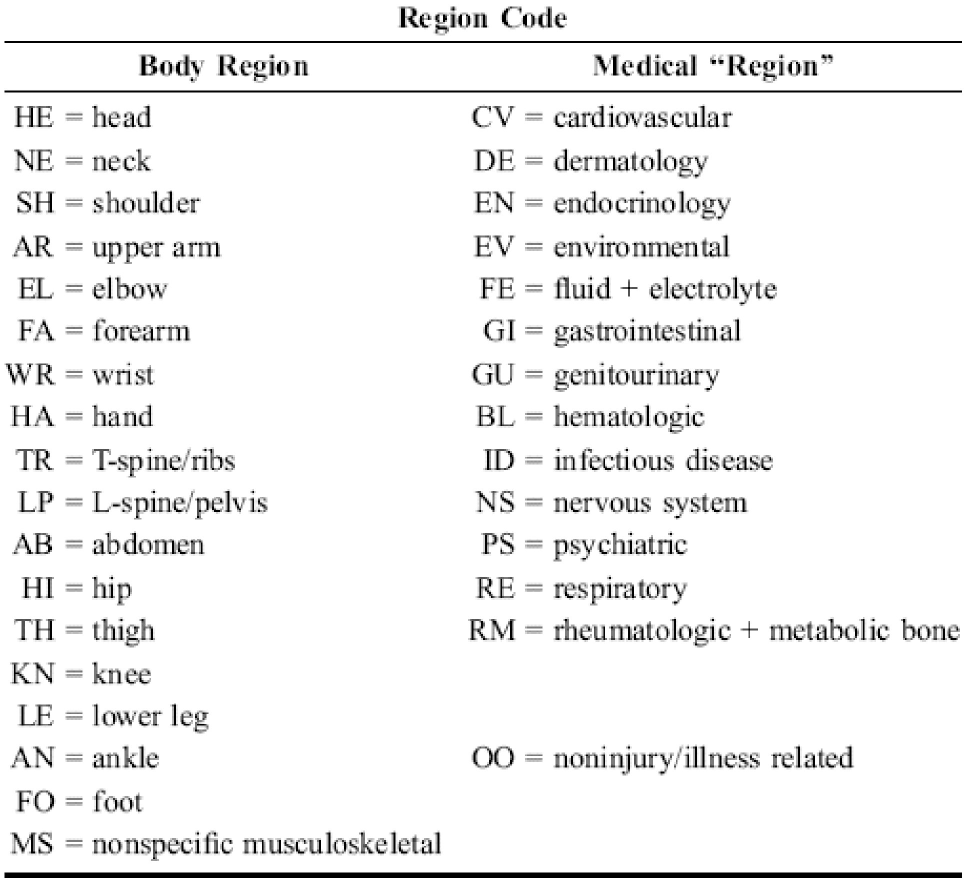


Figure 2.38: Sport Medicine Diagnostic Coding System. Design of the 3 pairs of characters. (Meuwisse and Wiley, 2007)

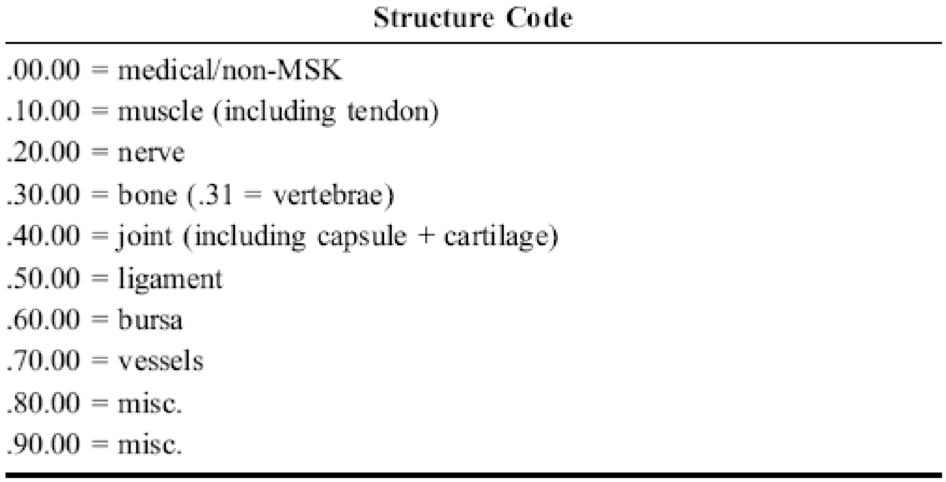
Table 2.3.1: Sport Medicine Diagnostic Coding System. First pair of digits = region code. (Meuwisse and Wiley, 2007)



Region Code

Body Region	Medical "Region"
HE = head	CV = cardiovascular
NE = neck	DE = dermatology
SH = shoulder	EN = endocrinology
AR = upper arm	EV = environmental
EL = elbow	FE = fluid + electrolyte
FA = forearm	GI = gastrointestinal
WR = wrist	GU = genitourinary
HA = hand	BL = hematologic
TR = T-spine/ribs	ID = infectious disease
LP = L-spine/pelvis	NS = nervous system
AB = abdomen	PS = psychiatric
HI = hip	RE = respiratory
TH = thigh	RM = rheumatologic + metabolic bone
KN = knee	
LE = lower leg	
AN = ankle	OO = noninjury/illness related
FO = foot	
MS = nonspecific musculoskeletal	

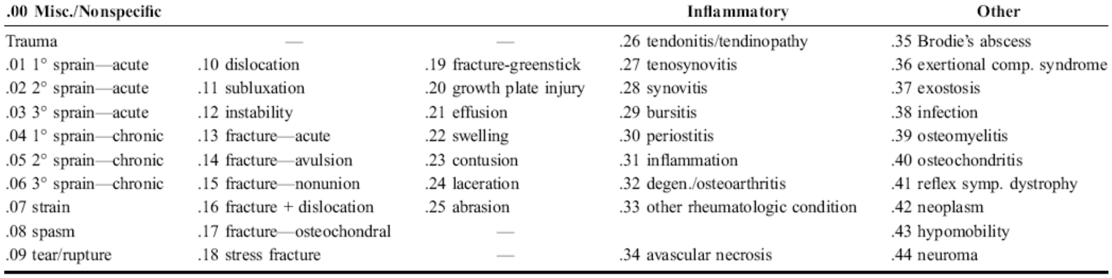
Table 2.3.2: Sport Medicine Diagnostic Coding System. Second pair of digits = structure code. (Meuwisse and Wiley, 2007)



Structure Code

.00.00 = medical/non-MSK
.10.00 = muscle (including tendon)
.20.00 = nerve
.30.00 = bone (.31 = vertebrae)
.40.00 = joint (including capsule + cartilage)
.50.00 = ligament
.60.00 = bursa
.70.00 = vessels
.80.00 = misc.
.90.00 = misc.

Table 2.3.3: Sport Medicine Diagnostic Coding System. Third pair of digits = diagnosis code. (Meuwisse and Wiley, 2007)



.00 Misc./Nonspecific			Inflammatory	Other
Trauma	—	—	.26 tendonitis/tendinopathy	.35 Brodie's abscess
.01 1° sprain—acute	.10 dislocation	.19 fracture-greenstick	.27 tenosynovitis	.36 exertional comp. syndrome
.02 2° sprain—acute	.11 subluxation	.20 growth plate injury	.28 synovitis	.37 exostosis
.03 3° sprain—acute	.12 instability	.21 effusion	.29 bursitis	.38 infection
.04 1° sprain—chronic	.13 fracture—acute	.22 swelling	.30 periostitis	.39 osteomyelitis
.05 2° sprain—chronic	.14 fracture—avulsion	.23 contusion	.31 inflammation	.40 osteochondritis
.06 3° sprain—chronic	.15 fracture—nonunion	.24 laceration	.32 degen./osteoarthritis	.41 reflex symp. dystrophy
.07 strain	.16 fracture + dislocation	.25 abrasion	.33 other rheumatologic condition	.42 neoplasm
.08 spasm	.17 fracture—osteochondral	—		.43 hypomobility
.09 tear/rupture	.18 stress fracture	—	.34 avascular necrosis	.44 neuroma

One of the main reasons for this design was to allow sorting and classification for analysis purposes. Region codes exist to describe each body segment. In addition, the SMDCS allows for documentation of the common medical problems related to sport. Although the intent was to be distributed to other groups or in different settings at no cost, it has not been used a lot in the sport medicine literature. Minor changes have been made over the past 15 years to add new codes. The first major revision was completed in 2006 to add additional columns of code groupings to allow the codes to fit the broader (less detailed) categories of injury that were decided by consensus within the sports of football (soccer) and rugby.[242, 244]

It is assumed that an injury-recording system mixing the highly accurate SMDCS injury diagnoses (especially for growth-related overuse injuries) and the results of the IOC consensus statement in terms of other injury criteria may be of primary interest in order to record accurately the injuries in adolescent athletes.

Take home message

- ✓ None of the existing injury reporting systems appears to be 100% satisfying for recording accurately and specifically the injuries occurring in youth track and field.
- ✓ The Sport Medicine Diagnostic Coding System (SMDCS) permits accurate reporting of the injury diagnosis, defined by its region, its structure and its type.
- ✓ An injury-recording system mixing the SMDCS injury diagnoses (especially for growth-related overuse injuries) and the different injury criteria existing in some other systems may be highly satisfying.

Ce qu'il faut retenir

- ✓ Aucun des systèmes d'encodage des blessures actuellement en place n'apparait être satisfaisant à 100% pour enregistrer avec exactitude et spécificité les blessures survenant chez les jeunes en athlétisme.
- ✓ Le « Sport Medicine Diagnostic Coding System » (SMDCS) permet un enregistrement précis du diagnostic d'une blessure en définissant sa localisation (région et structure) et son type.
- ✓ Un système d'encodage des blessures qui combinerait le diagnostic du SMDCS (spécialement pour les blessures liées à la croissance) et les autres critères indispensables figurant dans différents systèmes serait très satisfaisant.

2.3.3 Definition of injury

Injuries occur when energy is transferred to the body in amounts or at rates that exceed the threshold for human tissue damage.[244] In sport injuries, one usually refers to mechanical energy transfer. These conceptual definitions usually give way to management of injuries that meet certain time-loss from activity or medical treatment criteria. Indeed, a recent consensus statement on injury definitions and data collection procedures in football (soccer) suggested that injuries are: ‘‘*Any physical complaint sustained by a player that result from a football match or football training, irrespective of the need for medical attention or time-loss from football activities.*’’[244]

Several definitions of injury have been proposed in the past that were sometimes similar; this heterogeneity in the terminology may be confusing. For Junge et al.,[176] an injury was defined as ‘‘*any musculoskeletal complaint newly incurred due to competition and/or training during the tournament that received medical attention regardless of the consequences with respect to absence from competition or training*’’. This injury definition includes some very important aspects: (1) all injuries that received medical attention (not only time loss or reduced performance), (2) newly incurred (exclusion of pre-existing and not fully rehabilitated injuries), (3) injuries occurring in competition or training and (4) exclusion of illnesses and diseases.[175, 176] The advantage of this broad definition of injury is that it becomes possible to assess the effect of the full spectrum of injuries from mild contusions to fractures.[163, 175] This might be of importance in assessing the long-term consequences of injuries, as an analysis of injury sequences showing that minor injuries are often followed by moderate or major ones[85] and acute complaints are a predictor of subsequent injuries.[83] So an ‘‘all encompassing’’ injury definition does not leave it to the physician to judge which injuries should or should not be included.[163, 176] The availability of additional information regarding time loss (estimated duration of subsequent absence from sport) allows expression of the incidence of time-loss injury and the possibility of comparing the results with studies that use that definition. Zemper in 2005 noted that none of the nine studies selected for his review paper about track and field injuries used exactly the same definition of an injury, making it difficult to compare data across the studies.[376]

He suggested that the most commonly used (and recommended) definition of a reportable injury in sport injury epidemiology was: "*an injury incurred during participation in the sport, requiring medical attention at some level (e.g. coach, school nurse, trainer and physician) and keeping the athlete from normal full participation for the remainder of that competition/training session or for one or more days following the injury*".[376] The notion of time loss keeps the data recording system from being inundated with minor injuries that do not interfere with normal participation. Using definitions involving longer time loss periods (e.g. two days, one week) are not recommended because they may miss many of the more subtle injuries.

Finally, the definition recommended by Dick et al.[77] in the ISS seems to constitute a good synthesis. They proposed that a reportable injury should be defined as "*one that (1) occurred as a result of participation in an organized practice or competition and (2) required medical attention by a team certified athletic trainer or physician and (3) resulted in restriction of the student-athlete's participation or performance for 1 or more calendar days beyond the day of injury. If an off day followed the injury event, athletic trainers were asked to assess whether the injured athlete would have been able to participate*".[77]

2.3.4 Criteria of injury

Numerous injury criteria are available in the literature.[77, 176, 376] It is proposed to enumerate and detail the main ones in the following sections.

2.3.4.1 Type of injury

The lack of consensus and inconsistencies in the type of reportable injury terminology (like regarding the injury definition) provide major hindrances for making comparisons or combining data across studies. For instance, Dick et al.[77] described a large number of injury types in their ISS (i.e. 32 types) (Figure 2.39), but it is worth noting that only two grades are proposed in terms of sprain or strain gravity and no children- or adolescent-related specific types of injuries are mentioned.[77]

INJURY DEFINITION: A reportable injury in the ISS is defined as one that:

1. Occurs as a result of participation in an organized intercollegiate practice or contest;
2. Requires medical attention by a team athletics trainer or physician; and
3. Results in any restriction of the athlete's participation or performance* for one or more days beyond the day of injury.
4. **Any dental injury regardless of time loss.**

* See POINTS OF EMPHASIS.

School Code: ______________________

Select one: Fall season Spring season

1. Year:
(1) FR (2) SO (3) JR (4) SR (5) Fifth

2. Age: ________years **4. Weight:** __________pounds

3. Height: _____inches **5. Date of injury:** __________ (month/day)

6. Injury occurred during:
(1) Preseason (before first regular-season match)
(2) Regular season
(3) Postseason (after final regular-season match)
(99) Other: ______________________

7. Injury occurred in:
(1) Competition—varsity
(3) Practice

8. COMPETITION ONLY—Where did this injury occur?
(1)Home
(2)Away
(3) Neutral site
(99) Other: _______

9. Injury occurred during:
Competition: (1) Warm-up
(2) Game 1
(3) Game 2
(4) Game 3
(5) Game 4
(6) Game 5
Practice: (7) First half
(8) Second half
(99) Other: ___

10. This injury is a:
(1) New injury
(2) Recurrence of injury from this season
(3) Recurrence of injury from previous season (this sport)
(4) Complication of previous injury (this sport)
(5) Recurrence of other-sport injury
(6) Recurrence of nonsport injury
(7) Complication of other-sport injury

11. Has student-athlete had unrelated injury recorded this season?
(1) Yes (2) No

12. *Not applicable to this sport; proceed to next question.*

13. How long did this injury keep student-athlete from participating in the sport? (If end of season, give best estimate.)
(1) 1-2 days
(2) 3-6 days
(3) 7-9 days
(4) 10 days or more
(5) Catastrophic, nonfatal
(6) Fatal

14. This injury involved:
(1) Contact with another competitor
(2) Contact with playing surface
(3) Contact with apparatus/ball
(4) Contact with other in environment (e.g., wall, fence, spectators)
(5) No apparent contact (rotation about planted foot)
(6) No apparent contact (other)
(99) Other: ______________________

15. Principal body part injured (for 1-10, complete Head-Injury Information; for 31 or 32, complete Knee-Injury Information):
(1) Head
(2) Eye(s)
(3) Ear(s)
(4) Nose
(5) Face
(6) Chin
(7) Jaw (TMJ)
(8) Mouth
(9) Teeth
(10) Tongue
(11) Neck
(12) Shoulder
(13) Clavicle
(14) Scapula
(15) Upper arm
(16) Elbow
(17) Forearm
(18) Wrist
(19) Hand
(20) Thumb
(21) Finger(s)
(22) Upper back
(23) Spine
(24) Lower back
(25) Ribs
(26) Sternum
(27) Stomach
(28) Pelvis, hips, groin
(29) Buttocks
(30) Upper leg
(31) Knee
(32) Patella
(33) Lower leg
(34) Ankle
(35) Heel/Achilles' tendon
(36) Foot
(37) Toe(s)
(38) Spleen
(39) Kidney
(40) External genitalia
(41) Coccyx
(42) Breast
(99) Other: ____________

HEAD INJURY (answer only if response in question 15 was 1-10)

16. This student-athlete was diagnosed as having:
(1) 1° cerebral concussion. [No loss of consciousness, short post-traumatic amnesia (seconds up to two minutes).]
(2) 2° cerebral concussion. [Loss of consciousness (less than five minutes) and amnesia for up to 30 seconds].
(3) 3° cerebral concussion. [Loss of consciousness (more than five minutes) and extended amnesia.]
(4) No cerebral concussion
(5) Unknown

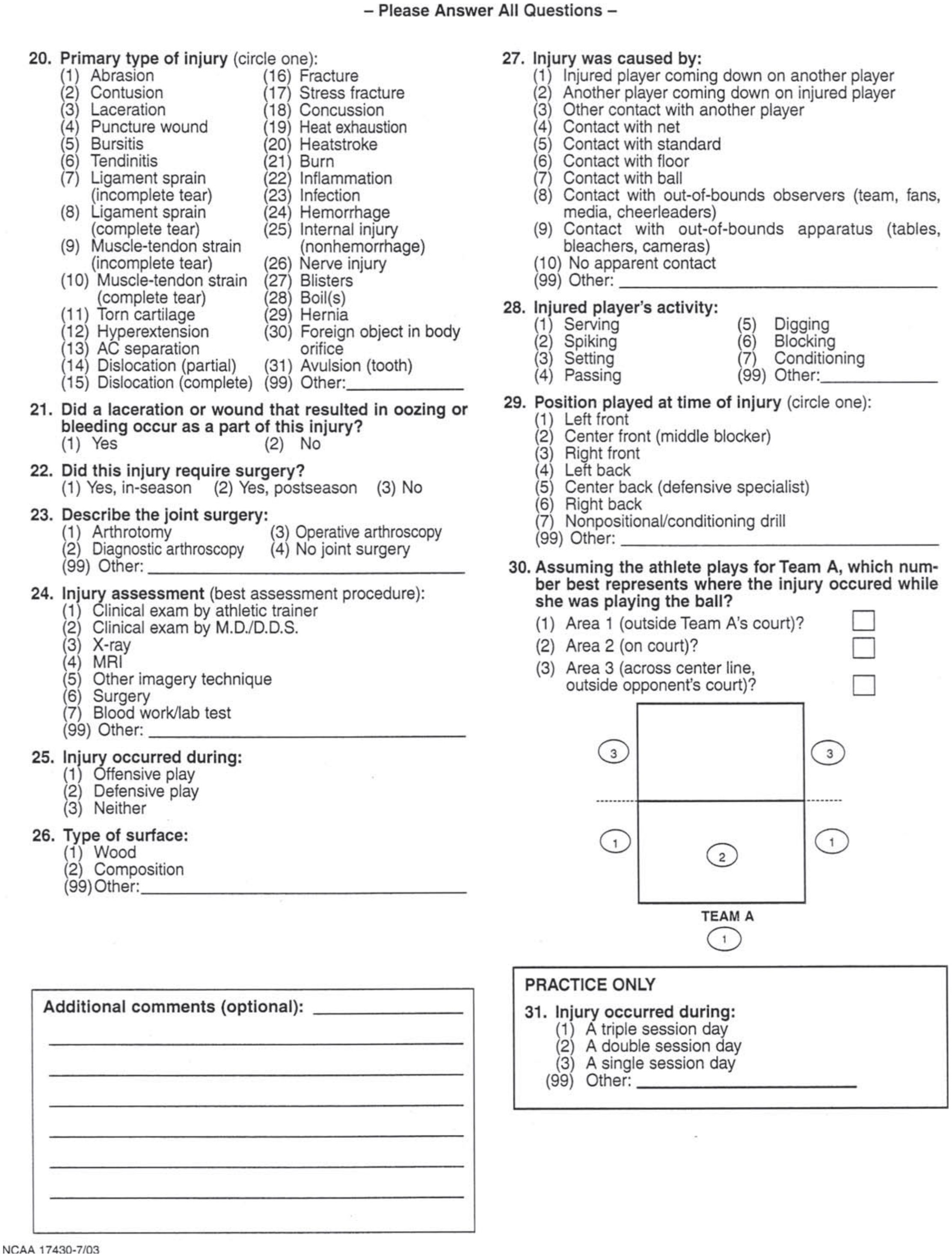
17. Was a mouthpiece (MP) worn?
(1) MP worn—dentist-fitted
(2) MP worn—self-fitted
(3) MP not worn

18. Type eye injury:
(1) Orbital fracture
(2) Cornea
(3) Ruptured globe
(4) Soft tissue
(99) Other: ___________

KNEE INJURY (answer only if response in question 15 was 31 or 32)

19. Circle ALL knee structures injured:
(1) Collateral
(2) Anterior cruciate
(3) Posterior cruciate
(4) Torn cartilage (meniscus)
(5) Patella and/or patella tendon
(6) None
(99) Other: ___________

– Please Answer All Questions –



– Please Answer All Questions –

20. Primary type of injury (circle one):
- (1) Abrasion
- (2) Contusion
- (3) Laceration
- (4) Puncture wound
- (5) Bursitis
- (6) Tendinitis
- (7) Ligament sprain (incomplete tear)
- (8) Ligament sprain (complete tear)
- (9) Muscle-tendon strain (incomplete tear)
- (10) Muscle-tendon strain (complete tear)
- (11) Torn cartilage
- (12) Hyperextension
- (13) AC separation
- (14) Dislocation (partial)
- (15) Dislocation (complete)
- (16) Fracture
- (17) Stress fracture
- (18) Concussion
- (19) Heat exhaustion
- (20) Heatstroke
- (21) Burn
- (22) Inflammation
- (23) Infection
- (24) Hemorrhage
- (25) Internal injury (nonhemorrhage)
- (26) Nerve injury
- (27) Blisters
- (28) Boil(s)
- (29) Hernia
- (30) Foreign object in body orifice
- (31) Avulsion (tooth)
- (99) Other:__________

21. Did a laceration or wound that resulted in oozing or bleeding occur as a part of this injury?
(1) Yes (2) No

22. Did this injury require surgery?
(1) Yes, in-season (2) Yes, postseason (3) No

23. Describe the joint surgery:
- (1) Arthrotomy
- (2) Diagnostic arthroscopy
- (3) Operative arthroscopy
- (4) No joint surgery
- (99) Other: __________

24. Injury assessment (best assessment procedure):
- (1) Clinical exam by athletic trainer
- (2) Clinical exam by M.D./D.D.S.
- (3) X-ray
- (4) MRI
- (5) Other imagery technique
- (6) Surgery
- (7) Blood work/lab test
- (99) Other: __________

25. Injury occurred during:
- (1) Offensive play
- (2) Defensive play
- (3) Neither

26. Type of surface:
- (1) Wood
- (2) Composition
- (99) Other:__________

Additional comments (optional): __________

27. Injury was caused by:
- (1) Injured player coming down on another player
- (2) Another player coming down on injured player
- (3) Other contact with another player
- (4) Contact with net
- (5) Contact with standard
- (6) Contact with floor
- (7) Contact with ball
- (8) Contact with out-of-bounds observers (team, fans, media, cheerleaders)
- (9) Contact with out-of-bounds apparatus (tables, bleachers, cameras)
- (10) No apparent contact
- (99) Other: __________

28. Injured player's activity:
- (1) Serving
- (2) Spiking
- (3) Setting
- (4) Passing
- (5) Digging
- (6) Blocking
- (7) Conditioning
- (99) Other:__________

29. Position played at time of injury (circle one):
- (1) Left front
- (2) Center front (middle blocker)
- (3) Right front
- (4) Left back
- (5) Center back (defensive specialist)
- (6) Right back
- (7) Nonpositional/conditioning drill
- (99) Other: __________

30. Assuming the athlete plays for Team A, which number best represents where the injury occured while she was playing the ball?
- (1) Area 1 (outside Team A's court)? ☐
- (2) Area 2 (on court)? ☐
- (3) Area 3 (across center line, outside opponent's court)? ☐

PRACTICE ONLY

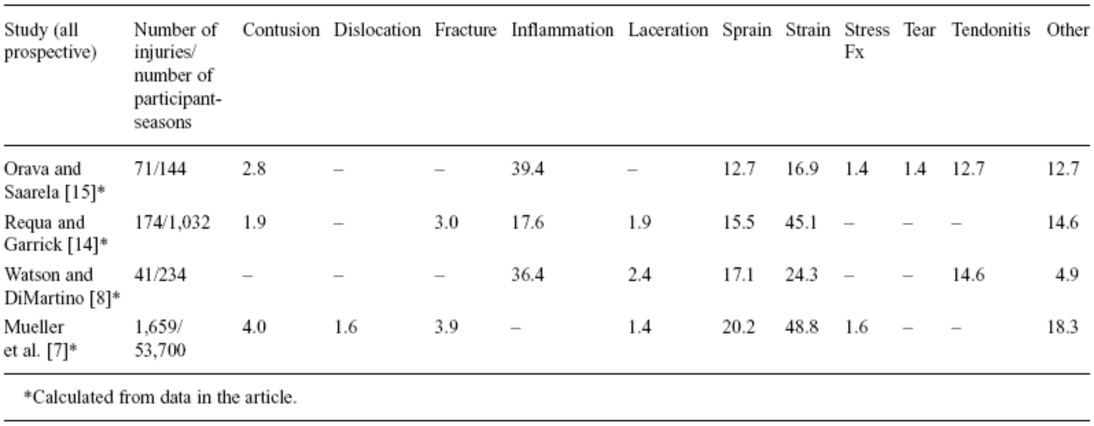
31. Injury occurred during:
- (1) A triple session day
- (2) A double session day
- (3) A single session day
- (99) Other: __________

NCAA 17430-7/03

Figure 2.39: Individual injury form – NCAA Injury Surveillance System. (Dick et al. 2007)

In his review of the injury literature in youth track and field in 2005, Zemper only reported 11 types of injuries (Table 2.3.4) including some very vague terms like "*inflammation*".[376]

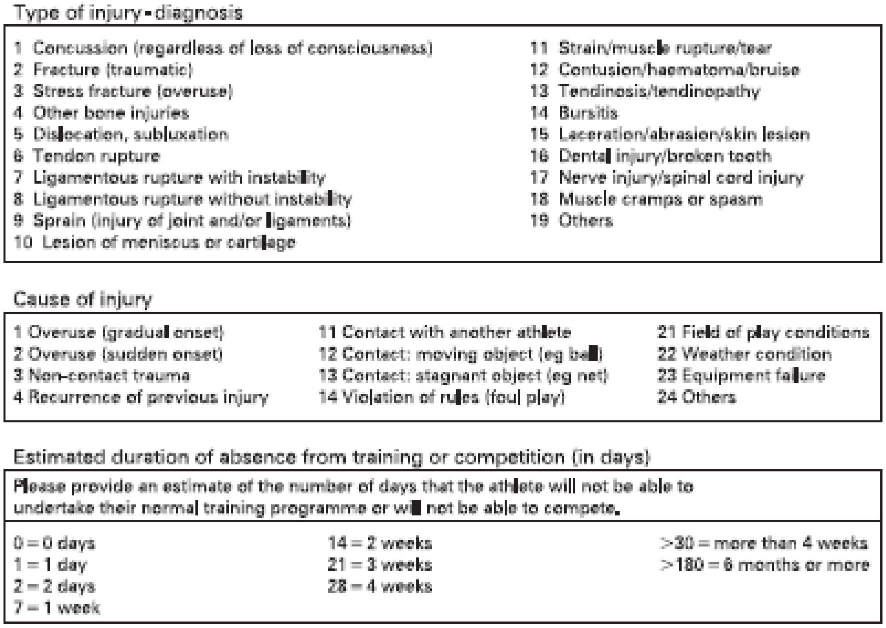
Table 2.3.4: A percent comparison of injury types in youth track and field. (Zemper, 2005)



Study (all prospective)	Number of injuries/ number of participant-seasons	Contusion	Dislocation	Fracture	Inflammation	Laceration	Sprain	Strain	Stress Fx	Tear	Tendonitis	Other
Orava and Saarela [15]*	71/144	2.8	–	–	39.4	–	12.7	16.9	1.4	1.4	12.7	12.7
Requa and Garrick [14]*	174/1,032	1.9	–	3.0	17.6	1.9	15.5	45.1	–	–	–	14.6
Watson and DiMartino [8]*	41/234	–	–	–	36.4	2.4	17.1	24.3	–	–	14.6	4.9
Mueller et al. [7]*	1,659/ 53,700	4.0	1.6	3.9	–	1.4	20.2	48.8	1.6	–	–	18.3

*Calculated from data in the article.

The only paper dealing with adolescent track and field athletes and reporting specific growth-related injuries is the one of Orava et Puranen,[290] but it dates from 1978. Again, Junge et al.[176] tried to bring some more clarity in this terminology and proposed that the physician describes the type of injury in words and give the respective code(s) of the 19 injury types (Figure 2.40) stated on the back of the provided form. These authors mentioned that their selection of injury types was based on the review of other injury reporting systems[77, 149, 177, 209] and the related consensus statements for football and rugby which allowed comparison with other established coding systems such as SMDCS.[119, 120]



Type of injury - diagnosis

1 Concussion (regardless of loss of consciousness)
2 Fracture (traumatic)
3 Stress fracture (overuse)
4 Other bone injuries
5 Dislocation, subluxation
6 Tendon rupture
7 Ligamentous rupture with instability
8 Ligamentous rupture without instability
9 Sprain (injury of joint and/or ligaments)
10 Lesion of meniscus or cartilage
11 Strain/muscle rupture/tear
12 Contusion/haematoma/bruise
13 Tendinosis/tendinopathy
14 Bursitis
15 Laceration/abrasion/skin lesion
16 Dental injury/broken tooth
17 Nerve injury/spinal cord injury
18 Muscle cramps or spasm
19 Others

Cause of injury

1 Overuse (gradual onset)
2 Overuse (sudden onset)
3 Non-contact trauma
4 Recurrence of previous injury
11 Contact with another athlete
12 Contact: moving object (eg ball)
13 Contact: stagnant object (eg net)
14 Violation of rules (foul play)
21 Field of play conditions
22 Weather condition
23 Equipment failure
24 Others

Estimated duration of absence from training or competition (in days)

Please provide an estimate of the number of days that the athlete will not be able to undertake their normal training programme or will not be able to compete.

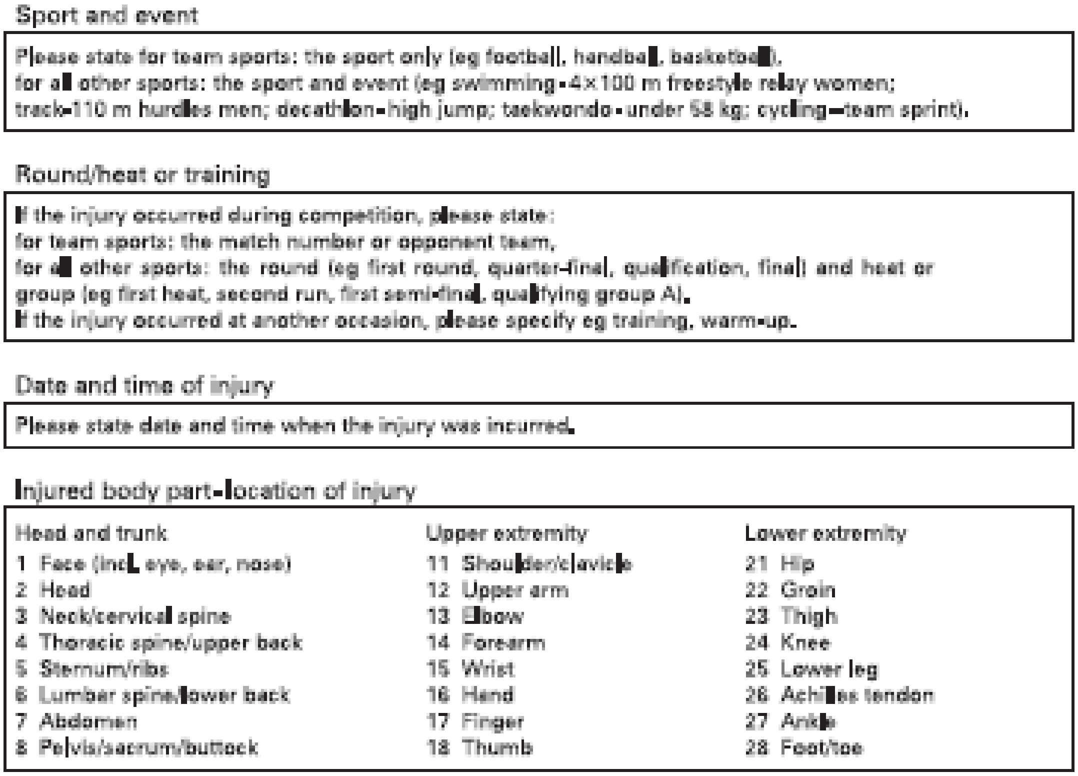
0 = 0 days
1 = 1 day
2 = 2 days
7 = 1 week
14 = 2 weeks
21 = 3 weeks
28 = 4 weeks
>30 = more than 4 weeks
>180 = 6 months or more

Figure 2.40: Daily injury report for the Olympic Games – Part including the type of injury, the diagnosis, the cause of injury and the estimated duration of absence. (Junge et al., 2008)

Nevertheless, despite these efforts, the system proposed by Junge et al. provided the physician with finally only 19 types of injuries with no further details about the sprain or strain grades and again no specific injury types regarding youth population. It is worth noting that again the SMDCS seems to be the most comprehensive available system in terms of injury type.[244]

2.3.4.2 Site of injury (injury location)

There seems to be a little more consensus around the topic of the injury sites than for the injury types. Most of the authors have divided the body in several anatomical regions or parts in a fairly similar way, nevertheless the lack of available terms focusing on specific growth-related injuries (e.g. tibial tubercle, heel or patella tip) among the main systems is an oversight,[77, 176, 229, 376] despite the 43 sites reported in the ISS for instance (Figure 2.39).[77] As for the injury types, the IOC consensus statement required the physician to describe the location of the injury precisely in words but then, afterwards, provides the respective code(s) of the 28 injury locations (Figure 2.41) (eight each for head and trunk, upper limb and lower limb) specified on the back of the provided form.[176] Even though the diagnosis of the physician was initially very accurate, the must “fit” to the pre-established list could alter the reliability of the recording. It is assumed that the SMDCS should be considered as the reference in terms of injury site, as almost all the possible injury locations are listed in that system, including very specific growth-related sites such as lesser trochanter, anterior inferior iliac spine and tibial tubercle.[244]



Sport and event

Please state for team sports: the sport only (eg football, handball, basketball),
for all other sports: the sport and event (eg swimming–4×100 m freestyle relay women;
track–110 m hurdles men; decathlon–high jump; taekwondo–under 58 kg; cycling–team sprint).

Round/heat or training

If the injury occurred during competition, please state:
for team sports: the match number or opponent team,
for all other sports: the round (eg first round, quarter-final, qualification, final) and heat or group (eg first heat, second run, first semi-final, qualifying group A).
If the injury occurred at another occasion, please specify eg training, warm-up.

Date and time of injury

Please state date and time when the injury was incurred.

Injured body part–location of injury

Head and trunk	Upper extremity	Lower extremity
1 Face (incl. eye, ear, nose)	11 Shoulder/clavicle	21 Hip
2 Head	12 Upper arm	22 Groin
3 Neck/cervical spine	13 Elbow	23 Thigh
4 Thoracic spine/upper back	14 Forearm	24 Knee
5 Sternum/ribs	15 Wrist	25 Lower leg
6 Lumbar spine/lower back	16 Hand	26 Achilles tendon
7 Abdomen	17 Finger	27 Ankle
8 Pelvis/sacrum/buttock	18 Thumb	28 Foot/toe

Figure 2.41: Daily injury report for the Olympic Games – Part including the sport event, the circumstances, the date and the site of injury. (Junge et al., 2008)

2.3.4.3 Severity of injury

As previously explained and cited by Zemper[376] in his literature review about track and field injuries in adolescents, it is difficult to make comparisons between studies because injury severity is assessed with different breakdowns of the number of days lost. Nevertheless, the work carried out by the IOC consensus group on that topic must be commended, as they have provided a clear classification based on the injury-related duration of absence (Figure 2.40).[176] All injuries that result in the athlete being unable to undertake their normal training programme or being unable to compete for at least the day after injury are classified as time loss injuries.[176] The severity of an injury is defined as the number of days the athletes were unable to undertake their normal training programme or to compete. Injury severity is classified as minor (1–7 days, opportunity to subdivide into 1–3 and 4–7 days), moderate (8– 28 days), severe (>28 days) and career-ending injuries.[176]

2.3.4.4 Incidence of injury or injury rate

As reported by Junge et al,[176] incidence of injury or injury rate has been defined on epidemiological concepts in sports medicine by Kuhn et al.[202] as the *‘‘number of new cases that developed over a specific period of time’’*. This figure can then be expressed relative to either the “at risk” population or the “exposure time”.[176] In studies on sports injuries, the incidence of injury was usually expressed as (i) number of injuries per 100 or 1000 athletes, (ii) number of injuries per 100 or 1000 athlete-exposures or (iii) number of injuries per 1000 hours training and/or competition.[176] In order to decrease the risk of disparities due to the differences between sports, it has been agreed that an athlete’s individual risk of injury in multi-sport events should be best expressed and compared as ‘‘injuries in competition per 1000 athlete participations or exposures’’.[176] An athlete participation or exposure is defined as one athlete participating in one practice or game where there is the possibility of sustaining an athletic injury.[229] For example, 10 competition injuries during 600 competition athlete exposures resulted in an injury rate of (10/600) x 1000, or 16.7 competition injuries per 1000 athlete exposures.

This consensus makes critical the accurate recording and reporting of training and competitions exposures, usually carried out by the coaches. In addition, it has been also agreed that injury rates should be calculated separately for training and competition.[119, 174]

2.3.4.5 Other criteria

Injury onset (i.e. acute or gradual), injury situation (i.e. training or competition),[376] season period,[77] recurrence, contact or non-contact injury, surgery or not, type of surface, movement pattern or activity and some other criteria have been sometimes taken into considerations in some studies or reports[176]. Although interesting, these criteria will not be described further in this thesis.

Take home message

- ✓ The main criteria defining an injury are the type, the site, the severity and the rate.
- ✓ Despite successive consensus statements, there is no clear and unique model regarding these criteria among the different systems currently in use.

Ce qu'il faut retenir

- ✓ Les principaux critères définissant une blessure sont son type, sa localisation, sa sévérité et son taux de survenue.
- ✓ Malgré les rapports de consensus successifs, il n'existe pas de modèle clair et unique à propos de ces critères parmi les différents systèmes actuellement en place.

2.3.5 Epidemiology in youth track and field

Available literature about epidemiology in adolescent track and field athletes is scarce. In 2005, Zemper carried out a literature review on "*injuries to youth (<18 years old) in track and field or athletics*."[376] He began with searches of the Medline and SPORT Discus databases for English language articles using the search terms (adolescent or youth) and (track or field or running) and injuries and he collected only nine prospective or retrospective studies that either stated an injury rate or provided enough information to allow some estimation of an injury rate.[376] This search was repeated up until 2011 but only one more article[344] was found and one report.[346] In addition, it is worth mentioning again that the main obstacles (after the scarcity of articles) were the lack of consistency in definition and terminology used in the papers and the absence of differentiation between running athletes and field athletes injuries.

Indeed, the running events are track events and the field events consist of throwing events, horizontal and vertical jumps. The majority of running injuries are attributable to overuse of the musculoskeletal system. Field events involve the generation of maximum force in a short period of time and most of the injuries sustained in these events are the result of the high stresses generated by maximal muscle contractions.[376]

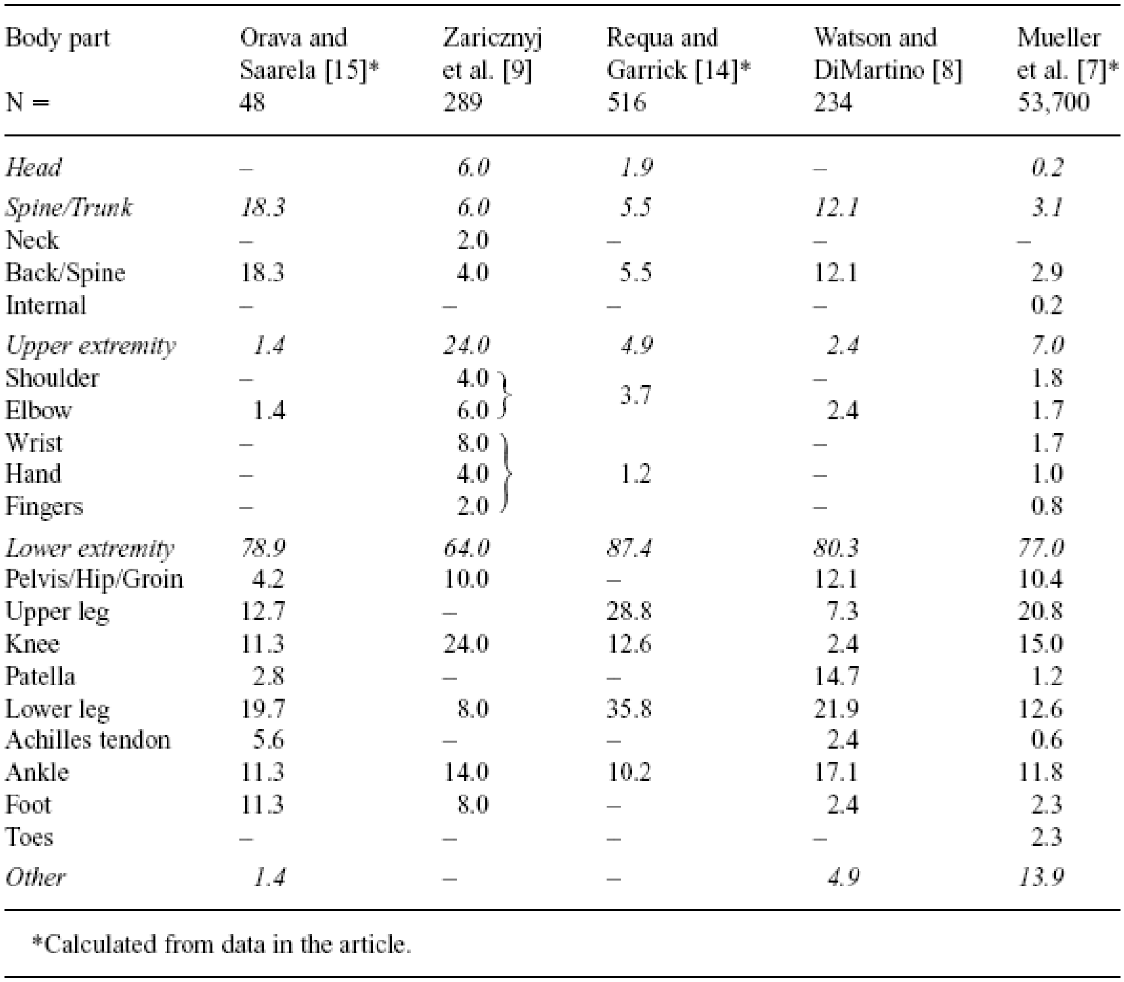
2.3.5.1 Type of injury

Zemper reported that muscle strains appeared to be a predominant type of injury across all the collected studies.[376] "*Inflammation*" also was a major type of injury in three of the studies, but it appears that this terminology is too vague and not appropriate, especially in young athletes. Ligament sprains were also a common type of injury across all the studies. Theisen et al. found in their retrospective epidemiological report involving adolescents and young adults, that 71.4% of the injuries sustained by track and field athletes were "overuse" injuries.[346] Nevertheless, the very small sample size (n = 14) must make us very cautious in the interpretation of this data. Orava and Puranen reported that about 33% of the injuries were growth disturbances or osteochondroses, about 15% were anomalies, deformities or earlier osteochondritic changes, which caused first symptoms during the physical exercise and 50% were typical overuse injuries that may be sustained by adult athletes as well.[290] Although their study is already old, these authors must be commended for having considered specific injuries related to adolescents like apophysitis or Scheuermann's disease.

2.3.5.2 Site of injury

Five of the studies reviewed by Zemper provided information on the body part injured and allowed the calculation of the distribution in percentage of total injuries (Table 2.3.5).[11, 19, 68, 266, 290, 306, 361, 371, 375, 376] The great majority of injuries were reported in the lower extremities, as they accounted for 64–87% of all injuries. It is fairly consistent that the highest percentages of injuries occur in the upper leg, knee, lower leg and ankle. These findings were confirmed by Tenforde et al. with tibial stress syndrome, ankle sprain, patellofemoral pain, Achilles tendonitis, iliotibial band syndrome and plantar fasciitis being the most reported injuries in this study about high school athletes currently participating in long-distance running or cross-country.[344] From the North Carolina High School Athletic Injury Study report, upper-leg (22.9%), foot-ankle-lower leg (18.7%), pelvis-hip-groin (15.9%) and knee (15.1%) were the most frequently injured sites in male track and field athletes aged from 14 to 18 years.[266] This data emphasized the high rate of injury sustained by the lower extremity structures, especially the ankle.

Table 2.3.5: A percent comparison of injury location in youth track and field. (Zemper, 2005)



Body part N =	Orava and Saarela [15]* 48	Zaricznyj et al. [9] 289	Requa and Garrick [14]* 516	Watson and DiMartino [8] 234	Mueller et al. [7]* 53,700
Head	–	*6.0*	*1.9*	–	*0.2*
Spine/Trunk	*18.3*	*6.0*	*5.5*	*12.1*	*3.1*
Neck	–	2.0	–	–	–
Back/Spine	18.3	4.0	5.5	12.1	2.9
Internal	–	–	–	–	0.2
Upper extremity	*1.4*	*24.0*	*4.9*	*2.4*	*7.0*
Shoulder	–	4.0	3.7	–	1.8
Elbow	1.4	6.0		2.4	1.7
Wrist	–	8.0	1.2	–	1.7
Hand	–	4.0		–	1.0
Fingers	–	2.0		–	0.8
Lower extremity	*78.9*	*64.0*	*87.4*	*80.3*	*77.0*
Pelvis/Hip/Groin	4.2	10.0	–	12.1	10.4
Upper leg	12.7	–	28.8	7.3	20.8
Knee	11.3	24.0	12.6	2.4	15.0
Patella	2.8	–	–	14.7	1.2
Lower leg	19.7	8.0	35.8	21.9	12.6
Achilles tendon	5.6	–	–	2.4	0.6
Ankle	11.3	14.0	10.2	17.1	11.8
Foot	11.3	8.0	–	2.4	2.3
Toes	–	–	–	–	2.3
Other	*1.4*	–	–	*4.9*	*13.9*

*Calculated from data in the article.

2.3.5.3 Severity of injury

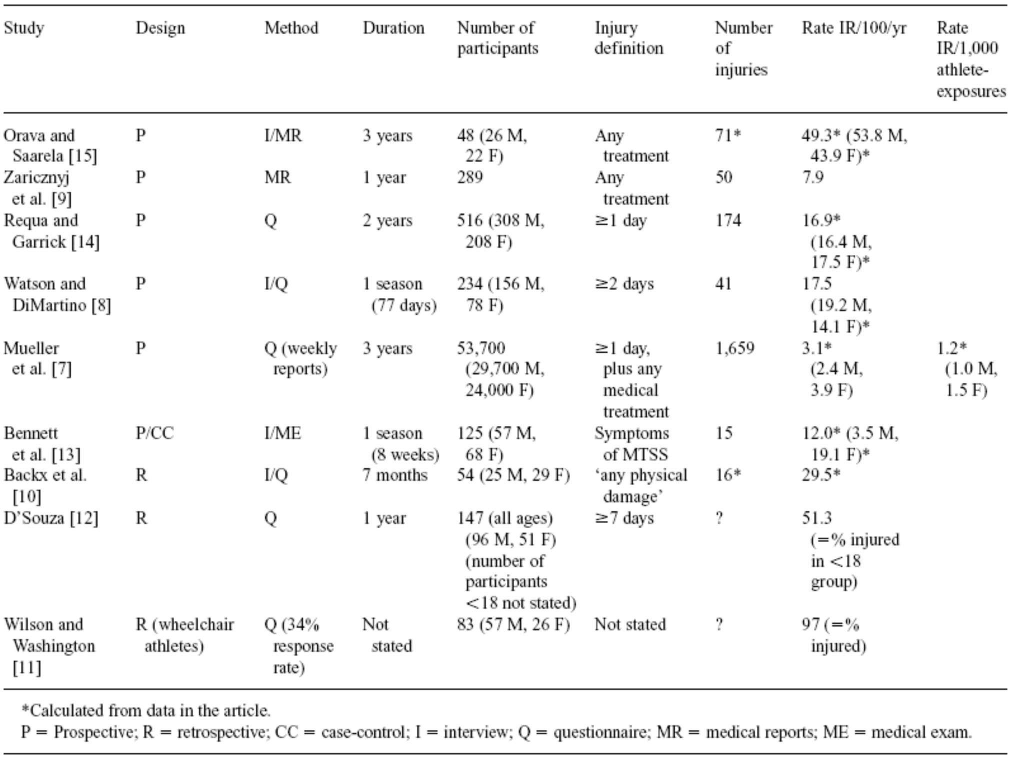
Available data regarding injury severity based on time loss is very scarce, as only two studies provided information on this criterion.[266, 306] Requa and Garrick reported that boys and girls had a similar pattern, with 16% of injuries with duration of absence more than 10 days and 35% of injuries with more than 5 days lost.[306] The more recent and much larger study by Mueller et al. showed a different trend, with 50% of injuries in boys lasting one week or longer.[266] In addition to the scarcity of data, as already noted by Zemper, it is difficult to make comparisons with these studies because they used different breakdowns of the number of days lost.[376]

2.3.5.4 Incidence of injury or injury rate

As previously stated,[376] only nine studies reported track and field injuries in children, with either an injury rate or information to estimate an injury rate (Table 2.3.6).[11, 19, 68, 266, 290, 306, 361, 371, 375, 376] Only one study displayed the calculation of injury rates per 1000 exposures where the authors reported a rate of 1.2 injury per 1000 exposures.[266] The data provided by the North Carolina High School Athletic Injury Study report allowed us to calculate the injury rate for this population of high-school male athletes.[266] It shows a very low rate of 0.9 lower limb injuries per 1000 exposures (for both training and competitions). The strength of this report was the huge sample size (100 schools), which represents 596097 Athlete-Exposures in male track and field athletes.[266]

Rates per 100 per year were given in three of the studies,[11, 19, 68, 266, 290, 306, 361, 371, 375, 376] but sufficient information regarding numbers of participants and injuries was provided in the other studies to allow calculation of these rates. This rate was 31.6 (3.1 – 97.0) injuries per 100 participants per year on average, which is minimally useful in accordance with the great disparities between studies.[11, 19, 68, 266, 290, 306, 361, 371, 375, 376]

Table 2.3.6: A comparison of injury rates in track and field in adolescents. (Zemper, 2005)



Study	Design	Method	Duration	Number of participants	Injury definition	Number of injuries	Rate IR/100/yr	Rate IR/1,000 athlete-exposures
Orava and Saarela [15]	P	I/MR	3 years	48 (26 M, 22 F)	Any treatment	71*	49.3* (53.8 M, 43.9 F)*	
Zaricznyj et al. [9]	P	MR	1 year	289	Any treatment	50	7.9	
Requa and Garrick [14]	P	Q	2 years	516 (308 M, 208 F)	≥1 day	174	16.9* (16.4 M, 17.5 F)*	
Watson and DiMartino [8]	P	I/Q	1 season (77 days)	234 (156 M, 78 F)	≥2 days	41	17.5 (19.2 M, 14.1 F)*	
Mueller et al. [7]	P	Q (weekly reports)	3 years	53,700 (29,700 M, 24,000 F)	≥1 day, plus any medical treatment	1,659	3.1* (2.4 M, 3.9 F)	1.2* (1.0 M, 1.5 F)
Bennett et al. [13]	P/CC	I/ME	1 season (8 weeks)	125 (57 M, 68 F)	Symptoms of MTSS	15	12.0* (3.5 M, 19.1 F)*	
Backx et al. [10]	R	I/Q	7 months	54 (25 M, 29 F)	'any physical damage'	16*	29.5*	
D'Souza [12]	R	Q	1 year	147 (all ages) (96 M, 51 F) (number of participants <18 not stated)	≥7 days	?	51.3 (=% injured in <18 group)	
Wilson and Washington [11]	R (wheelchair athletes)	Q (34% response rate)	Not stated	83 (57 M, 26 F)	Not stated	?	97 (=% injured)	

*Calculated from data in the article.
P = Prospective; R = retrospective; CC = case-control; I = interview; Q = questionnaire; MR = medical reports; ME = medical exam.

Take home message

- ✓ Available literature about epidemiology in adolescent track and field athletes is scarce.
- ✓ The great majority of injuries were reported in the lower extremities, especially at knee and foot-ankle.
- ✓ The lower limb injury rate remains very low in youth track and field (for both training and competitions) if compared with team/contact sports.
- ✓ It has been assumed that 33% of the injuries sustained by adolescent athletes were growth disturbances or osteochondroses, about 15% were anomalies, deformities or earlier osteochondritic changes and 50% were typical overuse injuries.

Ce qu'il faut retenir

- ✓ La littérature disponible au sujet de l'épidémiologie des blessures chez les jeunes en athlétisme est très limitée.
- ✓ Une grande majorité de blessures ont été rapportées comme survenant au niveau du genou et du complexe pied-cheville.
- ✓ Le taux de blessures des membres inférieurs en athlétisme est très faible (entrainements + compétitions) en comparaison de celui des sports d'équipes ou de contact.
- ✓ Il a été avancé que 33% des blessures contractées par de jeunes athlètes étaient des pathologies de croissance ou des ostéochondroses, environ 15% étaient des anomalies, déformations ou des suites d'anciennes ostéochondroses et 50% étaient des pathologies de surmenage typiques.

2.3.6 Specific injuries in adolescents

When reviewing all the articles published about the injuries in adolescent track and field athletes, Zemper observed in 2005 that sprains and strains were some of the most reported injuries.[376] Nevertheless, it is worth noting that these types of injuries are usually considered as “adults” injuries. As suggested by Orava et Puranen,[290] it is likely that specific growth-related injuries coexist in this population with injuries that may affect adult athletes as well. Even though typical growth-related adolescent injuries are now well listed in the medical literature,[47,46] it is assumed that they are still frequently underestimated and underreported in the articles dealing with sports epidemiology.[171] The following sub-sections aim to emphasize the uniqueness of the adolescent athlete in order to further clarify his specific injuries.

2.3.6.1 The uniqueness of the young athlete

The young athlete is particularly vulnerable to sports injuries because of the physical and physiological processes of growth.[116] Several injury risk factors are unique to the young athlete including susceptibility to growth plate injury, nonlinearity of growth or limited thermoregulatory capacity.

As widely reported in the medical literature,[47,46, 116] but also in the IAAF “*specific considerations for the child and adolescent athlete*” guidelines,[168] body areas specifically affected in adolescents (i.e. bone tissue and apophyses) are different than in adults (i.e. muscles and tendons). The muscle-tendon units elongate secondarily in response to bone growth leading to tightness of the muscles in adolescents, especially in muscles crossing two joints.[168] This tightness then exposes the apophyseal cartilage to a strong traction from the muscle-tendon unit, resulting in either an acute avulsion fracture or traction apophysitis, depending on whether the muscular traction applied is sudden and intense or chronic and repetitive.[47,46, 116] This was named the “*tissue preload concept*” (i.e. the amount of force sustained by a tissue in a normal relaxed state of the body).[151] Another area especially susceptible to fractures is the line of weakness between the epiphyseal plate and the formed bone (e.g. growth plate).[151] The resistance of growth plate cartilage to stress is lower than articular cartilage to compression and shearing and adjacent bone to shear and tension forces.[47] In addition, the growth plate may be two to five times weaker than surrounding fibrous tissue.[285] Therefore, when disruptive forces are applied to an extremity, failure may occur through the growth plate.[47] The IAAF guidelines also emphasize that the long bones are more porous in adolescent, so buckling fractures are more common and more flexible undergoing a higher risk of plastic deformation as part of a fracture.[168] Finally, thicker, growing articular cartilage in adolescents leads to chondral or osteo-chondral fragmentation from overuse, especially at the distal femoral condyle, radial head and humeral head.[168]

Beside these risks related to the ossification process occurring during adolescence period, some physiological characteristics of the young athletes must be mentioned as well. The normal growth pattern is nonlinear; it means that differential growth of the body segments (head, trunk and lower extremities) occurs throughout growth and affects body proportions accordingly. It can be considered as a biomechanical injury risk factor.[47, 217] Exercising children and adolescents do not adapt as effectively as adults when exposed to high temperature. Indeed, a child/adolescent will generate more heat for a given activity, yet is less able to dissipate body heat particularly in a hot environment.[47, 217, 358] As children/adolescents usually do not drink enough to replenish fluid loss, they may experience dehydration and increased risk of heat illness and injury.

All these potential risk considerations (i.e. the ones related to the ossification process and physiological ones) taken together with the lack of information/knowledge of many coaches of youth sports about these growth and development characteristics of their athletes may explain the high injury rate in this population.[46]

2.3.6.2 The specific adolescent injuries

As shown in the anatomy-related chapter of this thesis, the growing parts of the bone include the physis and the epiphysis. Two types of epiphyses are found in the extremities: traction and pressure.[46] Firstly, traction epiphyses (or apophyses) are located at the site of attachment of major muscle tendons to bone and are subjected primarily to tensile forces (Figure 2.42). Acute or chronic injuries affecting traction growth plates are not generally associated with disruption of longitudinal bone growth.[46] Overuse apophyseal conditions, such as Osgood-Schlatter disease at the tibial tubercle, Sever's disease at the calcaneus and medial epicondylopathy in the throwing arm are common in young athletes and may be the source of significant discomfort and time lost from training.[46] Chronic repetitive muscular traction exerted on an immature skeleton, usually at the time of a growth spurt, may result in traction apophysitis.[7, 47] Also, sudden intense muscular traction exerted on an immature skeleton (i.e. during a period of rapidly increasing muscular strength) may result in an acute avulsion fracture of a growth plate, an injury not possible in adulthood.[7, 47] The pressure epiphyses are situated at the end of long bones and are subjected to compressive forces. The growth plate is located between the epiphysis and metaphysis and is the essential mechanism of endochondral ossification.[46, 285]

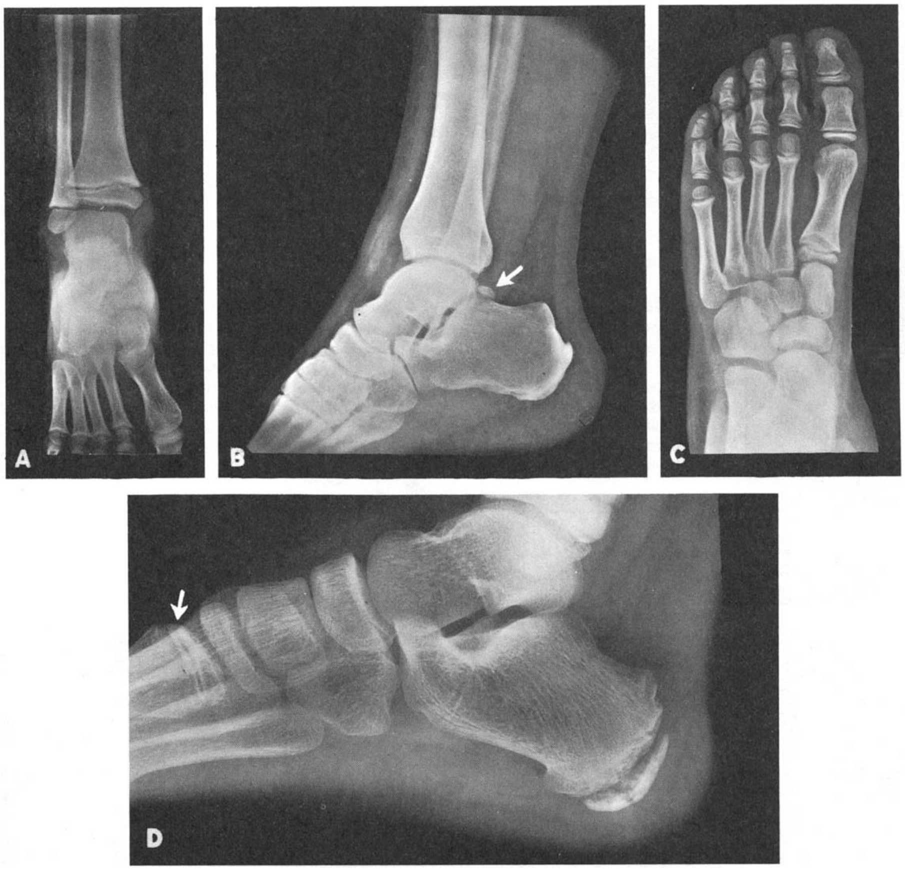


Figure 2.42: Child and adult X-ray of foot and ankle. A, Child's ankle. Note the epiphyses for the inferior ends of the fibula and tibia. The epiphysial line of the fibula is in line with the ankle joint. B, lateral view of an adult ankle. C, Child's foot. Note the epiphyses for the metatarsals and phalanges. D, lateral view of child's foot. Adapted from Warwick and Williams (1989)[360]

In contrast with traction growth plates, injury to pressure epiphyses and their associated growth plates may result in growth disturbance. Sport training, if of sufficient duration and intensity, may precipitate pathological changes of the growth plate. This overuse injury appears to occur through repetitive loading, which alters metaphyseal perfusion, which can in turn interfere with the mineralisation of the hypertrophied chondrocytes.[46] In some situations, this ischaemic condition may lead to osseous necrosis and deformity within the developing ossification centre and to growth irregularities in the physis. These changes may be localised and cause asymmetric growth, or they may involve the entire physis and result in an overall slowdown of the rate of growth or even complete cessation of growth in this area.[46] Acute growth plate injuries do occur in sport and may account for as much as 30% of injuries, as reported in one study.[46, 54] However, the proportion of physeal injuries is probably much less, ranging from 1% to 12% of injuries depending on the sport.[46] The injury mechanisms producing a separation of the growth plate in non-mature athletes are similar to those that in an adult may result in a complete tear of a ligament or in a joint dislocation, e.g. as a result of a fall usually while running or cutting.[46] A classification system was elaborated for describing the acute physeal injuries (i.e. Salter-Harris classification) from severity type I showing a complete separation of the epiphysis from the metaphysis without any bone fracture to severity type V showing a compression of the growth plate and thereby interrupting further growth (Figure 2.43). Some diseases are also typical of childhood and adolescence such as Scheuermann's disease (i.e. juvenile osteochondrosis of the spine) or spondylolysis, but they will not be further detailed here.

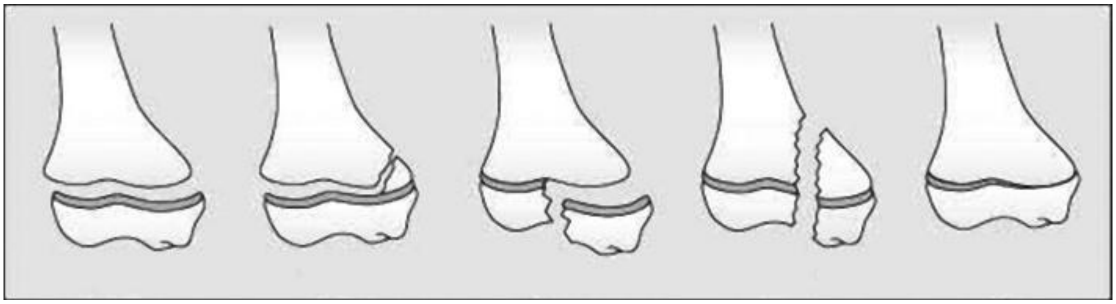


Figure 2.43: An illustration of the types of growth plate injury as classified by Salter and Harris. (Caine et al. 2006)

Take home message

- ✓ Growth-related injuries are frequently underestimated and underreported in the articles dealing with sports epidemiology.
- ✓ The young athlete is particularly vulnerable to sports injuries because of the physical and physiological processes of growth (e.g. susceptibility to growth plate injury, nonlinearity of growth or limited thermoregulatory capacity).
- ✓ Chronic repetitive muscular traction exerted on an immature skeleton, usually at the time of a growth spurt, may result in traction apophysitis.
- ✓ Injury to pressure epiphyses and their associated growth plates may result in growth disturbance.

Ce qu'il faut retenir

- ✓ Les blessures liées à la croissance sont fréquemment sous-évaluées et sous-représentées dans les articles traitant de l'épidémiologie sportive.
- ✓ Le jeune athlète est particulièrement exposé aux blessures sportives et vulnérable en raison du processus de croissance physique et physiologique qu'il traverse (risque de pathologie des cartilages de croissance, croissance non-linéaire ou capacité limitée de thermorégulation).
- ✓ Les tractions musculaires répétées exercées sur le squelette immature du jeune athlète, en général en période de pic de croissance, risque de conduire à une apophysite par traction.
- ✓ Les blessures de compression des épiphyses et de leurs cartilages de conjugaison peuvent aboutir à des désordres de croissance.

2.3.7 The main foot-ankle injuries sustained by adolescent track and field athletes

As suggested by Orava and Puranen,[290] a number of injuries sustained by the adolescent athlete are injuries that may be sustained by adult athletes as well, but would be less common in adolescents than in their adult counterparts. The main traumatic injuries reported are ankle sprains, calf strains and foot or ankle fractures, while the main overuse injuries are medial tibial stress syndrome, stress fractures foot-ankle tendinopathies. These injuries at the foot-ankle +/- lower leg level are well known and this is not the purpose of this work to detail them.

Among athletic injuries, the foot is the third most common cause of time lost in sport, with the ankle and knee being more common. Overall, foot and ankle injuries have been described as the second most frequent reason for a visit to the primary care physician in young athletes.[131] It is worth repeating that typical growth-related adolescents' injuries are probably and widely underreported in the articles dealing with sports epidemiology, mainly because no specific terminology of adolescent injury type is available in most of the reporting systems.

2.3.7.1 Data extracted from the sports epidemiology literature

In their review about overuse injuries in high school athletes participating in long-distance running, Tenforde et al. reported that tibial stress injury, ankle sprain, Achilles tendonitis and plantar fasciitis accounted for 34%, 28%, 6% and 3% respectively in adolescent boys aged from 13 to 18 years.[344] This means that at least 71% of the sustained injuries occurred at the foot-ankle/lower leg site, which seems to be an overestimation in comparison with other available data. Nevertheless, it is worth noting that the sample population encompasses only runners, cancelling almost all the upper limb injuries and decreasing the trunk injuries if compared with a track and field population. In the review of the available literature regarding adolescent injuries in track and field up until 2005, Zemper found that 39.5% (from 29.6% to 47.9%) of the reported injuries occurred at the foot-ankle/lower leg region (calculated from the data of the article);[376] this percentage dropped down to 19.8% (10.2% – 28.1%) if the lower leg injuries were not included.[21,171-177266, 306] This data appears to corroborate the range of the ankle injuries percentage reported by Theisen et al.,[346] who found that 31.2 % of the injuries sustained in the Luxembourg adolescent population involved in individual sports occurred at the ankle level. As this data does not consider only track and field but also other individual sports like triathlon, gymnastics or karate, this is bit speculative to guess the exact proportion of track and field-related injuries. Finally, only the report by Mueller et al. provided enough data for evaluating the rate of ankle injuries in adolescent athletes (but only those sustained during practice).[266] These authors reported 115 ankle injuries during 596097 Athlete Exposures, which means a rate of 19.29 injuries per 100000 Athlete Exposures or 0.2 injuries per 1000 Athlete Exposures. This rate may seem very low, but it must be kept in mind that it does not encompass the injuries sustained during competitions, where the injury rate is known to be around four times higher than training.[376] At this stage and as mentioned above, the absence of data about the specific growth-related injuries was obvious, when scrutinising only the "non-medical" sports science epidemiological studies. It must be however recognized that the two sources cited, described this situation.[290,168] The IAAF emphasizes in its recommendations about "*specific considerations for the child and adolescent athlete*" that sports medicine physicians must be familiar with the normal patterns of growth and development of the child and adolescent, in order to detect any abnormal patterns, make appropriate judgments and guide the coaches in the design of safe and effective training programmes.[168] Unfortunately, the lack of details provided by the IAAF regarding the growth-related injuries was however regrettable in the chapter 10 (*Specific injuries by anatomic site/ankle & foot injuries*), dealing with clinical examination and treatment recommendations could be seen as an oversight.[168] In the study carried out prospectively during three years in Finland, Orava and Puranen examined 147 cases of exertion (i.e. overuse) injuries in < 15 years old athletes, including 64.6 % of track and field athletes.[290] In general, they reported that about 33% of the injuries were growth disturbances or osteochondroses, about 15% were anomalies, deformities or earlier osteochondritic changes, which caused first symptoms during physical exercise and 50% were typical overuse injuries that may be also sustained by adult athletes.[290] Of the track and field boys included in that study, 44.2% of the sustained injuries affected the foot-ankle region, while 61.1% of the total amount of injuries occurring at foot-ankle site in the whole male population (i.e. track and field and other sports) were Sever's disease.[290]

2.3.7.2 Data extracted from the medical literature

Despite the two latter sources (i.e. IAAF recommendations and Orava and Puranen's article), it is clear that the non-medical literature is quite poor in considering and reporting exhaustively the sport-related adolescent injuries, mainly by neglecting the growth-induced injuries. Therefore it appears critical to list the typical youth (i.e. growth-related) foot-ankle injuries sustained by adolescent athletes reported in the medical literature.

2.3.7.2.1 Apophysites

2.3.7.2.1.1 Sever's disease

Calcaneal apophysitis, or Sever's disease is common in children between the ages of 8 and 12 years and accounts for more than 8% of the overuse injuries in children and adolescents.[131, 299] It is usually described as an apophysitis resulting from repetitive micro trauma at the heel, which causes micro avulsions at the bone-cartilage junction (Figure 2.44). It occurs when the repetitive injuries outpace the ability of the bone to heal.[366] Nevertheless, new evidences indicate that Sever's disease actually may result from repetitive compression to the actively remodelling metaphysis.[131, 299] These authors suggested that Sever's disease actually is a chronic repetitive injury (compression) to the actively remodelling trabecular metaphyseal bone rather than a traction injury to the apophysis.[131, 286] This assumption was confirmed by Scheuer and Black[319] who defined the Sever's disease as a stress fractures in the epiphysis following repeated pounding activities. It is worth noting here that Sever's disease regularly results in referred pains/symptoms in adjacent structures, such as Achilles tendon – which may sometimes and wrongfully be diagnosed as a tendinopathy.

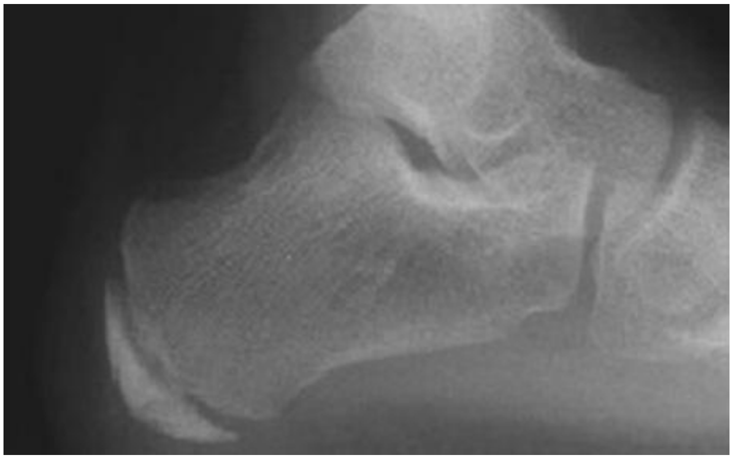


Figure 2.44: Radiography of a Sever's disease case. Adapted from e-radiography.net

2.3.7.2.1.2 Accessory navicular

This is the most common accessory bone in the foot. It lies on the medial, plantar border of the navicular at the site of *tibialis posterior* tendon insertion (Figure 2.45).[289,295] Few become symptomatic. It has been suggested that tensile failure in the cartilaginous synchondrosis was the cause of pain.[144, 289] In the adolescent athletic population, symptoms may arise secondary to pressure over the bony prominence, a tear in the actual synchondrosis, or *tibialis posterior* tendonitis.[55, 289] In this case, the athlete will present with pain and a prominence over the navicular in a pronated foot.

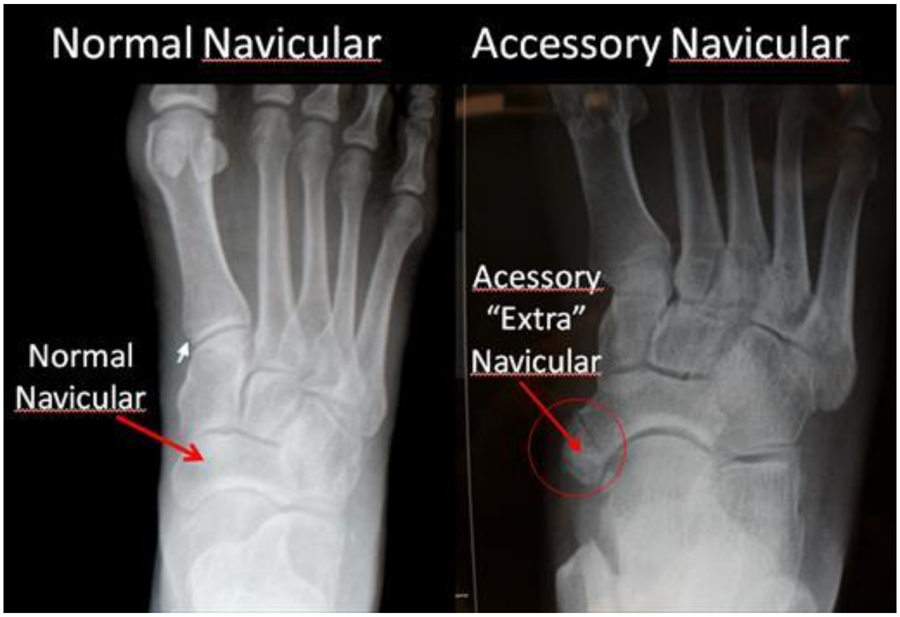


Figure 2.45: Radiography of accessory navicular. Adapted from e-radiography.net

2.3.7.2.1.3 Iselin's disease

Iselin's disease is a traction apophysitis of the tuberosity of the fifth metatarsal which is commonly diagnosed in athletically active older children and adolescents.[289,295] The secondary centre of ossification is located on the lateral plantar aspect of the tuberosity of the fifth metatarsal and this apophysis is located within the insertion site of the *peroneus brevis* tendon. The centre appears in boys at 12 years and usually fuses to the shaft around 14 years. The patient will usually be a young athlete involved in sports with running, cutting and jumping, resulting in an inversion stress to this area. Iselin's disease can be differentiated from an avulsion fracture of the base of the fifth metatarsal because the apophysis is located parallel to the long axis of the shaft and an avulsion fracture is usually transverse in nature.[289]

2.3.7.2.2 Osteochondroses

2.3.7.2.2.1 Freiberg's infraction

Freiberg's infraction is avascular necrosis of the second metatarsal epiphysis. The epiphysis is located at the distal end of the metatarsal.[289,295] Etiology is usually secondary to the repetitive trauma of sport or foot pronation with a hypermobile first metatarsal, resulting in transfer of pressure to the second metatarsal, in usually 13 year old adolescents. Less commonly, this can also occur at the third, fourth, or fifth metatarsal heads as well.

2.3.7.2.2.2 Osteochondritis dissecans

Osteochondritis dissecans (OCD) of the talus may result from an inversion stress to the ankle.[289] This is actually a "transchondral fracture" secondary to trauma.[233] More commonly, onset of pain is insidious. Young athletes may present with pain over the anterolateral or posteromedial talus. Osteochondritis dissecans of the metatarsal head is part of the differential diagnosis of first metatarsophalangeal joint pain.

2.3.7.2.3 Traumatic injuries

2.3.7.2.3.1 Ankle fractures

In the adolescent, the distal tibial and fibular growth plates form a plane of weakness, resulting in injury patterns markedly different from those seen in adults.[289] As already mentioned,[47,46] ligaments in the skeletally immature may be stronger than the physis, increasing the risk of physeal injury rather than ligamentous sprain.[289] Fractures of the distal tibial and fibular physes constitute 4% of all ankle injuries.[289]

2.3.7.2.3.2 Metatarsal fractures

Metatarsal fractures are common in children and adolescents participating in sports. This can occur indirectly as a result of torsional forces and avulsions or from direct trauma.[295,292] The incidence of first metatarsal fractures is highest with children under 5 year of age. The fifth metatarsal, however, is the most common metatarsal fracture in children and adolescents. The fifth metatarsal has its epiphysis distally and its apophysis located proximally. An inversion stress can cause the *peroneus brevis* to avulse the base of the metatarsal, resulting in a transverse fracture.[321] The normal apophysis is diagonal in nature, aiding in its distinction from a fracture. The second type of fracture affecting the fifth metatarsal bone occurs at the junction of the metaphysis and diaphysis and is named a “Jones fracture”. It is due to the vertical ground force applied on a weight bearing foot. This fracture is less common in the skeletally immature athlete and the average age of occurrence is 15-21 year, mainly in subjects involved in athletics.[289]

Take home message

- ✓ Calcaneal apophysitis, or Sever's disease is common in children between the ages of 8 and 12 years.
- ✓ Metatarsal fractures are common in children and adolescent involved in sports.

Ce qu’il faut retenir

- ✓ L’apophysite calcanéenne ou maladie de Sever est très commune chez les enfants âgés de 8 à 12 ans.
- ✓ Les fractures des métatarsiens sont communes chez les enfants et les adolescents pratiquant un sport.

2.3.8 Hyperpronation-related injuries

In the former sections, it has been tried to describe as exhaustively as possible the overuse and growth-related injuries sustained in track and field. It is however worth noting that a considerable part of the injury prevention strategies proposed in the following sections are in relation with hyperpronation. It is therefore of interest to briefly describe the main hyperpronation-related injuries, whereas some relations of cause (hyperpronation) and effect (injury) are still debated,[161] as stipulated by Hintermann and Nigg in the preamble of their review of literature “*Excessive pronation (ankle joint eversion) has been typically associated with the development of overuse injuries in locomotion. Individuals with injuries typically have pronation movement that is about 2 to 4° greater than that of those with no injuries. However, between 40 and 50% of runners with excessive pronation do not have overuse injuries”.* In this regard, Stovitz and Coetzee provided an interesting contribution by drawing a diagram of the interrelationships between the causes and effects of hyperpronation (Figure 2.46).[340] Even this diagram should probably be completed with some more topics, it displays clearly how hyperpronation interacts with several factor as a cause, as an effect or sometimes both.

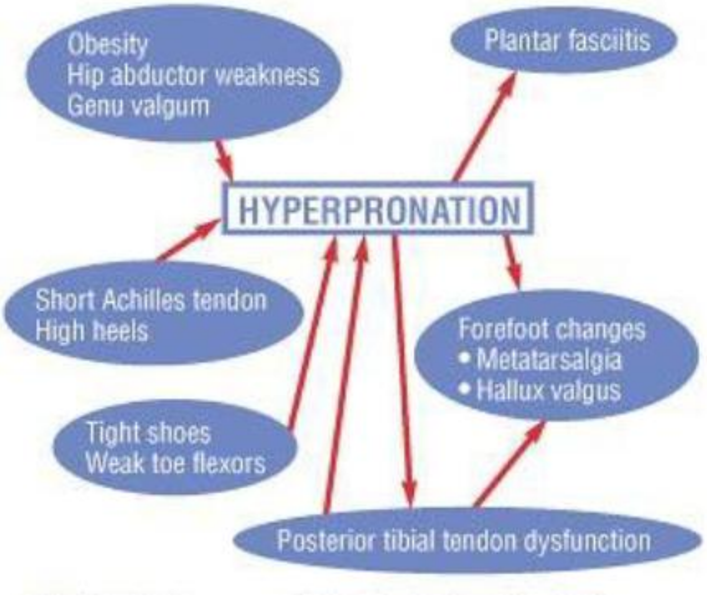


Figure 2.46: Diagram of the interrelationships between the causes and effects of hyperpronation. (Stovitz and Coetzee, 2004)

2.3.8.1 Foot-ankle injuries related to hyperpronation

In accordance with the research of Stovitz and Coetzee,[340] deleterious effects of hyperpronation have been implicated in three very common disorders of the feet: plantar fasciitis, posterior tibial tendinopathy and medial metatarsalgia (these authors listed also the *hallux valgus* syndrome but this will not be detailed here). Plantar fasciitis results from a degeneration of the fibrous aponeurosis that courses the medial longitudinal arch. This pathology is seen in patients who have a rigid cavus foot and in those with hyperpronation and either deformity may increase the stress on the plantar fascia. Excessive body weight, *genu valgus* and *gastrocnemius-soleus* tightness are all indirectly associated with increased foot pronation and are known precipitants of plantar fasciitis.[130, 248, 273, 340]

Regarding the posterior tibial tendinopathy, the main insertion for the posterior tibial tendon is on the medial navicular bone but proper functioning of this tendon is necessary for dynamic stabilization of the medial longitudinal arch. Thus, a strong posterior tibial tendon is necessary to protect against hyperpronation. Conversely, hyperpronation from other causes may result in posterior tibial tendon weakness, because the tendon becomes overstretched. Also, with hyperpronation, the forces move medially and the second metatarsal (sometimes the first and the third as well) may assume an excessively large percentage of the force, resulting in metatarsalgia or even stress fractures.[273, 340] Some of these points confirmed or were confirmed by the findings of Hintermann and Nigg, where the authors reported the following overuse injuries to be potentially linked to hyperpronation: medial tibial stress syndrome, *tibialis posterior* tendinopathy, Achilles bursitis and tendinopathy and metatarsal stress fractures.[161] All the biomechanical theories about the relationships between hyperpronation and foot-ankle injuries will not be detailed here. Nevertheless, the potential mechanism leading to Achilles tendinopathy and resulting from hyperpronation appears to be of primary interest. Indeed, Clement et al.[64] and then several authors[178, 213] reported that the hyperpronation at stance phase may generate exaggeration of the so-called "whipping" action of the Achilles tendon and lead to intratendinous microtears (Figures 2.47 and 2.48).

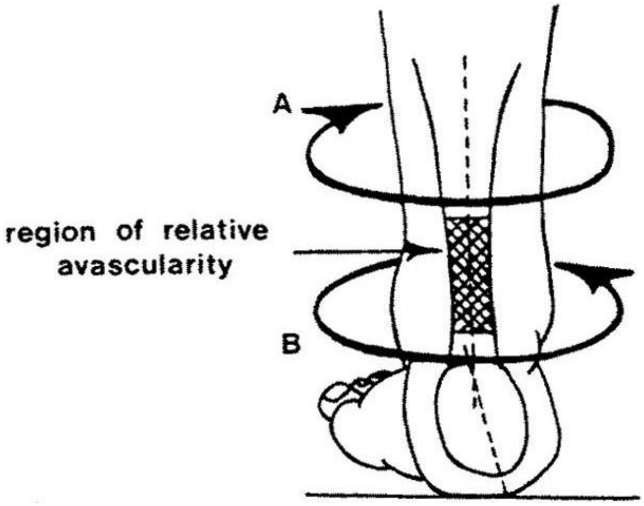


Figure 2.47: Whipping mechanism at the Achilles tendon. (Dr. Christensen personal website http://www.ccptr.org/KDC/kimd)

Figure 2.48: Whipping toy illustration. Adapted from www.google.com

2.3.8.2 Upper segments injuries related to hyperpronation

While studying the lower-extremity mechanics of runners with excessive rearfoot eversion, McClay and Manal defined excessive eversion to be greater than 18°.[225] These authors found that the excessively everted runners also exhibited significantly greater knee flexion, abduction (valgus) and internal rotation than runners with normal rearfoot motion (i.e. 8-12° eversion). As confirmed by Williams et al. and Nigg,[273, 369] these increased motions may lead to abnormal patellofemoral joint alignment and then result in patellofemoral syndromes. The findings of Hintermann and Nigg[161] confirmed that increased pronation was associated with upper segments overuse injuries like patellofemoral disorders,[273] iliotibial friction syndrome and lower extremity stress fractures. Recently, numerous authors confirmed that excessive internal lower leg rotation is induced in a large extent by hyperpronation and may cause numerous injuries at the upper levels.[189, 196, 312, 348] Moreover, based on several studies, these authors represented very clearly on a figure the potential chain reaction of the upper segments to induced hyperpronation (Figure 2.49).[189] This drawing displays the internal rotation at the tibia (through the subtalar joint), inducing internal thigh rotation through the knee joint.

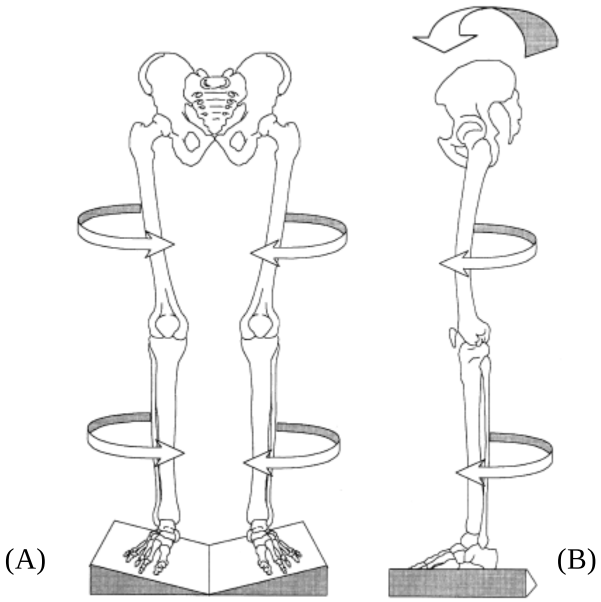


Figure 2.49: Schematic representation of the proposed chain reaction of the upper segments to induced hyperpronation: (A) internal rotation at the tibia through the subtalar joint, inducing internal thigh rotation through the knee joint; (B) bilateral internal rotation of the thigh imposing anterior tilt of the pelvis. (Khamis and Yizhar, 2007)

At the end, it is worth noting that some of the aforementioned interrelations between hyperpronation and subsequent injuries are still discussed. Even some progress has been done since 1998 when Hintermann and Nigg published their review paper, one may remember one of the conclusions: “*Indeed, anatomical/biomechanical alterations appear to be casually related to injury. In running, overpronation may result in some cases of running related overuse injuries but probably in no more than 10% of cases”*.[161]

It has been decided not to describe into details the injuries or injury risks related to excessive supination, as it was just done above regarding hyperpronation. Most of these injuries are induced by the rigidity of the supinated foot and the excessive lateral roll-over process during the stance phase.[128] The main injuries are accordingly linked to the lack of absorption phase (e.g. plantar fasciitis, Sever’s disease) or the overload of the lateral regions of the foot (e.g. fifth metatarsal stress reactions or fractures).[66, 69, 268] The upper segments may also be affected by the consequences of a supinated foot, sustaining for instance iliotibial or medial tibial stress syndromes.

Take home message

- ✓ Deleterious effects of hyperpronation may be implicated in injuries of the foot-ankle: plantar fasciitis, medial metatarsalgia and metatarsal stress fractures, medial tibial stress syndrome, *tibialis posterior* tendinopathy, Achilles bursitis and tendinopathy.
- ✓ Deleterious effects of hyperpronation may be implicated in injuries of the upper segments: patellofemoral disorders, iliotibial friction syndrome and lower extremity stress fractures.
- ✓ Deleterious effects of excessive supination may be implicated in injuries as well: plantar fasciitis, Sever’s disease, fifth metatarsal stress reactions or fractures, instance iliotibial or medial tibial stress syndromes.

Ce qu’il faut retenir

- ✓ Les effets délétères de l’hyperpronation jouent certainement un rôle dans certaines pathologies du pied et de la cheville comme les aponévrosites plantaires, les métatarsalgies médiales, les fractures de fatigue des métatarsiens, les périostites tibiales, les tendinopathies du *tibialis posterior*, les bursites retro-calcanéennes et les tendinopathies d’Achilles.
- ✓ Les effets délétères de l’hyperpronation jouent certainement un rôle dans certaines pathologies les segments sus-jacents comme les syndromes fémoro-patellaires, les syndromes de l’essuie-glace et fractures de fatigues du segment jambier.
- ✓ Les effets délétères de la supination excessive jouent aussi certainement un rôle dans certaines pathologies comme les aponévrosites plantaires, les maladies de Sever, les fractures de fatigue du cinquième métatarsien, les syndromes de l’essuie-glace et les périostites tibiales.

2.3.9 Relationships between injuries and maturity status

As already mentioned several times in this manuscript, the growth period constitutes an at-risk period in adolescent athletes, especially if they are undertaking high training loads at the same time. In addition, it seems that during this growth period, the factors that increase the risk of injuries are the maturity status and the maturity offset (i.e. years from/to the peak height velocity). Chronological age has been described as an inaccurate indicator of biological status; therefore a valid assessment of the biological status of young athletes is required.[171, 255] In the following sections, it is proposed to provide some definitions regarding specific terms related to the adolescent maturation process and measurements, and then to review the relationships between maturation and injury occurrence.

2.3.9.1 Maturation, maturity status, maturity offset

2.3.9.1.1 Growth and maturation

Beunen and Malina stated that *"growth refers to measurable changes in size, physique and body composition and various systems of the body, whereas maturation refers to progress toward the mature state."*[23] They suggested that maturation is variable among bodily systems and also in timing and tempo of progress and that the processes of growth and maturation are related and both influence physical performance.[23]

2.3.9.1.2 Biological age and skeletal age

Growth is considered as the progressive incremental change in size and morphology that occur throughout the development of the individual, overall growth is positively correlated with age, but the relationship consists of two components: increase in size and increase in maturity, but while these two elements are closely integrated, they do not necessarily advance in synchrony. Individuals reach developmental milestones, or biological ages, along the maturity continuum at different chronological ages.[319] It means that the concept of biological age is used as an indicator of how far along the developmental continuum an individual has progressed. Most frequently, biological age is expressed as skeletal age, but it may be also expressed as dental age.[319] As recently defined by Malina,[216] *"the skeletal age is an indicator of biological maturation, the level of maturity of the bones of the hand and wrist. The skeletal age of an individual represents the chronological age at which a specific level of maturity of the hand-wrist bones was attained by the reference sample upon which the method of assessment was developed."*

2.3.9.1.3 Maturity status

As size and maturation are integrated but not necessarily synchronized, it results in some individuals being "advanced" or "delayed" along this process. In other words, the timing of growth varies between individuals of the same chronological age, which results in a different maturity (or maturational) status: early, normal or late.[319] Individuals are usually classified as "early maturers" if their skeletal/biological age is more than 1 year above chronological age, “normal maturers” if their skeletal/biological age is within 1 year of their chronological age and “late maturers” if their skeletal/biological age is more than one year below their chronological age (Figure 2.50).[171]

2.3.9.1.4 Peak Height Velocity and age at Peak Height Velocity

The Peak Height Velocity (PHV) is defined as the maximum rate of growth in height during the adolescent spurt. This peak corresponds to an age called age of PHV (APHV or PHV age).[255] This requires serial measurements for a number of years surrounding the occurrence of peak velocity and thus are unusable in a one-off measurement in time. [23,216]

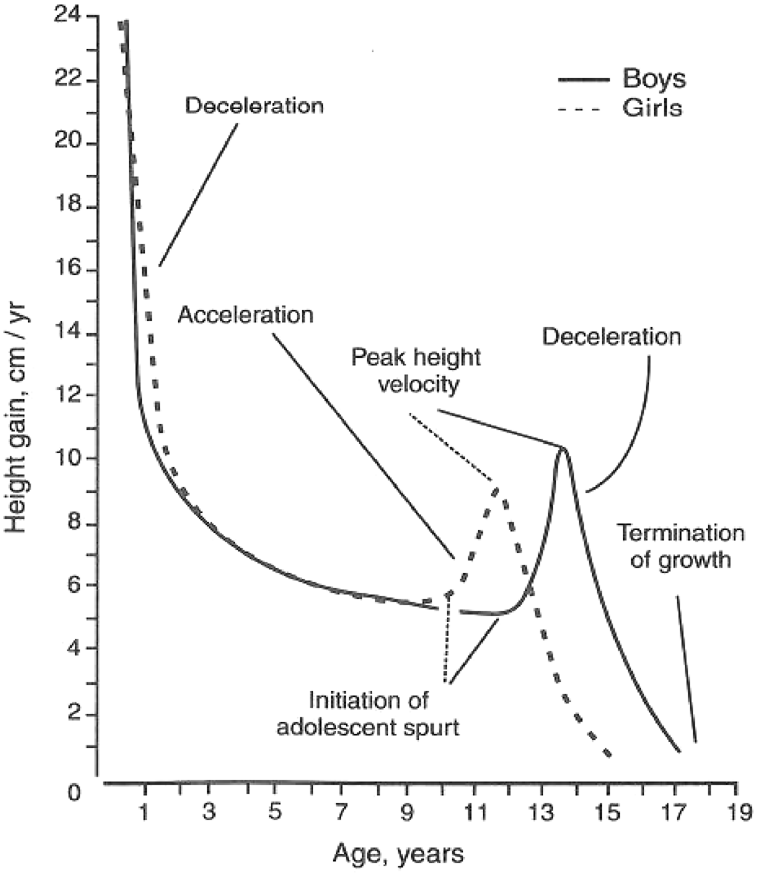


Figure 2.50: Velocity curve for height. (Tanner, Whitehouse and Takaishi, 1966)[342]

2.3.9.2 Methods for assessing maturation

As already mentioned, chronological age is of limited use in the assessment of growth and maturation and the need to assess maturation is of primary interest when dealing with children and adolescents.[255] Two types of methods exist for performing this assessment: non-invasive and invasive.

2.3.9.2.1 Non-invasive methods

Dental age and morphological age are broader measurement techniques, but with limited applicability.[255] The assessment of secondary sex characteristics (e.g. Tanner stages) is limited to the adolescent period (i.e. childhood is excluded) and it may be considered to be personally intrusive by adolescent children and their parents, despite the fact that self-assessment is more and more used.[216, 255] Secondary sex characteristics do not reflect the timing of growth. Somatic methods such as age of peak height velocity or the differential growth associated with regional growth require serial measurements for a number of years surrounding the occurrence of peak velocity and thus are unusable in a one-off measurement in time.[217, 255] Age of PHV is the most commonly used indicator of maturity in longitudinal studies of adolescence.[217] It provides an accurate benchmark of the maximum growth during adolescence and provides a common landmark to reflect the occurrence of other body dimension velocities within and between individuals.[255] This method will be further detailed in the *methods* section of the manuscript.

Nevertheless, the PHV method is far from satisfactory, as it indicates maturation timing and is an after-the- fact indicator. Estimation requires longitudinal data spanning at least 5–6 years around the spurt. Anthropometric data has been shown to be good determinants of PHV, but this requires serial precise measurements (i.e. chronological age, height, sitting height and weight) performed by accredited examiner, several times per year and during the years around the occurrence of PHV. The predictive equation proposed by Mirwald et al.[255] regarding PHV was highly criticised due to its lack of reliability, if one variable (e.g. sitting height) had a high degree of measurement error or when the date of birth is inaccurate particularly in athletes native to Africa where birth dates are not routinely reported, resulting in wrong chronological age.[22, 255]

2.3.9.2.2 Invasive methods

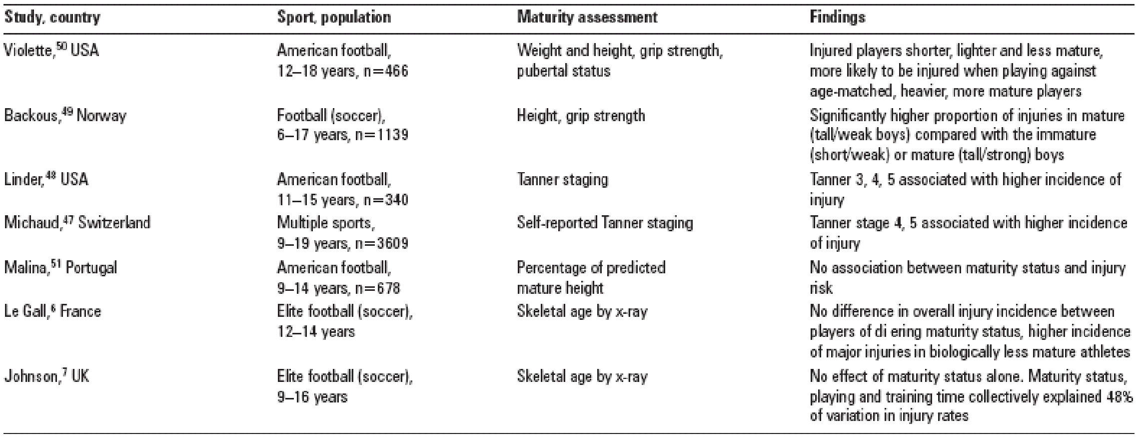
Skeletal age assessment is the single best maturational index but it is costly and requires specialized equipment and interpretation.[98, 216, 255] In addition, although the methodology covers the entire period of growth from birth to maturity, this method does not provide an indicator of the pubertal status of the players in term of his individual maturation timing, i.e. when specific maturational events occur. Skeletal age assessment is basically a method to estimate the level of maturity that a child has attained at a given point in time.[216] Three methods are commonly used to estimate the skeletal age: Greulich-Pyle (GP) and Fels based on American children[98, 216] and Tanner-Whitehouse (TW) based originally on British children and afterwards on samples of several origins.[216, 341] The methods are similar in principle: a hand-wrist radiograph is matched to a set of criteria.[216] However, criteria and procedures for deriving the skeletal age vary with each method.[171,216] The GP method is sometimes called the “atlas method” and it was developed on American White children. The atlas includes plates (standards) representing several boys and girls from birth to maturity. The method is applied by assigning a skeletal age to each individual bone of the hand-wrist (29 bones).[143, 171,216] Usually in practice, GP skeletal ages are improperly based on the skeletal age of the standard plate to which the film of a youngster most closely matches. The TW method was originally based on British children,[216, 341] while the most recent version was based on samples of European (British, Belgian, Italian, Spanish), Argentine, Japanese and well off American youth. Criteria for the stages of maturation of 13 long bones, radius, ulna and metacarpals and phalange of the first, third and fifth digits and seven carpals excluding the pisiform were described. Scores are assigned for the stage of each bone and summed into a maturity score that is converted to skeletal age.[216] The Fels method is based on longitudinal records of 355 boys and 322 girls from USA. Specific maturity indicators for the radius, ulna, carpals and metacarpals and phalanges of the first, third and fifth arrays were described. Grades are assigned to each depending on age and sex. Ratios of linear measurements of the widths of the epiphysis and metaphysis of the long bones are also used and presence (ossification) or absence of the pisiform and adductor sesamoid is noted.[216] Grades and width measurements are entered into a program that calculates skeletal age and standard error.[216] Contributions of specific indicators in computations are weighted depending on age and sex. The standard error provides an estimate of the error in an assessment; it is a unique feature not available with other methods.[171,216]

Skeletal age in general, as estimated via X-ray, is subject to errors of measurement. Due to the different determination methods, the possibility to use different bones (more than 20 bones can be used) and important inter-individual difference in the rate of bone growth, using skeletal age as the gold standard method is not that straightforward.[23, 39, 217] In addition, skeletal age is an absolute measure of maturation and a method to estimate the level of maturity which an adolescent has attained at a given point in time. It means that skeletal age can be defined as the chronological age at which a specific level of skeletal maturity is attained by the reference sample upon which the method of assessment is based. This does not provide an indicator of the pubertal status of the players in terms of his individual maturation timing, which is also of interest when taking care of adolescent athletes. In this case, the use of the maturity offset (i.e. age from/to PHV) is the only possible way to accurately locate a player in relation to this specific maturational event and the age of PHV was described as the most commonly used indicator of maturity in longitudinal studies of adolescence.[39, 49, 50, 217]

2.3.9.3 Existing data regarding the relationships between injury and maturation

Literature assessing the relationship between injury occurrence or severity and maturity status is scarce. Only a few authors have published on this topic in the last 25 years, mainly in soccer, sometimes in multisport but, to the best of our knowledge, never in track and field. It is worth noting that the IOC assembled an expert group in December 2009, aiming to provide a "*consensus statement on age determination in high-level young athletes*".[98] One of the sections of this consensus statement referred to health and safety of the elite adolescent athlete and reviewed the main studies dealing with the effect of maturity status on injury risk. Some of these results will be further detailed in the following section (Table 2.3.7).[98]

Table 2.3.7: Effect of maturity status on injury risk. (Engebretsen et al., 2010)



Study, country	Sport, population	Maturity assessment	Findings
Violette,[50] USA	American football, 12–18 years, n=466	Weight and height, grip strength, pubertal status	Injured players shorter, lighter and less mature, more likely to be injured when playing against age-matched, heavier, more mature players
Backous,[49] Norway	Football (soccer), 6–17 years, n=1139	Height, grip strength	Significantly higher proportion of injuries in mature (tall/weak boys) compared with the immature (short/weak) or mature (tall/strong) boys
Linder,[48] USA	American football, 11–15 years, n=340	Tanner staging	Tanner 3, 4, 5 associated with higher incidence of injury
Michaud,[47] Switzerland	Multiple sports, 9–19 years, n=3609	Self-reported Tanner staging	Tanner stage 4, 5 associated with higher incidence of injury
Malina,[51] Portugal	American football, 9–14 years, n=678	Percentage of predicted mature height	No association between maturity status and injury risk
Le Gall,[6] France	Elite football (soccer), 12–14 years	Skeletal age by x-ray	No difference in overall injury incidence between players of differing maturity status, higher incidence of major injuries in biologically less mature athletes
Johnson,[7] UK	Elite football (soccer), 9–16 years	Skeletal age by x-ray	No effect of maturity status alone. Maturity status, playing and training time collectively explained 48% of variation in injury rates

2.3.9.3.1 Relationships between injury and maturation and maturity status

Based on the self-evaluation of the Tanner stages in adolescents practicing different sports, Michaud et al.[249] found that the risk of injury appears to be linked to biological development (pubertal stage) more than to actual size and weight, body mass index, or chronological age. Linder et al. added that junior high-school football players who have recently experienced sexual maturation may be at higher risk of injury in contact sports.[210] Backous et al. measured height and strength in young soccer players and assumed that tall boys deficient in grip strength were late maturers.[10] They did not measure the maturity status of their subjects but postulated that skeletally mature but muscularly weak boys were more susceptible to injury while playing soccer with peers of the same chronological age. Assessing the skeletal age in a similar population, Johnson et al. identified a potential difference at the expense of early maturers, who may sustain injuries to a greater extent than late or normal maturers.[172] The authors also emphasized also that a degree of caution is required in using maturity status variables when clearly other factors could play a part in explaining the results (i.e. playing and training time). Le Gall et al. found a non-significant higher incidence of major injuries in early and normal maturers, when compared with late maturers.[205] Then it may be concluded, like the authors of the IOC consensus statement, that: "*The evidence for the influence of biological maturity on injury risk is somewhat conflicting. Whereas a number studies demonstrate a higher incidence of injury with increased maturity, other* *studies have found either an increased risk of injury in less mature athletes, or no effect of maturation on overall injury*".[176]

2.3.9.3.2 Relationships between injury risk and maturity offset

Information about the closeness of the PHV (i.e. maturity offset) have also been reported to be of interest by several authors, because of the potential augmented injury risk during the period surrounding the PHV. Although not perfect, the use of the age from/to PHV is therefore the only possibility today to accurately locate a player in relation to this specific maturational event; knowledge of skeletal age does not help in this case.[217] Several theories have been proposed in order to support this assumption of increased injury risk around the PHV age. Firstly, the susceptibility of the growth plate to injury appears to be especially pronounced during periods of rapid growth.[46] An increase in the rate of growth is accompanied by structural changes that result in a thicker and more fragile plate.[14, 46] In addition, bone mineralisation may lag behind bone linear growth during the pubescent growth spurt, rendering the bone temporarily more porous and more subject to injury.[46] Studies of the incidence of physeal injuries in humans indicate the peak fracture rate probably occurring at the time of PHV.[14] The acceleration of the growth rate around the PHV may also increase susceptibility to growth plate injury by causing an increase in muscle-tendon tightness about the joints and an accompanying loss of flexibility.[46, 151, 250] If an excessive muscular stress is applied (i.e. increased tissue preload), a muscle-tendon imbalance is produced that may predispose to injury.[46, 65, 151] As proposed by Michaud et al., the third hypothesis is linked with adolescent neuropsychological development: the rapid modification of the dimensions of the body during puberty, especially around PHV, can lead to clumsiness because of the time required for the adolescent to integrate his body image.[249]

Take home message

- ✓ The maturity status and the maturity offset appear to be in relations with the risk of injury in adolescent athletes, but the evidences for the influence of biological maturity on injury risk are somewhat conflicting.
- ✓ Biological age, skeletal age, maturity status, maturity offset, peak height velocity are the main concepts to be familiar with, when dealing with growth and maturation.
- ✓ There are invasive and non-invasive methods used when studying maturation.
- ✓ Skeletal age assessment is the single best maturational index but it is costly and requires specialized equipment and interpretation.
- ✓ There may be an increased injury risk around the age of peak height velocity.

Ce qu’il faut retenir

- ✓ Le niveau de maturité et la période de maturité semblent être en relation avec le risque de blessures chez les jeunes athlètes, mais les preuves scientifiques relatant l’influence réelle de la maturité biologique sur le risque de blessure sont encore controversées.
- ✓ L’âge biologique, l’âge osseux, le niveau de maturité, la période de maturité et l’âge du pic de croissance sont les principaux critères à connaitre lorsque l’on traite de la croissance et de la maturation.
- ✓ Les méthodes utilisées pour étudier la maturation peuvent être invasives ou non-invasives.
- ✓ L’estimation de l’âge osseux est le meilleur index de maturation mais il est couteux et requiert un équipement et une interprétation spécifiques.
- ✓ Il pourrait y avoir un risque accru de blessures aux alentours de l’âge du pic de croissance.

2.3.10 Limitations and perspectives

As already mentioned on several occasions in this manuscript, the major issue which has challenged many researchers involved in sports injury research is the lack of consensus in study methodologies, regarding injury definition or severity for instance. Most of the studies are limited by the sample size (e.g. only one school or one city or one geographic area) and the short period of data collection e.g. only one year (or season), occasionally two.[229] Another problem with many studies is the source used to obtain injury data. Some rely on insurance claim forms,[229] which has the disadvantage of not representing the true injury rate since not all athletic injuries result in insurance claims. Some studies rely on a coach's assessment or recognition of an injury even though it is known that they do a poor job of recognizing most treatable injuries.[229, 306] In addition, many of the injuries sustained in adolescents are overusing growth-related injuries.[251, 284] As these injuries usually have an insidious onset, this makes it very difficult to pinpoint the real date of injury. In the end, the lack of consideration of the sports science/sports medicine literature and injury reporting systems towards the typical adolescent injuries is regrettable, while numerous medical papers or books abound with data about these growth-related overuse injuries. There are also, of course, some limitations when dealing with maturation, regardless of the method, as previously mentioned. Invasive and non-invasive methods showed limitations. The correlation between invasive and non-invasive methods have been recently studied and controversial results were found. Data derived from a sample of 90 young soccer players [age range: 12.1–17.3years] in our academy showed that age from/to PHV is well correlated (r =0.69, 90%CI; 0.59–0.77) with skeletal age estimated from a hand and wrist radiograph.[39] Malina et al. reported that invasive and non-invasive indicators were related, but that the concordance of these maturity classifications was poor. They concluded that non-invasive indicators of maturity status have limitations for the purpose of designing training and competition programmes.[218]

Of course, all these aforementioned limitations provide a lot of future research questions in the field of adolescent athletes' injury collection and reporting. It is firstly assume that a real and complete synthesis of the highly accurate Sport Medicine Diagnostic Coding System in terms of injury diagnosis and the IOC consensus statement regarding other criteria may result in an almost perfect injury tracking system for adolescent athletes. Along the same lines, a system tracking the maturation process using both invasive and non-invasive methods appears very appropriate. Skeletal age obtained at the beginning of the season and if possible one or two more times per year as individuals may quickly shift from one group to the other, would provide the best estimation of the maturity status of the athletes. Additionally, quarterly PHV estimation may allow the sport science/sport medicine staff to classifying each athlete in pre-, circum- or post-PHV group, in order to adapt the training loads and the injury prevention strategy accordingly. Indeed, as mentioned by Junge et al.[176] "*Standardised injury surveillance provides not only important epidemiological information, but also directions for injury prevention and the opportunity for monitoring long-term changes in the frequency and circumstances of injury.*" This will be the purpose of the following chapter.

2.3.11 Injury prevention

Common foot-ankle musculoskeletal injuries affecting adolescent have been described in the former sections and some of their predisposing factors have already been described. Similar to other injuries, sports injuries are potentially avoidable and this is the purpose of injury prevention strategies. As proposed by Adirim and Cheng,[2] a multi-level approach is needed for sports-related injuries. For youth sports injuries specifically, six potential mechanisms for reducing injuries have been proposed:[2, 157] the pre-season physical/medical examination, medical coverage of the competitions, adequate coaching, proper hydration, proper officiating and proper equipment and field/surface playing conditions. Injury mechanisms and predisposing factors are also topics of primary interest as stated by Van Mechelen and Bahr,[12, 13, 352] considering that "*once it has been recognised through injury surveillance that sports injuries constitute a threat to the health of athletes, the causes must be established as a next step towards injury prevention. This includes information on why a particular athlete may be at risk in a given situation (risk factors) or how injuries happen (injury mechanisms).*"

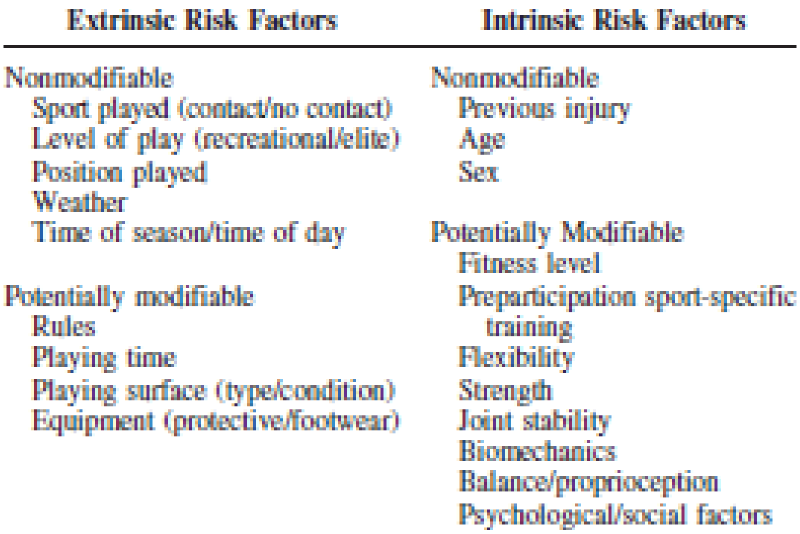
The following sections of this chapter will aim at:

- defining some specific terms related to sports injury prevention,
- reviewing briefly the history of sports injury prevention research and detailing the two main approaches (epidemiological and multifactorial models)
- listing the main foot-ankle risk factors affecting adolescent athletes
- and illustrating the use of adapted countermeasures as soon as risk factors and mechanisms have been clearly identified – by using here the example of hyperpronation while running.

2.3.11.1 Definitions and terminology

Sports-injury prevention was defined by the *online medical dictionary* (from *medical dictionary.com*) as the intervention aiming to reduce the risk of sport-related injury in athletes. One of the main contributors in recent research regarding this topic proposed that sports-injury prevention includes obtaining information on why a particular athlete may be at risk in a given situation (risk factors) and how injuries happen (injury mechanisms).[12, 13] Risk factors (or predisposing factors) in sport have been defined as any factors that may increase the potential for injury. They can be extrinsic or intrinsic to the athlete, modifiable (if potentially altered by injury prevention strategies) or non-modifiable (Table 2.3.8).[88, 238]

Table 2.3.8: Potential risk factors for injury in child and adolescent sport. (Emery, 2003)



Extrinsic Risk Factors	Intrinsic Risk Factors
Nonmodifiable	Nonmodifiable
Sport played (contact/no contact)	Previous injury
Level of play (recreational/elite)	Age
Position played	Sex
Weather	
Time of season/time of day	Potentially Modifiable
	Fitness level
Potentially modifiable	Preparticipation sport-specific training
Rules	Flexibility
Playing time	Strength
Playing surface (type/condition)	Joint stability
Equipment (protective/footwear)	Biomechanics
	Balance/proprioception
	Psychological/social factors

The mechanism or inciting event of an injury is also a critical factor to analyse. A precise description of the mechanism is thought to be a key component for understanding the causes of the injury.[12, 13, 200] The different categories of inciting events will be displayed in the figure 2.54.

2.3.11.2 History of injury prevention

The pioneers of the most commonly cited model of sports injury prevention are undeniably van Mechelen, who proposed the famous sequence of injury prevention research in four steps in 1992 (Figure 2.51).[352] This system based on injury surveillance, identification of risk factors and implementation of prevention strategies is sometimes called the "epidemiological" system. These authors proposed that, firstly, the magnitude of the problem must be identified and described; secondly, the injury risk factors and mechanisms must be identified; thirdly, the proposed measures for reducing risk/severity injuries must be proposed; fourthly, the effect of the measures must be evaluated by repeating the first step.[352]

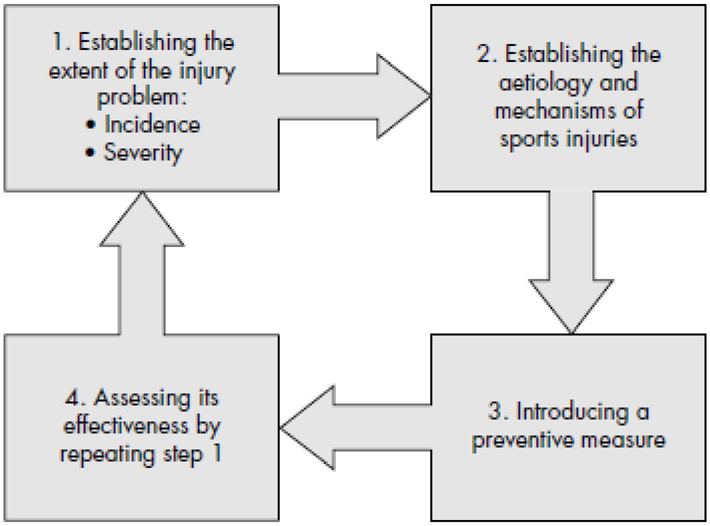
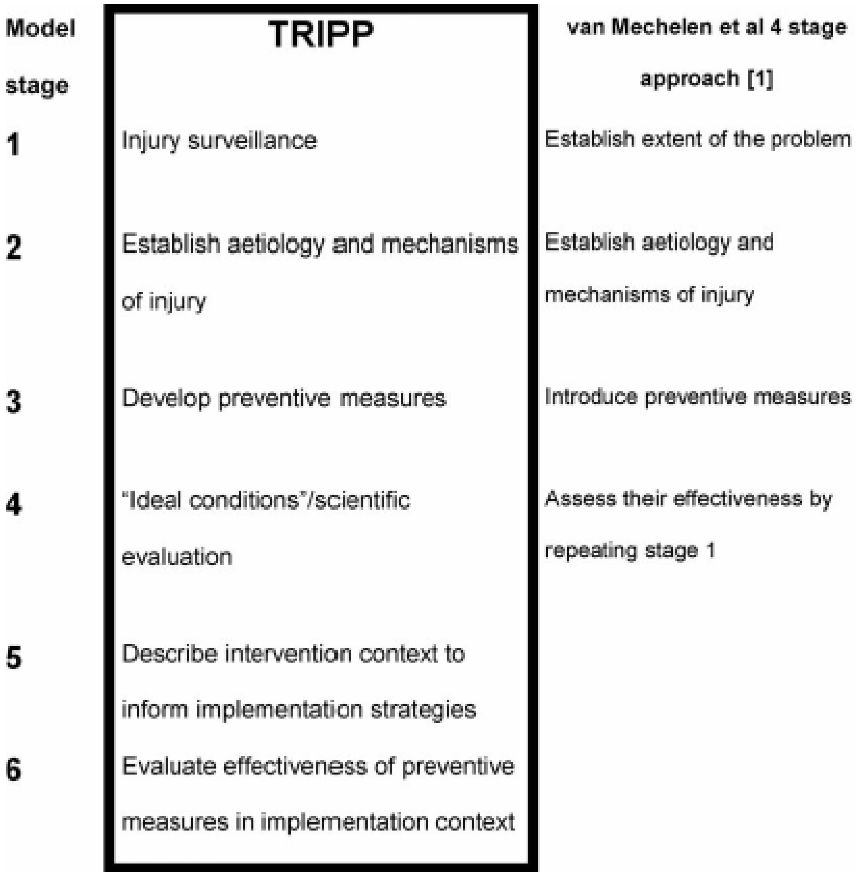


Figure 2.51: The four steps sequence of injury prevention research. (van Mechelen, 1992)

Almost 15 years later, Finch redesigned van Mechelen's model (i.e. implementing the Translating Research into Injury Prevention Practice (TRIPP) framework) and pinpointed the possible gap between the interventions suggested by scientific research and their actual implementation in ''real-life'' situations (Figure 2.52).[109]



Model stage	TRIPP	van Mechelen et al 4 stage approach [1]
1	Injury surveillance	Establish extent of the problem
2	Establish aetiology and mechanisms of injury	Establish aetiology and mechanisms of injury
3	Develop preventive measures	Introduce preventive measures
4	"Ideal conditions"/scientific evaluation	Assess their effectiveness by repeating stage 1
5	Describe intervention context to inform implementation strategies	
6	Evaluate effectiveness of preventive measures in implementation context	

Figure 2.52: The Translating Research into Injury Prevention Practice (TRIPP) framework for research leading to real-world sports injury prevention. (Finch, 2006)

In 2008, van Tiggelen et al. made the last modification (to date) to this system.[353] The model they proposed focused on overuse injury prevention and complemented the modifications proposed by Finch by incorporating risk-taking behaviour and compliance of the individual as limiting factors in sports injury prevention (i.e. emphasizing successive efficacy, efficiency, compliance and effectiveness processes assessment) (Figure 2.53).

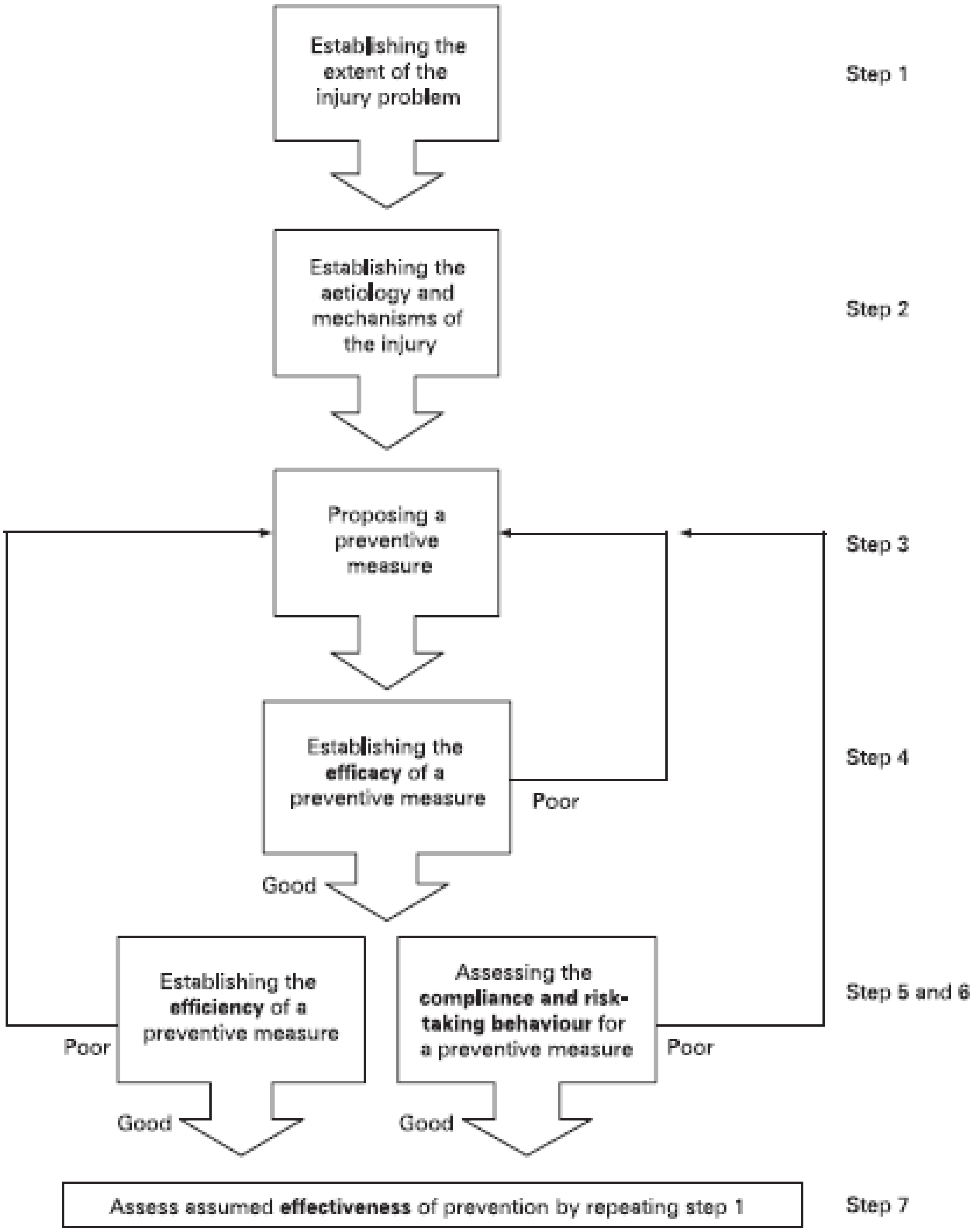


Figure 2.53: Sequence of prevention of overuse injuries. (van Tiggelen et al., 2008)

This system, even redesigned and improved twice successively, remains quite theoretical and “epidemiological research” focused. In addition, it is worth noting that, as previously reported by van Mechelen himself and above mentioned, the most critical step in this system is to establish the causes, i.e. risk factors and injury mechanisms.

This is probably why, only two years after the publication by van Mechelen, a group of researchers from Calgary published a "multifactorial" or also called "biomechanical" model of causation attempting to account for the interaction of multiple risk factors (intrinsic and extrinsic) and highlighting the importance of the injury-inciting event.[237] Bahr and Krosshaug complemented this system by emphasizing the characteristics of the inciting event as a component of the causal pathway (Figure 2.54).[12, 13, 200] In this model, the internal risk factors may be necessary, but seldom sufficient, to produce injury. Then, external risk factors act on the predisposed athlete and are classified as enabling (i.e. facilitating) the manifestation of injury.[12, 13, 243] It is finally the combination of internal and external risk factors that makes the athlete susceptible to injury, but this is usually not sufficient to produce injury. It is proposed in this model that the sum and the interaction between these risk factors only prepares the athlete for the injury, whereas the inciting event is the final link in the chain that causes the injury.[243,232,233]

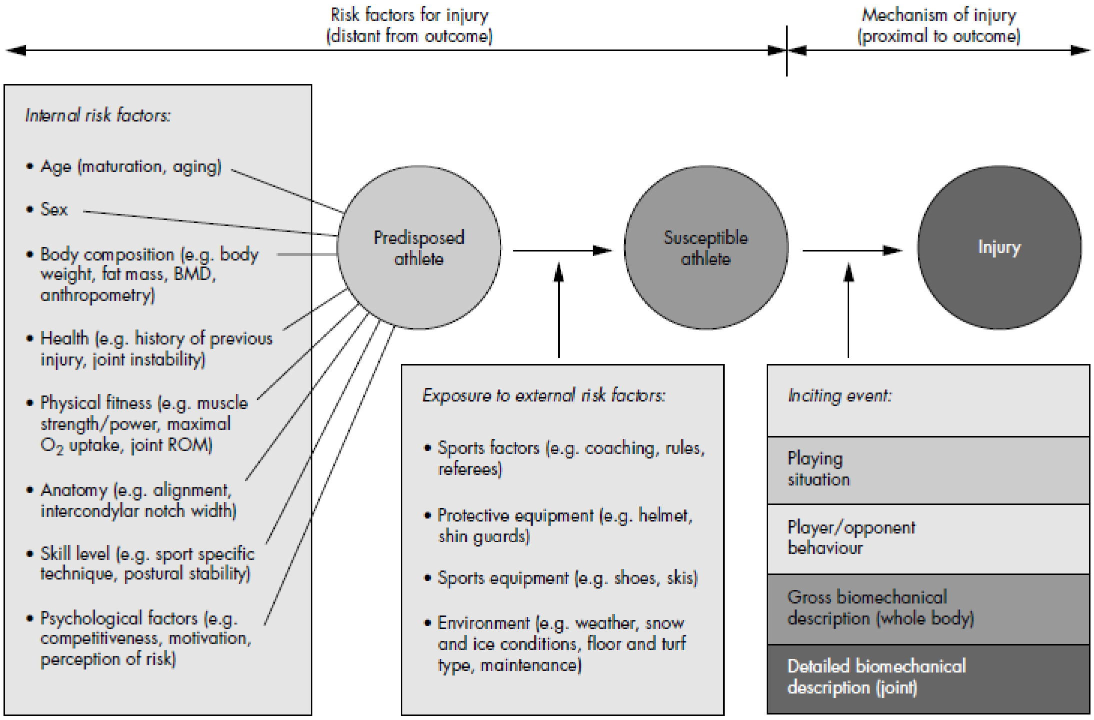


Figure 2.54: Comprehensive model for injury causation. BMD, Body mass density; ROM, range of motion. (Bahr and Krosshaug, 2005)

More recently, in 2007, Meuwisse et al.[243] considerably modified their system for proposing what is, so far, the most up-dated model of sport-injury prevention, or to be more precise, sport-injury causation/aetiology. Indeed, this model should be considered as a component of the global "epidemiological" sport-injury prevention model, initaiated by van Mechelen[352] and improved by Finch et al.[109] and van Tiggelen et al.[353] Meeuwisse et al. named this new version "*Dynamic, recursive model of aetiology in sport injury*" (Figure 2.55).[243] The rationale for the latter improvement is that the former model was based on a linear paradigm, i.e. events followed each other sequentially from a beginning point to an end point. The new recursive model shows that there may be recurrent changes in susceptibility to injury (when participating in sports activity without injury) and that these exposures can produce adaptations, which continually change risk.[243] Meuwisse et al. emphasized another point of primary interest for the staff in charge of designing and conducting the sports injury prevention strategies: they postulated that the optimal intervention approach may be individual in nature, positioning the individual or the athlete in the middle of the concept ("predisposed athlete" and "susceptible athlete" circles in the figure 2.55).[243] They assume that effective prevention strategies may require individual customization on the basis of individual levels and variability of risk factors over time.

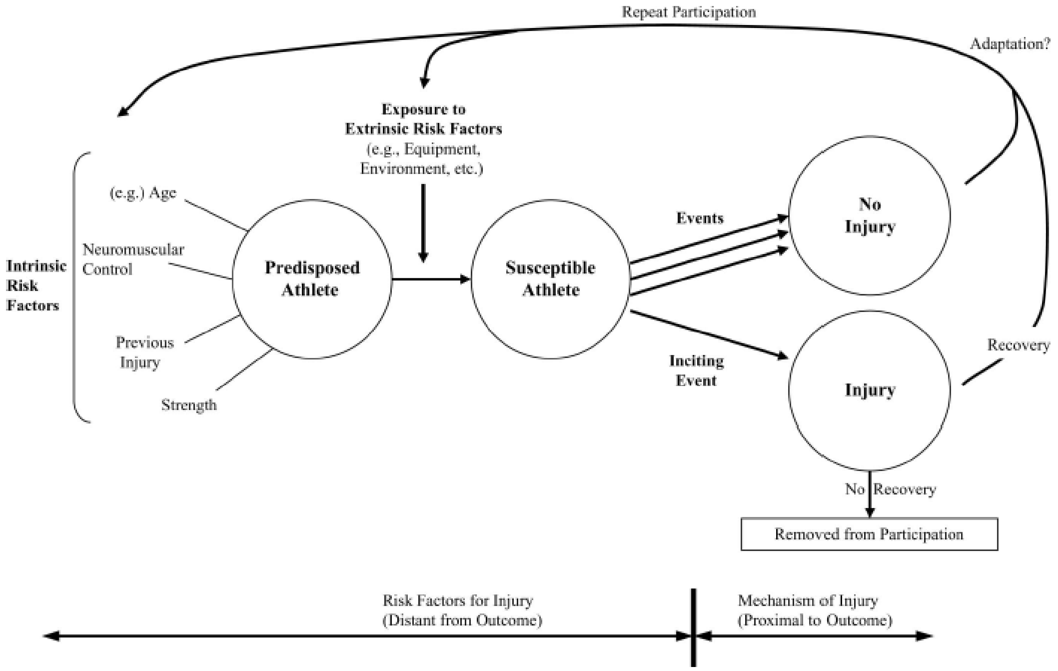


Figure 2.55: A dynamic, recursive model of aetiology in sport injury. (Meuwisse et al., 2007)

As a conclusion of this section, it is important to mention that some authors looked in the same direction as Meuwisse et al. or Bahr et al. regarding the multifactorial and biomechanical aspects of injury prevention concept.[243, 232, 233] Given that injury results from an energy transfer to the tissue, McIntosh assumed that he mechanical properties of human tissue govern how the body responds to physical loads (Figure 2.56).[228] In this case, it is the relation between load and load tolerance that determines the injury outcome of an event and McIntosh to conclude: "*The key point to consider with regard to biomechanical factors is that they must explain how the event either resulted in a mechanical load in excess of that tolerated under normal circumstances or reduced the tolerance levels to a point at which a normal mechanical load cannot be tolerated.*"[232, 233] The strength of this point of view is to emphasize the concept of (training and/or biomechanical) load, load tolerance and injury tolerance level; in other words, how appropriate training (in quantity and quality) and an individual injury prevention program may positively interpose between an athlete and its potential injuries.

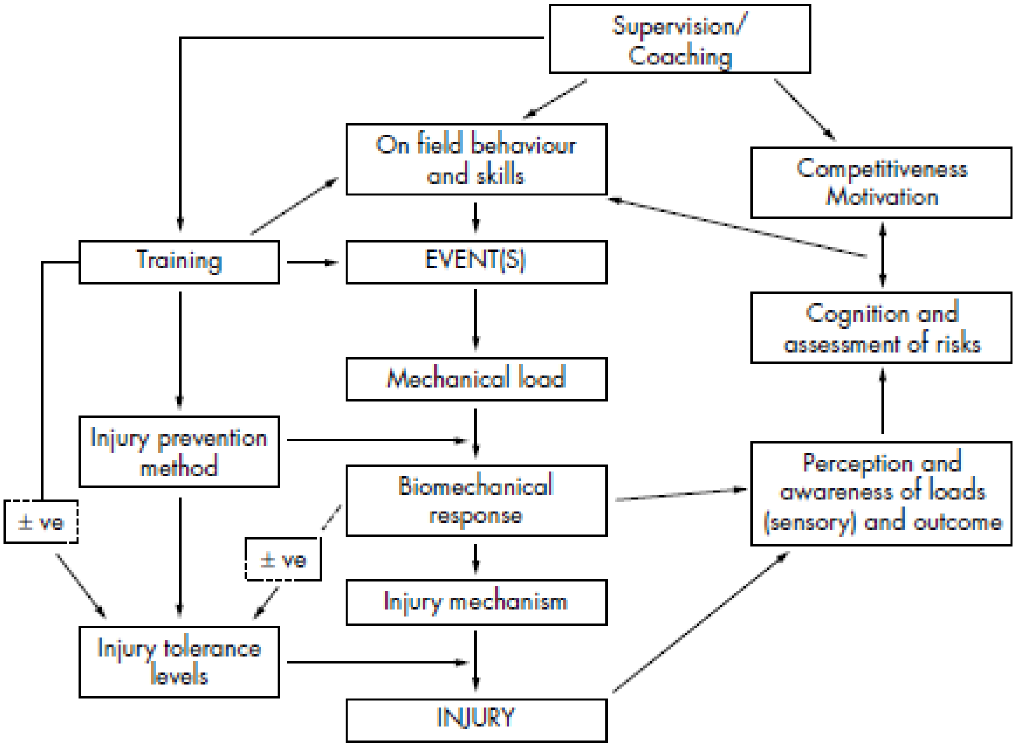


Figure 2.56: Schematic of injury model. The +/- symbol indicates that training or a biomechanical response during an event may increase or decrease the injury tolerance level. (Mc Intosh, 2005)

2.3.11.3 Foot-ankle injury modifiable risk factors in adolescent athletes

Extrinsic (i.e. sports context, protective equipment, rules and regulations, playing surface and coaching education and training) and non-modifiable intrinsic risk factors (e.g. physical and physiological processes of growth, previous injury, age and sex) will not be detailed here, even some of them are of interest in the injury prevention context (e.g. shoes, training loads or contents prescribed by the coaches) (Table 2.3.8).[88, 116, 227] For further details about the influence of physical and physiological processes of growth as potential non-modifiable risk factors, please refer to the section 2*.3.6.1. The uniqueness of the young athlete*.

Several risk factors have already been detailed in chapter 2 (e.g. fatigue related risk factors, hyperpronation or excessive supination), but it would be relevant to revisit them again in the following list to summarize the main foot-ankle injury modifiable risk factors, applicable in adolescent athletes:[116]

- General fitness level. Preseason or start of the season, appropriate and progressive conditioning lowers injury incidence.[116, 155, 368]
- Flexibility. Deficit of flexibility affecting not only the triceps surae, but also some other muscles inserting on the foot-ankle bones (e.g. *tibialis posterior*) may relate to increased risk of apophysitis in accordance with the "pre-load theory".[151] The lack of flexibility of the triceps surae may also predispose to other injuries such as medial tibial stress syndrome,[345] lateral ankle sprain,[368] Achilles tendinopathy or plantar fasciitis, even if these last two injuries are not frequent in adolescent athletes.
- Muscle strength. Strength deficit at the foot-ankle stabilisers may be considered as a risk factor related to almost all the foot-ankle injuries, because it results in failure in the shock absorption process and joint stabilization,[15, 368] or early fatigue-related alterations.[107]
- Muscle stiffness. It is known that too much stiffness (in the spring mass model aspect) may result in injury because increased leg stiffness is typically associated with reduced lower extremity excursions and increased peak forces,[44, 45] which have been associated with increased shock to the lower extremity.[44, 45, 156] Moreover, it has been suggested that too much stiffness may be associated with

bony injuries, while too little stiffness may be associated with soft tissue injuries.[44, 45, 369] In this case, there may be an ideal range of stiffness, to be determined, allowing optimal performance while minimizing the risk for injury.

- Joint stability, balance and coordination. Joint laxity, altered proprioception or joint position sense dramatically predispose athlete to foot-ankle sprains with or without fractures.[79, 116, 159, 368]
- Anatomical or biomechanical abnormalities. Anatomical or biomechanical abnormalities (e.g. pes cavus/planus, hyperpronation or excessive supination) have been recognized as potentially altering the running, jumping or even throwing biomechanics and techniques and then increase the injury risk.[41, 66, 128, 161, 271, 280]
- Psychological and social factors. Major life stress could increase the risk for a sports injury by up to 70%, especially in fragile adolescent athletes.[116]

2.3.11.4 Injury prevention countermeasures

As the design and implementation of injury prevention strategies is a very wide field, it is proposed to detail firstly the main countermeasures related to specific injuries or injury risks to adolescent athletes and secondly to provide an example of the available injury prevention strategies for preventing one the main foot-ankle risk factors which is hyperpronation.

From the literature, including the recent paper by Frisch et al,[116, 332, 365] it is known that the passive and the active prevention strategies coexist and complement each other. Passive strategies do not require any active adaptations from the athlete, as he/she is automatically protected once the prevention strategy is adopted. Conversely, active strategies require the athlete’s participation and cooperation. Samples of both strategies will be presented in the following sections.

2.3.11.4.1 Growth-related injuries countermeasures

There are two main ways of the implementation of growth-related injury prevention strategies in adolescent athletes (at the foot-ankle level or in any other body region): the first one is through the coaches and the second one in through the sports medicine-sports science team.

Frisch et al.:[116] stated: "*The effectiveness of an injury prevention programme depends not only on its content but also on the success of its more or less permanent acceptance and implementation within the sports community"*. The influence of the coach (positively or negatively) on the prevention countermeasures effectiveness is critical and his/her compliance to the program is essential. Some preventive measures proposed by Caine et al. may be worthy of consideration by the coaches and are summarised below:[46]

- Individualized training and skill development should be promoted in order to reduce the risk of physeal injury;
- Training loads should be reduced and skill progressions delayed for young athletes experiencing periods of rapid growth (assessed by quarterly measurement of height).
- Very wide variety of drills and exercises should be proposed during training for avoiding overuse injury, emphasizing quality and not quantity.
- Annual training plan should be divided in clear periods and cycles with precise targets and well-defined rest periods (i.e. periodization) to prevent overtraining.

The sports medicine-sports sciences stakeholders have to accomplish their part of the task as well regarding the growth-related injury prevention. This may be listed in a few general points, as proposed by Caine et al.:[46]

- Periodic physical examinations should be carried out. It may allow growth plate stress reactions to be diagnosed at an early stage. Then adequate adaptations might be implemented to the training programme to assist in the recovery process.

- Individual or group-based physical conditioning, i.e. weak muscle strengthening (e.g. plyometrics), stiff muscles stretching and proprioceptive/motor control exercises may help to reduce physeal injury.[96, 116, 117, 155, 160, 219, 227, 288, 329, 363]
- Responsible staff (medical staff first but also coaches) should have the basic knowledge about specificities of the adolescent athlete population, in order to ensure correct injury rehabilitation and safe return to practice.
- The medical staff should promote the idea that a long term follow up is necessary to monitor the child's recuperation and growth.

In the end, it is worth noting that the communication between the coach and the medical staff must be permanently open so that the adolescent athletes can be assessed at the earliest opportunity.[46] Finally, three important factors have been reported as influencing critically the success of an injury prevention strategy:

- the compliance of the athletes (and the coaches),[116, 160, 219, 288, 329]
- the injury prevention programme to be supervised, structured and followed in a group of peer athletes, instead of home exercises,[116]
- and the possibility for variation and progression in the exercise set in order to enhance motivation.

As long as most of these aforementioned conditions are present, it seems that injury prevention strategies may succeed. Such programmes (if well designed and conducted) should be implemented either before the season start during 18–20 sessions (up to 90 min duration) over 6–7 weeks [116, 155, 160] or over 10–20 min in each practice session continuously during the season.[116, 219, 329]

Take home message

- ✓ Sports-injury prevention was defined as the intervention aiming to reduce the risk of sport-related injury in athletes.
- ✓ Risk factors have been defined as any factors that may increase the potential for injury. They can be extrinsic or intrinsic to the athlete, modifiable or non-modifiable.
- ✓ Injury prevention research is still widely based on the “four step sequence” proposed by van Mechelen in 1992.
- ✓ Collecting and analysing information on why a particular athlete may be at risk in a given situation (risk factors) or how injuries happen (injury mechanisms) is critical in injury prevention research.
- ✓ General fitness level, flexibility, muscle strength and stiffness, joint stability, anatomical alignments, psychological and social factors are thought to be the main foot-ankle injury modifiable risk factors, applicable in adolescent athletes.
- ✓ Individualized training, adequate training load management, wide variety of drills and exercises, proper periodization, periodic physical/medical examinations, regular physical condition maintenance, appropriate knowledge of the support staff about adolescent specificities, good compliance of the athletes and continuous communication between support staff and coaches are thought to be the best countermeasures against sports injuries.

Ce qu'il faut retenir

- ✓ La prévention des blessures sportives se définit comme l'intervention visant à réduire le risque de blessures liées aux sports chez les sujets.
- ✓ Les facteurs de risques sont définis comme étant tous les facteurs qui pourraient augmenter le risque de survenue d'une blessure. Ils peuvent être extrinsèques ou intrinsèques à l'athlète, modifiables ou non-modifiables.
- ✓ La recherche dans le domaine de la prévention des blessures est encore largement basée sur la « séquence en quatre étapes » proposée par van Mechelen en 1992.
- ✓ Rassembler et analyser les informations relatant pourquoi un athlète serait particulièrement à risque dans une situation donnée (facteurs de risque) et comment la blessure survient (mécanisme de la blessure) est déterminant dans le domaine de la recherche sur la prévention des blessures.
- ✓ Le niveau de condition physique générale, la souplesse, la force et la raideur musculaires, la stabilité articulaire, l'alignement segmentaire ainsi que les facteurs psychologiques et sociaux sont considérés comme étant les principaux facteurs de risque modifiables chez les jeunes athlètes.
- ✓ Un entrainement individualisé, une gestion adéquate des charges d'entrainement, une variété large d'exercices et de gammes, une bonne périodisation, des tests physiques et médicaux réguliers, un entretien régulier de la condition physique générale, une connaissance suffisante de la part des membres du staff à propos des spécificités liées à l'adolescence, une bonne collaboration de la part des athlètes et une communication permanente entre l'entraineur et son entourage sont considérés comme les meilleures contremesures contre les blessures sportives.

2.3.11.4.2 How hyperpronation can be prevented

The why and the how of an injury risk factor at the foot-ankle level has previously been discussed. It was also mentioned how hyperpronation may induce chain reactions leading to injuries at the upper levels (e.g. lower legs, knees, pelvis). In the following sections, the main equipment and techniques aiming to counteract hyperpronation will be listed.

2.3.11.4.2.1 Shoes

Motion control shoes are designed to control the degree of pronation at the foot by incorporating more rigid components into the midsole of the shoe. It has been suggested that running shoes with increased density in the midsole are effective in decreasing variables associated with excessive pronation (e.g. excessive rearfoot movement) during running (Figure 2.57).[44, 57, 59, 314]

Figure 2.57: Comparison between normal and cushioned shoes. Adidas Supernova control (left) and Supernova cushion (right). (Cheung and Ng, 2010)

The mechanism of motion control shoes is based on different deformation rates between lateral and medial midsoles[276, 334, 337] and wedging heel counter[274, 275, 336, 337] so as to control the relative rates of mid-foot and rearfoot motion.

While training, runners may use 3 different type of shoes, with different characteristics (Figure 2.58): spikes (exclusively on the synthetic track), running/training shoes (which encompass most of the running shoes on the market, with well-cushioned midsoles) or racing flats (which are extremely lightweight and designed with less support and less cushioning than training shoes).[300, 367]

Figure 2.58 The three types of shoes commonly used in track and field; A, racing flats; B, normal training/running shoes; C, spikes. Adapted from Queen (2009) (A and B) and from Adidas website (www.adidas.fr) (C)

Wiegerinck et al. examined the differences in plantar loading in young adults when they ran at a self-selected running speed (i.e. 3.3 $m.s^{-1}$) wearing racing flats and traditional training shoes.[367] The lateral midfoot, medial, middle and lateral forefoot, hallux and lesser toes all demonstrated a significant increase in peak pressure in the racing flat. The maximum force was decreased in the racing flats in the medial midfoot, however, the maximum force was significantly greater in the lateral forefoot, the hallux and the lesser toes in the racing flats. These results were mainly confirmed by a similar study held by Queen et al. (Figure 2.59).[300, 367]

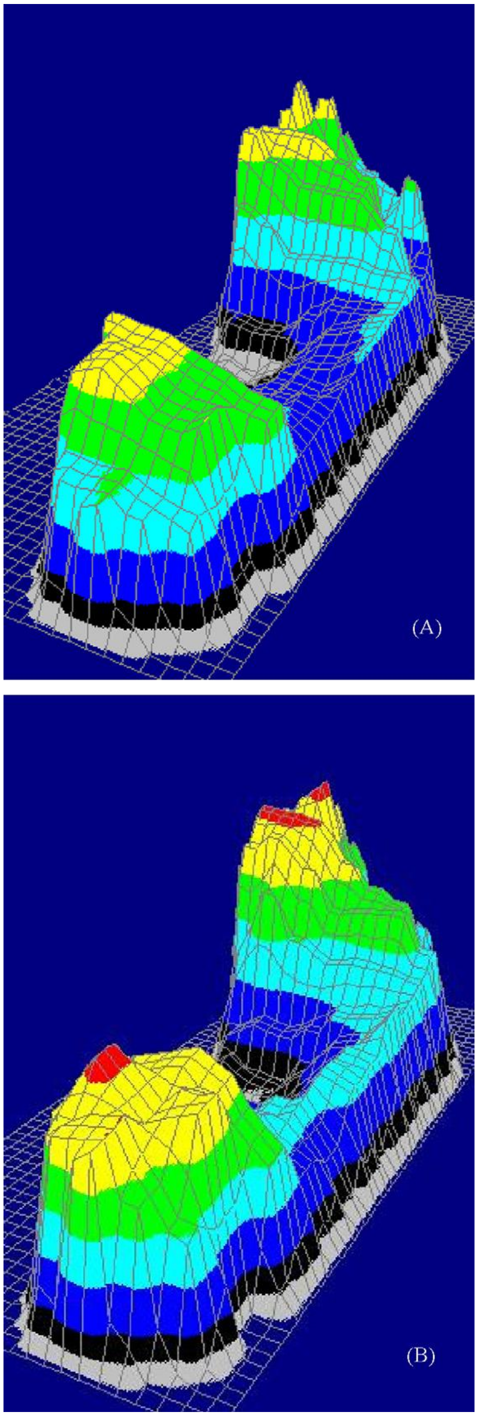


Figure 2.59: Examples of plantar loading. (A) Nike Air Pegasus, training shoe and the (B) Nike Air Zoom Katana IV, racing flat. (Wiegerinck et al., 2009)

The authors suggested that decreased maximum force in the medial midfoot in the racing flats may be due to the decreased arch support in this type of shoe. Increased arch support in the training shoe could have resulted in increased contact area in the medial midfoot, potentially resulting in a maximum force increase. It may also be concluded that the lighter racing flat has decreased cushioning and support.[300, 367] So it may be assumed that racing flats may not control the hyperpronation while training shoes may achieve this control, due to their better cushioning and rearfoot motion control.

2.3.11.4.2.2 Insoles

Recently, insoles (i.e. insoles, pads, orthotics or orthoses) have been broadly used by clinicians to treat mechanical misalignments, such as abnormal foot pronation.[60, 276, 369] Many publications about this technique showed non-systematic results, but it seems that in terms of specific hyperpronation control, the input of orthotics is valuable. In a study on 20 young hyperpronated adults jogging at around 9.5 km.h^{-1}, Nordsiden et al. found that the application of a foot pad (dome-shape placed immediately proximal to the head of the first metatarsal) was effective in reducing mean and peak pressures in that area (when compared to U-shaped and Donut pads) (Figures 2.60 and 2.61).[279]

Figure 2.60: Metatarsal pad. (Nordsiden et al., 2010)

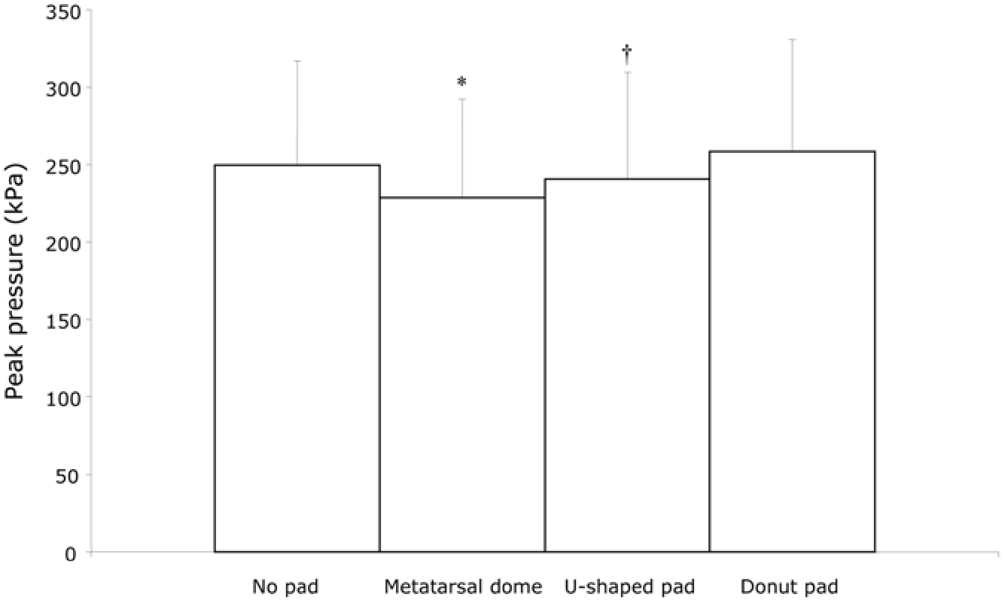


Figure 2.61: Running peak pressure, metatarsophalangeal joint. *The metatarsal dome produced a significant decrease in peak pressure compared with no pad and the donut shaped pad. †The U-shaped pad produced a significant decrease in peak pressure only compared with the donut-shaped pad. (Nordsiden et al., 2010)

Eng et al. examined the effect of foot orthotics (posted medially in the hindfoot and forefoot) on the range of motion of the talocrural/subtalar joint and the knee joint in three dimensions during running at 1.8 $m.s^{-1}$ in adolescent females.[97] They observed reductions of 1 to 3 degrees with orthotic use for the talocrural/subtalar joint during running. Williams et al. compared three-dimensional kinematics and kinetics of the rearfoot and knee during running while varying orthotics intervention (wearing no, standard and inverted orthotics) in eleven young adults running at 3.35 $m.s^{-1}$ and presenting a history of pain related to hyperpronation (Figures 2.62 and 2.63).[369] They concluded that inverted orthoses significantly decrease the inversion moment and work at the rearfoot and increase knee adduction and abduction moment when compared with standard and no orthoses conditions.[369] More recently, Chevalier and Chockalingam explored the recognized effects of foot orthoses on lower-limb kinematics in a systematic review and their findings confirmed that foot orthoses were effective to control rearfoot pronation.[60]

Figure 2.62: Posterior view of orthotic devices. A left inverted orthoses is on the left and is characterized by a more aggressive lateral tilt of the entire device. The external posting is the white material on the heel of the right standard orthosis on the right. (Williams et al., 2003)

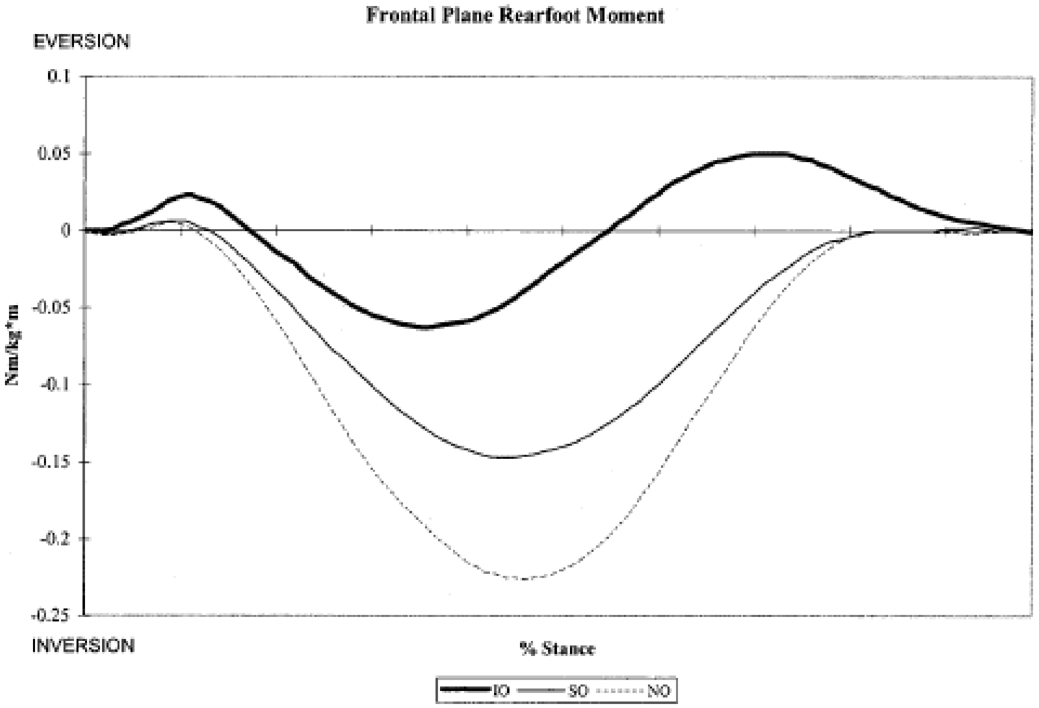


Figure 2.63: Rearfoot inversion/eversion moment curves in three different conditions. IO, inverted orthoses; SO, standard orthoses; NO, no orthoses. It demonstrates a greatly reduced inversion moment during the first 50% of stance.. Note the eversion moment late in stance in the IO condition. (Williams et al., 2003)

2.3.11.4.2.3 Tape

Few studies have investigated the effect of anti-pronation taping techniques (i.e. Low-Dye taping or techniques derived from the Low-Dye taping) on dynamic measures of foot motion and posture (Figure 2.64). A number of studies have used plantar pressure patterns as an indirect measure of foot pronation during walking and found that Low-Dye taping medialised heel strike and anterior forefoot forces and diminished midfoot forces in subjects with a normal foot.[315, 355] Whilst these results cannot be extrapolated to excessive pronators, medially-located peak plantar pressures have previously been found to occur in the midfoot of excessive pronators.[310] Thus the decrease in pressure that occurred in the midfoot of normal feet may also occur in excessively pronated feet.[315] Nevertheless, until recently very little was known about whether this anti-pronation effect was achieved, although anecdotally, clinical observations suggest that the technique is effective in reducing symptoms associated with excessive pronation.[8, 315] In 2005, Vicenzino et al. partially answered the question showing that the augmented Low-Dye tape was effective in controlling pronation during both static and dynamic activity, as the tape induced changes in static foot posture paralleled those during walking and jogging.[355] These findings were confirmed in 2007 by the same author using foot plantar pressure measures and more recently by Kelly et al. who reported a significant increase in average peak plantar pressure in the lateral midfoot region while jogging on a treadmill at 10 km.h^{-1} and wearing a Low-Dye tape (Figure 2.65).[184, 356]

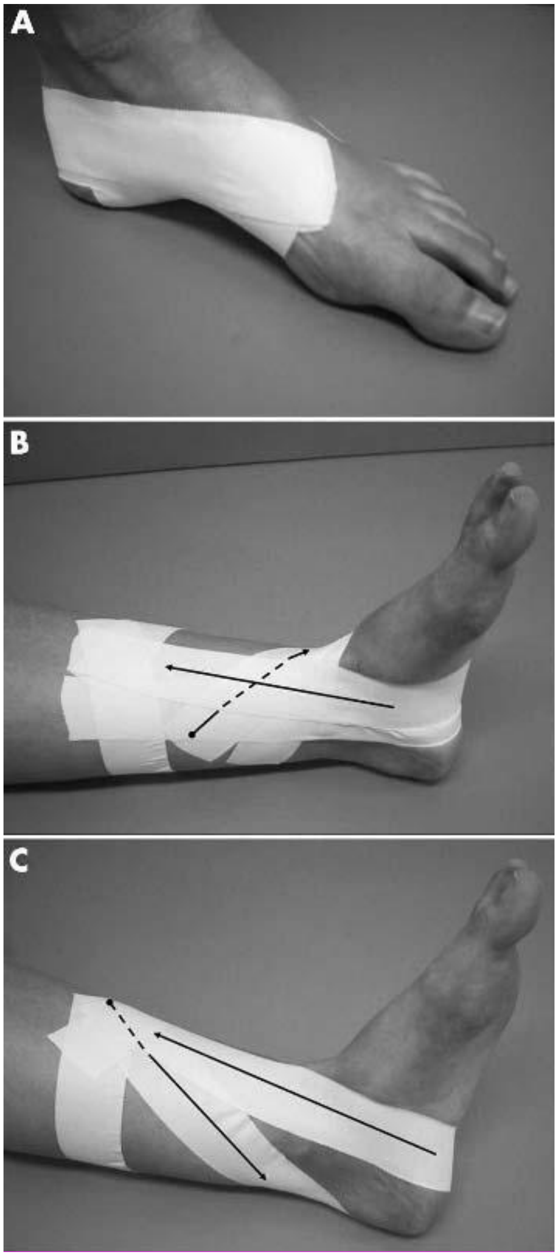


Figure 2.64: Augmented Low-Dye taping technique. (A) LowDye technique, (B) Reverse six technique, (C) Calcaneal sling technique. Adapted from Vicenzino et al. (2005)

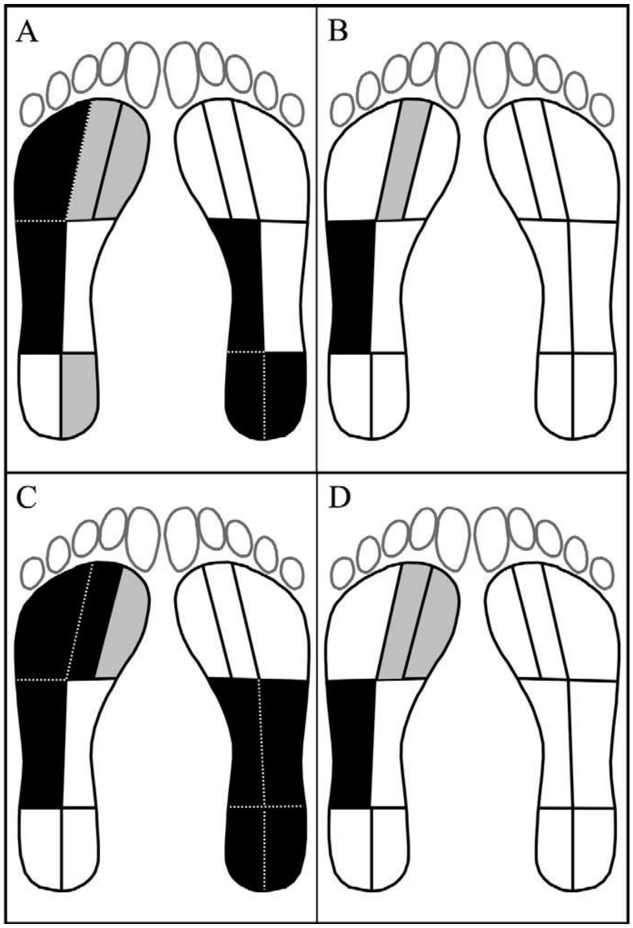


Figure 2.65: Foot plantar pressure distribution changes from pre-application to post-application of Augmented Low-Dye tape. foot on the left = taped, foot on the right = control in mean maximum pressure (A, B) and peak pressure (C, D) shown as increase (black), decrease (gray) and no change (white) for walking (A, C) and jogging (B, D) gait. Adapted from Vicenzino et al. (2007)

2.3.11.4.2.4 Lower limb stabilisers strengthening

As well as the use of pronation control–related shoes, orthotics and tapes, researchers proposed another strategy that may contribute to decrease pronation in runners: the use of the muscles (i.e. through the specific reinforcement of these muscles). Feltner et al. examined the effect of two types of strength training programs (isokinetic and non-isokinetic) for the inversion and eversion muscle groups for the control of pronation during the support phase of running at 3.8 m.s^{-1} on a treadmill in 18 year old runners.[107] After 8 weeks of training, the authors reported a significant increase in invertor and evertor force in the isokinetic group, as well as significant decrease in rearfoot and pronation/supination angles at heel strike.[107] They then concluded that a strength training program may reduce pronation at the instant of touchdown and that it should be considered in addition to other aforementioned strategies. Recently, Snyder et al. noted that a contributing factor to lower extremity injury may be an inability to control the motion of the lower extremity segments in the frontal and transverse planes (e.g. foot pronation).[327] Therefore, they tested a closed-chain hip rotation exercise program on 15 healthy women in order to determine if motions and moments including rearfoot eversion would be changed following hip strengthening. They found firstly that the hip abductors and external rotators were strengthened following this 6-wk strengthening program and secondly that it resulted in an alteration of lower extremity joint loading, including the reduction of rearfoot eversion range of motion.[327] Interestingly, 25 years ago, Robbins and Hanna have tested a program based on barefoot walking and running, in order to assess the effects of this “natural” strengthening program directly on the medial longitudinal arch shape.[308] They found a positive change indicated by a significant shortening of the medial longitudinal arch with increased barefoot weight bearing activity or lengthening with cessation of increased barefoot weight bearing activity. They concluded that an adaptation involving foot arch deflection was an important adaptation providing impact absorption. Medial rising and shortening due to activation of intrinsic musculature allows the foot to act as a dynamic impact strengthening structure, which consequently reduces the pronation/hyperpronation.[308] Surprisingly, despite electromyostimulation (EMS) now being widely used for strength training or rehabilitation of lower limbs muscles in athletes,[211, 293] only two studies using this technique for stimulating the medial longitudinal arch muscles were found.[56, 121] Gaillet et al. showed that only one session of EMS on the abductor hallucis muscle of 30 flat-footed subjects in standing position resulted in increased plantar pressure on the anterior–medial part of the sole and lateral displacements of the anterior maximal pressure point, which was consistent with foot inversion.[121] Even the underlying mechanisms justifying these results remained unclear; these findings appeared promising in terms of hyperpronation control. By applying EMS (e.g. high-frequency low intensity wide pulse stimulation, WPS) on the abductor hallucis muscle in 10 healthy adults, Chesters et al. obtained a significant effect on frontal plane forefoot-rearfoot anti-phase coupling during the middle (34-66%) section of stance phase while walking.[56] They concluded that this program induced an increased stability to foot function – through a pronation motion control.

These findings (although they are not related to running activity) support the concept that strengthening some ankle, hip or foot intrinsic muscles can have a significant impact on foot mechanics and should not be overlooked in training and prevention programs.

2.3.11.4.2.5Foot-strike pattern adaptation/changes

Using the evolution theory, Bramble and Lieberman or Lieberman et al. showed that the medial longitudinal arch of the foot has been under stimulated since humans use cushioned shoes, or even shoes, when running which induces a heel-strike (rearfoot-strike) landing pattern in most of the runners (Figure 2.66).[34, 208] In non-rearfoot strikers (e.g. midfoot or forefoot strikers), the medial arch stretches passively during the entire first half of stance. In contrast, the arch can stretch passively only later in stance during rearfoot-strike running, when both the fore-foot and the rear-foot are on the ground.[34, 208] The main point of this theory is that many running shoes have arch supports and stiffened soles that may lead to weaker foot muscles, reducing arch strength. This weakness contributes to excessive pronation and places greater demands on the plantar fascia.[199, 208] These authors also suggest that an excessive protection/support of the medial arch of the foot will not stimulate enough the muscles responsible for stability and this finally leads to hyperpronation, due to medial arch compliance and deflection. Therefore, it has been proposed that running barefoot or wearing footwear mimicking barefoot running (i.e. minimalist footwear running) is to be recommended.[199, 208, 226, 333] Additionally, it is worth noting that midfoot or forefoot landing does not seem to alter the running economy nor the running performance.[150, 333] Indeed, Hasegawa et al. showed that the percentage of rearfoot strikers decrease as the running speed increased; conversely, the percentage of midfoot strikers increases as the running speed increases, as measured at the 15-km point on an elite-level half marathon.[150]

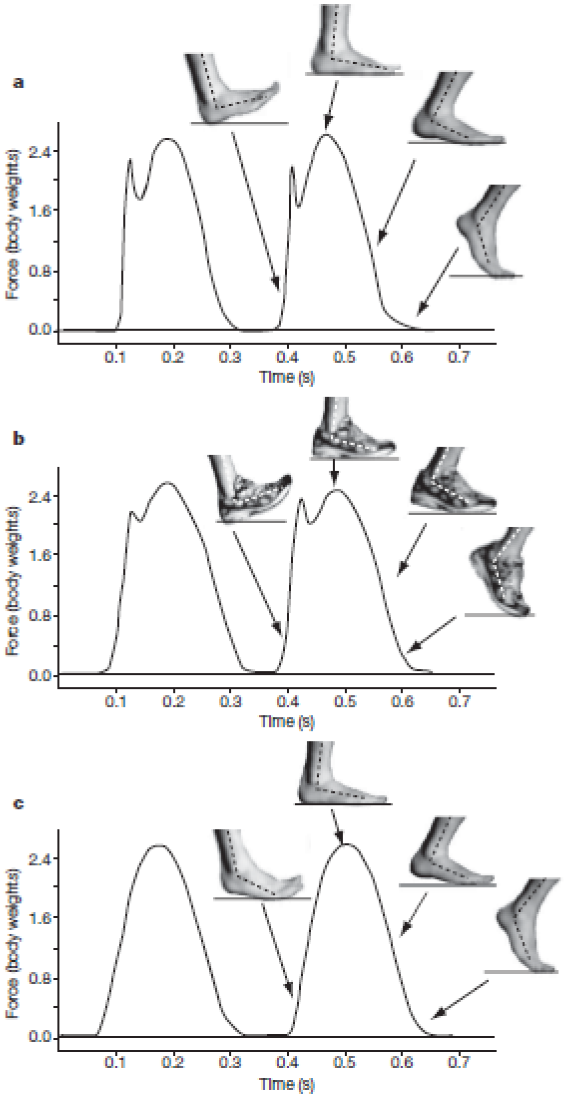


Figure 2.66: Vertical ground reaction forces and foot kinematics for three foot strikes. a, RFS during barefoot heel–toe running; b, RFS during shod heel–toe running; c, FFS during barefoot toe–heel–toe running. Both RFS gaits generate an impact transient, but shoes slow the transient's rate of loading and lower its magnitude. FFS generates no impact transient even in the barefoot condition. (Liebermann et al., 2010)

Hoffman and Millet noticed that the main positive effects attributed to barefoot running (e.g. decrease of peak vertical force and foot angle at initial contact or decrease of the mechanical energy absorbed at the knee) can be achieved by simply increasing the stride rate or wearing shoes of harder soles rather than going barefoot (Figure 2.66).[199] Interestingly, Hoffman and Millet stipulated also that "*given the number of contractions that would be involved, even in a short run, those contractions could not possibly be accomplished at a very high proportion of maximal strength and certainly not high* *enough to induce strength gains*”.[199] They then contested the assertion that foot intrinsic muscle strengthening may be a potential benefit from barefoot running.

Take home message

- ✓ It is assumed that racing flats may not control hyperpronation while training shoes may achieve this control, due to their better cushioning and rearfoot motion control.
- ✓ Despite some controversial results, it is likely that foot orthoses are effective in controlling rearfoot pronation.
- ✓ Anti-pronation taping techniques (i.e. Low-Dye taping) seem to be effective in controlling pronation during both static and dynamic activity, including walking and jogging.
- ✓ Ankle invertor and evertor muscle isokinetic strength training program may reduce pronation at the instant of touchdown.
- ✓ Hip abductors and external rotators strengthening induces the reduction of rearfoot eversion range of motion while running.
- ✓ Activation of intrinsic foot musculature (through barefoot walking and running) may reduce the pronation/hyperpronation.
- ✓ Excessive protection/support of the medial arch of the foot (in the shoe) may under-stimulate the muscles with relation to its stability and then this finally leads to hyperpronation, due medial arch compliance and deflection.
- ✓ Running barefoot, increasing the stride rate or wearing shoes of harder soles contribute to more “natural” midfoot-strike technique and probably enhance the contribution of the foot intrinsic muscles during the stance phase.

Ce qu’il faut retenir

- ✓ Il est suggéré que les chaussures de course légères ne contrôlent probablement pas correctement l’hyperpronation contrairement aux chaussures de course plus lourdes et plus classiques qui peuvent mieux satisfaire à cette exigence en raison d’un meilleur amorti et d’un meilleur contrôle de l’arrière-pied.
- ✓ Malgré des résultats controversés, il est probable que les orthèses plantaires soient efficaces pour contrôler la pronation de l’arrière-pied.
- ✓ Les techniques de contention limitant la pronation (Low-Dye taping) semblent contrôler efficacement celle-ci au cours d’activités statiques et dynamiques, y compris la marche et la course à allure lente.
- ✓ Le renforcement des inverseurs et des éverseurs en mode isocinétique semble réduire la pronation au moment de l’attaque du sol.
- ✓ Le renforcement des abducteurs et rotateurs externes de hanche provoque une diminution de l’amplitude d’éversion calcanéenne pendant la course.
- ✓ L’activation des muscles intrinsèques du pied (par l’intermédiaire de la marche et de la course pieds nus) semble réduire la pronation et l’hyperpronation.
- ✓ La protection ou le support excessif de l’arche médiale du pied (dans la chaussure) pourrait provoquer une sous-utilisation des muscles responsables de sa stabilité active et ainsi favoriser l’hyperpronation, due à la souplesse de l’arche et son affaissement.
- ✓ Courir pieds nus, courir en augmentant sa fréquence de foulée ou courir en portant des chaussures à semelle plus rigide contribue à mettre en place une pose du pied plus naturelle par le medio-pied d’abord et augmente probablement la contribution des muscles intrinsèques pendant la phase d’appui.

Part 3. Personal contribution

3.1 General methodology

3.1.1 Population

All participants volunteered for the studies and were healthy and pain free during the testing period. They had no history of musculoskeletal dysfunction or injuries of the lower limbs in 2 months preceding the study. This must not be taken into consideration regarding the study 6, where data were retrospectively analysed. Participants' anthropometric data and characteristics are reported in Table 3.1.1. Anthropometric measurements were obtained by an accredited anthropometrist (International Society for the Advancement of Kinanthropometry). The participants in the study 1 were French regional level trail and ultra-trail adult runners. The participants in the study 2 to 10 were highly-trained track and field adolescent athletes from the ASPIRE Academy for Sports Excellence – Doha – Qatar.

Table 3.1.1: Anthropometric data and characteristics of the participants of the 10 studies of this thesis.

Study	Sport	Number	Age	Body mass	Height
1	Trail runners	8	42.5 ± 5.9	76.9 ± 7.0	177.8 ± 5.9
2, 3 & 5	Distance runners	11	16.9 ± 2.0	54.6 ± 8.6	170.6 ± 10.9
4	Sprinters, hurdlers	11	15.4 ± 1.7	52.7 ± 14.1	164.2 ± 9.3
6	All track & field events	110	15.7 ± 1.7	63.9 ±10.0	172.1 ± 7.9
7	All track & field events	10	15.3 ± 1.6	65.4 ± 26.2	171.7 ± 8.8
8	All track & field events	20	16.6 ± 1.6	75.9 ± 24.8	177.6 ± 9.2
9	Throwers & sprinters – different foot shapes	8	15.8±1.1	92.8±13.3	178.4±6.2
10	Sprinters, hurdlers, jumpers, distance runners	16	15.2 ±1.7	51.8 ±11.3	164.5 ±8.0

3.1.2 Data collection and analysis

3.1.2.1 Neuromuscular fatigue-related materials and data

3.1.2.1.1 Isokinetic dynamometry (Studies 1 and 2)

Neuromuscular fatigue remains a complex phenomenon defined as the reduction in the maximum force that a muscle can exert.[25] Classically strength losses have been assessed using isometric contractions but isokinetic dynamometry has become a worthwhile method for the assessment of muscle fatigue.[32] This type of assessment, calculating changes in peak torque from pre- to post-exercise have been shown to be relevant for assessing muscle force imbalances.[142] Recently, specific isokinetic protocols to assess muscle fatigability have been proposed and involve a predetermined number of reciprocal maximal concentric contractions, at a given angular velocity.[32, 33, 73] Despite the emergence of such tests, isokinetic measures have been rarely used for assessing the torque changes induced by a running bout.[152, 287] Isokinetic dynamometry was used in the studies 1 and 2. Calibration of the isokinetic dynamometer was performed before data collection. The same examiner conducted the tests for all subjects. The range of motion of the ankle joint was set at 10^{o} dorsal flexion and 20^{o} plantar flexion. Before the initial testing, the PF and DF maximal isokinetic strength measurement procedure was explained to each subject.[82] The dynamometer axis was aligned with the axis of plantar-dorsal flexion of the ankle joint. Straps stabilized ankle, leg, knee, pelvis and chest. Handles were set on both sides to hold on to. Participants were instructed to push as hard as possible under verbal encouragement. The 90° position of the ankle joint was regarded as the neutral 0° position (Figures 3.1 and 3.2).

Figure 3.1: Ankle plantar-dorsi flexion isokinetic assessment - Position “0” of the ankle.

Study 1

Participants reported to the laboratory before and immediately after a 5-h hilly run. During each visit, all subjects underwent maximal voluntary and electrically evoked isometric strength tests for both PF and DF at the ankle (see after), as well as maximal voluntary isokinetic strength and fatigue resistance tests. No specific familiarisation session was undertaken but all subjects had already participated in the previous experiments involving long distance run and electrical stimulation/force measurements.

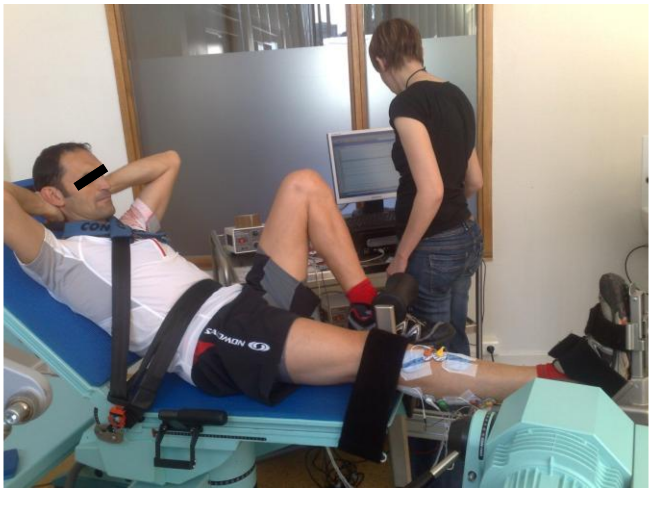


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Figure 3.2: Isokinetic testing (study 1) - Positioning of the participant with the knee in extension. Note the position of the electrodes. NB: During the test, the participant held the handles.

Warm-up - A general warm-up was performed on a cycle-ergometer for 6 min at ~60% of the maximal heart rate followed by a specific warm-up consisting of three graded submaximal and three maximal concentric contractions at $60^o.s^{-1}$ for the PF and at $90^o.s\text{-}^1$ for the DF on an isokinetic Con-Trex® dynamometer (Con-Trex MJ; CMV AG, Dübendorf, Switzerland).

Maximal voluntary isometric contraction (MVC-ISO) - MVC-ISO strength of PF and DF was measured. Subjects were placed in a supine position, right knee being extended at 0^o, and the leg in a horizontal position with the thigh being supported. The ankle joint was fixed at 90^o (neutral position) and this was confirmed by the angle measurement device of the Con-Trex (Figure 3.2). The gravity correction mode was activated in the software of the isokinetic device prior to testing. On Con-Trex MJ, gravity is measured for all angles of the angular sector, which makes the value more accurate, specifically to reflect stretching or compression resistance of tissues structures (muscle or others). Each subject completed three plantar flexions and then three dorsal flexions with the right ankle separated by 30 s.

Isokinetic contraction testing - PF and DF maximal voluntary isokinetic concentric contraction (MVC-CON) strength and fatigue resistance were evaluated for the right ankle on the Con- Trex® dynamometer with the Con-Trex® software, which calculated and displayed torque and joint displacement values. The subject's position was the same as that described for the isometric testing. After a 1.5-min rest following the isometric testing, PF and DF MVC-CON strength was recorded at $60^o.s^{-1}$ for the PF and at $90^o.s^{-1}$ for the DF over three repetitive PF contractions followed by three repetitive DF contractions. After a 1.5-min rest, PF and DF isokinetic fatigue resistance (i.e. fatigability) was assessed over 30 contractions in concentric mode at $60^o.s^{-1}$ for the PF and at $90^o.s^{-1}$ for the DF.[32]

Study 2

PF and DF maximal voluntary isokinetic concentric (MVC-CON) and eccentric contraction (MVC-ECC) strength and fatigue resistance were evaluated for the right ankle on the Humac Norm System dynamometer (CSMI, Soughton, MA, USA). Each participant was in supine position, hip and knee flexed at 60°, and lower leg supported in horizontal position as described in the Humac Norm System owner's manual and in previous research (Figure 3.3).[82,362] Then PF and DF MVC-CON and MVC-ECC were recorded at 60°·s^{-1} and at 120°·s^{-1} (over three contractions) as in previous studies.[148, 362]


[redacted] [redacted]

Figure 3.3: Isokinetic testing (study 2) - Positioning of the participant with the knee in flexion.

Analysis

The angular velocities were chosen based on the basis of the previous studies.[82,316] Peak torque of each contraction for PF and DF was obtained and analysed for the highest value (peak) as well as the average value (mean) amongst the three contractions for PF and DF in study 1 and only for the highest value (peak) in study 2. Based on the changes in torque over 30 contractions in study 1 and 50 contractions in study 2, a fatigue index was calculated for PF and DF as follows:[32]

Fatigue index = (100 x (total PT ÷ ideal PT)) – 100

where Total PT = Sum of PT over all the contractions.

Ideal PT = number of contractions x best PT.

3.1.2.1.2 Electrical stimulation applied to the muscle motor points

It is possible to clarify whether a decrease in MVC force is completely attributable to the loss of muscle contractile properties (i.e. peripheral fatigue), or whether central drive may contribute to this decrease (i.e. central fatigue). A reliable assessment of the neuromuscular fatigue in humans is the percutaneous stimulation of nerve or muscle.[6, 137, 357] Electromyography (EMG) and measurements of voluntary and evoked forces are usually associated in this method. The electrical twitch superimposed to a MVC is compared with the twitch evoked on the relaxed muscle. This allows the calculation of the level of voluntary activation and this is called the twitch interpolation technique.[137, 247] If the electrical stimulus elicits an increase in force greater than MVC, then central fatigue has occurred. Electrical stimulation can also be evoked on the relaxed muscle to explore peripheral fatigue, by analysing the changes in the integrated electromyographic signal (iEMG), or root mean square (RMS) and the compound action potential (M-wave) during voluntary and evoked contractions, respectively.[137, 357]

In the study 1, each subject completed three isometric plantar flexion and then three isometric dorsal flexion with the right ankle separated by 30 s, followed by two direct muscle stimulations to assess force generation by potentiated high-frequency (Db100) and low-frequency (Db10) doublets as described below (Figure 3.2). The highest value of the three 5-s MVC-ISO was used for further analysis, and maximal torque was calculated for the best MVC trial over a 0.5-s period around the peak. Electrical stimulation was applied percutaneously to the muscle motor points of *tibialis anterior* for DF and the two *gastrocnemius* for PF via 5 x 5 cm self-adhesive stimulation electrodes (Medicompex SA, Ecublens, Switzerland) and the anode, a 10 x 5 cm self-adhesive stimulation electrode (Medicompex SA, Ecublens, Switzerland), was located either below the patella (for DF) or on the *soleus* tendon (for PF). A constant current stimulator (Digitimer DS7A, Hertfordshire, UK) was used to deliver a square-wave stimulus of 1,000-ls duration with maximal voltage of 400 V. A shunt was used to stimulate the two motor points of the *gastrocnemius* with the same stimulator.

The optimal stimulation intensity was determined from maximal twitch torque measurement (see below) and was reassessed before the post-run measurements, and supramaximal intensity (50% greater intensity than the current at maximum twitch torque) was delivered. For both PF and DF, stimulations included high-frequency (100 Hz, 10-ms inter-stimulus interval) followed by low-frequency (10 Hz, 100-ms inter-stimulus interval) doublets delivered to the relaxed muscle in a potentiated state. Unfortunately, due to co-activation during stimulation, recording of the muscle Db from DF was not possible. Co-activation was determined by visual inspection. The peak torque of the potentiated high- (PDb100) and low- (PDb10) frequency doublets, and the ratio between PDb100 and PDb10 (Db10:100) were obtained for PF. The potentiated twitch was reported to be more sensitive index of contractile fatigue than the unpotentiated twitch.[201]

3.1.2.1.3 EMG (Study 1)

At the peripheral level, surface EMG recordings during evoked contractions have been used to indirectly explore neuromuscular fatigue.[357] The role of central fatigue in neuromuscular perturbations can be studied using the twitch interpolation technique, the ratio of the EMG signal during MVC normalized to the M-wave amplitude or the comparison of torques achieved with maximal voluntary and electrically-induced contractions (Figure 3.2).[137]

In the study 1, EMG data were recorded continuously from the right *tibialis anterior*, *gastrocnemius lateralis* and *soleus* during the isometric and isokinetic testing using a PowerLab system (16/30 - ML880/P, ADInstruments, Bella Vista, Australia) with a sampling frequency of 2000 Hz. Bipolar silver chloride surface electrodes of 10-mm diameter (Type 0601000402, Contrôle Graphique Medical, Brie-Comte-Robert, France) were taped lengthwise on the skin over the muscle belly following SENIAM recommendations, with an inter-electrode distance of 25 mm.[158] The reference electrode was attached to the malleolus. The electrode positions were marked on the skin so that they could be placed in the same place after the run. Low impedance (<5 kΩ) at the skin-electrode surface was obtained by abrading the skin with thin sand paper and cleaning with alcohol. The EMG signal was amplified (Octal Bioamp, ML138, ADInstruments) with a bandwidth frequency ranging from 5 to 500 Hz (input impedance = 200MΩ, common mode rejection ratio = 85 dB, gain = 1000), transmitted to a PC and analysed with a LabChart6 software (ADInstruments).

The maximal root mean square values (RMS_{max}) of EMG signal of *tibialis anterior*, gastrocnemius lateralis and *soleus* were calculated over a 0.5 s period around the maximal voluntary torque of both MVC-ISO (RMS_{max}-ISO) and MVC-CON (RMS_{max}-CON), and over the 30 concentric contractions in the fatigue resistance test (RMS_{FRI}). The RMS values were not normalised to the maximal peak-to-peak amplitude of the M-wave because the percutaneous muscle stimulation did not allow obtaining high-quality M-waves. In addition, the mean power frequency (MPF) of the total power spectrum was calculated for *tibialis anterior* during DF MVC-ISO and for *gastrocnemius lateralis* and *soleus* during PF MVC-ISO.

3.1.2.1.4 Stride parameters and spring mass model (Studies 3 and 5)

As already explained in details in section 222, the musculo-tendinous structures of the lower limb alternately store and return elastic energy during running, acting as springs loaded by the weight and inertia of the body mass. This is called the “spring-mass model” (SMM). While assessing the fatigue–related running mechanics alterations, temporo-spatial parameters are of primary interest (e.g. increased contact time near to cessation when performing an exhaustive running trial), in addition to SMM parameters.[9, 123] In the study 3 and 5, flight (Tf) and contact (Tc) times were determined from the X-Pedar mobile software (Novel Win, Novel GmbH, Munich, Germany).[139] The pedobarometric data collection will be explained in the next section. Step frequency (SF = 1 / (Tc + Tf) in Hz) and step length (SL = $V_{forward}$ / SF in m) were calculated. In the study 3, from these measurements of Tc, Tf (in s), forward running velocity $V_{forward}$ and from subjects’ body mass m (in kg) and lower limb length (in m), measured as the great trochanter-to-ground distance in a standing position, spring-mass parameters were calculated using the computation method proposed by Morin et al.[258] This method based on a modelling of the ground reaction force signal during the contact phase by a sine function, allows computation of vertical stiffness (K_{vert}, $kN.m^{-1}$) as the ratio of the peak vertical force (Fzmax in N) to the maximal downward displacement of centre of mass (CM) during contact (Δz in m).

$K_{vert} = Fz_{max} / \Delta z$

with

$Fz_{max} = m \,.\, g \,.\, (\pi \,.\, 2^{-1}) \,.\, [(Tf / Tc) + 1)]$

and

$\Delta z = - (Fz_{max} \,.\, m) \,.\, (Tc^2 \,.\, \pi^2) + g \,.\, (Tc^2 / 8)$

Leg stiffness (K_{leg}, kN.m^{-1}) was calculated as the ratio of Fz_{max} to the peak displacement of the leg spring ΔL (in m) during contact

$K_{leg} = Fz_{max} / \Delta L$

with

$\Delta L = L_0 - \sqrt{}[L_0^2 - (V_{forward} \,.\, Tc / 2)^2] + \Delta z$

It was assumed that the vertical velocity of CM was zero at the time of Fz_{max}. In this equation, L_0 (initial leg length from great trochanter to ground distance in a standing position) was determined from subject's stature as $L_0 = 0.53$ x stature.[373]

3.1.2.1.5 Others

3.1.2.1.5.1 Determination of velocity at maximal oxygen uptake (Studies 2 and 3)

In studies 2 and 3, each participant completed an incremental test to exhaustion on a treadmill (h/p/Cosmos, Nussdorf-Traunstein, Germany) in order to determine maximal oxygen uptake and its associated velocity. It consisted of an initial one minute workload of 8 km.h^{-1} followed by increases of 1 km.h^{-1} every minute (1% slope). Gas exchange was measured using a breath-by-breath analyser (Oxycon Pro, Jaeger, Hoechberg, Germany).

3.1.2.1.5.2 Lactates (studies 2 & 3)

In the studies 2 and 3, a constant pace running exercise to exhaustion (T_{lim}) was performed at 95% of the velocity associated with maximal oxygen uptake with 1% slope on a treadmill (h/p/Cosmos, Nussdorf-Traunstein, Germany). A blood sample was collected for lactate measurement (Lactate Pro, Arkray Inc, Japan) during the 3 min period following running cessation.

3.1.2.1.5.3 Rating of perceived exertion

In the study 1, the participants reported their level of exertion immediately after the 5-h hilly simulated competitive run (e.g. close to exhaustion or completely exhausted).
In the studies 2 and 3, the rating of perceived exertion (RPE, 6-20 Borg scale) was recorded every minute during the T_{lim}, following the recommendations of Borg.[31]

3.1.2.2 Static and dynamic foot patterns-related material and data (Studies 2, 3, 4, 5 and 10)

3.1.2.2.1 Plantar pressure distribution measures

The pedobarometry portable technology is relatively recent and provides the researchers with the opportunity to assess the in vivo foot loading patterns of athletes. Several studies have shown that this foot plantar pressure measurement technology was accurate, highly repeatable, and valid to measure human movements.[167]

Material

In the studies 2-5 and 10, insole plantar pressure distribution was recorded using the X-Pedar Mobile System (Novel GmbH, Munich, Germany) (Figure 3.4). Each pressure insole consisted of a 2-mm-thick array of 99 capacitive pressure sensors. Before commencement of data collection, the insoles were calibrated according to the manufacturer’s guidelines. This involved loading the insoles to a range of known pressure values, which resulted in an individual calibration curve for all sensors within the shoe (TruBlu Calibration, Novel GmbH, Munich, Germany). One insole was placed under the right foot of all participants, wearing the same type of neutral running shoes or the same model of spikes (study 4), except in the study 3 where insoles were embedded in both shoes. The data logger for data storage was in a harness on the back of the participant (Figure 3.4). Plantar pressures were sampled at 50 Hz via a cable in studies 2, 3 and 5 (tests performed on a treadmill) and via Bluetooth technology in studies 4 and 10 (tests performed on an indoor track [Mondo, Sportek Surfaces, Ashfield, MA, USA]).

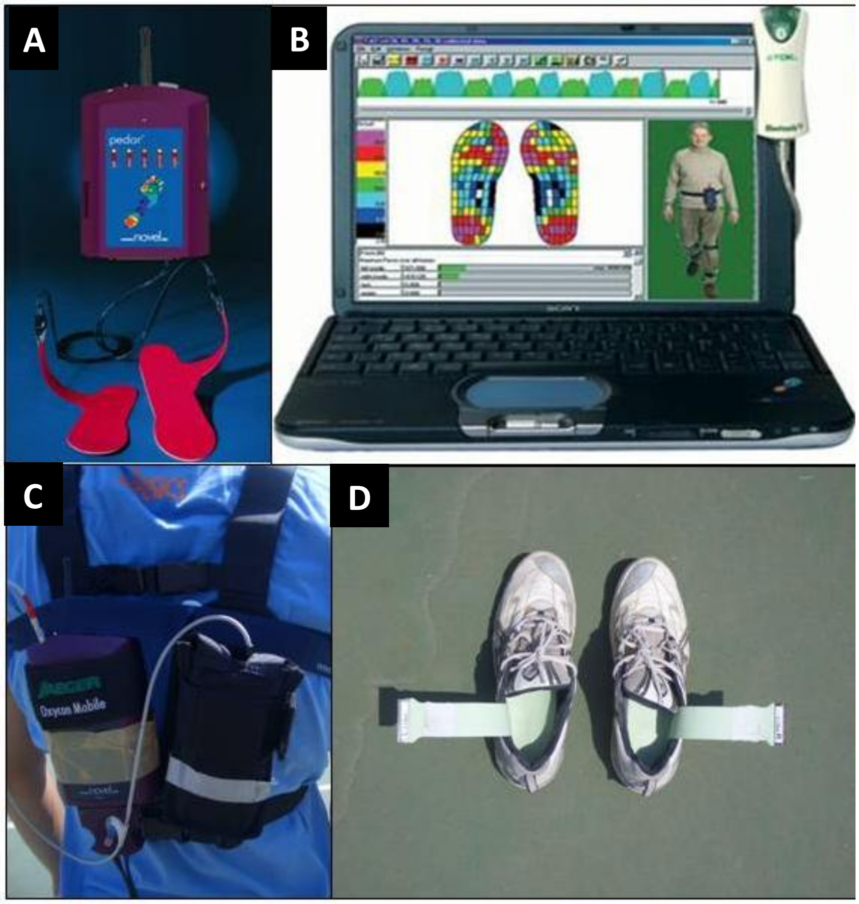

Figure 3.4: X-Pedar - Foot plantar pressure measurement technology. A: data recorder, cables and electronic insoles; B: X-Pedar softaware illustration; C: data recorder set-up; D: Set-up of the electronic insoles in the shoes. Adapted from Girard[132]

Data collection

Studies 2 and 3

During the T_{lim}, insole plantar pressure distribution was recorded (Figure 3.1.5). Plantar pressure data were recorded over a 30 s period corresponding to 78-84 steps at two occasions: (i) 1 min after the exercise start and then (ii) as soon as the participant reported 18 as RPE. This 30 s window ended in a range of 25 to 45 s prior exhaustion.

Study 4

In the study 4, the participants performed two sets of 2x60 m maximal sprint on an athletics track with training and spike shoes in a randomized order.

Study 5

In the study 5, insole plantar pressure distribution was recorded for 30 s after a minute of running at either 60% or at 95% of the velocity associated with maximal oxygen uptake (Figure 3.5).

Study 10

In the study 10, plantar pressure parameters were measured during 60 m full sprint in the control group and the tested group (foot-ankle strengthening training). After a warm-up, the subjects performed three maximal 60 m sprints on a synthetic indoor athletics track, starting in a standing position.

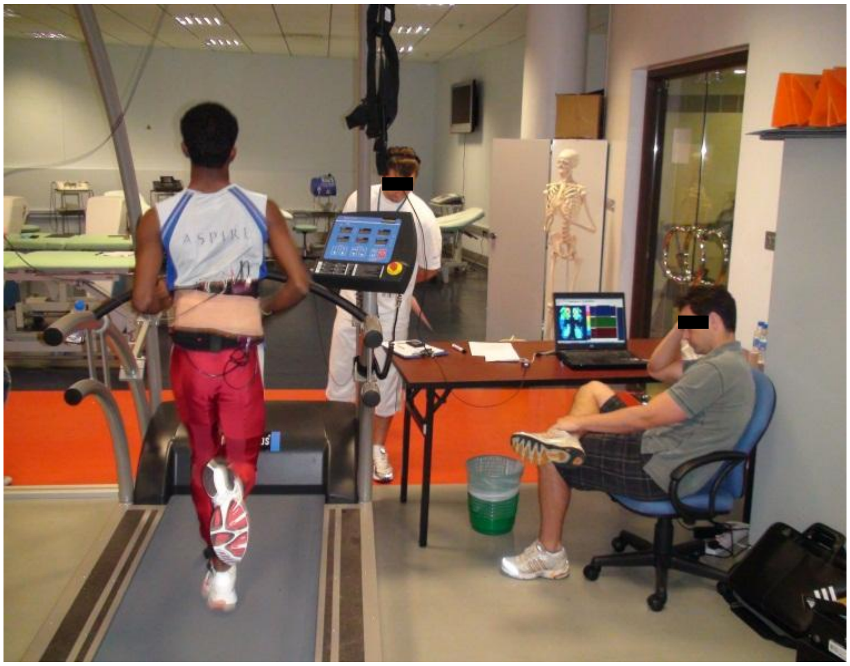
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Figure 3.5: Experimental set-up for the studies 2, 3 and 5. Note the X-Pedar data recorder at the back of the runner and the real time recording of the plantar pressure parameter.

Data analysis

For all the studies reporting foot plantar pressure distribution data, a global (whole foot) analysis was performed. For all the studies reporting foot plantar pressure distribution data, except the study 3, a regional analysis was performed utilizing nine separate ‘‘masks’’ or areas of the foot, i.e. medial and lateral heel, medial and lateral mid-foot, medial, central and lateral forefoot, hallux and lesser toes (Groupmask Evaluation, Novel GmbH, Munich, Germany) (Figure 2.15).[133] Mean area (in cm^2), contact area (in cm^2), contact time (in ms), maximum force (in N), mean force (in N), mean pressure (in kPa), peak pressure (in kPa) and relative load (i.e. force time integral in each individual region divided by the force time integral for the total plantar foot surface, in %) were determined for the nine selected regions. In the study 5, as RL(FTI) does not take into account the size of an area it is applied to, a more meaningful calculation of the relative load (RL(PTI)) was performed while replacing FTI by (FTI/CA) in the above mentioned calculation of RL(FTI), and where PTI means pressure time integral.[245]

Study 4

For examining the loading patterns data of 13-14 steps during the last 30 m was averaged from several trials by electronic insoles inserted into the right shoe. The running times for the last 30 m were measured by timing gates (Speed Light, Swift Performance Equipment, Lismore, Australia).

Study 10

The sprint time for the last 30 m was measured with a dual-beam timing gate system with simultaneous plantar pressure data collection. Sprints were also videotaped in order to define the corresponding right foot steps during the last 30 m and to assess the stride frequency. Stride frequency was calculated by dividing the stride count (i.e. number of steps of the last 30 m over the fastest sprint) by the sprint time (i.e. sprint performance in the last 30 m over the fastest sprint). The fastest sprint was chosen for the analysis of the foot loading patterns. All the right foot contacts during the last 30 m of the fastest sprint were averaged for further analysis.

3.1.2.2.2 Medial arch stiffness and foot mobility magnitude (Study 3)

Foot mobility is a critical component in the evaluation of foot function. The clinical assessment of foot mobility requires the use of simple and reliable techniques.[235] While numerous techniques for the assessment of foot posture have been described in the (e.g. the arch index, the bony arch index, valgus index, longitudinal arch angle, and the arch height index), only two techniques are commonly used to assess foot mobility: the navicular drop and navicular drift.[53, 67, 235, 330] Navicular drop will be detailed in the section 3.1.2.2.3. Navicular drift is the assessment of the medial-lateral movement of the midfoot.[235, 246] Mc Poil and Cornwall proposed to use these two measures to calculate a composite value of vertical and medial-lateral mobility of the midfoot: the foot mobility magnitude (FMM) measure.[235]

For the purpose of the study 3, three instruments including weight bearing, and non-weight bearing arch height gauges and a midfoot width measurement device were manufactured. Each of those included a digital calliper (AmPro T74615 Stainless Steel Digital Caliper, Frenway Products Inc. Taipei) (Figure 3.6 A, B and C). The FMM measurement procedure, which was performed before and immediately after the exhaustive run, is succinctly summarized below; for a full description of the method the reader is referred to Mc Poil and Cornwall.[235] Each subject was asked to stand on a foot measurement platform (heels placed in heel cups) so that dorsal arch height and midfoot width could be measured in bilateral lower limb weight bearing (Figure 3.6 D and E). Afterwards, the non-weight bearing measurements of these two parameters were recorded with subjects sitting with both lower legs hanging in a perpendicular relaxed position (Figure 3.6 F and G). The procedure used for the weight bearing measures was then repeated. As recommended previously, a single measure in weight bearing but the average of two measures in non-weight bearing (both in cm) have been obtained by the same investigator, with SEM established at 0.1cm.[235] A high level of reliability (Intraclass Correlation Coefficient > 0.97) has been reported for this measurement technique.[235] A method based on the Pythagorean Theorem was used to calculate the FMM:

$\text{FMM} = \surd(\text{DiffAH})2 + (\text{DiffMFW})2$

where DiffAH and DiffMFW are the changes in dorsal arch height and in midfoot width between weight bearing and non-weight bearing, respectively.

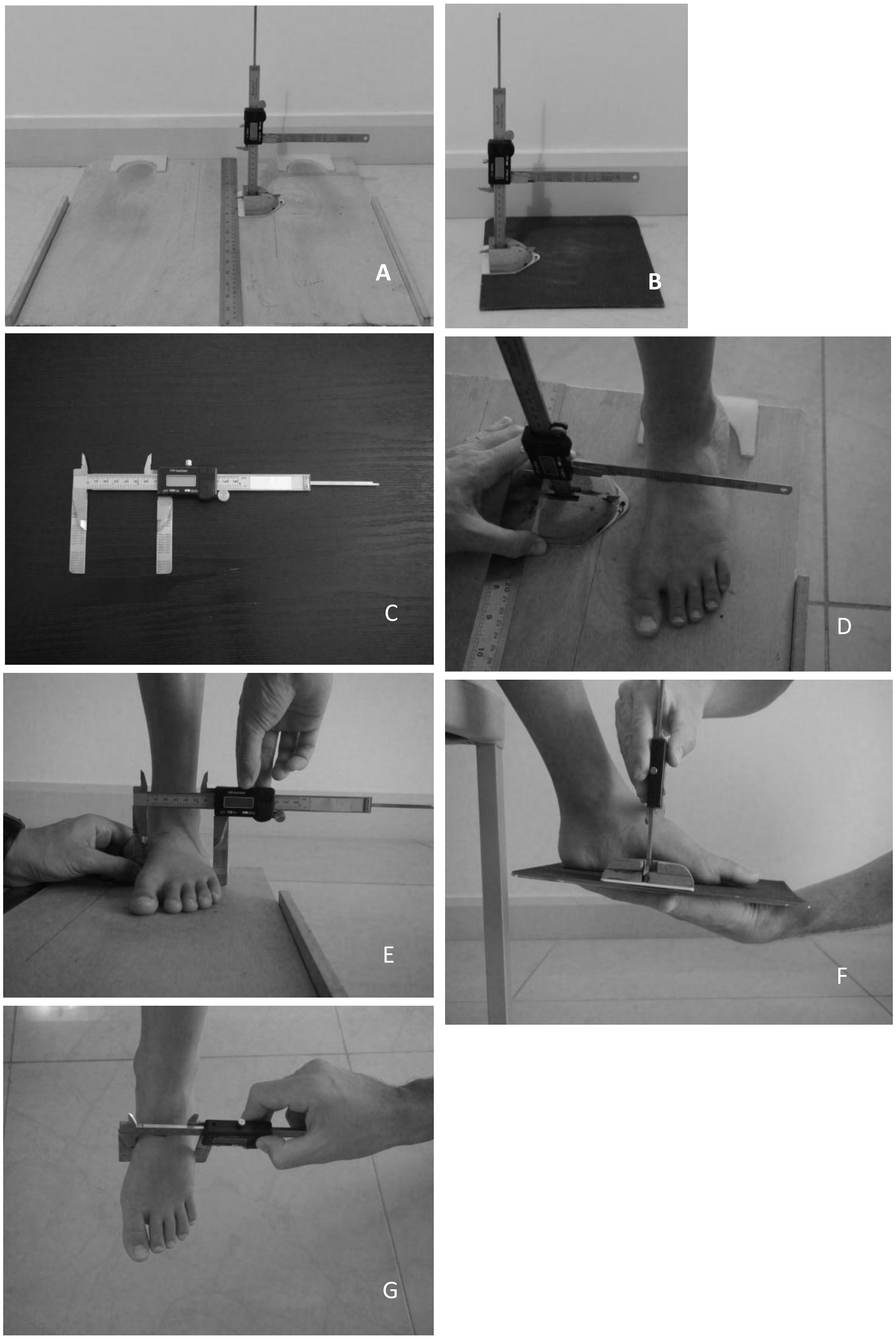

Figure 3.6: The foot mobility magnitude (FMM) measurement. (A) the weight bearing arch height gauge, (B) the non-weight bearing arch height gauge, (C) the midfoot width measurement device, (D) the weight bearing arch height measurement technique, (E) the weight bearing midfoot width measurement technique, (F) the nonweight bearing arch height measurement technique, (G) the non-weight bearing midfoot width measurement technique.

3.1.2.2.3 Navicular drop (Study 9)

Navicular drop is a measure of the sagittal plane mobility of the midfoot by quantifying the vertical change in the height of the navicular tuberosity.[36, 235, 326] As described by Brody, this technique was utilized to evaluate excessive pronation and it was shown to be taken reliably by clinicians with varied experience.[36, 322] In the study 9, all the navicular drop measures were performed by the same examiner, with intratester ICC of 0.95 measured during a preliminary test on 13 subjects. The barefoot subject stood in front of the examiner, who placed a mark on the skin at the most inferior border (edge) of the most prominent medial aspect of the navicular tubercle (Figure 3.7). The examiner then measured and recorded the height difference between this skin mark in sitting position both feet on the ground (subtatar neutral and non-weight bearing position determined by palpating the talus as described by Snook Grover and in single leg standing position with the MLA relaxed.[326] The vertical movement of the navicular tubercle in the sagittal plane was denoted as navicular drop.[111, 322, 326] This difference was measured three times on the dominant foot of each participant and the average measure was recorded.

Figure 3.7: Navicular drop measurement.

3.1.2.2.4 Foot strike pattern (Study 5)

It has been reported that almost 75% of runners exhibited a heel strike pattern and 23.5% and 1.5% being midfoot and forefoot strikers, respectively.

Prior to participation in the study 5, six participants were identified as rearfoot strikers and the remaining five as mid/forefoot strikers, using the procedure described by Hasegawa et al.[150] These authors considered that:

- Rearfoot strike was defined as a foot strike in which the point of the first contact of the foot with the ground was the heel or rear third part of the sole only and in which the midfoot or forefoot portion did not have any contact at foot strike.
- Midfoot strike was defined as a foot strike in which the point of the first contact of the foot with the ground was not only the rear third of the sole but the midfoot or entire part of the sole.
- Forefoot strike was defined as a foot strike in which the point of the first contact of the foot with a ground was the forefoot or front half of the sole and in which the heel did not have any contact at the foot strike (Figure 3.8).

Figure 3.8: Sample picture of foot strike patterns. Rearfoot strike, midfoot strike and forefoot strike from top to down. (Hasegawa et al., 2007)

3.1.2.3 Epidemiological and maturation-related data (Studies 6 and 9)

3.1.2.3.1 Injury reporting system

As already cited in the injury prevention-related section, a proper assessment of sports injuries provides not only important epidemiological information, but also directions for injury prevention. From an epidemiological point of view, the aim of the study 6 was to collect injury data in order to describe the type and severity of foot-ankle and lower leg injuries sustained by young track and field athletes in Aspire Academy, which is the Qatar national training centre for the best adolescent athletes. The data were prospectively collected during the three seasons 2005/06, 2006/07 and 2007/08. At that time, the injury reporting system in use in Aspire Academy should have been used for this study. It was a composite from several existing systems, mainly based on the soccer model.[177] It is worth reminding that the consensus statement of the IOC was published in 2008,[176] the consensus football statement in 2006 and that the book of Caine and Maffulli (including the most exhaustive report to date about track and field injuries by Zemper) was available from 2005 only.[47,119, 376]

The study 6 involved prospective collection of injury data over a period of three years for 110 adolescent males who were track and field athletes: sprint/hurdles (n = 25), jumps and combined events (n = 15), distance (n = 24), throws (n = 23), and beginners (n = 23; i.e. first-season athletes not assigned to a specific event). The figure 3.9 displayed the list of the available criteria for reporting an injury. An accredited physiotherapist specialised in track and field was responsible for recording the injuries in the database on a daily basis and used a standardized injury reporting form including several injury criteria (e.g. type, site, side, mechanism, origin, severity) (Figure 3.9). The epidemiological data cited in the study 9 were collected and analysed using the same process and they have been displayed in a descriptive manner afterwards.

The information must to be recorded for every new visit in the Physiotherapy

Type of injury	Site of injury	Side	Limb dominance	Mechanism	Type of movement	Origin	Type of training	Circumstance	Surface	Type of shoes	Day	Duration of absence	Classification of the injury
Contusion	Head	Left	Dominant	Impulse Propulse	Walking	Training	Core session	Non-contact injuries	Grass	Spikes	Sunday am	0 day Disorder	First Injury
S.L.D	Cervical spine	Right	Non-Dominant	Overuse	Jogging	Competition Game	S & C	Contact injuries	Artificial	Jogging boots	Sunday pm	1 day to 3 days Minor injury	Early recurrent within 2 months
D.O.M.S	Thoracic spine	Both		Collision	Running	Outside of sport	Others		Track	Indoor boots (e.g.handball)	Monday am	4 days to 7 days Moderate injury	Recurrent 2 months to 1 year
Spasm	Chest	No		Twist	Sprinting				Wood paneling	Football screw in studs	Monday pm	8 days to 3 weeks Major injury	Delayed recurrent more than 1 year
Strain I	Lumbar spine			Others	Turning				Water	Football blades boots	Tuesday am	more than 3 weeks Severe injury	
Strain II	Shoulder				Cut off				Concrete	Football moulded boots	Tuesday pm		
Strain III / Rupture	Arm				Jumping				Sand	Artificial pitch boots	Wednesday am		
Tendinopathy	Elbow				Landing				Others	No shoes	Wednesday pm		
Sprain I	Forearm				Heading					Others	Thursday am		
Sprain II	Wrist				Passing						Thursday pm		
Sprain III	Hand				Shooting						Friday am		
Instability / Subluxation / Dislocation	Fingers				Dribbling						Friday pm		
Periostitis	Abdomen				Tackling						Saturday am		
Fracture	Pelvis				Sliding						Saturday pm		
Concussion	Groin				Diving								
Capsulitis	Hip				Tackled								
Bursitis	Thigh				Kicked								
Meniscus	Knee				Impact								
Others	Tibial tubercle				Stretching								
	Lower leg				Falling								
	Ankle				Hit by ball								
	Foot				Starting								
	Heel				Taking off								
	Toes				Jumping a hurdle								
	Abductor				W-L techniques								
	Adductor				Straight acceleration								
	Quadriceps				Straight deceleration								
	Hamstrings				Hit by club / racquet								
	Calf				Stuck to wall								
	Patellar tendon				Back hand								
	Achilles tendon				Lunges (split)								
					Unclear movement								
					Throwing								

S.L.D = Self Limiting Disorders (or trivial injuries): Infraclinical injury , with poor objective findings on examination resolving with or without therapy.

D.O.M.S = Delayed Onset Muscular Soreness

W-L techniques = Weight-Lifting techniques

S & C = Strength & Conditioning

Figure 3.9: Criteria of injury used in the study 6.

Athlete-exposures (AE) were recorded by the coaches and assistant coaches and forwarded to the medical staff on a monthly basis. An AE was defined as one athlete participating in one practice or competition where there is the possibility of sustaining an athletic injury. An injury was defined as a trauma occurring during athletics training/competition, requiring one or more physiotherapy treatments and keeping the athlete from participation for one or more training sessions/competitions. Injury severity was defined in accordance with time loss: an injury was considered as minor if the athlete was out of training/competition for one to three days, moderate for duration of absence of four to seven days, major or severe for duration of absence of one to three weeks and greater than three weeks respectively. Due to the young age of the subjects and the low severity of their injuries when compared with adults, the short durations of absence due to injuries (less than three weeks) were voluntary very detailed in the scale (less than 3 days, 4 days to 7 days and 8 days to 3 weeks). The following injury sites were recorded: Foot/ankle/lower leg; Pelvis/Hip/lumbar; Hamstrings & Quads; Knee; Shoulder; Others. For this study, only those injuries pertaining to the toes, the foot, the ankle, the calf, the Achilles tendon and the lower leg were analysed, selected by the coding of the injury location from the dataset. All such foot-ankle and lower leg injuries were included in the analysis. Absence through illness or injuries sustained outside of the training centre setting was not recorded.

3.1.2.3.2 Anthropometrical measurement

Frequent anthropometrical measurements are needed in order to accurately track the adolescent development and maturation. Anthropometrical measurements were taken by an ISAK (International Society for the Advancement of Kinanthropometry) accredited anthropometrist every third month. Two measurements were taken for each anthropometric variable. A third measurement was required if the first two differed by more than 4 mm for height and sitting height. The two measurements for each anthropometric measure were averaged. If three measures were taken, the median value was used.[255] The sum of seven skinfold thicknesses (triceps, subscapular, biceps, supraspinale, abdominal, front thigh, and medial calf) were measured with Harpenden callipers (British Indicators Ltd., West Sussex, UK). Stretch heights were measured during inhalation using a Holtain limited stadiometer (Holtain Limited, Crosswell, Crymych, United Kingdom). For each subject, chronological age, height and sitting height to the nearest mm were measured. Intra-observer technical error of measurement was calculated with test-retest of 20 full anthropometrical profiles by the anthropometrist. The age of PHV was individually determined using the predictive equation proposed for males by Mirwald et al.:[255]

Maturity Offset = -29.769 + 0.0003007 x Leg Length and Sitting Height interaction - 0.01177 x Age and Leg Length interaction + 0.01639 x Age and Sitting Height interaction + 0.445 x Leg by Height ratio, where R = 0.96, R2 = 0.915, and SEE = 0.490.

By using the age of PHV as the maturational benchmark, each measurement occasion was described as years from PHV by subtracting the age of PHV from the chronological age at each measurement occasion. The difference in years was defined as a value of maturity offset. Then the maturity status was calculated and the subjects were classified into three categories: early, normal, or late. Early and late maturers were classified as such if their PHV age was more than one year older or younger, respectively, than the mean PHV age of the whole group of participants. Normal maturers refer to a PHV age within one year of the mean PHV age of the whole group of participants.

3.1.2.4 Flexibility measurement-related materials and data (Studies 7 and 8)

3.1.2.4.1 The “Angle at Force Standardized Endpoint” procedure for flexibility assessment

The lack of flexibility affecting the lower limb muscles may relate to increased risk of apophysitis due to an excessive “pre-load” tension applied at the insertion of the tendon on the bone (apophysis).[151] The lack of flexibility of the triceps surae was described to predispose to medial tibial stress syndrome, lateral ankle sprain, Achilles tendinopathy or plantar fasciitis.[345, 368] So the question of an “optimal” level the flexibility must be addressed. The accuracy and the reliability of flexibility measures is therefore of primary interest for clinicians. Today, to assess muscle groups flexibility, several methods using different devices, have been proposed.[18, 28, 61, 112, 114, 204, 214] For example, the range of motion of the joint of interest can be measured using goniometers / inclinometers or a (video) camera coupled with a motion analysis software.[20, 28, 61] While the endpoint measurement is usually subjectively defined by the patient’s tolerance to stretch (which limits the accuracy of the method), few studies have measured the endpoint angle with the application of a standardized force or torque.[114,

[204] While eliminating any possible subjective factors, these latter procedures were demonstrated to be more accurate than the method involving the patients' feedback.[18]
In the study 7, the flexibility of eight lower limb muscle groups was tested on both sides in participants, on two occasions (3 days apart). The first step consisted in the video capture of the lower limb in the appropriate position. Secondly, the video clips were computer-analysed to measure the angle(s) of interest. The measurement endpoint was reflected by the angle of the joint of interest with the application of a standardized force on the distal part of the segment. The force was applied just proximal to the malleolus level for each tested muscle groups, except for the hip flexors and calf muscles. The force was applied on the anterior side of the thigh just above the patella for the hip flexors and on the heads of metatarsals at the plantar side of the foot for the *gastrocnemius* and *soleus* muscles. A specific force was defined for each muscle group using published data when available,[114] or empirically, i.e. using the largest force that all athletes of the academy were likely to tolerate[18, 112]. A hand-held dynamometer (Compact force gauge, Mecmesin, Slinfold, United Kingdom) with a scale marked in 0.01-N increments was used to apply the standardized force (Figure 3.10). Since difference in force less than 0.1-N are unlikely quantifiable, the measures were rounded at the nearest 0.1-N.[359] The dynamometer was calibrated each day before each test.

Figure 3.10: Flexibility assessment - the hand-held dynamometer.

The video capture of the flexibility angle measurement was performed by one pair of operators. The first operator mobilized the lower limb using the dynamometer in order to reach the standardized stretch force. Simultaneously, the second operator recorded the movement with a digital video camera (Digital video camera recorder, DCR-SR220E, Sony corporation, Tokyo, Japan) positioned orthogonally in front of the joint rotational axis. As soon as the requested force (displayed on the dynamometer screen) was reached and stabilized, the first operator announced “ok” to the video recorder, who stopped the recording (Figure 3.11). Using the above-mentioned procedure, the eight muscle groups were tested as following.

Figure 3.11: Flexibility assessment – Operators performing the video capture of the flexibility angle measurement. Hip medial rotators.

The adductors flexibility measure was performed with the athlete supine. A horizontal white line was drawn to set the longitudinal axis of the bench. The body was aligned with the white line, one leg hangs off the side of the table, and the lower limb to be tested was passively abducted with the knee in a neutral position. The dynamometer was used to further abduct the lower limb to be examined with a force of 39.2 N. The adductors measure was the angle formed between the body line and the abducted lower limb (Figure 3.12).

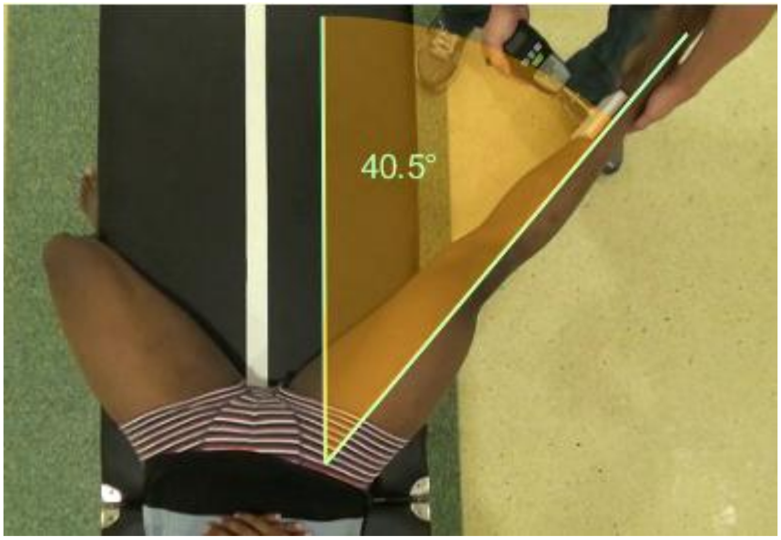

Figure 3.12: Adductors flexibility assessment.

The hip flexors measure was performed with the athlete supine. The pelvis was aligned with the end of the table, one lower limb was maintained by the operator in maximal flexed position towards the abdomen, and the lower limb to be tested was extended in neutral rotation. The dynamometer was used to further extend the lower limb to be examined with a force of 98.1 N. The hip flexors measure was the angle formed between the body and the extended lower limb (Figure 3.13).

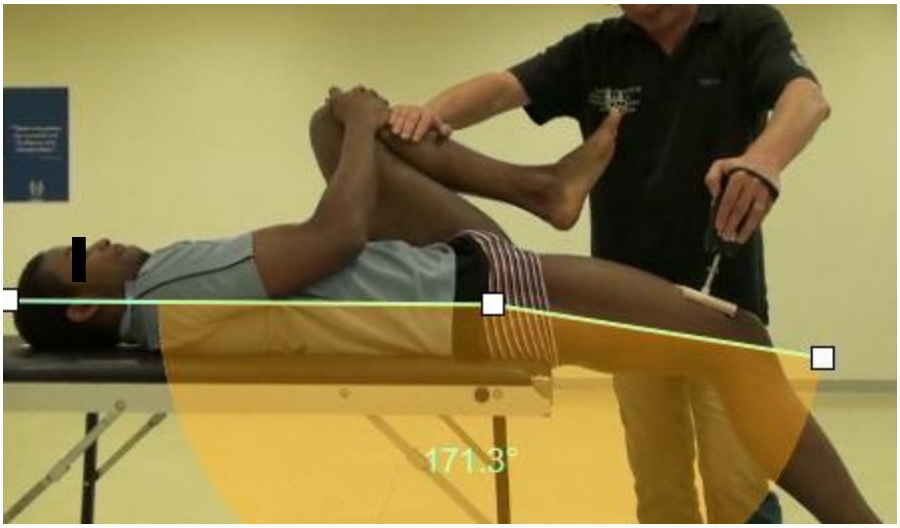
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Figure 3.13: Hip flexors flexibility assessment.

The hip medial rotators measure was performed with the athlete supine. The body was aligned with the white line, the knee and the hip were flexed to 90^o and stabilized, and the lower limb to be tested was passively externally rotated at the hip. The dynamometer was then used to further externally rotate the lower limb to be examined using a force of 49.1 N. The hip medial rotators measure was the angle formed between the body line and the externally rotated lower limb (Figure 3.14).

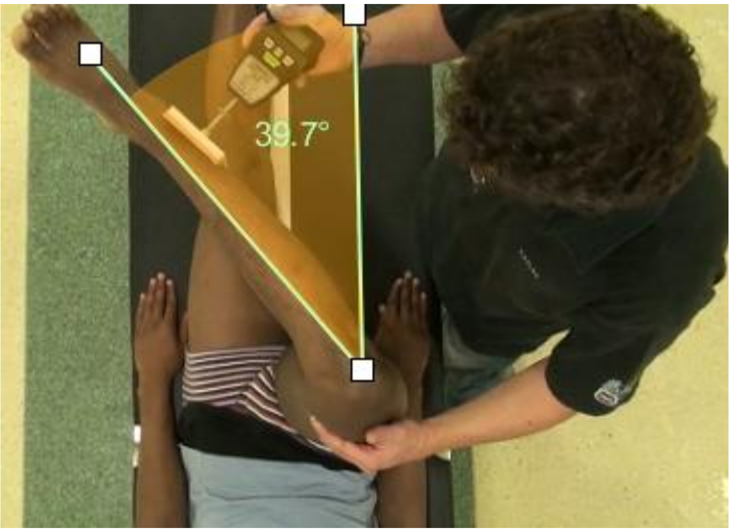


Figure 3.14: Hip medial rotators flexibility assessment.

The hip lateral rotators measure was performed with the athlete supine. The body was aligned with the white line, the knee and the hip were flexed to 90^o and stabilized, and the lower limb to be tested was passively internally rotated at the hip. The dynamometer was then used to further internally rotate the lower limb to be examined using a force of 49.1 N. The hip lateral rotators measure was the angle formed between the body line and the internally rotated lower limb (Figure 3.15).

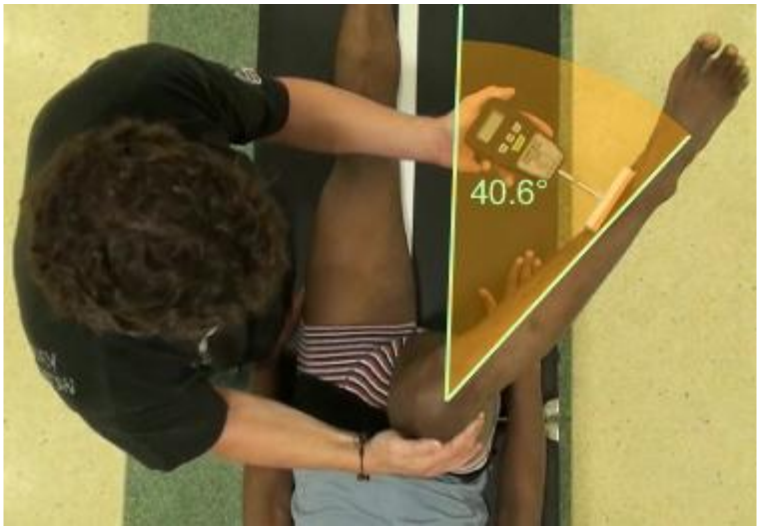
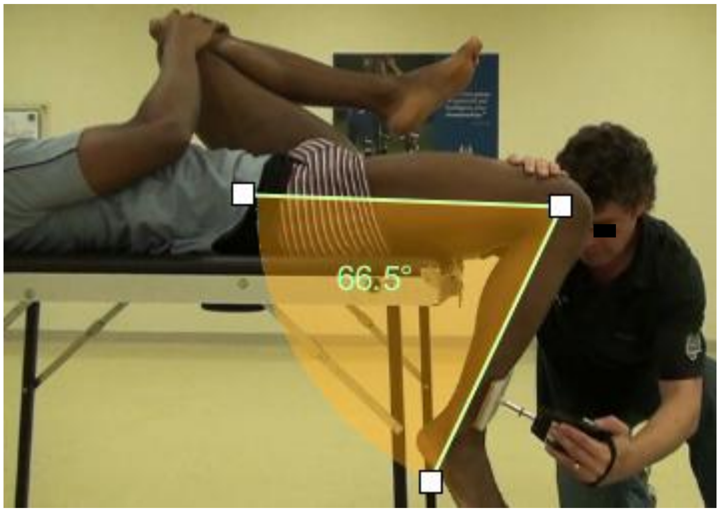


Figure 3.15: Hip lateral rotators flexibility assessment.

The quadriceps measure was performed with the athlete supine. The mid-thigh was aligned with the end of the table, one lower limb was maintained by the operator in maximal flexed position towards the abdomen and the lower limb to be tested hangs off the end of the bench in neutral rotation. The dynamometer was used to passively flex the knee to be examined with a force of 78.5 N. The quadriceps measure was the knee flexion angle (Figure 3.16).



[redacted]

Figure 3.16: Quadriceps flexibility assessment.

The hamstring measure was performed with the athlete supine. The lumbar spine was kept flat on the bench with one lower limb extended, with the other hip flexed to 90°. Keeping the hip flexed at 90°, the dynamometer was used to further extend the knee to be examined with a force of 68.7 N. The hamstring measure was the angle formed by the extended knee (Figure 3.17). This position of the subject during the stretch manoeuvre placed tension primarily on the muscle-tendon unit without involvement of posterior capsular constraints about the knee.[214] It is however worth mentioning that this measure does not take into account the potential effect of the gravity on the tested leg. This limit resulted in the design and set-up of the study 8.

Figure 3.17: Hamstring flexibility assessment.

The *gastrocnemius* measure was performed with the athlete prone and the knees extended. The operator manually verified a subtalar neutral position and the dynamometer was used to passively dorsiflex the ankle to be examined with a force of 147.2 N. The *gastrocnemius* measure was the angle formed by the dorsiflexed ankle (Figure 3.18).

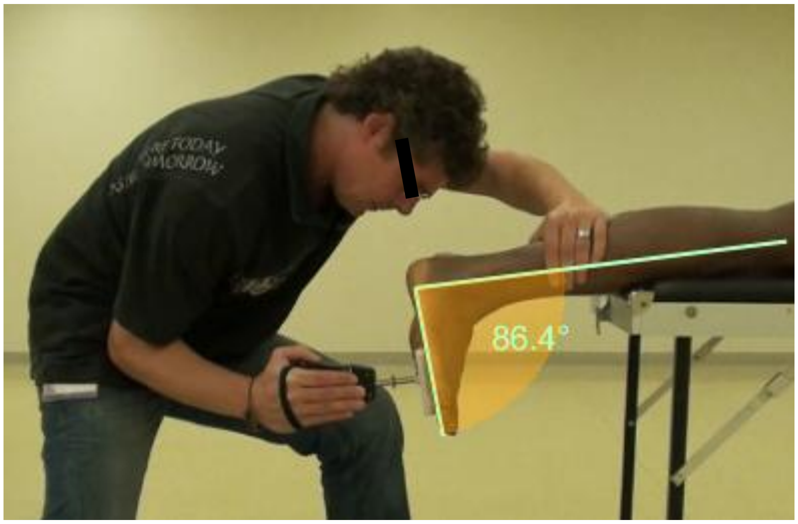

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Figure 3.18: ***Gastrocnemius*** **flexibility assessment.**

The *soleus* measure was performed with the athlete prone. The leg to be tested has the knee flexed to 90^o. The operator manually verified a subtalar neutral position and the dynamometer was used to passively dorsiflex the ankle to be examined with a force of 147.2 N. The *soleus* measure was the angle formed by the dorsiflexed ankle (Figure 3.19).

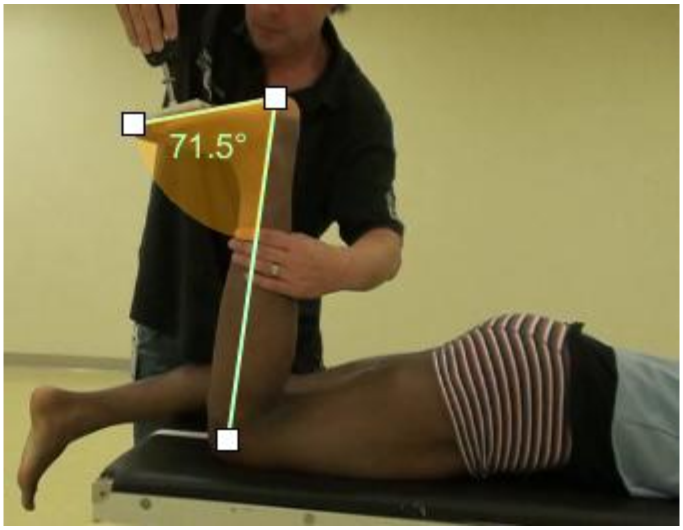

Figure 3.19: ***Soleus*** **flexibility assessment.**

Following the video capture of the flexibility angle measurement, different groups of physiotherapists (i.e. analysers), used a digital motion analysis software (Dartfish Software, TeamPro Classroom 5.5, Fribourg, Switzerland) to measure the angle of interest (Figure 3.20). The final angles for each muscle group of each participant were expressed to the nearest 0.1 degree. Measurements were taken according to identifiable anatomic landmarks, avoiding the estimation of each exact joint rotational axis. The ability to zoom in on the electronic image made identification of anatomic landmarks very easy.

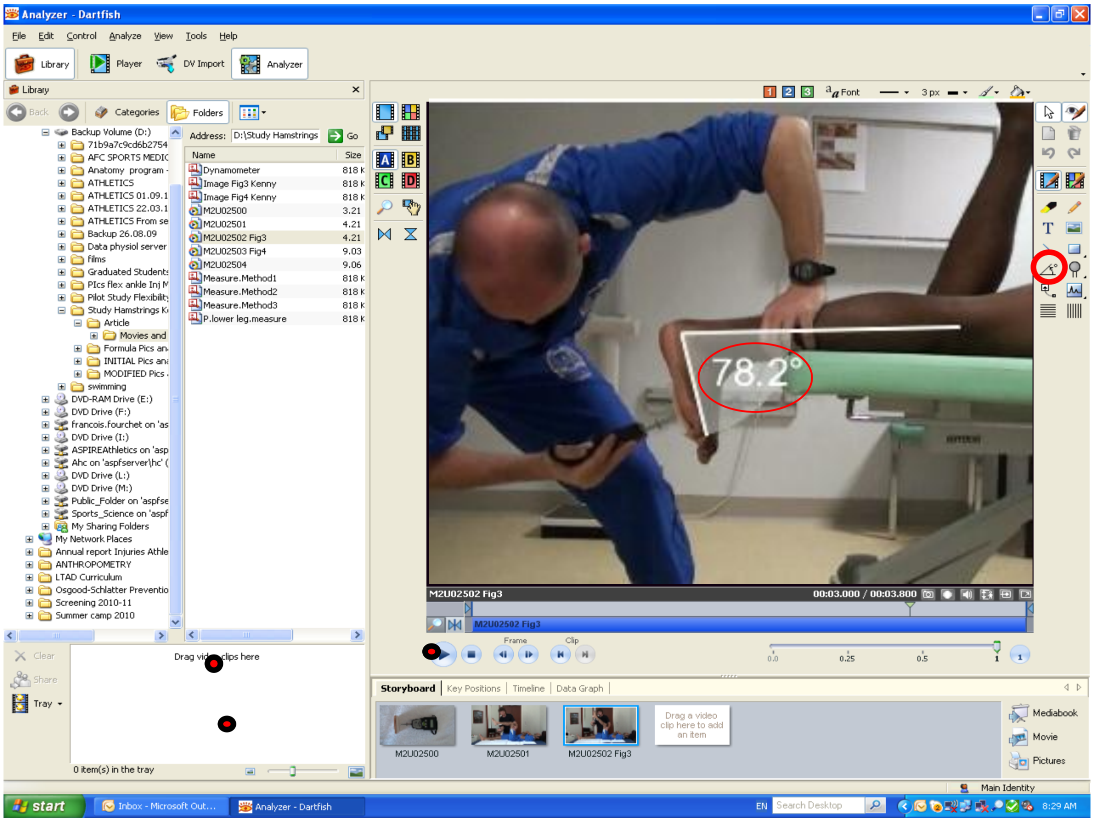

Figure 3.20: Flexibility assessment – Digital video analysis procedure.

3.1.2.4.2 Hamstring flexibility tests: influence of gravity correction (Study 8)

While this study is not related to the foot-ankle complex, it has been thought of interest to briefly mention the improvement of the procedure here. As shown in the figure 3.21, the hamstrings flexibility assessment was included in the study 7. However, one may note that this method does not take into account the potential effect of the gravity on the tested leg. Indeed, the closer to the vertical, the lower the relative weight of the lower leg. As it was already shown in isokinetic testing,[374] it is critical to correct values of passive knee extension test biased by gravitational effects, in order to obtain a more accurate assessment of hamstring tightness. The study 8 therefore aimed to compare original passive knee extension test described in study 7 (Method 1, M1) with two adapted methods including the gravity effect on the lower leg (Methods 2 and 3).

In the method 2, the passive knee extension test was performed with the lower leg weight being directly measured using the dynamometer. In the reference position (Figure 3.21), the hand-held dynamometer was therefore applied on the lower leg (proximal to the lateral malleolus) to determine the weight of the lower leg at this point (WP) [N]. After that, the hamstring tightness was assessed on the same way as M1(with the 68.7 N force) to find passive knee angle (α). To determine the applied force (F) to be added to the 68.7 N, the cosine of alpha was multiplied by the weight of the lower leg:

$F = \text{Cos}\ \alpha \cdot WP$

Finally the passive knee angle with the new applied force (68.7 + F) was evaluated. The video analysis software was used to determine the angle for M2, such as in the study 7.


[redacted]
[redacted]

Figure 3.21: Reference position of the passive knee extension flexibility test – measure of the lower leg weight.

In the method 3, the passive knee extension test was performed with the lower leg weight being determined from anthropometrical table. The subjects were weighted [N] and measured [m] (Holtain Limited, Crosswell, Crymych, UK). Then, the weight (W =

6.1% of body weight), length (L = 28.5% of body size) and centre of mass location (from the knee: 60.6% of the length of the complex "lower leg-foot") of the complex "lower leg-foot" were determined from the anthropometrical table.[372] To determine the lower leg weight at the dynamometer pushing place (WP2) (proximal to the lateral malleolus) [N], the following formula was used:

$WP2 = [W \cdot (0.606 \cdot L)]/L$

The hamstring tightness was then assessed on the same way as M1 with the 68.7 N of pushing to find the alpha (α) angle. To determine the applied force (F2) to add to this 68.7 N, the following formula was used:

$F2 = \cos \alpha \cdot WP2$

3.1.3 Injury prevention interventions (Studies 9 and 10)

As suggested by several authors,[5, 51, 52] while running, an athlete alternately gains and loses external kinetic energy. The musculo-tendinous structures of the lower limb therefore store and return alternately elastic energy during the stretch-shortening cycle. Cavagna explored recently the role of the contractile machinery (i.e. contractile component of the muscles) in this stretch-recoil process during running.[51] It was concluded that the behaviour of the contractile fibres was different in accordance with the running speed. At low running speeds (i.e. less than ~14 $km.h^{-1}$) muscle activation is likely to be moderate with the result that some of the length change of the muscle–tendon units is sustained by muscle fibres. At speeds greater than ~14$\cdot km \cdot h^{-1}$, muscle activation may be increased to such an extent that muscle fibres are held almost isometric, so that the length change is taken almost completely by tendons, as assumed in the spring-mass model. In other words, the role of the contractile machinery at high speeds is to provide a force large enough to exploit a large fraction of the force–length relation of the elastic elements for the storage of mechanical energy. While the role of the elastic structures is predominant during the stance phase in running, these findings emphasize the important action of the contractile structures in that process. It appears then that the strengthening of these structures at the foot and lower leg levels must not be neglected and this is the purpose of the following sections.

3.1.3.1 Neuromuscular electromyostimulation reinforcement

It has been reported that neuromuscular electromyostimulation reinforcement (NMES) of MLA muscles induced a lateral displacement of anterior maximal pressure point of the stimulated foot (e.g. inversion) in standing position.[121] To our knowledge, only this study used NMES of the intrinsic foot muscles despite that NMES is now widely used for strength training or rehabilitation of lower limbs muscles in athletes.[211, 293] It was demonstrated that a limited dose of NMES may be sufficient for inducing significant changes on muscles strength, i.e. a short-term NMES program (3 sessions per week during 3 weeks) on knee extensors significantly enhanced isokinetic strength and 12 sessions of approximately 12 min of NMES on ankle plantar flexors and knee extensors enhanced the jumping performance).[35, 215] In addition, Gaillet et al. reported that a single 20 min NMES session of the MLA muscles induced immediate specific changes in baropodogram indices (e.g. lateral displacements of the anterior maximal pressure point), some of which persisted 2 months later.[121] In the studies 9 and 10, NMES reinforcement sessions of the MLA muscles were performed with the participant adopting a standing isometric position with both feet on the ground and the hands on the wall in front of him. This position, 0° to 20° ankle dorsiflexion, avoids the "back fall" and the cramps during the electrically induced contraction. One portable stimulator (Compex 2, Medicompex SA, Ecublens, Switzerland) (Figure 3.22) was used to deliver NEMS (15 min; 75 EMS contractions completed during each training session; rise time = 0.25 s and descending time = 0.75 s). Two electrodes were placed behind the head of the first metatarsal of both legs.

Figure 3.22: Neuromuscular electromyostimulation reinforcement of the medial arch muscles of the foot – position of the electrodes.

In order to maximize muscle tension without accompanying detrimental effects on fatigue onset, biphasic symmetric regular-wave pulsed currents (85 Hz) lasting 400 µs were delivered.[294] Each 4-s steady tetanic stimulation was followed by pause lasting 8-s, during which subjects were sub maximally stimulated at 4 Hz on the MLA muscles. Subjects were consistently asked to increase the current amplitude within each training session and between sessions to attain the highest tolerable level without discomfort. In the study 10, the NMES reinforcement of the *soleus* was performed using two self-adhesive electrodes placed under the medial and lateral muscle bellies of the gastrocnemius and the same protocol and positioning were followed.

3.1.3.2 Foot-ankle strengthening training

In addition to the intrinsic MLA foot muscles, the plantar fascia and the foot ligaments, several extrinsic muscles are involved in the stretch-recoil process during the running stance phase (e.g. *gastrocnemii* and *soleus*, *posterior tibialis*, *flexor hallucis longus*, *peroneus longus* and *brevis*).[190-193] As studies have already reported that specific foot/ankle muscle strengthening induced performance enhancement in terms of strength and joint position sense, it is likely that the active and voluntary reinforcement of these muscles may be beneficial for athletes.[79, 107]

In the study 10, each session of the resistance training protocol lasted 25 min and was implemented in the normal strength and conditioning sessions. Six foot/ankle strength exercises were implemented.

- Inversion and eversion exercises consisted of concentric and eccentric contractions using elastic tubing (Thera- Band Tubing Resistive Exerciser, The Hygenic Corporation, Akron, OH). Resistance was progressively increased (Figure 3.23). Three sets of 10 repetitions per ankle were performed at each session.

Figure 3.23: Foot-ankle strengthening programme - inversion and eversion strengthening exercises - using elastic tubing.

- Double leg toe raises were performed at the edge of stairs in the full range of motion (3 sets of 10 repetitions) (Figure 3.24)

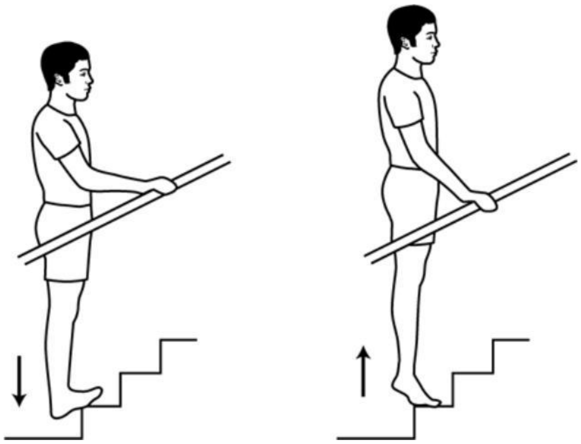

Figure 3.24: Foot-ankle strengthening programme - Double leg toe raises.

- Single leg toe lowers were performed at the edge of stairs in the full range of motion (3 sets of 10 repetitions) (Figure 3.25).

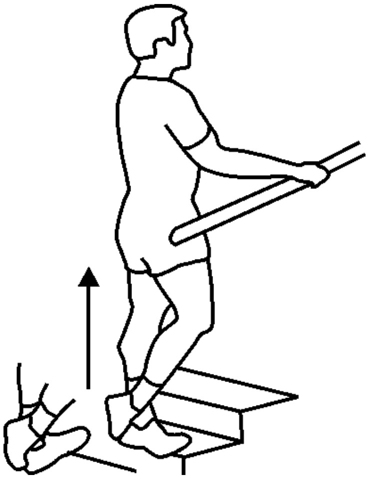

Figure 3.25: Foot-ankle strengthening programme - Single leg toe lowers.

- Horizontal calf jump were performed as shown in figure 3.26, with the athlete stopping after each jump and restarting from a static position. Two sets of 10 repetitions were performed at each session and a special attention was paid to the proper lower limb alignment during the exercises.

Figure 3.26: Foot-ankle strengthening programme – Horizontal calf jumps.

- Vertical calf jumps were performed on the spot and repeated over 2 sets of ten repetitions. A special attention was paid to the proper lower limb alignment and core stability during the exercises (Figure 3.27).

Figure 3.27: Foot-ankle strengthening programme – Vertical calf jumps.

3.2 Experimental studies

The main body of this thesis is made up of ten original experimental studies merged in three general concepts (figure 3.28):

3.2.1 Assessment of three running-related risk factors

3.2.1.1 Effects of fatigue on the foot-ankle mechanics

Study 1

Effects of a 5-hour hilly running bout on ankle dorsal and plantar flexors force and fatigability *(article published)*

Study 2

Impact of high intensity running on plantar flexor fatigability and plantar pressure distribution *(article submitted)*

Study 3

Changes in leg spring behaviour, plantar loading and foot mobility magnitude induced by a treadmill exhaustive run in adolescent middle-distance runners *(article submitted)*

3.2.1.2 Effect of shoe type on plantar pressure distribution

Study 4

Comparison of foot plantar distribution between training and spikes shoes in young sprinters *(article published)*

3.2.1.3 Effect of running velocity on plantar pressure distribution

Study 5

Comparison of plantar pressure distribution in adolescent runners at low vs. high running velocity *(article published)*

3.2.2 Injury and maturation in adolescent athletes

Study 6

Foot-ankle injuries and maturation in young track and field athletes *(article published)*

3.2.3 Injury prevention strategies design and implementation

3.2.3.1 Design and validation of a novel method for assessing adolescent flexibility

Study 7

Reliability of a novel procedure to monitor lower limb muscle groups flexibility in highly-trained adolescent athletes. *(article in press)*

Study 8

Passive Knee Extension Test to Measure Hamstring Tightness: Influence of Gravity Correction *(article in press)*

3.2.3.2 Effects of foot-ankle strengthening training on medial arch stiffness and foot plantar pressure distribution

Study 9

Plantar muscles electro-stimulation and navicular drop *(article published)*

Study 10

Effects of combined foot-ankle electromyostimulation and resistance training on the in-shoe plantar pressure patterns during sprint in young athletes *(article published)*

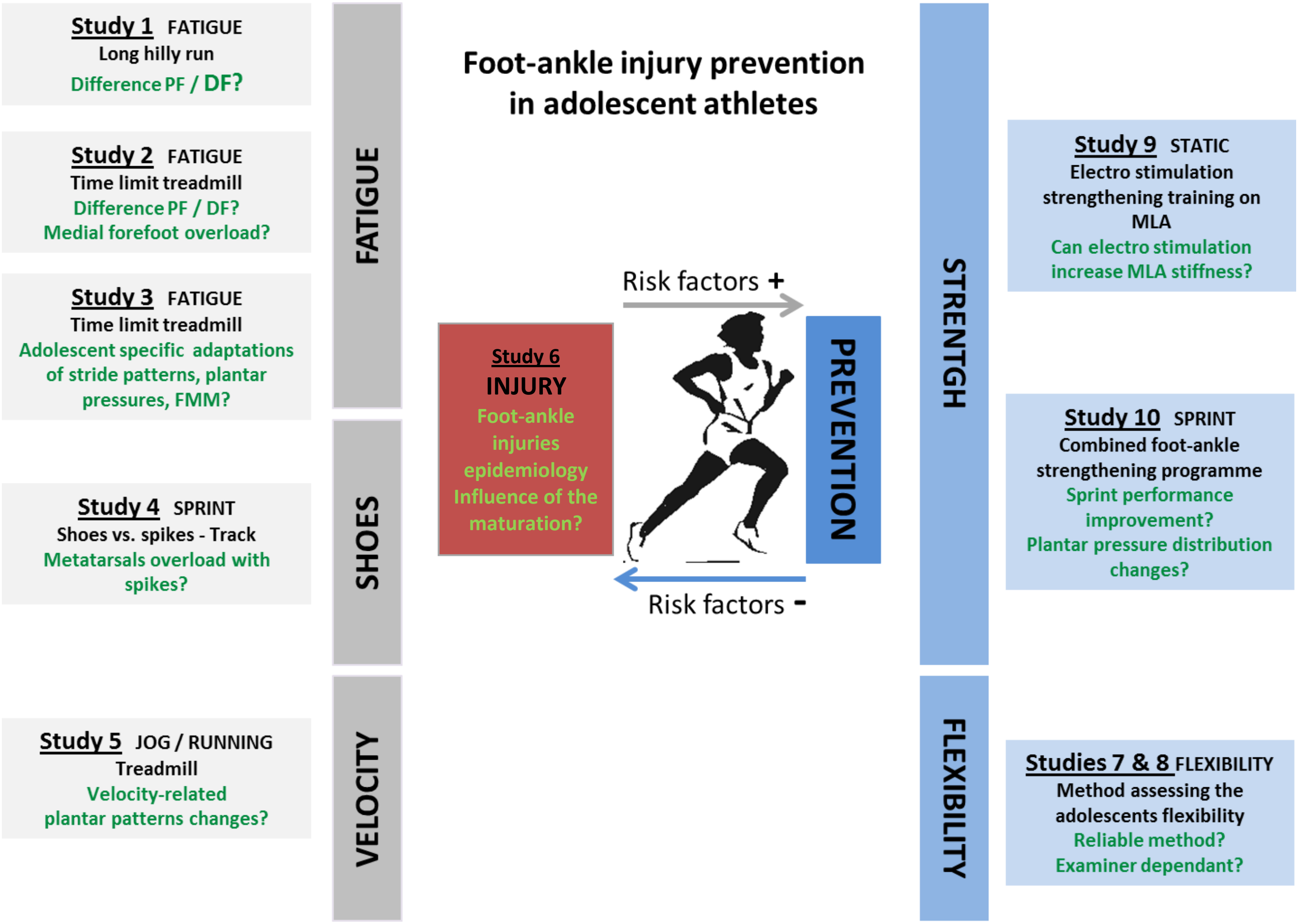

Figure 3.28: Targets of the studies arising from this work.
PF: ankle plantar flexor, DF: ankle dorsi flexor, FMM: foot mobility magnitude, MLA: medial longitudinal arch

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ORIGINAL ARTICLE

Effects of a 5-h hilly running on ankle plantar and dorsal flexor force and fatigability

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Abstract This study aimed to examine the effects of a 5-h hilly run on ankle plantar (PF) and dorsal flexor (DF) force and fatigability. It was hypothesised that DF fatigue/fatigability would be greater than PF fatigue/fatigability. Eight male trail long distance runners (42.5 ± 5.9 years) were tested for ankle PF and DF maximal voluntary isokinetic contraction strength and fatigue resistance tests (percent decrement score), maximal voluntary and electrically evoked isometric contraction strength before and after the run. Maximal EMG root mean square (RMS_{max}) and mean power frequency (MPF) values of the tibialis anterior (TA), gastrocnemius lateralis (GL) and soleus (SOL) EMG activity were calculated. The peak torque of the potentiated high- and low-frequency doublets and the ratio of paired stimulation peak torques at 10 Hz over 100 Hz (Db10:100) were analysed for PF. Maximal voluntary isometric contraction strength of PF decreased from pre- to post-run ($-17.0 \pm 6.2\%$; $P < 0.05$), but no significant decrease was evident for DF ($-7.9 \pm 6.2\%$). Maximal voluntary isokinetic contraction strength and fatigue resistance remained unchanged for both PF and DF. RMS_{max} SOL during maximal voluntary isometric contraction and RMS_{max} TA during maximal voluntary isokinetic contraction were decreased ($P < 0.05$) after the run. For MPF, a significant decrease for TA ($P < 0.05$) was found and the ratio Db10:100 decreased for PF ($-6.5 \pm 6.0\%$; $P < 0.05$). In conclusion, significant isometric strength loss was only detected for PF after a 5-h hilly run and was partly due to low-frequency fatigue. This study contradicted the hypothesis that neuromuscular alterations due to prolonged hilly running are predominant for DF.

Keywords Fatigue · Isokinetic · EMG · Evoked stimulation · Injury · Foot

Introduction

Long distance running popularity continues to increase throughout the world, but it also increases risks of injuries, especially due to overuse of the lower extremities (van Gent et al. 2007). In a review on running injuries, van Gent et al. (2007) reported that the predominant site of lower

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extremity injuries was the knee, but high injury incidence was also observed around the lower leg (shin and calf) and foot, ranging from 9.0 to 32.2% and 5.7 to 39.3%, respectively. Some studies have investigated injuries in ultra-marathons or other types of long distance running activities, and have shown that typical ultra-marathon injuries are tendonitis/tenosynovitis of the ankle dorsal flexor (Beischer et al. 2009; Bishop and Fallon 1999; Fallon 1996; Kobayashi et al. 2007). Fallon (1996) documented that marked overuse and excessive eccentric loading were associated with the aetiology of typical ultra-marathon injuries. However, the underpinning mechanisms of the ankle injuries are unclear.

Muscle fatigue by altering the muscle's shock-absorbing capability during running has been hypothesised to be a causative factor for many running injuries (Christina et al. 2001). For example, lower leg and sacrum shock accelerations increased as a result of fatigue in long distance running (Mizrahi et al. 2000b). It appears that the fatigue combined with extreme or repetitive loads leads to injury (Swanson and Caldwell 2000). It is possible that fatigue in ankle dorsal flexor (DF) and plantar flexor (PF) is induced in running, but literature on neuromuscular fatigue of these muscles following ultra-marathons is scarce. A few studies on this topic have been conducted on flat or slightly hilly terrains focusing on PF (Martin et al. 2009; Saldanha et al. 2008). It was reported that level ultra-endurance running would place a greater stress on PF compared with knee extensors (24-h running exercise on treadmill) (Martin et al. 2009). Central fatigue can explain some PF strength loss after prolonged running (Saldanha et al. 2008), but usually less than in knee extensors (Martin et al. 2009; Millet 2011).

To the best of our knowledge, only Mizrahi et al. (2000a) examined both PF and DF fatigue in prolonged running. They found that the tibialis anterior average integrated electromyogram signal (iEMG) significantly decreased from the 20th min onwards compared to the 5th min of running, while no significant changes in iEMG were found for gastrocnemius. The authors concluded that the resulting imbalance between these muscles might expose the bone to an enhanced risk of stress fractures. Kennedy et al. (2011) reported that PF and DF torque production capacity was reduced to approximately the same magnitude after a bi-directional alternating isometric PF/DF fatigue protocol lasting for ~8 min, but the mechanisms responsible for this decrease were different between these two muscle groups. Their results suggested that central fatigue played an important role in the decreased PF torque, while the decrease in DF torque appeared to be more related to peripheral fatigue. Neuromuscular fatigue remains a complex phenomenon defined as the reduction in the maximum force that a muscle can exert (Bigland-Ritchie et al. 1983). Classically strength losses have been assessed using isometric contractions but isokinetic dynamometry has become a worthwhile method for the assessment of muscle fatigue (Bosquet et al. 2010). The typical protocol to assess muscle fatigue resistance involves the realisation of a predetermined number of reciprocal maximal concentric contractions at a given angular velocity.

Another factor to influence fatigue in a long distance run is the landscape of the course (Beischer et al. 2009; Buczek and Cavanagh 1990; Gottschall and Kram 2005; Mizrahi et al. 2000b). It has been reported that downhill running (DR) induces more foot/ankle/lower leg injuries than level running (Buczek and Cavanagh 1990; Gottschall and Kram 2005; Mizrahi et al. 2000b), because of greater eccentric muscle contractions imposed in DR. On the other hand, the major locomotor muscles shorten while exerting force during uphill running (UR), in which they consume more energy, resulting in higher metabolic fatigue (Gottschall and Kram 2005). Some authors speculated that tibialis anterior tendonitis/tenosynovitis in runners might be due to an increase in training distance particularly with UR and DR (Beischer et al. 2009; Fallon 1996; Bishop and Fallon 1999). However to date, the effects of a long distance run including UR/DR on PF and DF fatigue have not been reported.

Given the considerable number of trail marathons nowadays and since it appears that long distance running-induced fatigue and slope running are the two risk factors of foot/ankle/lower leg injuries, the purpose of this study was to investigate the effects of a 5-h hilly simulated competitive run on (1) PF and DF voluntary and electrically evoked forces and surface electromyogram (EMG) and (2) resistance to fatigue (fatigability). Due to the potential deleterious influence of downhill running on DF and to the high DF tendons overuse injury rate when performing long running, we hypothesized that DF fatigue/fatigability would be greater than PF fatigue/fatigability.

Methods

Subjects

Eight male long distance trail runners (age 42.5 ± 5.9 year, height 177.8 ± 5.9 cm, body mass 76.9 ± 7.0 kg) participated in the experiment. All subjects were healthy and pain-free during the testing period. They had no history of musculoskeletal dysfunction or injuries of the lower limbs in 2 months preceding the study. Prior to the experiment, the subjects were familiarised with the purpose of the study, details regarding the data collection, and safety measures regarding the experimental set-up. Subsequently, written informed consent was obtained from all the subjects. The study was conducted according to the Declaration of Helsinki. Ethical approval for the project was obtained from the local committee on Human Research.

Experimental protocol

Subjects reported to the laboratory before and immediately after a 5-h running on hilly trails. During each visit, all subjects underwent maximal voluntary and electrically evoked isometric strength tests (see below) for both PF and DF at the ankle, as well as maximal voluntary isokinetic strength and fatigue resistance tests (Fig. 1). No specific familiarisation session was undertaken but all subjects had already participated in the previous experiments involving long distance run and electrical stimulation/force measurements (Millet 2011; Millet et al. 2002).

5-h hilly simulated competitive run

The 5-h run was performed at an unofficial trail located at a hillside consisting of a 1.7-km circuit, with 75 m of positive and negative elevation change, and a 1.8-km slope (220-m elevation change) to reach the circuit and came back to the laboratory for the post-run testing.

Isometric contraction testing

A general warm-up was performed on a cycle-ergometer for 6 min at ~60% of the maximal heart rate followed by a specific warm-up consisting of three graded submaximal and three maximal concentric contractions at 60° s^{-1} for the PF and at 90° s^{-1} for the DF. The range of motion of the ankle joint was set at 10° dorsal flexion and 20° plantar flexion. Maximal voluntary isometric contraction (MVC-ISO) strength of PF and DF was measured by an isokinetic Con-Trex® dynamometer (Con-Trex MJ; CMV AG, Dübendorf, Switzerland). Subjects were placed in a supine position, right knee being extended at 0°, and the leg in a horizontal position with the thigh being supported, and the dynamometer axis was aligned with the axis of plantar-dorsal flexion of the ankle joint, using straps stabilising the ankle, leg, knee, pelvis and chest. The ankle joint was fixed at 90° (neutral position) and this was confirmed by the angle measurement device of the Con-Trex. The gravity correction mode was activated in the software of the isokinetic device prior to testing. On Con-Trex MJ, gravity is measured for all angles of the angular sector, which makes the value more accurate, specifically to reflect stretching or compression resistance of tissues structures (muscle or others). Subjects were instructed to push as hard as possible for 5 s under verbal encouragement. Each subject completed three plantar flexion and then three dorsal flexion with the right ankle separated by 30 s, followed by two direct muscle stimulations to assess force generation by potentiated high-frequency (Db100) and low-frequency (Db10) doublets as described below. The highest value of the three 5-s MVC-ISO was used for further analysis, and maximal torque was calculated for the best MVC trial over a 0.5-s period around the peak.

Electrical stimulation was applied percutaneously to the muscle motor points of tibialis anterior (TA) for DF and the two gastrocnemius for PF via 5 × 5 cm self-adhesive stimulation electrodes (Medicompex SA, Ecublens, Switzerland) and the anode, a 10 × 5 cm self-adhesive stimulation electrode (Medicompex SA, Ecublens, Switzerland), was located either below the patella (for DF) or on the soleus (SOL) tendon (for PF). A constant current stimulator (Digitimer DS7A, Hertfordshire, UK) was used to deliver a square-wave stimulus of 1,000-μs duration with maximal voltage of 400 V. A shunt was used to stimulate the two motor points of the gastrocnemius with the same stimulator. The optimal stimulation intensity was determined from

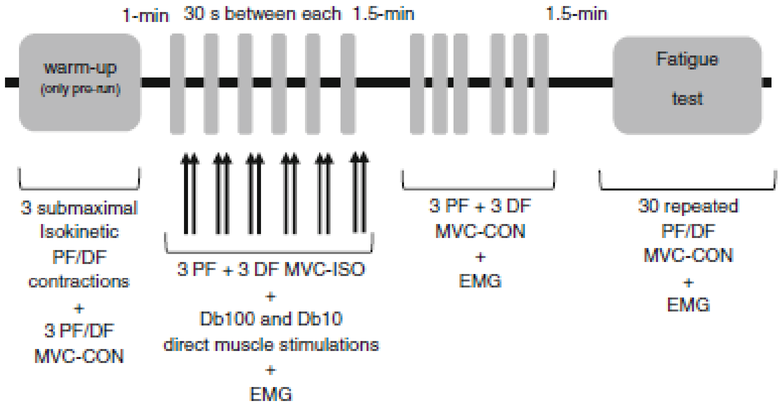

Fig. 1 Experimental protocol performed before and after a 5-h hilly run. *PF* ankle plantar flexor, *DF* ankle dorsal flexor, *MVC-CON* maximal voluntary isokinetic concentric contraction, *MVC-ISO* maximal voluntary isometric contraction, *Db10* low-frequency doublet, *Db100* high-frequency doublet

maximal twitch torque measurement (see below) and was reassessed before the post-run measurements, and supramaximal intensity (50% greater intensity than the current at maximum twitch torque) was delivered. For both PF and DF, stimulations included high-frequency (100 Hz, 10-ms inter-stimulus interval) followed by low-frequency (10 Hz, 100-ms inter-stimulus interval) doublets delivered to the relaxed muscle in a potentiated state. Unfortunately, due to co-activation during stimulation, recording of the muscle Db from DF was not possible. Co-activation was determined by visual inspection. The peak torque of the potentiated high- (P_{Db100}) and low- (P_{Db10}) frequency doublets, and the ratio between P_{Db100} and P_{Db10} (Db10:100) were obtained for PF. The potentiated twitch was reported to be more sensitive index of contractile fatigue than the unpotentiated twitch (Kufel et al. 2002).

Isokinetic contraction testing

Before the initial testing, the PF and DF maximal isokinetic strength measurement procedure was explained to each subject (Dvir 2004). PF and DF maximal voluntary isokinetic concentric contraction (MVC-CON) strength and fatigue resistance were evaluated for the right ankle on the Con-Trex® dynamometer with the Con-Trex® software, which calculated and displayed torque and joint displacement values. Calibration of the isokinetic dynamometer was performed before data collection. The same examiner conducted the tests for all subjects. The subject's position was the same as that described for the isometric testing. After a 1.5-min rest following the isometric testing, PF and DF MVC-CON strength was recorded at 60° s^{-1} for the PF and at 90° s^{-1} for the DF over three repetitive PF contractions followed by three repetitive DF contractions. The angular velocities were chosen based on the basis of the previous studies (Dvir 2004; Salavati et al. 2007). Peak torque of each contraction for PF and DF was obtained and the highest value (peak) as well as the average value (mean) amongst the three contractions for PF and DF was used for further analysis. After a 1.5-min rest, PF and DF isokinetic fatigue resistance (i.e. fatigability) was assessed over 30 contractions in concentric mode at 60° s^{-1} for the PF and at 90° s^{-1} for the DF (Bosquet et al. 2010). Based on the changes in torque over 30 contractions, a fatigue resistance index (FRI) was calculated using the formula shown below for PF and DF (Bosquet et al. 2010): $\text{FRI} = [100 \times (\text{Total PT/Ideal PT})] - 100$, where Total PT: the sum of PT over 30 contractions, Ideal PT: best PT × 30.

Electromyogram

Electromyogram data were recorded continuously from the right TA, gastrocnemius lateralis (GL) and SOL during the isometric and isokinetic testing using a PowerLab system (16/30—ML880/P, ADInstruments, Bella Vista, Australia) with a sampling frequency of 2,000 Hz. Bipolar silver chloride surface electrodes of 10-mm diameter (Type 0601000402, Contrôle Graphique Medical, Brie-Comte-Robert, France) were taped lengthwise on the skin over the muscle belly following SENIAM recommendations (Hermens et al. 2000), with an inter-electrode distance of 25 mm. The reference electrode was attached to the malleolus. The electrode positions were marked on the skin so that they could be placed in the same place after the run. Low impedance (<5 kΩ) at the skin-electrode surface was obtained by abrading the skin with thin sand paper and cleaning with alcohol. The EMG signal was amplified (Octal Bioamp, ML138, ADInstruments) with a bandwidth frequency ranging from 5 to 500 Hz (input impedance = 200 MΩ, common mode rejection ratio = 85 dB, gain = 1,000), transmitted to a PC and analysed with a LabChart6 software (ADInstruments).

The maximal root mean square values (RMS_{max}) of EMG signal of TA, GL and SOL were calculated over a 0.5-s period around the maximal voluntary torque of both MVC-ISO (RMS_{max}-ISO) and MVC-CON (RMS_{max}-CON), and over the 30 concentric contractions in the fatigue resistance test (RMS_{FRI}). The RMS values were not normalised to the maximal peak-to-peak amplitude of the M-wave because the percutaneous muscle stimulation did not allow to obtain high-quality M-waves. In addition, the mean power frequency (MPF) of the total power spectrum was calculated for TA during DF MVC-ISO and for GL and SOL during PF MVC-ISO.

Statistical analysis

Mean ± SD values were calculated for all variables of interest. A paired t test was first performed to compare between pre- and post-run for all dependent variables (MVC-ISO strength, MVC-CON strength, FRI, RMS_{max}-ISO, RMS_{max}-CON, RMS_{FRI}, Db10, Db100, Db10:100, MPF). Since conditions of application of two-way repeated measures ANOVA (fatigue × muscle) were not respected, percent decreases in MVC-ISO and MVC-CON (peak and mean) torque from pre- to post-run were compared among muscles using a Wilcoxon test. The statistical analysis was performed using a SigmaStat software (Jandel Corporation, San Rafael, CA). Statistical significance was set at $P < 0.05$.

Results

The subjects ran 37.5 ± 5.5 km with 1,730 ± 230 m of elevation over the 5 h and reported after the run that they were close to exhaustion ($n = 5$) or completely exhausted ($n = 3$).

MVC-ISO and MVC-CON strength

PF MVC-ISO decreased from pre- (148.8 ± 25.3 N m) to post-run (123.3 ± 20.9 N m, $P < 0.05$; Fig. 2), however, DF MVC-ISO did not change significantly (pre: 47.7 ± 9.1 N m, post: 44.1 ± 9.5 N m). In contrast, peak MVC-CON did not show significant changes for both PF (pre: 113.7 ± 13.6 N m, post: 101.1 ± 12.6 N m) and DF (pre: 27.1 ± 4.3 N m, post: 25.5 ± 4.1 N m), and this was also the case for mean MVC-CON (Fig. 2).

Electrically evoked torque

P_{Db10} in PF decreased from pre- (51.6 ± 9.0 N m) to post-run (47.1 ± 8.9 N m, $P < 0.05$), but no significant changes were evident for P_{Db100} (pre: 53.4 ± 9.9 N m, post: 52.7 ± 13.0 N m). The ratio Db10:100 for PF decreased significantly after run (Fig. 3). Unfortunately, due to co-activation during stimulation, evoked forces data for DF were not usable.

EMG

As shown in Table 1, significant ($P < 0.05$) decreases in $\mathrm{RMS}_{\max}$ were found for SOL and TA during PF MVC-ISO and TA during DF MVC-CON. No significant changes were found for other $\mathrm{RMS}_{\max}$ variables. MPF decreased significantly ($P < 0.05$) from pre (140.9 ± 10.1 Hz) to post (134.7 ± 9.9 Hz) for TA during DF MVC-ISO, but the change from pre to post did not reach a significant level during PF MVC-ISO neither for GL (from 111.9 ± 13.4 to 105.0 ± 16.6 Hz, $P = 0.09$) nor for SOL (from 133.6 ± 29.5 to 127.1 ± 21.5 Hz, $P > 0.05$).

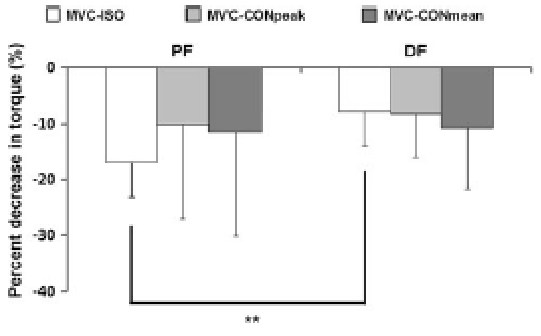

Fig. 2 Mean (±SD) percent decrease in isometric maximal voluntary contraction (MVC-ISO) torque, maximal isokinetic peak torque ($\mathrm{MVC\text{-}CON}_{\mathrm{peak}}$) and mean isokinetic peak torque ($\mathrm{MVC\text{-}CON}_{\mathrm{mean}}$) from before to after a 5-h hilly run for plantar flexor (PF) and dorsal flexor (DF). **Significant ($P < 0.01$) difference between PF and DF

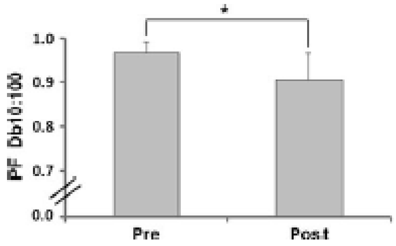

Fig. 3 Db10:100 ratio (means ± SD) for the ankle plantar flexor before (Pre) and after (Post) a 5-h hilly run. *Significant ($P < 0.05$) difference between Pre- and Post-run. Due to co-activation during stimulation, P_{Db10}, P_{Db100} and Db10:100 data were not usable for DF

Changes in fatigability

Fatigue resistance index was lower ($P < 0.01$) for PF (−16.1 ± 4.6%) than DF (−24.6 ± 5.8%) before the run, meaning that DF was less resistant to fatigue than PF in the test; however, the index did not change from pre- to post-run for both muscle groups (Fig. 4). No significant changes in $\mathrm{RMS}_{\mathrm{FRI}}$ were found from pre- to post-run with the exception of a slight but significant change for GL (pre: −16.4 ± 2.8%, post: −19.2 ± 3.7%, $P < 0.05$) (Table 2).

Discussion

The purpose of this study was to examine the effects of a prolonged 5-h hilly running on fatigue and fatigability of PF and DF muscles of experienced long distance trail runners. A significant decrease in MV-ISO strength was observed from pre to post run for PF only, despite a better resistance to fatigue over 30 maximal contractions for PF. The decrease in PF isometric strength was at least in part attributed to failure of excitation–contraction coupling as suggested by the low-frequency fatigue. These results contradicted our hypothesis that DF would be fatigued more than PF after the 5-h run.

To the best of our knowledge, this was the first study comparing PF and DF for neuromuscular function in a prolonged hilly run. Previous studies have demonstrated that PF was subjected to fatigue after a prolonged level running (Finni et al. 2003; Saldanha et al. 2008). Some existing biomechanical and physiological data related to hilly running may highlight the present findings. Swanson and Caldwell (2000) observed that the EMG amplitude of the gastrocnemius and soleus muscles during the support phase was greater during UR when compared with that in level running at the same velocity of 4.5 m s^{-1}. Costill

Table 1 EMG root mean square of soleus, gastrocnemius and tibialis anterior muscles during maximal isometric (RMS_{max}-ISO) and concentric (RMS_{max}-CON) planter flexion and dorsal flexion before (Pre) and after (Post) a 5-h hilly run

Parameter	Movement	Pre	Post	*P* value
RMS_{max}-ISO soleus (mV)	Plantar flexion	**0.32 ± 0.10**	**0.24 ± 0.09**	**0.03**
RMS_{max}-ISO gastrocnemius (mV)		0.56 ± 0.29	0.33 ± 0.16	NS
RMS_{max}-ISO tibialis anterior (mV)		**0.07 ± 0.03**	**0.04 ± 0.01**	**0.02**
RMS_{max}-CON soleus (mV)		0.26 ± 0.07	0.23 ± 0.10	NS
RMS_{max}-CON gastrocnemius (mV)		0.52 ± 0.21	0.36 ± 0.15	NS
RMS_{max}-CON tibialis anterior (mV)		0.07 ± 0.02	0.05 ± 0.03	NS
RMS_{max}-ISO soleus (mV)	Dorsal flexion	0.08 ± 0.03	0.07 ± 0.02	NS
RMS_{max}-ISO gastrocnemius (mV)		0.06 ± 0.03	0.05 ± 0.02	NS
RMS_{max}-ISO tibialis anterior (mV)		0.57 ± 0.14	0.36 ± 0.17	NS
RMS_{max}-CON soleus (mV)		0.07 ± 0.02	0.06 ± 0.03	NS
RMS_{max}-CON gastrocnemius (mV)		0.07 ± 0.06	0.04 ± 0.02	NS
RMS_{max}-CON tibialis anterior (mV)		**0.47 ± 0.11**	**0.26 ± 0.12**	**0.03**

A significant difference between before and after is shown in bold

NS non-significant

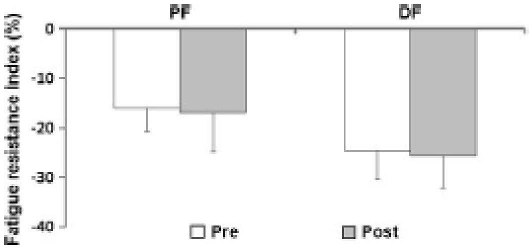

Fig. 4 Fatigue resistance index (mean ± SD) before (Pre) and after (Post) a 5-h hilly run for the plantar flexor (PF) and dorsal flexor (DF). No significant changes from Pre- to Post-run was evident

et al. (1974) reported that when running on a treadmill at 75% of mode-specific VO_{2max}, glycogen depletion and percentage of the muscle volume activated were greater in UR compared with level running. Regarding the comparison between downhill running and level running, Buczek and Cavanagh (1990) showed that the negative work done by the PF during stance was significantly greater for downhill running (26.1 ± 3.2 J) than for level running (12.6 ± 6.6 J). It has been reported that although downhill running results in less metabolic fatigue, the PF eccentrically contracts during each stride and sustains high mechanical stress resulting in ultra-structural muscle damage (Mizrahi et al. 2000b, 2001). Because of the large component of downhill running in the 5-h run (−1,730 m), it seems reasonable to assume that eccentric load to the PF was large in the present study. This data is consistent with the decrease in the ratio Db10:100 in the present study which suggests that the 5-h run induced excitation–contraction coupling failure for PF (Verges et al. 2009). Indeed, low-frequency fatigue is usually detected after eccentric exercises (Martin et al. 2004a, b, 2005; Corona et al. 2010; Verges et al. 2009). A recent study (Corona

Table 2 Changes in root mean square over 30 repeated maximal concentric contractions (RMS_{FRI}) for soleus, gastrocnemius and tibialis anterior muscles during planter flexion and dorsal flexion before (Pre) and after (Post) a 5-h hilly run

Parameter	Movement	Pre	Post	*P* value
RMS_{FRI} soleus (%)	Plantar flexion	−21.1 ± 5.8	−22.9 ± 7.6	NS
RMS_{FRI} gastrocnemius (%)		**−16.4 ± 2.8**	**−19.2 ± 3.7**	**0.02**
RMS_{FRI} tibialis anterior (%)		−30.5 ± 21.0	−34.7 ± 15.6	NS
RMS_{FRI} soleus (%)	Dorsal flexion	−29.8 ± 15.1	−22.4 ± 6.3	NS
RMS_{FRI} gastrocnemius (%)		−47.1 ± 30.6	−45.2 ± 22.8	NS
RMS_{FRI} tibialis anterior (%)		−17.5 ± 4.4	−16.2 ± 3.7	NS

A significant difference between before and after is shown in bold

FRI fatigue resistance index

NS non-significant

et al. 2010) suggests that this might be related to a reduced level of the proteins involved in transverse (T)-tubule and sarcoplasmic reticulum membrane apposition named junctophilins. Kennedy et al. (2011) reported that central fatigue played an important role in the decreases in PF torque after a bi-directional alternating ankle fatigue protocol. Our results confirm previous studies on ultra-marathons (Martin et al. 2009; Millet 2011) and suggest that the prolonged running induced central fatigue in PF. However, in the present study, this was only based on maximal EMG which presents some limitations. In fact, examining the change in maximal EMG response during voluntary contractions can attest central drive reduction but only when this variable is normalized to maximal M-wave, i.e. EMG response to a single stimulus, especially during fatigue studies (Millet 2011).

Not only $\mathrm{RMS}_{\max}$ of soleus but also $\mathrm{RMS}_{\max}$ of TA decreased during PF MVC-ISO. This result, i.e. a decrease of both the agonist and antagonist muscle activity during maximal contraction, has been previously reported during a fatigue protocol (Patikas et al. 2002). It may be related to the regulation of co-activation during a muscle action by the nervous system, i.e. the existence of a centrally mediated descending "common drive" for agonists and antagonists muscles even if some degree of regulation of the drive may exist at the level of the motoneurones that innervate the antagonist muscles (Levenez et al. 2005). Slight (−4 to −6%) but significant changes in MPF were found for TA and a trend was observed for GL. These results may be related to central (changes in motor units firing frequency and/or synchronisation) or peripheral (action potential conduction velocity, physical changes at the electrode levels) alterations.

Despite the changes in some $\mathrm{RMS}_{\max}$ and MPF parameters after the 5-h run, no decreases in MVC-ISO and MVC-CON were found for DF after the 5-h run, although we expected to see greater effect of the run on DF than PF. To the best of our knowledge, some studies investigated DF fatigue in a prolonged level running (Mizrahi et al. 2000a; Reber et al. 1993; Ross et al. 2007), but no previous studies have reported DF fatigue after a hilly run. Mizrahi et al. (2000a) reported that mean power frequency of the tibialis anterior significantly decreased from the 20th min and onwards compared to the 1st min. Tibialis anterior was activated at greater than 20% manual muscle test for more than 85% of the gait cycle at the training pace which was described as predisposing to fatigue overload (Reber et al. 1993). Also, a 17% decrease in DF MVC occurred following a marathon performed on a treadmill set at 1% slope (Ross et al. 2007). In the present study, DF MVC-ISO strength remained unchanged and MVC-CON strength also did not show any decrease after the run. These results suggest that DF is less subjected to fatigue during a prolonged hilly run than a level or a slight uphill run, and that DF fatigue is less than that of PF. This occurs despite a lower resistance to fatigue over 30 maximal contractions for DF than PF as shown in the pre-run FRI. The lower neuromuscular fatigue in DF than PF may stem from lower mechanical stress to DF. In the present experiment, the participants ran the same distance but with longer duration for uphill than downhill, which lead to an increased percentage of stride spent in stance and enhanced PF muscular loading (Swanson and Caldwell 2000). It seems possible that the muscular activity of DF was not augmented/compensated to the same extent in downhill phases because the shock-absorbing phase was mainly controlled by the knee extensors (Mizrahi et al. 2000b).

The main interests of our study were to take place in a natural environment and close to competitive conditions, and to impose a hilly terrain on the runners. Compared to treadmill, a "natural" environment induced a lower stress due to greater shock absorption when running on soft ground (Place et al. 2004). Nevertheless, there were some limitations in this study that need to be considered when interpreting the findings. Firstly, our data were limited by a small sample size. In addition, motor point stimulation did not allow us to normalise EMG to M-wave peak-to-peak amplitude. Due to the motor point stimulation and probably co-activation, evoked force on dorsal flexor muscles was not suitable for analysis. Also artefacts such as the cross-talk (e.g. contamination by the signal from another muscle that is in close proximity) and the effects of sweating and temperature changes are critical in analysing EMG signal.

In terms of injury prevention, it appears that the tendonitis/tenosynovitis of the foot dorsal flexor (the typical ultra-marathon injury) is probably not a direct consequence of DF fatigue in hilly prolonged running events. So it appears that the most realistic mechanism leading to this specific injury remains the "mechanical theory" (Bishop and Fallon 1999; Fallon 1996; Kobayashi et al. 2007), subjecting a smaller segment of each DF tendon to friction and irritation as it passes under the extensor retinaculum.

In conclusion, the present study evaluated PF and DF neuromuscular function after a 5-h hilly running bout and found that strength loss occurred only in PF, which was partly attributed to excitation–contraction coupling failure. The results did not support our hypothesis based on clinical observations—supported by the lower fatigue resistance in DF after a 'classic' fatigue resistance test over 30 maximal contractions and by the high rate of ankle dorsal flexor tendons injuries among long distance trail runners—that DF would demonstrate greater decrease in muscle function after the 5-h run compared with PF. We speculate that a greater proportion of UR in time and duration limited the DF fatigue and augmented the PF loads. Future studies involving a larger number of participants and combining an extreme duration and large sections of flat running should be undertaken.

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Impact of high intensity running on plantar flexor fatigability and plantar pressure distribution

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Impact of high intensity running on plantar flexor fatigability and plantar pressure distribution

Abstract

Context: Fatigue-related changes in plantar pressure distribution have never been examined in adolescent athletes.

Objectives: This study aimed to investigate how a high-intensity running exercise to exhaustion modifies ankle plantar-flexor and dorsi-flexor strength and fatigability, as well as plantar pressure distribution in adolescent runners.

Design: Case series study.

Setting: Academy research laboratory.

Patients or other participants: Eleven male adolescent distance runners were tested.

Interventions: All participants performed an exhausting run on treadmill. They also underwent maximal voluntary isokinetic strength and fatigue resistance tests (over 50 contractions) on plantar-flexor and dorsi-flexor firstly in a non-fatigued state and secondly immediately after the exhausting run.

Main outcome measures: Peak torque was recorded for each repetition for dorsi-flexor and plantar-flexor. Fatigue index was calculated. Plantar pressure measurements were recorded 1 min after the run start and prior to exhaustion. Plantar parameters (e.g. mean area, contact time, mean pressure, relative load) were determined for the nine selected regions.

Results: Peak torques remained unchanged from pre- to post- in both muscle groups whereas fatigue index changed in plantar-flexor (+28.1%, P = .01; power: 0.76) but not in dorsi-flexor (+16.1%). For the whole foot, mean area increased (+1.9%, P = .03; power: 0.73) and mean pressure decreased (-3.4%, P < .01; power: 0.93) from 1 min to end whereas mean area (+9.5%, P < .01; power: 0.90) and relative load (+7.2%, P < .01; power: 0.80) increased under the medial midfoot, and contact time increased under the central forefoot (+8.3%, P = .01; power: 0.77) and the lesser toes (+8.9%, P < .01; power: 0.83).

Conclusions: Fatigue resistance in the plantar-flexors significantly declined after a high intensity running bout performed by adolescent athletes. This phenomenon was associated with alterations in the medial arch function and with an increase in contact times at the forefoot and the toes.

Keywords: medial longitudinal arch, isokinetic, adolescent, ankle

INTRODUCTION

While running in a fatigued state, changes in plantar pressure distribution have been reported, including increased peak plantar pressure and impulse values in the forefoot, as well as concomitant reductions under the toe areas.[1, 2] This shift in load from the toes to the metatarsal heads may arise from fatigue in lower limb and foot musculature, i.e. the toe flexor muscles[2] or the ankle plantar-flexor (PF).[1] This may be explained by reductions in stretch-shortening capabilities of the PF, subsequently leading to reduced efficiency in toe-off.[3] Two other mechanisms have been proposed in former researches:[4, 5] Firstly, in fatigued conditions, participants may change the landing pattern from a heel-toe to midfoot landing strategy.[4] Secondly, increased first metatarsal loading may reflect an increase in foot pronation, induced by fatigue of the musculature responsible for the control of this movement.[5, 6]

Fatigue occurring as a result of high intensity running can lead to significant alterations in lower limb biomechanics, including increased impact forces[6] and increased rear-foot motion.[7] These alterations may lead to overload on bony structures in the legs and feet, increasing the potential for overuse injury,[1] especially in adolescent distance runners with immature skeletal development.[7] Indeed, in adolescent athletes, endurance sports (i.e. involving recurrent, regular cyclic stressing of the lower extremities) appear to lead preferentially to stress fractures in the region of the metatarsal bones.[7]

Isokinetic dynamometry assessments, calculating changes in peak torque from pre- to post-exercise have been shown to be relevant for assessing muscle force imbalances.[8] Recently, specific isokinetic protocols to assess muscle fatigability have been proposed and involve a predetermined number of reciprocal maximal concentric contractions, at a given angular velocity.[9-11] Despite the emergence of such tests, isokinetic measures have been rarely used for assessing the torque changes induced by a running bout.[3, 12] Moreover, to our knowledge, the relationship between lower limb muscle fatigability and alterations in plantar pressure distribution during a run to exhaustion have not been investigated. Therefore, the purpose of this study was to determine the extent to which running to exhaustion modifies PF and dorsi-flexor (DF) strength and fatigability, as well as plantar pressure distribution.

METHODS

Subjects

Based on the results of a previous study,[13] a priori analyses were used to determine sample sizes. Assuming a difference in means of 10 N·m in ankle peak torque measurements, required sample size was 8-11 for $\alpha = 0.05$ and statistical power = 0.8. Therefore eleven male adolescent distance runners (age: 16.9 ± 2.0, body mass: 54.6 ± 8.6 kg, height: 170.6 ± 10.9 cm, maximal aerobic speed: 18.7 ± 1.5 $km.h^{-1}$) completed the study. All participants were healthy and pain-free during the testing period.

Prior to the experiment, the participants were familiarized with the purpose and significance of the study and safety measures regarding the experimental set-up. Informed consent was sought and obtained from all participants. The study was accepted by the local ethics committee. The ethical guidelines followed by the investigators conformed to the recommendations of the Declaration of Helsinki about human investigations.

Experimental protocol

Three testing sessions were organized within a week. First, the participants completed an incremental test to exhaustion on a treadmill in order to define their velocity at maximal oxygen uptake ($v\dot{V}O_{2max}$). The second session was performed in a non-fatigued state using a bicycle ergometer (Cyclone 530 C, Cybex International, Medway, MA, USA) and a treadmill (h/p/Cosmos, Nussdorf-Traunstein, Germany) for the warm-up (Fig. 1A). Isokinetic measurements were then performed. The third session was performed in a fatigued state and included a constant pace running exercise to exhaustion (T_{lim}), then within 3 min of completion the isokinetic measurements and a blood lactate sampling (Fig. 1B). A familiarization protocol was conducted a few days before the first session in order to introduce the experimental procedures for the participants (Fig. 1). All participants had already participated in previous experiments involving treadmill running, in-shoe dynamic pressure measurement and isokinetic testing.

Determination of velocity at maximal oxygen uptake

During the first testing session, each participant completed an incremental test to exhaustion on a treadmill (h/p/Cosmos, Nussdorf-Traunstein, Germany) in order to determine maximal oxygen uptake (63.3 ± 4.4 $ml.min^{-1}.kg^{-1}$) and its associated velocity (18.7 ± 0.9 $km.h^{-1}$). It consisted of an initial one minute workload of 8 $km.h^{-1}$ followed by increases of 1 $km.h^{-1}$ every minute (1% slope). Gas exchange was measured using a breath-by-breath analyser (Oxycon Pro, Jaeger, Hoechberg, Germany).

Running exercise to exhaustion

T_{lim} took place during the testing session three and consisted of a constant pace running exercise to exhaustion at 95% $v\dot{V}O_{2max}$ with 1% slope on a treadmill. The participants ran until they had to terminate the run because of fatigue. During the T_{lim}, RPE was recorded every minute.[14] The lactate concentration was determined after 3 min from a capillary blood sample using the same procedure as after the $v\dot{V}$ O2max determination test.

Maximal isokinetic strength and fatigue resistance tests

PF and DF maximal voluntary isokinetic concentric (MVC-CON) and eccentric contraction (MVC-ECC) strength and fatigue resistance were evaluated for the right ankle on the Humac Norm System dynamometer (CSMI, Soughton, MA, USA) (Fig. 1C). Each participant was in supine position, hip and knee flexed at 60°, and lower leg supported in horizontal position as described in the Humac Norm System owner's manual and in previous research.[15, 16] The dynamometer axis was aligned with the axis of plantar-dorsal flexion of the ankle joint. Straps stabilized ankle, leg, knee, pelvis and chest. Handles were set on both sides to hold on to. Participants were instructed to push as hard as possible under verbal encouragement. The gravity correction mode was activated in the software of the isokinetic device prior to testing. The range of motion of the ankle joint was set at 10° dorsiflexion and 20° plantar flexion during familiarization and tests. The 90° position of the ankle joint was regarded as the neutral 0° position. Then PF and DF MVC-CON and MVC-ECC were recorded at $60°\cdot s^{-1}$ and at $120°\cdot s^{-1}$ (over three contractions) (Fig. 1C) as in previous studies.[15-17] Peak torque of each contraction (PT) for PF and DF was obtained and the highest value amongst the three contractions for PF and DF was used for further analysis.

PF and DF isokinetic fatigue resistance (i.e. pre- and post-fatigability) was assessed over 50 maximal contractions in concentric mode at $30°\cdot s^{-1}$ for the PF and at $120°\cdot s^{-1}$ for the DF. Different velocities were chosen for isokinetic contractions of PF and DF muscles in order to reach similar time to fatigue for both muscle groups as done previously.[9, 17] Based on the changes in torque over 50 contractions, a fatigue index was calculated for PF and DF as follows:[10]

Fatigue index = (100 x (total PT ÷ ideal PT)) – 100

where Total PT = Sum of PT over 50 contractions.

Ideal PT = number of contractions x best PT.

Plantar pressure distribution measures

During the T_{lim}, insole plantar pressure distribution was recorded using the X-Pedar Mobile System (Novel GmbH, Munich, Germany). Each pressure insole consisted of a 2-mm-thick array of 99 capacitive pressure sensors. Before commencement of data collection, the insoles were calibrated according to the manufacturer's guidelines. One insole was placed under the right foot of all participants, wearing the same type of neutral running shoes. The data logger for data storage was in a harness on the back of the participant. Plantar pressures were sampled at 50 Hz. Plantar pressure data were recorded over a 30 s period at two occasions: (i) 1 min after the exercise start (ONSET) and then (ii) as soon as the participant reported 18 as RPE corresponding to 78-84 steps (ENDPOINT). This 30 s window ended in a range of 25 to 45 s prior exhaustion. A regional analysis was performed utilizing nine separate "masks" or areas of the foot, i.e. medial and lateral heel, medial and lateral mid-foot, medial, central and lateral forefoot, hallux and lesser toes (Groupmask Evaluation, Novel GmbH, Munich, Germany).[18] Mean area (in cm^2), contact area (in cm^2), contact time (in ms), maximum force (in N), mean force (in N), mean pressure (in kPa), peak pressure (in kPa) and relative load (i.e., force time integral in each individual region divided by the force time integral for the total plantar foot surface, in %) were determined for the nine selected regions.

Statistical analysis

Mean ± SD values were calculated for all variables of interest. An independent samples t-test was used to examine the differences in plantar loading parameters for the whole foot between ONSET and ENDPOINT conditions (as percent change from ONSET values) and in PF and DF strength and fatigue resistance parameters between pre- and post- conditions (as percent change from pre- values). A two-way repeated measures ANOVA was performed with condition (ONSET vs. ENDPOINT) and foot regions (masks one to nine) as the repeated factors and the foot loading parameters designated as dependent variables. This analysis revealed the global effect of foot region and the interaction between ONSET and ENDPOINT conditions and foot regions. When significant main effects were observed, Tukey post hoc analyses were used to identify differences among means. Pearson correlation coefficients were used to examine the relationships between isokinetic pre-values and changes in plantar pressure parameters from ONSET to ENDPOINT. The statistical analyses were performed using SigmaStat software (Jandel Corporation, San Rafael, CA). Effect size (ES) was calculated for each test in order to determine the magnitude and the practical relevance of the significant findings. Statistical significance was accepted at $P < .05$. Statistical power was calculated for $\alpha = 0.2$ and $\beta = 0.2$

RESULTS

Running performance

The mean running speed during T_{lim} was 17.8 ± 1.4 $km.h^{-1}$. Participants ran at that speed for 8.8 ± 3.4 min until exhaustion. The mean lactate was 11.6 ± 2.7 $mmol.L^{-1}$ and the mean RPE before exhaustion was 19.3 ± 0.6.

Maximal isokinetic strength and fatigue resistance tests

MVC-CON and MVC-ECC remained unchanged from pre- to post- in both muscle groups: In concentric mode, from 50.5 ± 14.3 to 52.2 ± 11.4 N·m at $60^{o}.s^{-1}$ and from 38.5 ± 11.1 to 40.9 ± 11.2 N·m at $120^{o}.s^{-1}$ in PF, and from 20.6 ± 6.2 to 21.5 ± 5.5 N·m at $60^{o}.s^{-1}$ and from 15.6 ± 3.5 to 16.4 ± 3.7 N·m at $120^{o}.s^{-1}$ in DF. In eccentric mode, from 87.0 ± 23.3 to 87.8 ± 28.4 N·m at $60^{o}.s^{-1}$ and from 80.9 ± 22.2 to 74.5 ± 22.0 N·m at $120^{o}.s^{-1}$ in PF, and from 41.6 ± 11.4 to 41.2 ± 12.0 N·m at $60^{o}.s^{-1}$ and from 44.0 ± 13.3 to 44.8 ± 12.6 N·m at $120^{o}.s^{-1}$ in DF. From pre- to post-, fatigue index changed in PF (-23.8 ± 6.0% vs. -30.5 ± 4.7%, $P = .01$; power: 0.76) with 63.5 ± 14.6 and 61.3 ± 16.3 N·m as initial values respectively, but not in DF (-27.6 ± 6.9% vs. -32.0 ± 5.4%; 14.9 ± 2.9 and 15.5±3.1 N·m).

Plantar pressure distribution measures

Plantar pressure parameters for each foot region at ONSET and ENDPOINT are presented in Table 1. Regarding the whole foot, mean area increased significantly ($P = .03$; power: 0.73) at ENDPOINT when compared with ONSET, whereas mean pressure was significantly reduced ($P < .01$; power: 0.93). During the fatigued conditions, mean area ($P < .01$; power: 0.90) and relative load ($P < .01$; power: 0.80) increased under the medial midfoot (Fig. 2A and 2B) whereas contact time increased under the central forefoot ($P = .01$; power: 0.77) and the lesser toes ($P < .01$; power: 0.83) (Fig 2C). During the fatigued conditions, a trend in less mean force was noted in the medial ($P = .06$; Power: 0.36) and central ($P = .09$; power: 0.28) forefoot and in the Hallux ($P = .07$; power: 0.35) (Fig. 2D).

Percent change in fatigue index for PF was negatively correlated with percent change in mean pressure under the whole foot ($r = -0.68$, $P = .02$), percent change in mean force ($r = -0.61$, $P = .04$) and mean area ($r = -0.65$, $P = .03$) at the Hallux and percent change in mean area at the toes ($r = -0.62$, $P = .04$), and positively correlated with percent change in mean area at the medial midfoot ($r = 0.68$, $P = .02$).

T_{lim} duration was correlated to the percent changes in plantar pressure parameters from ONSET to ENDPOINT at the medial midfoot (CA: $r = 0.74$, $P < .01$ and maximum force: $r = 0.79$, $P < .01$).

DISCUSSION

This study aimed to determine the extent to which a running exercise to exhaustion modifies PF and DF strength and fatigability, and foot plantar pressure distribution. In this group of adolescent middle distance runners, no significant isokinetic strength loss was observed in either PF or DF from pre-run to post- run. However, the fatigue index calculated over 50 repetitions reduced significantly in PF but not in DF. Interestingly, these results would be similar if calculated over the 30 first contractions only (+29.7% in PF; $P = .04$, power: 0.49 vs. +17.3% in DF; $P = .16$), as recently recommended.[10] These changes affecting only PF are in line with previous studies in adults where PF were subjected to fatigue after prolonged [19, 20], or shorter (i.e. 13 min) level running.[1] As suggested,[4] one may assume that, in order to cope with fatigued conditions at such high running speed, the participants have unconsciously engaged a midfoot landing strategy during the test, which consequently altered the loading demands in the PF. Overall, it appears that high-intensity running-induced fatigue leads to different adaptations in PF and DF in terms of fatigue resistance. This imbalance between PF and DF may compromise the protective action of these muscles to the lower leg and affect the foot loading patterns.[21]

A significant increase of the relative load and the mean area under the medial midfoot (i.e. MLA) was observed when participants neared exhaustion. The MLA is a deformable structure which can flatten up to 10 mm and change its length approximately 4 mm during mid-stance.[22] It plays a significant role in the transfer of ground reaction forces through the foot to the rest of the body.[23] The unchanged pressure and force under the medial midfoot in fatigued state indicates that, while more loaded, the MLA maintained its mechanical properties and its functionality as a load absorbing structure. The positive correlation between the exercise duration and the percentage changes of contact area and maximum force from ONSET to ENDPOINT at the medial midfoot confirmed that MLA makes an important contribution in load absorption when a runner becomes fatigued. Interestingly, the greater post-fatigability of the PF (*i.e.* increased fatigue index from pre- to post-) was positively correlated with a larger mean contact area under the MLA. This finding points in the direction of a close and reciprocal interaction between PF and MLA. Recently, Kelly et al. reported that running with foot orthoses for 60 minutes leads to significant reductions in ankle plantar-flexor fatigue.[24] They hypothesised that, that increased foot pronation may lead to fatigue in the ankle plantar-flexor. More precisely they suggested that a compliant MLA (increased pronation) may deteriorate the quality of force transmission through the foot at the stance phase. So the plantar-flexors may have to produce more work for maintaining a constant running velocity. This suggestion also aligns well with the findings of our study, which has shown that participants who displayed increased foot pronation at the end of their run, also displayed increased ankle plantar-flexor fatigue. An alternative view point has been proposed by Weist et al, who suggested that with decreased plantar-flexor activity during fatigue, the supinatory action of these muscles is diminished and the pronation is more pronounced, resulting in an increased loading under the MLA.[1] This efficient MLA absorption role may also partly explain the absence of load/pressure increase under the medial and central forefoot (i.e. metatarsal heads), in opposition to the findings of numerous studies about running-induced fatigue.[1, 2] Moreover mean area increased under the whole foot from pre- to post- whereas forces remained unchanged. This resulted in decreased mean pressures under the whole foot from pre to post, which may constitute an appropriate adaptation of the foot plantar patterns in order to prevent the bony structures from oveload.

We also observed a significant increase of the whole foot contact times when running in a fatigued state. This was due to a significant increase in contact times under the central forefoot and the lesser toes. It has already been reported in the literature that such an increase in contact times may result from altered stretch-shortening-cycle.[3, 25] However, increased contact times likely allowed for the participants to maintain a constant horizontal impulse despite the decrease in neuromuscular capacity as a result of fatigue.[26] Additionally, we noted a trend of mean force reduction under the medial forefoot, the central forefoot and the Hallux. This may suggest again that the aforementioned fatigue-induced adaptations tended to decrease the foot/ankle propulsive capacity (limiting the performance) but it may also prevent the metatarsal heads from excessive loading.

Overall the findings of the present study emphasized the considerable role of the MLA for ensuring a proper absorption phase. This may help preventing numerous lower extremity pathologies such as metatarsal stress injuries or medial tibial stress syndrome [27], which are of high prevalence in adolescent athletes.[28] Practically, it seems that the augmented compliance of the medial longitudinal arch under fatigue may result in an increased work load of the plantar-flexor, leading to localized fatigue. Therefore, as an injury prevention strategy, we recommend implementing strengthening exercises of the intrinsic foot musculature in order to reinforce the MLA and to facilitate its load absorbing role at the stance phase, especially in a fatigued state. Electromyostimulation of the abductor hallucis has been described as a promising technique in this matter,[27, 29] even though this type of reinforcement must be applied carefully in immature adolescent athletes.

In conclusion, the ankle PF resistance to fatigue was affected by a high intensity running exercise to exhaustion. This phenomenon was associated with alterations in the medial arch function and with an increase in contact times at the forefoot and the toes.

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Figure legends

Figure 1. Experimental protocol performed before and after the running bout to exhaustion.

Testing session two, in the non-fatigued state (A)

Testing session three, in the fatigued state (B)

Detailed procedure of the isokinetic testing (C)

DF: ankle dorsi-flexor, HR_{max}: maximal heart rate, MVC-CON: maximal voluntary isokinetic concentric contraction, MVC-ECC: maximal voluntary isokinetic eccentric contraction, PF: ankle plantar-flexor, vVO_{2max}: velocity at maximal oxygen uptake.

Figure 2. Mean ± SD mean area (cm^2) (A), relative load (%) (B), contact time (ms) (C) and mean force (N) (D) for each foot region at the start (ONSET) and at the end (ENDPOINT) of the running bout to exhaustion. $^{\#}P < .1$, $^{*}P < .05$, $^{**}P < .01$ for difference between ONSET and ENDPOINT.

Figure 1

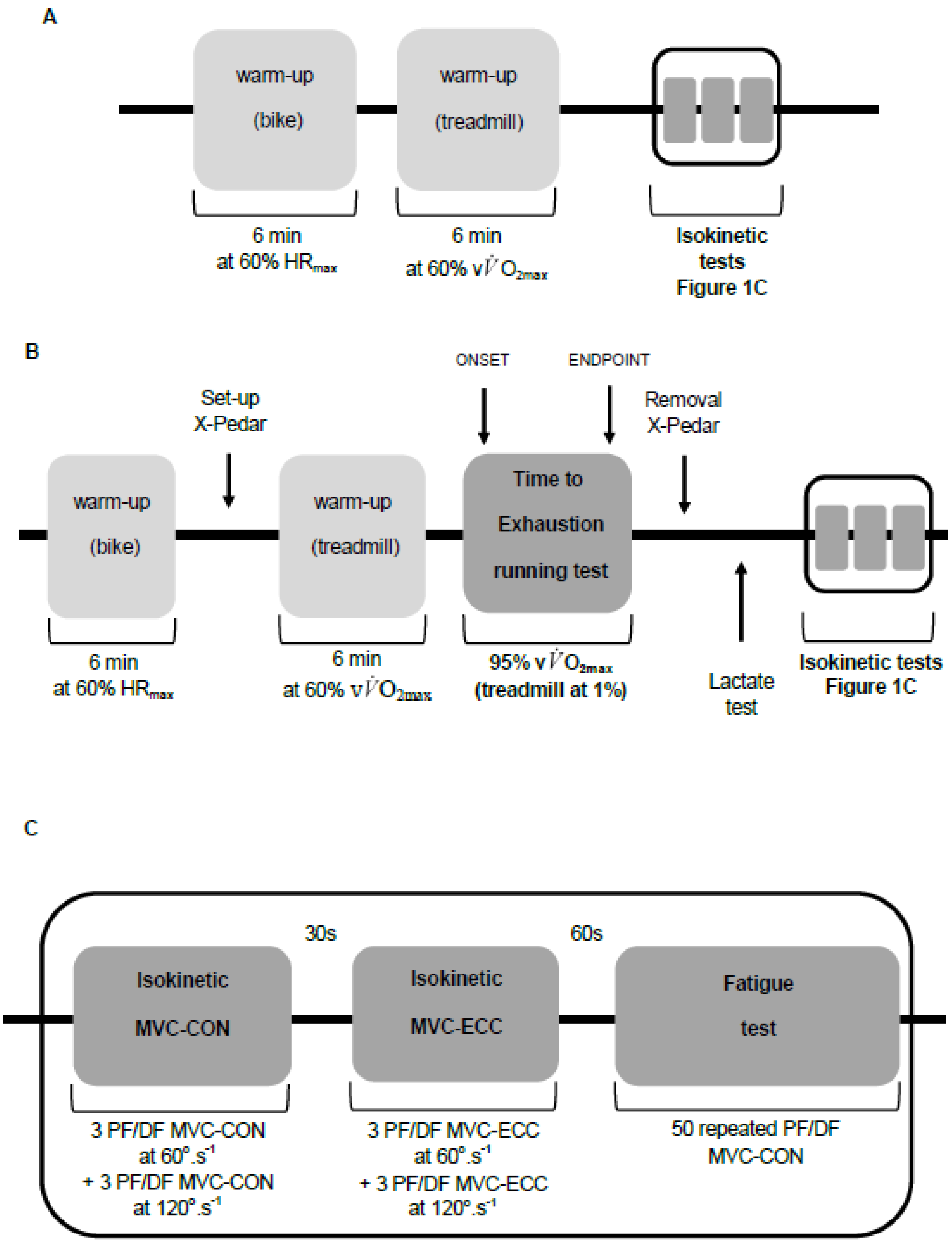
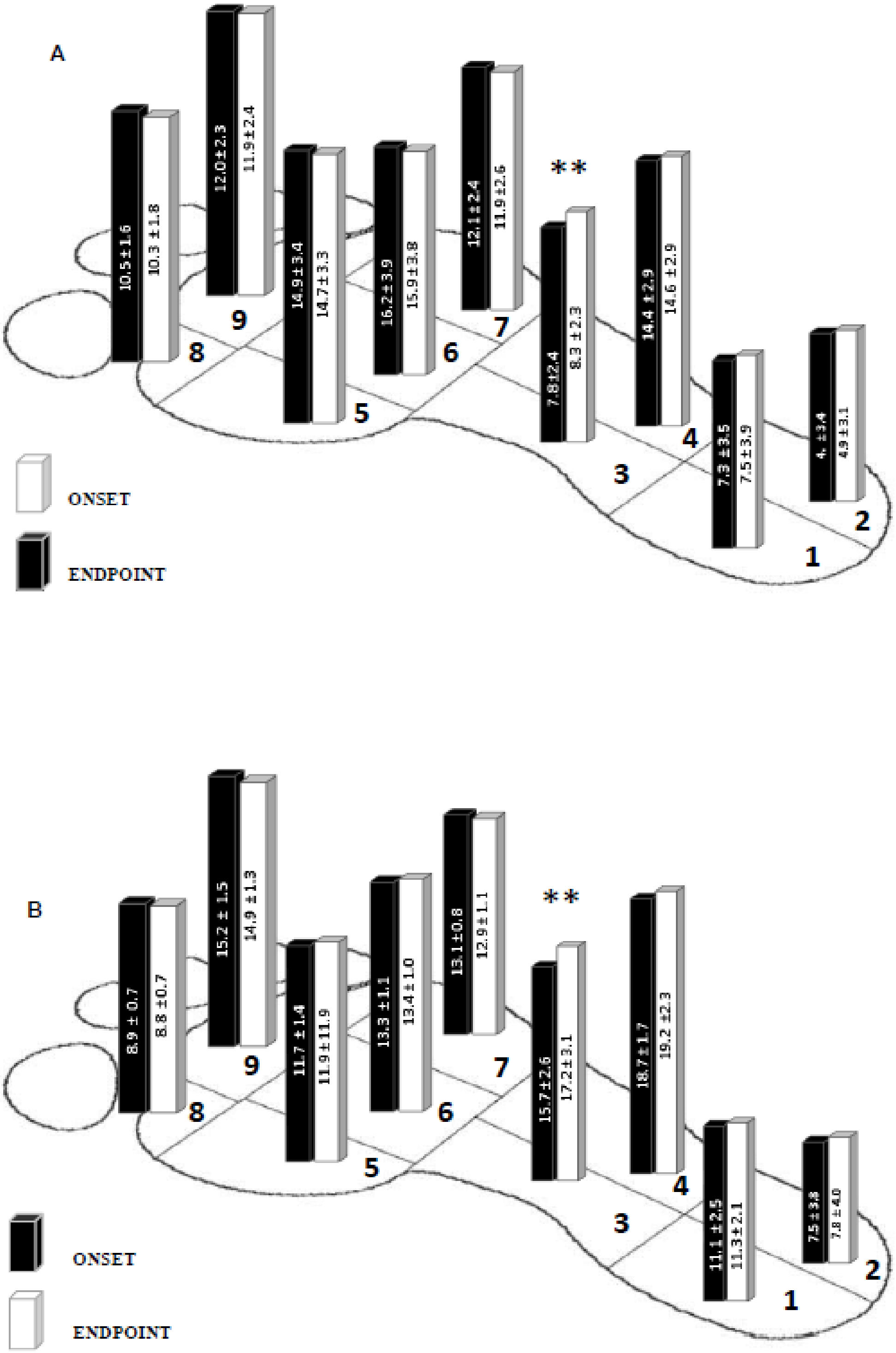
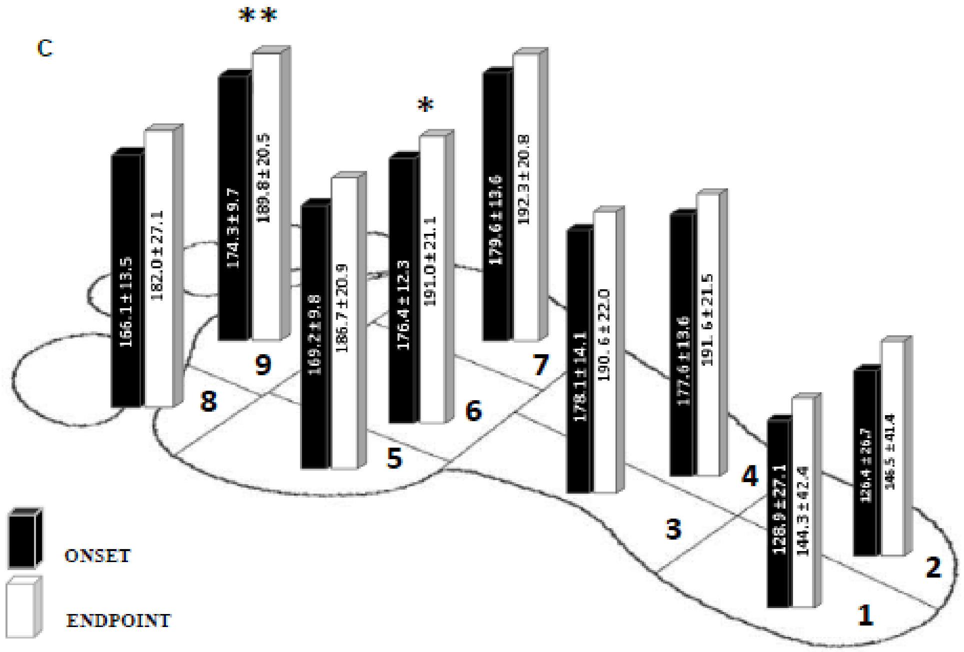

A
warm-up
(bike)
warm-up
(treadmill)
6 min
at 60% HR_{max}
6 min
at 60% $v\dot{V}O_{2max}$
Isokinetic
tests
Figure 1C
B
Set-up
X-Pedar
ONSET
ENDPOINT
Removal
X-Pedar
warm-up
(bike)
warm-up
(treadmill)
Time to
Exhaustion
running test
6 min
at 60% HR_{max}
6 min
at 60% $v\dot{V}O_{2max}$
95% $v\dot{V}O_{2max}$
(treadmill at 1%)
Lactate
test
Isokinetic tests
Figure 1C
C
30s
60s
Isokinetic
MVC-CON
Isokinetic
MVC-ECC
Fatigue
test
3 PF/DF MVC-CON
at 60°.s^{-1}
+ 3 PF/DF MVC-CON
at 120°.s^{-1}
3 PF/DF MVC-ECC
at 60°.s^{-1}
+ 3 PF/DF MVC-ECC
at 120°.s^{-1}
50 repeated PF/DF
MVC-CON

Figure 2


A
10.5 ± 1.6
10.3 ± 1.8
12.0 ± 2.3
11.9 ± 2.4
14.9 ± 3.4
14.7 ± 3.3
16.2 ± 3.9
15.9 ± 3.8
12.1 ± 2.4
11.9 ± 2.6
**
7.8±2.4
8.3 ± 2.3
14.4 ± 2.9
14.6 ± 2.9
7.3 ± 3.5
7.5 ± 3.9
4. ± 3.4
4.9 ± 3.1
8
9
5
6
7
3
4
1
2
ONSET
ENDPOINT
B
8.9 ± 0.7
8.8 ± 0.7
15.2 ± 1.5
14.9 ± 1.3
11.7 ± 1.4
11.9 ± 11.9
13.3 ± 1.1
13.4 ± 1.0
13.1 ± 0.8
12.9 ± 1.1
**
15.7 ± 2.6
17.2 ± 3.1
18.7 ± 1.7
19.2 ± 2.3
11.1 ± 2.5
11.3 ± 2.1
7.5 ± 3.8
7.8 ± 4.0
8
9
5
6
7
3
4
1
2
ONSET
ENDPOINT


C
**
*
166.1 ± 13.5
182.0 ± 27.1
174.3 ± 9.7
189.8 ± 20.5
169.2 ± 9.8
186.7 ± 20.9
176.4 ± 12.3
191.0 ± 21.1
179.6 ± 13.6
192.3 ± 20.8
178.1 ± 14.1
190. 6 ± 22.0
177.6 ± 13.6
191. 6 ± 21.5
128.9 ± 27.1
144.3 ± 42.4
126.4 ± 26.7
146.5 ± 41.4
9
8
5
6
7
4
3
2
1
ONSET
ENDPOINT

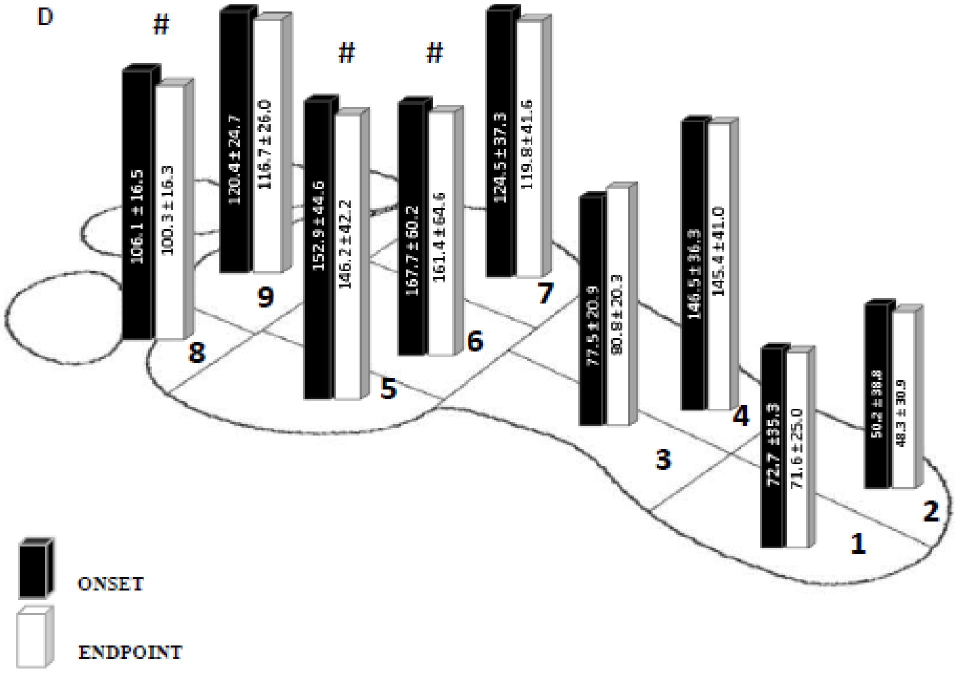

D
#
#
#
106.1 ± 16.5
100.3 ± 16.3
120.4 ± 24.7
116.7 ± 26.0
152.9 ± 44.6
146.2 ± 42.2
167.7 ± 60.2
161.4 ± 64.6
124.5 ± 37.3
119.8 ± 41.6
77.5 ± 20.9
80.8 ± 20.3
146.5 ± 36.3
145.4 ± 41.0
72.7 ±35.3
71.6 ± 25.0
50.2 ± 38.8
48.3 ± 30.9
9
8
5
6
7
4
3
2
1
ONSET
ENDPOINT

Table 1. Means (±SD) for Mean Area (cm^2), Mean Force (N), Mean Pressure (kPa), Relative Load (%) and Contact Time (ms) for each Foot Region at the Beginning (ONSET) and at the End (ENDPOINT) of the Running Exercise to Exhaustion.

					Foot	regions					
Parameters	**Measure**	**Whole foot**	**Medial heel 1**	**Lateral heel 2**	**Medial midfoot 3**	**Lateral midfoot 4**	**Medial forefoot 5**	**Central forefoot 6**	**Lateral forefoot 7**	**Hallux 8**	**Lesser toes 9**
Mean area (cm^2)	**ONSET**	115.3 ± 7.4	11.1 ± 2.5	7.5 ± 3.8	15.7 ± 2.6	18.7 ± 1.7	11.7 ± 1.4	13.3 ± 1.1	13.1 ± 0.8	8.9 ± 0.7	15.2 ± 1.5
	ENPOINT	117.5* ± 9.2	11.3 ± 2.1	7.8 ± 4.0	17.2** ± 3.1	19.2 ± 2.3	11.9 ± 1.3	13.4 ± 1.0	12.9 ± 1.1	8.8 ± 0.7	14.9 ± 1.3
Mean force (N)	**ONSET**	1020.2 ± 163.3	72.7 ± 35.3	50.2 ± 38.8	77.5 ± 20.9	146.5 ± 36.3	152.9 ± 44.6	167.7 ± 60.2	124.5 ± 37.3	106.1 ± 16.5	120.4 ± 24.7
	ENPOINT	991.9 ± 170.6	71.6 ± 25.0	48.3 ± 30.9	80.8 ± 20.3	145.4 ± 41.0	*146.2*$^{\#}$ *± 42.2*	*161.4*$^{\#}$ *± 64.6*	119.8 ± 41.6	*100.3*$^{\#}$ *± 16.3*	116.7 ± 26
Mean pressure (kPa)	**ONSET**	119.8 ± 18.1	96.8 ± 36.6	95.9 ± 40.2	66.7 ± 17.3	110.7 ± 22.8	203.9 ± 47.1	197.2 ± 56.6	143.4 ± 32.2	176.7 ± 28.6	111.7 ± 20.7
	ENPOINT	115.8** ± 18.5	102.8 ± 31.9	99.3 ± 31.7	64.9 ± 14.5	110.2 v 23.6	200.8 ± 45.2	193.7 ± 60.6	142.4 ± 35.6	175.1 ± 36	113.9 ± 25.2
Relative load (%)	**ONSET**	-	7.3 ± 3.5	4.9 ± 3.4	7.8 ± 2.4	14.4 ± 2.9	14.9 ± 3.4	16.2 ± 3.9	12.1 ± 2.4	10.5 ± 1.6	12.0 ± 2.3
	ENPOINT	-	7.5 ± 2.9	4.9 ± 3.1	8.3** ± 2.3	14.6 ± 2.9	14.7 ± 3.3	15.9 ± 3.8	11.9 ± 2.6	10.3 ± 1.8	11.9 ± 2.4
Contact time (ms)	**ONSET**	180.4 ± 13.1	128.9 ± 27.1	126.4 ± 26.7	178.1 ± 14.1	177.6 ± 13.6	169.2 ± 9.8	176.4 ± 12.3	179.6 ± 13.6	166.1 ± 13.5	174.3 ± 9.7
	ENPOINT	193.2 ± 20.4	144.3 ± 42.4	146.5 ± 41.4	190.6 ± 22.0	191.6 ± 21.5	186.7 ± 20.9	191.0 ± 21.1*	192.3 ± 20.8	182.0 ± 27.1	189.8** ± 20.5

$^{\#}$*P* < .1, *P < .05, ***P* < .01 for difference between ONSET and ENDPOINT.

Changes in leg spring behaviour, plantar loading and foot mobility magnitude induced by a treadmill exhaustive run in adolescent middle-distance runners

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Abstract:

This study aimed to determine adjustments in spring-mass model characteristics, plantar loading and foot mobility induced by an exhaustive run, and the effect that these changes have on performance. Eleven highly-trained adolescent middle-distance runners ran to exhaustion on a treadmill at a constant velocity (17.8 ± 1.4 $km.h^{-1}$, time to exhaustion = 8.8 ± 3.4 min). Plantar loading for the whole foot together with stride temporal parameters, which were used to estimate spring-mass model characteristics, were recorded 1 min after the start and prior to exhaustion using pressure insoles. Foot mobility magnitude (FMM) was measured before and after the run. Mean area ($p<0.05$), contact time ($p<0.01$), peak vertical force ($p<0.05$), centre of mass vertical displacement ($p<0.01$) and leg compression ($p<0.05$) increased significantly with fatigue, while flight time ($p<0.05$), leg stiffness ($p<0.01$) and mean pressure ($p<0.01$) decreased. Step length, step frequency and FMM remained unchanged after fatigue. FMM value before exercise was negatively correlated with changes in mean area ($r=-0.56$, $p=0.07$) and maximum force ($r=-0.64$, $p<0.05$). The stride pattern of adolescents when running on a treadmill at a high intensity and constant velocity deteriorates near exhaustion, as evidenced by impaired leg-spring behaviour (leg stiffness) and altered plantar loading. The constancy in step frequency and the increase in peak vertical force in fatigued state appeared to be specific adjustments to this adolescent highly-trained population. In addition foot mobility characteristics had an influence on plantar loading changes with fatigue.

Keywords: fatigue, spring mass model, stride mechanics, medial arch.

1. Introduction

The musculo-tendinous structures of the lower limb alternately store and return elastic energy during running. Accordingly, the lower limbs can be considered as springs loaded by the weight and inertia of the body mass. This paradigm refers to the “spring-mass model” (SMM) and has been used increasingly in recent years to describe the behaviour (stiffness regulation) of the lower limb musculoskeletal system during fatiguing runs.[1-12] Most of these studies examined the SMM parameters either over ultra-long distance events and reported increased leg and or vertical stiffness and step frequency with fatigue,[4, 9, 10] or over sprint running repetitions and showed, conversely, a constant peak vertical force and constant or decreased stride frequency and vertical stiffness in fatigued state.[2, 3, 11, 12] Halfway between these extremes, studies of SMM characteristics during middle-distance running trials have reported contrasting results.[1, 5-8, 13] On an athletic track, Slawinski et al. observed no variations in the main SMM parameters with fatigue, however their measures were obtained at slow velocities before and after a 2000m maximal running test of approximately seven minutes duration.[8] Nevertheless, as the running trial was self-paced in this study, subjects could adapt individually their velocity and running patterns (especially at race end) and it may have influenced the results. Other authors have explored SMM changes during constant pace exhaustive runs.[1, 5-7, 13] Two studies confirmed lower stride frequency and vertical stiffness with fatigue on a treadmill, but only at relatively low pace (i.e., ~80% of the velocity associated with the maximal oxygen uptake).[5, 6] To the best of our knowledge, only Rabita et al. assessed the SMM parameters changes at severe constant velocity (i.e., 95% of the velocity associated with the maximal oxygen uptake).[7] Their results, obtained on a track, confirmed the peak vertical force decrease with fatigue reported by Slawinski et al.,[8] but showed also higher stride frequency, constant vertical stiffness but decreased leg stiffness in fatigued state. These latter finding is in conflict with former studies and might be specific to high intensity running speed. It is worth noting that no studies have looked at fatigue induced alterations of SMM characteristics in adolescent runners. Only Ratel et al. reported findings compilation about the influence of fatiguing intermittent running on stride parameters in adults and children.[14] They observed a lower decline in step frequency with fatigue in children, but the underlying mechanisms remained unclear.[14]

Foot alignment during the stance phase (e.g. the sole interface with the ground)[15] may impact on leg spring behaviour. Any foot malalignments/weaknesses that negatively affect foot mobility may disturb the absorption or propulsion phases when running.[15] In example, excessive pronation resulting in a medial longitudinal arch flattening impairs the foot lateral stabilisation during upright stance.[15] In addition, this phenomenon is exacerbated by fatigue (i.e., affecting the plantar intrinsic foot muscles) as manifested by an increased navicular drop.[16] Consequently, this would modify the foot unroll and results in structural overload, which may influence injury risks,[17] especially in immature adolescent involved in middle distance running.[18] So the question of the relationship between fatigue-induced alterations in foot mobility (using the foot mobility magnitude [FMM] measurement)[19] with leg spring behaviour and plantar loading warrants new attention.

Therefore the purpose of this study was to determine to which extent running to exhaustion at severe, constant velocity on a treadmill modifies SMM parameters, plantar loading, and FMM in highly-trained adolescent athletes, and whether these changes are good predictors of exercise duration.

2. Methods

2.1 Subjects

Eleven male adolescent distance runners (age: 16.9 ± 2.0, body mass: 54.6 ± 8.6 kg, height: 170.6 ± 10.9 cm) completed the study. They were free of lower limb injury in the two months preceding testing. Written informed consent was obtained from all participants before the beginning of the testing. The project was approved by the local Scientific and Ethics committee, and the procedure complied with the *Declaration of Helsinki*.

2.2 Protocol

Two runs performed on a treadmill (h/p/Cosmos, Nussdorf-Traunstein, Germany) at 5-7 days apart were required. Each subject first completed an incremental test to exhaustion in order to determine maximal oxygen uptake (63.3 ± 4.4 $ml.min^{-1}.kg^{-1}$) and its associated velocity (18.7 ± 0.9 $km.h^{-1}$). It consisted of an initial one minute workload of 8 $km.h^{-1}$ followed by increases of 1 $km.h^{-1}$ every minute (1% slope). Gas exchange was measured using a breath-by-breath analyser (Oxycon Pro, Jaeger, Hoechberg, Germany). The second run was a constant velocity run (average speed: 17.8 ± 1.4 $km.h^{-1}$) until exhaustion performed at 95% of velocity associated with their maximal oxygen uptake (Figure 1). During exercise, RPE (6-20 Borg scale) was recorded every minute. Running pattern was assessed by recording/determining SMM and plantar pressure data over a 30 s period at two occasions: (i) 1 min after the exercise start (ONSET) and then (ii) as soon as the subject reported 18 as RPE (ENDPOINT) corresponding to 78-84 steps (Figure 1). This 30 s window ended in a range of 25 to 45 s prior exhaustion. A blood sample was collected for lactate measurement (Lactate Pro, Arkray Inc, Japan) during the 3 min period following ENDPOINT.

2.3 Plantar loading

Insole plantar loading of both feet was recorded using the X-Pedar Mobile insole (Novel GmbH, Munich, Germany) consisting of a 2-mm-thick array of 99 capacitive pressure sensors. All the participants wore the same type of universal shoes (Adidas, Supernova sequence). Plantar loadings were sampled at 50 Hz. An excellent reliability has been reported for this device.[20] Contact time (Tc in s), mean area (cm^2), contact area (cm^2), mean force (N), maximum force (N), mean pressure (kPa), peak pressure (kPa) were determined for the whole foot. Data from the left and right foot were averaged for subsequent analysis.

2.4 Stride parameters and spring-mass characteristics

Flight (Tf) and contact (Tc) times were determined from the X-Pedar mobile software (Novel Win, Novel GmbH, Munich, Germany).[2] Step frequency ($S_F = 1 / (Tc + Tf)$ in Hz) and step length ($S_L = V_{forward} / S_F$ in m) were calculated.

From these measurements of Tc, Tf (in s), forward running velocity $V_{forward}$ (*i.e.* 4.94 ± 0.40 $m.s^{-1}$) and from subjects' body mass m (in kg) and lower limb length (in m), measured as the great trochanter-to-ground distance in a standing position, spring-mass parameters were calculated using the computation method proposed by Morin et al.[21] This method based on a modelling of the ground reaction force signal during the contact phase by a sine function, allows computation of vertical stiffness (K_{vert}, $kN.m^{-1}$) as the ratio of the peak vertical force (Fz_{max} in N) to the maximal downward displacement of centre of mass (CM) during contact (Δz in m).

$$K_{vert} = Fz_{max} / \Delta z$$

with

$$Fz_{max} = m \cdot g \cdot (\pi \cdot 2^{-1}) \cdot [(Tf / Tc) + 1)]$$

and

$$\Delta z = - (Fz_{max} \cdot m) \cdot (Tc^2 \cdot \pi^2) + g \cdot (Tc^2 / 8)$$

Leg stiffness (K_{leg}, $kN.m^{-1}$) was calculated as the ratio of Fz_{max} to the peak displacement of the leg spring ΔL (in m) during contact

$$K_{leg} = Fz_{max} / \Delta L$$

with

$$\Delta L = L_0 - \sqrt{[L_0^2 - (V_{forward} \cdot Tc / 2)^2]} + \Delta z$$

It was assumed that the vertical velocity of CM was zero at the time of Fz_{max}. In this equation, L_0 (initial leg length from great trochanter to ground distance in a standing position) was determined from subject's stature as $L_0 = 0.53$ x stature.[22]

2.5 Foot mobility magnitude (FMM) measurements

For the purpose of this study, three instruments including weight bearing, and non-weight bearing arch height gauges and a midfoot width measurement device were manufactured. Each of those included a digital calliper (AmPro T74615 Stainless Steel Digital Caliper, Frenway Products Inc. Taipei) (Fig. 2A, 2B and 2C)

The FMM measurement procedure, which was performed before and immediately after the exhaustive run, is succinctly summarized below; for a full description of the method the reader is referred to Mc Poil et al.[19] Each subject was asked to stand on a foot measurement platform (heels placed in heel cups) so that dorsal arch height and midfoot width could be measured in bilateral lower limb weight bearing (Fig. 2D and 2E). Afterwards, the non-weight bearing measurements of these two parameters were recorded with subjects sitting with both lower legs hanging in a perpendicular relaxed position (Fig. 2F and 2G). The procedure used for the weight bearing measures was then repeated. As recommended previously,[19] a single measure in weight bearing but the average of two measures in non-weight bearing (both in cm) have been obtained by the same investigator, with SEM established at 0.1cm.[19] A high level of reliability (Intraclass Correlation Coefficient > 0.97) has been reported for this measurement technique.[19] A method based on the Pythagorean Theorem was used to calculate the FMM:

$$FMM = \sqrt{(DiffAH)^2 + (DiffMFW)^2}$$

where DiffAH and DiffMFW are the changes in dorsal arch height and in midfoot width between weight bearing and non-weight bearing, respectively.

2.6 Statistical analysis

Mean ± SD values were calculated for all variables. Paired *t*-test were used to examine the differences in plantar loading parameters for the whole foot and in stride parameters between ONSET and ENDPOINT, and the differences in FMM between before and after exercise. Pearson correlation coefficients were used to examine relationships between exercise duration and plantar loading parameters, SMM and

FMM parameters. Statistical analyses were performed using Sigmastat 3.5 software (Jandel Corporation, San Rafael, CA). Statistical significance was accepted at $p < 0.05$.

3. Results

The exhaustive run duration was 8.8 ± 3.4 min (4.8 – 16.3 min). The mean lactate level of the group was 11.6 ± 2.7 mmol.L^{-1} and the mean last RPE rate before stopping the running bout was 19.3 ± 0.6.

As shown in table 1, Tc ($p<0.01$), Fz_{max} ($p<0.05$), Δz ($p<0.01$), ΔL ($p<0.05$) and mean area ($p<0.05$) increased significantly from ONSET to ENDPOINT, while Tf ($p<0.05$), K_{leg} ($p<0.01$) and P_{mean} ($p<0.01$) decreased and K_{vert} remained constant.

FMM did not change (1.2 ± 0.3 vs. 1.3 ± 0.3 cm) from before to after exercise (Table 2).

There were no significant correlations between exercise duration, SMM characteristics and any other parameters ($p>0.05$). Conversely, FMM value before exercise was negatively correlated with mean area ($r=-0.56$, $p=0.07$) and maximum force ($r=-0.64$, $p<0.05$) changes with fatigue. Changes in mean pressure with fatigue were correlated with FMM ($r=0.68$, $p<0.05$) and DiffAH ($r=0.62$, $p<0.05$) changes after fatigue.

4. Discussion

The main results of the present study were that running at constant velocity until exhaustion leads to a constancy of the stride frequency and length, a decrease in leg stiffness despite an increase in the peak vertical force. In addition, significant relationships between foot mobility magnitude and several plantar loading parameters have been observed. In line with the majority of “time-to-exhaustion” protocols[1, 6, 7], Tc lengthened during the run which may have resulted from a reduced strength and/or stretch-shortening-cycle efficiency of the lower limb extensor muscles.[23] However, increased Tc likely allowed for the subjects to maintain a constant horizontal impulse despite the fatigue development.[7] S_f and S_L remained unchanged during the exhaustive run since the increase in Tc was compensated by a similar magnitude decrease in Tf. The preserved S_f and S_L observed here conflicts with existing reports showing decreased[5, 6] or slightly increased[7] S_f during constant velocity runs in adults. Despite a similar pace (i.e., 95% of velocity associated with maximal oxygen uptake), we may assume that our results differed from Rabita et al.[7] partly because of the nature of the population tested (e.g. adolescent distance runners vs. adult triathletes) and protocol used (test performed on treadmill using pressure sensors vs. indoor track using force platform). Differently from adult reports,[5-7] it appeared that adolescent runners involved in the present study did not or could not adapt their stride parameters (i.e., S_f and S_L) in fatigued state. However, this seems to corroborate the assumption of Ratel et al.,[14] reporting a lower decline in step frequency during fatiguing intermittent running (e.g., consecutive 10-s sprints on treadmill) in 12 yr boys than in adults, even if the underlying mechanisms are still unclear.

One key finding was also that K_{vert} remained unchanged during the run, while K_{leg} decreased significantly. Nevertheles, the mechanisms of the decreases in K_{leg} are different to those reported in Rabita et al.[7] Indeed, ΔL and Fz_{max} increased in fatigued state in our study whereas Fz_{max} decreased and ΔL remained unchanged in Rabita et al.[7] We observed that adolescent runners fatigue-induced adaptations (i.e., constant S_f and S_L and increased Fz_{max}) concentrated on force production at stance phase. This conflicted with most of severe intensity running studies, where adults decreased their Fz_{max} and S_f in order to reduce the impact forces and protect their lower limbs musculoskeletal structures.[8, 24, 25]

It is known that FMM is highly predictive of dynamic foot posture during running.[19] In the present study, FMM remained unchanged while mean pressure decreased due to an increase of mean area for the whole foot. These later results suggest that the local running-induced fatigue was not sufficient for inducing a significant medial longitudinal arch collapse. This contradicted the results of Headlee et al. where plantar intrinsic foot muscles fatigue was specifically provoked.[16] It is worth noting that the dorsal arch height was the most likely determinant of the FMM changes, as there was a trend of increase of this vertical parameter with fatigue, while the midfoot width remained unchanged (Table 2). In addition, the correlational results highlighted relevant relationships between initial midfoot mobility (FMM before exercise) or fatigue resistance capacities (before-after FMM changes) and plantar loading changes with fatigue. Indeed, it appeared that a lower midfoot mobility can (i) contribute to preserve the quality of the force transmission at the foot level and (ii) adequately play its role in the shock absorbing function of the foot by increasing and controlling the contact area at foot stance. The medial arch stiffness may then participate in the adjustment of ankle torsional stiffness as well, which was described as the primary mechanism for leg stiffness adjustment.[26] Additionally, it appeared that a high fatigue resistance of the midfoot was linked to a better control of the plantar loading with fatigue, which is of primary interest in terms of injury prevention.[17, 27, 28] These findings emphasize midfoot function (especially the medial arch) as an effective spring and foot stabiliser in a fatigued state.[29]

In summary, at the end of an exhaustive run, the adolescent male runners involved in this study kept constant step length and frequency but increased their contact time. They also displayed a leg stiffness decrease despite an increase of the peak vertical force, while their plantar pressures decreased towards an increased foot contact area. Moreover lower initial FMM measures and FMM fatigue-induced changes appeared to influence positively the force transmission and the plantar loading with fatigue. Despite the potential differences between exhaustive running trials on a treadmill and over ground in terms of stride or stiffness regulation, some findings of the present study appeared of interest for practical field applications. Firstly, while decreasing their leg stiffness, the adolescent runners increased significantly their Fz with fatigue. This leads to high impacts repetitions and higher injury risk,[24] (e.g., first and second metatarsal stress fractures, metatarsalgia or shin splints), especially in pre-pubertal and circumpubertal athletes where foot and ankle problems have been reported as the second most common musculoskeletal problem.[28] So one may hypothesize that the higher foot/ankle injury incidence observed in adolescents when compared to adults may come partly from a different stride frequency regulation, resulting in a less efficient shock absorbing phase with fatigue. Therefore, it seems appropriate to prescribe exercises soliciting the medial arch and aiming to increase stiffness and better absorption of impacts at high velocity.[8] Secondly, the role of the midfoot (especially the medial arch) must not be neglected as a factor of foot stability and stiffness adjustment, especially in terms of prevention of excessive pronation-related injuries.[28] In this view, barefoot intense running or sprints on soft surface (grass) might be specially relevant in adolescent runners, as a potential efficient way of strengthening the medial midfoot structures and lessening the specific overuse injuries in this population.[27]

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Figures caption:

Figure 1: General view of the main experimental trial.

Footnotes: FMM: foot mobility magnitude, RPE: rating of perceived exertion, ONSET: non-fatigued state running parameters recording, ENDPOINT: fatigued state running parameters recording, $v\dot{V}O_{2max}$: velocity associated with the maximal oxygen uptake.

Figure 2: The foot mobility magnitude (FMM) measurement with: (A) the weight bearing arch height gauge, (B) the non-weight bearing arch height gauge, (C) the midfoot width measurement device, (D) the weight bearing arch height measurement technique, (E) the weight bearing midfoot width measurement technique, (F) the non-weight bearing arch height measurement technique, (G) the non-weight bearing midfoot width measurement technique.

Figure 1.

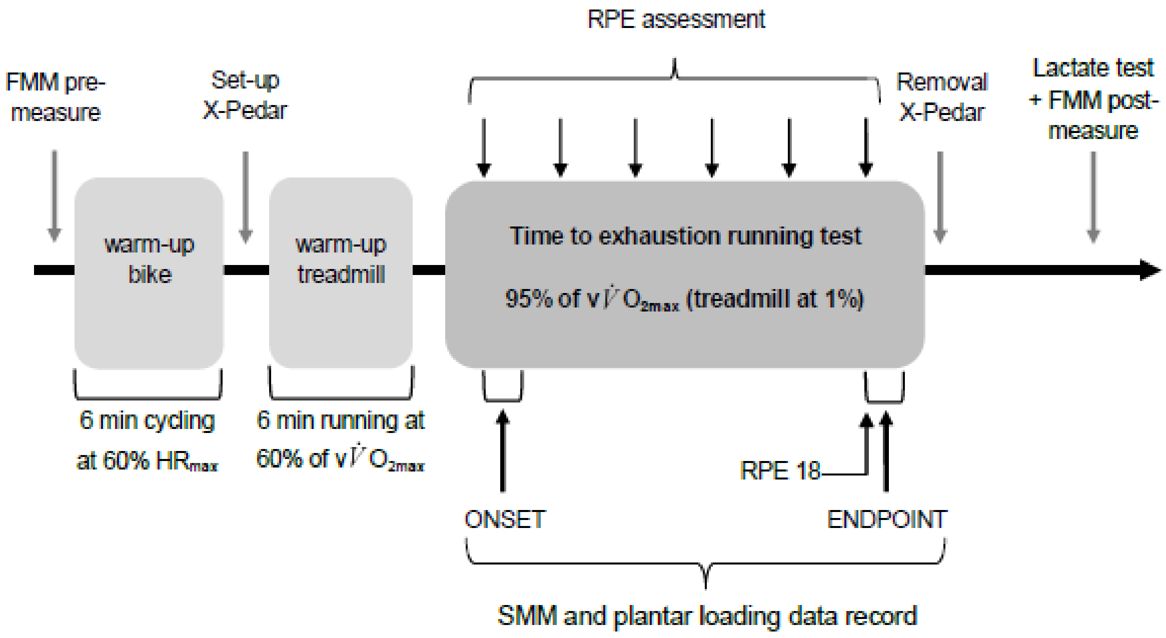
RPE assessment
FMM pre-measure
Set-up X-Pedar
Removal X-Pedar
Lactate test + FMM post-measure
warm-up bike
warm-up treadmill
Time to exhaustion running test
95% of v$\dot{V}O_{2max}$ (treadmill at 1%)
6 min cycling at 60% HR_{max}
6 min running at 60% of v$\dot{V}O_{2max}$
RPE 18
ONSET
ENDPOINT
SMM and plantar loading data record

Figure 2.

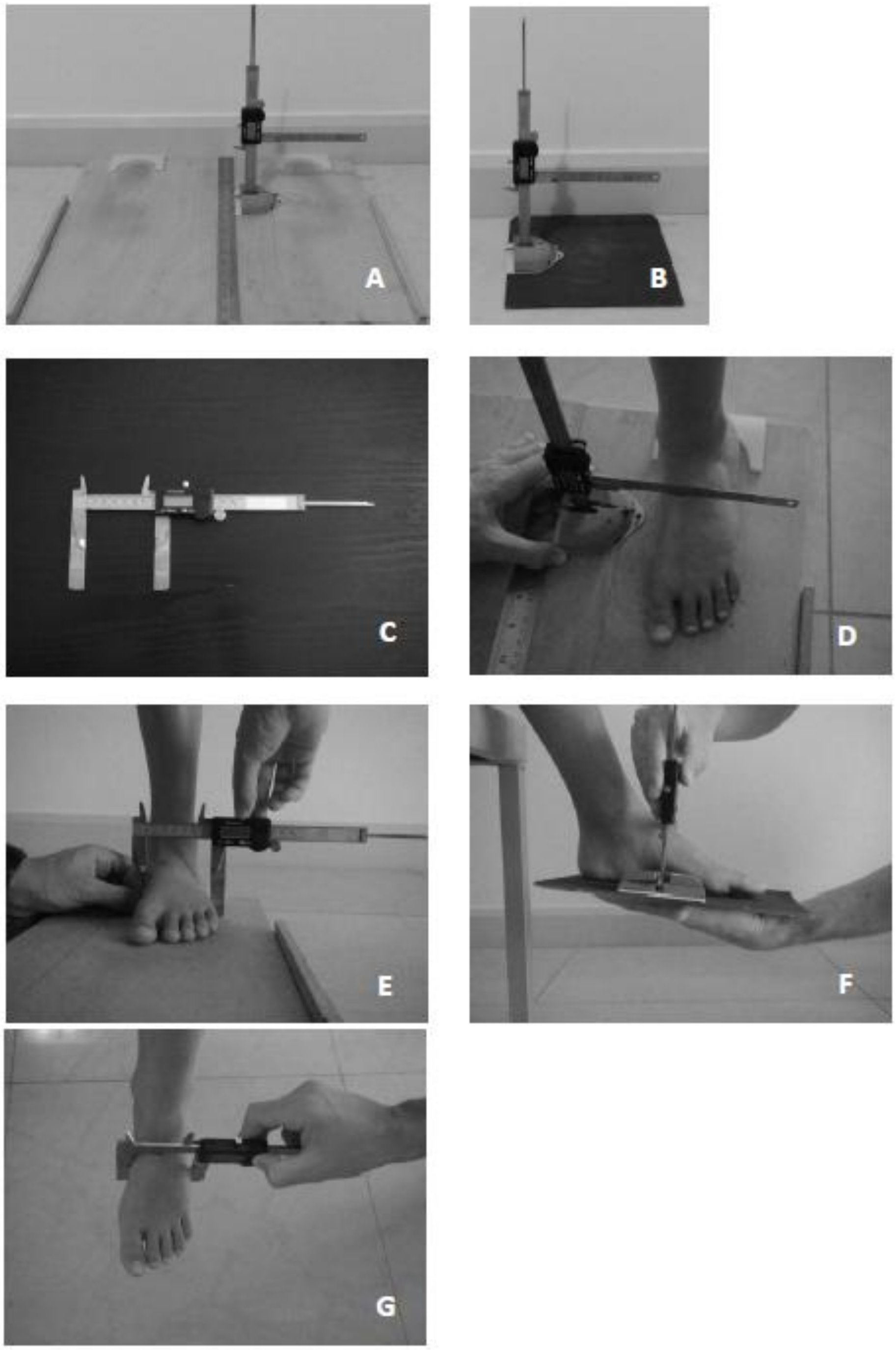

Table 1. Stride temporal, spring-mass model and foot loading parameters after 1 min (ONSET) and near exhaustion (ENDPOINT) during a treadmill constant velocity run.

Parameter	ONSET	ENPOINT	p value	% change
Tc (s)	0.183 ± 0.13	0.207 ± 0.032	<0.01	13.2 ± 13.1
Tf (s)	0.154 ± 0.014	0.137 ± 0.025	<0.05	-12.2 ± 17.5
S_F (Hz)	2.95 ± 0.14	2.91 ± 0.14	NS	-1.1 ± 3.9
S_L (m)	1.68 ± 0.15	1.70 ± 0.12	NS	1.3 ± 4.1
Fz_{max} (N)	1817 ± 250	2226 ± 763	<0.05	22.5 ± 24.7
Δz (m)	0.030 ± 0.003	0.035 ± 0.007	<0.01	17.3 ± 15.5
ΔL (m)	0.151 ± 0.019	0.200 ± 0.065	<0.05	31.2 ± 33.0
K_{vert} ($kN.m^{-1}$)	61.7 ± 8.7	63.1 ± 12.8	NS	1.9 ± 12.2
K_{leg} ($kN.m^{-1}$)	12.2 ± 2.2	11.2 ± 1.7	<0.01	-7.4 ± 6.7
mA (cm^2)	115 ± 7	118 ± 9	<0.05	1.9 ± 2.6
CA (cm^2)	170 ± 4	171 ± 4	NS	0.2 ± 1.5
F_{mean} (N)	1020 ± 163	992 ± 170	NS	-2.8 ± 6.5
F_{max} (N)	1607 ± 275	1592 ± 271	NS	-1.0 ± 3.4
P_{mean} (kPa)	120 ± 18	116 ± 19	<0.01	-3.3 ± 3.0
PP (kPa)	327 ± 73	331 ± 78	NS	1.1 ± 4.2

Subjects ran at 95% of the velocity associated with the maximal oxygen uptake. Tc, contact time; Tf, flight time; SF, step frequency; SL, step length; Fz_{max}, peak vertical force; Δz, centre of mass vertical displacement; ΔL, leg compression; Kvert, vertical stiffness; Kleg, leg stiffness; mA, mean area; CA, contact area; Fmean, mean force; Fmax, maximum force; Pmean, mean pressure; PP, peak pressure.

Table 2: Means (±SD) in cm for Foot mobility magnitude measurements before and after the exhaustive run.

Parameters	before	after	p value	% change
FMM (cm)	1.2 ± 0.3	1.3 ± 0.3	NS	4.0 ± 14.3
WB.AH (cm)	4.4 ± 3.0	4.5 ± 3.0	0.08	2.3 ± 1.7
NWB.AH (cm)	5.5 ± 3.3	5.5 ± 2.9	NS	0
DiffAH (cm)	1.0 ± 0.2	1.1 ± 0.2	0.09	6.4 ± 12.0
WB.MFW (cm)	8.6 ± 5.8	8.7 ± 6.2	NS	1.2 ± 0.9
NWB.MFW (cm)	7.9 ± 5.0	8.0 ± 5.8	NS	1.3 ± 1..0
DiffMFW (cm)	0.1 ± 0.0	0.1 ± 0.0	NS	-1.1 ± 3.9

FMM: foot mobility magnitude, WB.AH: change in foot dorsal arch height between before and after in weight bearing, NWB.AH: change in foot dorsal arch height between before and after in non-weight bearing, DiffAH: NWB.AH – WB.AH, WB.MFW: change in midfoot width between before and after in weight bearing, NWB.MFW: change in midfoot width between before and after in non-weight bearing DiffMFW: WB.MFW – NWB.MFW.

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Communication brève

Comparaison de la répartition des appuis plantaires entre chaussures d'entraînement et chaussures à pointes chez de jeunes sprinters

Comparison of foot plantar distribution between training and spike shoes in young sprinters

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Résumé

Introduction. – Comparer les caractéristiques plantaires entre chaussures d'entraînement et chaussures à pointes chez de jeunes sprinters.

Synthèse des faits. – Onze athlètes ont effectué deux séries de 2 × 60 m en sprint, en chaussures et en pointes, respectivement. La surface de contact était significativement inférieure en pointes au total et sous les orteils ; pression et force étaient significativement supérieures en pointes sous l'avant-pied antéromédial principalement.

Conclusion. – En pointes, des charges supérieures sont appliquées principalement sous les têtes des premier et deuxième métatarsiens. Cela pourrait avoir un intérêt pour éclaircir les mécanismes de blessures comme les métatarsalgies ou les fractures de fatigue de l'avant-pied.

Abstract

Aims. – To compare plantar patterns between training and spikes shoes in young sprinters.

Methods and results. – Eleven athletes performed two trials of 2 × 60 m maximal speed with training and spikes shoes, respectively. Contact area was significantly smaller with spikes in total and under the toes; pressure and force were significantly higher with spikes under the forefoot mainly in medial and lateral.

Conclusions. – Wearing spikes shoes, higher loads are applied mainly under the 1st and the 2nd metatarsal heads. This may have relevance in order to clarify the mechanisms of injuries like metatarsalgia or stress fractures of the forefoot.

Mots clés : Pressions plantaires ; Sprint ; Pointes ; Prévention

Keywords: Plantar pressures; Sprint; Spikes; Injury prevention

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1. Introduction

L'amélioration des équipements de podobarométrie a permis depuis quelques années de multiplier les mesures de répartition des appuis plantaires pendant le geste sportif. De nombreuses études réalisées au football comparent les pressions plantaires pour un même exercice sur pelouse et sur terrain synthétique et montrent des spécificités pour chacune des surfaces. L'un des enseignements majeurs de ce type de travail est de définir les facteurs de risque de blessures pour tenter par la suite de mettre en place une prévention adaptée.

En athlétisme, la surface est souvent la même (la piste) mais ce sont les chaussures utilisées qui peuvent varier : chaussures d'entraînement ou chaussures à pointes.

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Pourtant peu de données existent quant aux différences d'appui entre ces deux types de chaussures ; nous proposons donc de comparer la distribution des charges plantaires entre chaussures et pointes au cours de sprints effectués par de jeunes athlètes d'Aspire, puis de tenter d'isoler les facteurs de risque de blessures inhérents à un type de chaussure.

2. Matériels et méthodes

Onze athlètes (âge : 15,4 ± 1,7 ans ; poids : 52,7 ± 14,1 kg ; taille : 164,2 ± 9,3 cm) étaient volontaires pour participer à cette étude. Dans un ordre randomisé, ils ont effectué deux séries de sprints de 2 × 60 m à vitesse maximale, en chaussures d'entraînement et en chaussures à pointes, respectivement. Le test se déroulait sur une piste d'athlétisme indoor (Mondo, Sportek Surfaces, Ashfield, MA, États-Unis), et l'analyse a porté sur les 13 à 14 foulées des 30 derniers mètres de course (établies par vidéo caméra) ; la performance chronométrique étant mesurée au moyen de cellules électroniques (Brower, Colorado Spring, États-Unis). Les valeurs prises en compte furent les moyennes des deux sprints.

Les mesures de pression plantaire furent effectuées à l'aide d'une semelle sensible à 99 capteurs (X-Pedar, Novel GmbH, Munich, Allemagne) placée dans la chaussure droite. Chaque empreinte plantaire était divisée en neuf régions :

- M1 : partie médiale du talon ;
- M2 : partie latérale du talon ;
- M3 : partie médiale du médiopied ;
- M4 : partie latérale du médiopied
- M5 : tête du premier métatarsien ;
- M6 : têtes des deuxième et troisième métatarsiens ;
- M7 : têtes des quatrième et cinquième métatarsiens ;
- M8 : gros orteil ;
- M9 : orteils.

Les paramètres suivants ont été déterminés pour l'ensemble du pied et pour chacune des neuf régions : surface de contact, surface moyenne de contact, force maximale, force moyenne, pic de pression, pression moyenne maximale et charge relative à savoir l'intégrale de la force (la surface située en dessous de la courbe de force) pour chaque zone du masque divisée par l'intégrale de la force pour l'ensemble de la surface plantaire.

3. Résultats

Pour l'ensemble du pied, la surface de contact était plus réduite avec les pointes qu'avec les chaussures d'entraînement (140,2 ± 26,0 cm^2 vs 148,6 ± 26,3 cm^2, $p = 0{,}01$) alors que le pic de pression était plus important (533,9 vs 421,8 N, $p < 0{,}001$).

Avec les pointes, la surface moyenne de contact était plus faible en M8 (8,8 ± 1,5 cm^2 vs 9,4 ± 1,3 cm^2, $p < 0{,}01$) et en M9 (16,0 ± 1,9 cm^2 vs 16,7 ± 1,9 cm^2, $p = 0{,}01$).

Les niveaux de charge enregistrés au niveau du médiopied et de l'avant-pied étaient supérieurs en chaussures à pointes (force maximale en M4 : +34,5 %, en M5 : +35,8 %, en M6 : +36,4 % et en M7 : +13,4 % ; force moyenne en M5 : +25,9 % et en M6 : +34,4 % ; pression moyenne maximale en M3 : +28,7 %, en M4 : +32,3 %, en M5 : +38 %, en M6 : +37,8 % et en M7 : +14,5 %) tandis qu'elles étaient significativement inférieures sous les orteils (–14,7, –15,1 et –9,6 % en M9 pour la force maximale, la force moyenne et la pression moyenne maximale, respectivement) (Fig. 1). La charge relative était supérieure en chaussures à pointes sous l'avant-pied (M5 : +15,5 %, $p < 0{,}05$ et M6 : +19,8 %, $p < 0{,}001$) par rapport aux chaussures d'entraînement mais inférieure sous les orteils (–10,3 %, $p = 0{,}06$ et –21,5 % $p < 0{,}001$ en M8 et M9, respectivement).

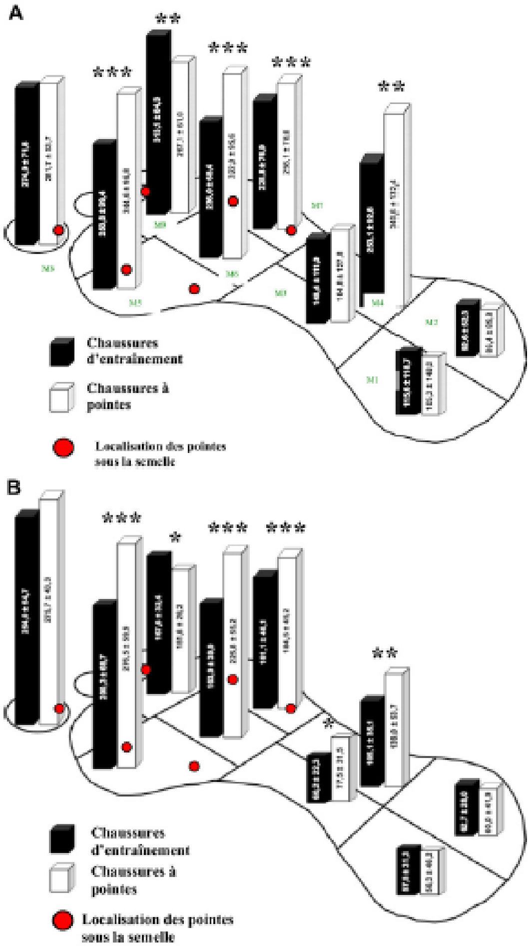

Fig. 1. Comparaison entre chaussures d'entraînement et chaussures à pointes pour neuf régions plantaires. A : force maximale (N) ; B : pression moyenne maximale (kPa).
*$p < 0{,}05$; **$p < 0{,}01$; ***$p < 0{,}001$.

4. Discussion

La course de sprint est caractérisée par une importante phase de propulsion ; les régions plantaires impliquées dans cette phase de poussée sont essentiellement l'avant-pied médial et central et plus ou moins les orteils [1].

Cette étude confirme que le port de chaussures à pointes lors de sprint augmente considérablement les contraintes sous les têtes des premier et deuxième métatarsiens et sous l'arche interne du pied comparativement à des chaussures d'entraînement.

Plusieurs facteurs pourraient être évoqués pour expliquer cette différence et tout d'abord la position des pointes sous la semelle des chaussures ; elles sont en effet situées uniquement sous le tarse antérieur et sous les orteils (Fig. 1). Cette répartition amplifie logiquement les forces et les pressions sous les zones où les pointes « accrochent » la piste.

Par ailleurs, les chaussures à pointes sont plus souples que les chaussures d'entraînement (semelle plus fine et moins rigide notamment). Aussi la torsion physiologique nécessaire entre avant-pied et arrière-pied est davantage permise dans les pointes que dans les chaussures, pendant la phase de contact au sol ; permettant ainsi une meilleure poussée naturelle par l'avant-pied médial et central [3].

Cependant, l'augmentation des contraintes sous les têtes des premier et deuxième métatarsiens n'en constitue pas moins un facteur de risque de blessure important, et l'entraînement est à cet égard beaucoup plus dangereux en pointes qu'en chaussures. Les pathologies de surmenage qui peuvent en découler sont, selon la littérature, les fractures de fatigue des premier et deuxième métatarsiens et les métatarsalgies des premier et deuxième rayons (directement) ainsi que les périostites tibiales ou les aponévrosites plantaires (indirectement) [4].

Enfin, les valeurs de pression et de force enregistrées sous les orteils sont plus faibles en pointes qu'en chaussures. Une précédente étude avait montré que la flexion de l'articulation métatarsophalangienne et donc les pressions exercées sur les phalanges étaient d'autant plus importantes que le niveau du sprinter était élevé [2]. On pourrait donc discuter que la jeunesse et la faible expérience en sprint des sujets testés induit soit une technique de poussée au sol encore perfectible avec notamment une phase finale (impliquant les orteils) incomplète, soit que simplement les chaussures à pointes se prêtent moins à une longue phase de « déroulé » du pied que les chaussures d'entraînement.

5. Conclusion

Cette étude permet de mettre en exergue les risques de surcharge des zones antéromédiales de l'avant-pied et du médio-pied induits par le port de chaussures à pointes ; ces contraintes pouvant conduire à des pathologies de surmenage. Ces données confirment l'expérience de terrain qui conseille de limiter l'utilisation des pointes dans l'entraînement en athlétisme, au risque d'exposer les sportifs à des blessures.

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Short communication

Comparison of plantar pressure distribution in adolescent runners at low vs. high running velocity

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ABSTRACT

This study aimed to compare foot plantar pressure distribution while jogging and running in highly trained adolescent runners. Eleven participants performed two constant-velocity running trials either at jogging (11.2 ± 0.9 km/h) or running (17.8 ± 1.4 km/h) pace on a treadmill. Contact area (CA in cm^2), maximum force (F_{max} in N), peak pressure (PP in kPa), contact time (CT in ms), and relative load (force time integral in each individual region divided by the force time integral for the total plantar foot surface, in %) were measured in nine regions of the right foot using an in-shoe plantar pressure device. Under the whole foot, CA, F_{max} and PP were lower in jogging than in running (−1.2% [$p < 0.05$], −12.3% [$p < 0.001$] and −15.1% [$p < 0.01$] respectively) whereas CT was higher (+20.1%; $p < 0.001$). Interestingly, we found an increase in relative load under the medial and central forefoot regions while jogging (+6.7% and +3.7%, respectively; [$p < 0.05$]), while the relative load under the lesser toes (−8.4%; $p < 0.05$) was reduced. In order to prevent overloading of the metatarsals in adolescent runners, excessive mileage at jogging pace should be avoided.

1. Introduction

Running contributes to maintain health and cardiopulmonary fitness [1]. Nevertheless, numerous overuse injuries have been reported (i.e. at the metatarsals level) when running regularly [2,3], especially in immature adolescent distance runners [4,5]. Nagel et al. explained this phenomenon by the increased peak pressure under the metatarsal bones during running [6]. Kernozek and Zimmer and Ho et al. reported that maximum force and pressure increased under all foot regions with increasing pace [1,7]. Ho et al. also observed increased foot inversion during stance phase (e.g. peak pressure increase at the lateral foot side) when jogging faster, among young non-trained females tested at 1.5, 2.0 and 2.5 m/s on a treadmill with 0% slope [1]. Unfortunately, the differences in the relative load for each region between different running velocities have never been reported. Therefore, the purpose of this study was to compare foot plantar pressure distribution between jogging and running in highly trained adolescents (e.g. around 14 h/week of training). We hypothesised that plantar pressure distribution would be affected by running velocity.

2. Methods

2.1. Participants and experimental protocol

Eleven male adolescent distance runners (age: 16.9 ± 2.0 years, body mass: 54.6 ± 8.6 kg, height: 170.6 ± 10.9 cm, maximal aerobic speed: 18.7 ± 1.5 km/h) performed two constant-velocity running trials either at 60% of their maximal aerobic speed (MAS) (jogging; 11.2 ± 0.9 km/h) or at 95% MAS (running; 17.8 ± 1.4 km/h) on a treadmill (h/p/Cosmos, Nussdorf-Traunstein, Germany) at 1% slope. Prior to participation in the study, six participants were identified as rear-foot strikers and the remaining five as mid/forefoot strikers, using the procedure described by Hasegawa et al. [8]. All participants were healthy during the testing period. Prior to testing, informed consent was obtained from all participants, and the study was conformed to the guidelines of the local Ethical Committee and to the recommendations of the Declaration of Helsinki.

2.2. Plantar pressure distribution measures

Insole plantar pressure distribution was recorded for 30 s after a minute of running at either 60% MAS or at 95% MAS, using the X-Pedar Mobile System (Novel GmbH, Munich, Germany). Before commencement of data collection, the insoles were calibrated according to the manufacturer's guidelines. One insole was placed under the right foot of all participants, wearing the same type of neutral running shoes. The data logger for data storage was in a harness on the back of the participant. Plantar pressures were sampled at 50 Hz. A regional analysis was performed utilising nine separate "masks" or areas of the foot (Groupmask Evaluation, Novel GmbH, Munich, Germany) (Fig. 1). Contact area (CA in cm^2),

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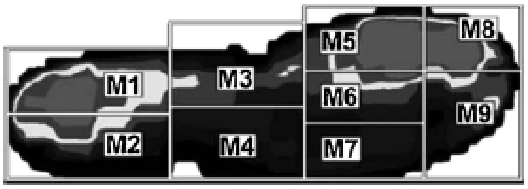

Fig. 1. Regions of interest at the foot were masked to the size of the Pedar insole (Groupmask Evaluation, Novel GmbH, Munich, Germany). The regions consisted of the following: M1 medial heel, M2 lateral heel, M3 medial midfoot, M4 lateral midfoot, M5 medial forefoot, M6 central forefoot, M7 lateral forefoot, M8 hallux and M9 lesser toes.

maximum force (F_{max} in N), peak pressure (PP in kPa), contact time (CT in ms), and relative load (RL(FTI): force time integral [FTI] in each individual region divided by FTI of the total plantar foot surface, in %) were determined for the nine selected regions. In addition, as RL(FTI) does not take into account the size of an area it is applied to, a more meaningful calculation of the relative load (RL(PTI)) was performed while replacing FTI by (FTI/CA) in the above mentioned calculation of RL(FTI), and where PTI means pressure time integral [9].

2.3. Statistical analysis

All data are presented as mean ± SD. A one way repeated measures analysis of variance was used to examine the differences in plantar loading parameters for the whole foot and for each region between jogging and running conditions. When significant main effects were observed, Tukey post hoc analyses were used to identify differences among means. Statistical analysis of the relationships between the foot-strike patterns and the differences in plantar running patterns between running velocities was not possible due to the small subgroups' sample size. The statistical analyses were performed using SigmaStat software (Jandel Corporation, San Rafael, CA). Statistical significance was accepted at $p < 0.05$.

3. Results

RL(FTI) was higher under M5 and M6 (+6.7% and +3.7% respectively, $p < 0.05$) but was lower under M9 (−8.4%; $p < 0.05$) in jogging than in running. The differences in RL were exactly in the same areas for RL calculated from FTI and from PTI (Fig. 2). However, the differences between jogging and running were statistically larger by using the alternative approach: +6.5% ($p < 0.01$) and +3.3% ($p < 0.05$) under M5 and M6 respectively, and −11.0% ($p < 0.01$) under M9. Under the whole foot, CA, F_{max} and PP were lower in jogging than in running (−1.2% [$p < 0.05$], −12.3%

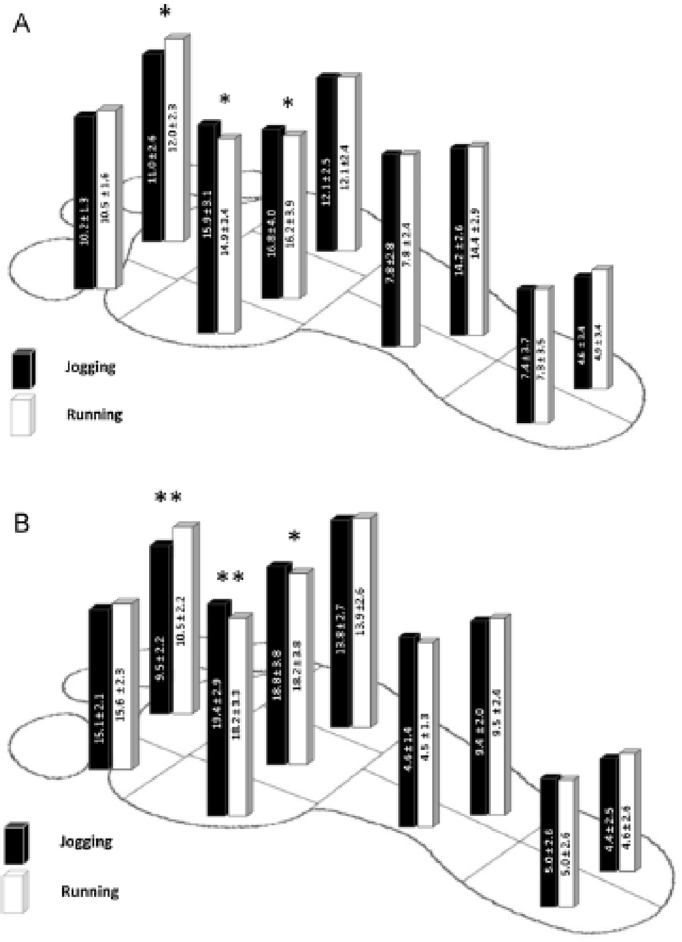

Fig. 2. Mean (±SD) relative load (%) calculated from (A) the force time integral (FTI) and (B) the pressure time integral (PTI) for each foot region during jogging and running. $^{*}p < 0.05$, $^{**}p < 0.01$ for significant differences between jogging and running.

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Table 1
Means (±SD) for contact area (cm^2), maximum force (N), peak pressure (kPa), contact time (ms), relative load calculated from the force time integral (%) for the whole foot and for the medial forefoot, the central forefoot and the lesser toes during jogging and running.

Foot region	Parameter	Jogging	Running	p
Whole foot	Contact area (cm^2)	168.2 ± 4.6	170.2 ± 3.8	<0.05
	Maximum force (N)	1430.8 ± 287.4	1607.3 ± 275.4	<0.001
	Peak pressure (kPa)	284.0 ± 67.5	327.0 ± 72.9	<0.01
	Contact time (ms)	225.8 ± 21.3	180.4 ± 13.1	<0.001
5	RL(FTI) (%)	15.9 ± 3.2	14.9 ± 3.4	<0.05
5	RL(PTI) (%)	19.4 ± 3.3	18.2 ± 3.2	<0.01
6	RL(FTI) (%)	16.8 ± 4.0	16.2 ± 3.9	<0.05
6	RL(PTI) (%)	18.8 ± 3.8	18.2 ± 3.9	<0.05
9	RL(FTI) (%)	11.0 ± 2.7	12.0 ± 2.3	<0.05
9	RL(PTI) (%)	9.5 ± 2.2	10.5 ± 2.2	<0.01

RL(FTI), relative load calculated from the force time integral. "Whole foot" means that each variable changed significantly between jogging and running not only for the whole foot but also for each region of the mask.

[$p < 0.001$] and −15.1% [$p < 0.01$] respectively) whereas CT was higher (+20.1%; $p < 0.001$) (Table 1).

4. Discussion

Regarding the whole foot, CA, F_{max} and PP were lower in jogging than in running whereas CT was higher, which is in line with the well-known biomechanical features [1,7,10]. Interestingly, we found an increase in relative load under the medial and central forefoot regions while jogging, while the relative load under the lesser toes was reduced. These findings expanded those of Ho et al. [1], which focused only on peak pressures and maximum force and showed an increased foot inversion during the stance phase when running at 2.5 m/s compared to 1.5 m/s. Contrary to Melai et al. findings [9], RL(PTI) only confirmed the results provided by RL(FTI) but did not provide any additional information on the cumulative mechanical loading. This study is limited by the fact that it was conducted on a treadmill and not in a "natural running environment". Differences in running mechanics between treadmill and natural running (e.g. different stride patterns and shock absorption modalities) have been described previously [11,12]. In order to prevent overloading of the metatarsals in adolescent runners [4,5], excessive mileage at jogging pace should be avoided. Also some jogging sessions may be implemented on a compliant surface as natural grass, in order to reduce the plantar pressure under the forefoot [13]. Finally, we recommend strengthening exercises of the foot musculature which has been shown to protect the first three metatarsals from overload during sprinting [14].

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Conflict of interest

We affirm that we have no financial affiliation (including research funding) or involvement with any commercial organisation that has a direct financial interest in any matter included in this manuscript.

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Foot/Ankle/Lower Leg Injuries and Maturation in Young Track and Field Athletes

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A substantial number of adolescents are injured each year as a result of participation in sports.[1,2] Adolescents participating in competitive track and field had a high rate of lower extremity injuries: approximately 40% affecting the foot/ankle/lower leg, 30% affecting the knee, and 10% affecting the thigh.[1,3] Difficulty arises when comparing various studies, because differing criteria have been used to define injury severity.[1,4] Time loss has been reported to range from more than five days for 30% of injuries to one week or longer for 50% of adolescents' injuries.[4]

KEY POINTS

- 40% of injuries that occur in track and field affect the foot, ankle, and lower leg.
- The relationship of maturation status to injury is unclear.
- Late maturation athletes sustained more foot, ankle, and lower leg injuries than their peers.
- In track and field, injury prevention strategies should consider maturity status.

Maturation status has been reported to influence injury rate in several sports, but the relationship between maturation and injury incidence probably varies among sports.[5-8] When providing guidance for young athletes, the athletic trainer or therapist should consider the biological maturation stage of the athlete and adjust individual training loads.[9] Anthropometric data have been shown to be good determinants of Peak Height Velocity (PHV), which can provide valuable information when determining an appropriate training volume for adolescents at a given maturation stage.[10] The PHV method requires serial measurements (i.e., chronological age, height, sitting height, and weight) during the years around the occurrence of peak growth velocity. Because standard deviations for age at PHV tend to be about one-half of values reported by longitudinal studies of maturation, this method appears to provide good accuracy for determination of maturation stage.[10,11] The procedure is noninvasive, simple to administer, and inexpensive.

Michaud et al.[5] reported that risk of injury appeared to be more closely associated with biological development (pubertal stage) than chronologic age, body mass index (BMI), height, or weight. Many studies dealing with soccer have explored the relationship between biological age and injuries.[6-8] Backous et al.[8] measured height and grip strength in young soccer players and assumed that tall young males who exhibited a strength deficiency were experiencing "late maturation" (i.e., assumption that they were still in an early maturation stage). They did not determine the maturation stages of their subjects but made the assumption that skeletally mature and weak young males were more susceptible to injury when playing soccer with peers of the same chronologic age. Johnson et al.[6] assessed the skeletal age of

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a similar population and found more injuries among individuals who exhibited early maturation (EM) than those who exhibited normal maturation (NM) or late maturation (LM). Unfortunately, they did not provide sufficient detail about the players' characteristics. Le Gall et al.[7] reported greater injury incidence for EM and NM individuals than those who exhibited LM, but the difference was not statistically significant. Limitations of this study included a possible overestimate of exposure time and lack of information about injury mechanisms. Although a relationship between maturation and injury risk has not been clearly established, EM athletes who participate in a team sport appear to possess elevated injury risk. Maturation level must be considered when working with adolescent athletes, but the possible influence on injury risk has not been investigated in young track and field athletes.

The purposes of this study were to describe the type and severity of foot/ankle/lower leg injuries sustained by young track and field athletes and to investigate the influence of maturation on injury occurrence. Contrary to the reported trend for elevated injury risk among EM athletes who participate in a team sport, we hypothesized that LM athletes would have a higher injury rate than EM athletes, due to a lesser capability to cope with training load.

Procedures and Findings

This study involved prospective collection of injury data over a period of three years for 110 adolescent males who were track and field athletes: sprint/hurdles (n = 25), jumps and combined events (n = 15), distance (n = 24), throws (n = 23), and beginners (n = 23; i.e., first-season athletes not assigned to a specific event). Prior to data collection, all subjects and their parents were provided with information about the study, and informed consent was obtained. A total of 74 injuries were reported among 110 male athletes who were between 13 and 18 years of age (15.7 ± 1.7 yr).

Anthropometric measurements were obtained by an accredited anthropometrist (International Society for the Advancement of Kinanthropometry). Age of PHV was used to define maturation, which was derived from the predictive equation for males developed by Mirwald et al.[10] Age of PHV was subtracted from chronologic age to classify the athletes in three maturation categories: early, normal, or late. EM and LM classifications were made on the basis of estimated PHV age in relation to mean PHV age for the entire cohort (i.e., more than one year older or younger). NM was defined as PHV age within one year of the mean PHV age for the entire cohort. Values for estimated PHV age were ≤ 13.2 for EM (n = 17), between 13.2 and 15.2 for NM (n = 79), and ≥ 15.2 for LM (n = 14).

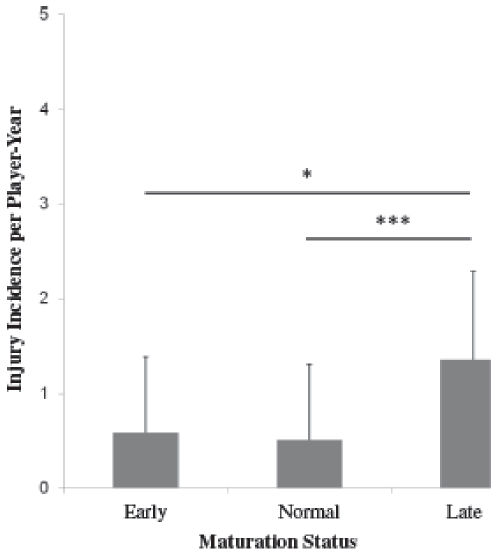
An "injury" was defined as a trauma occurring during track and field training or competition, which required one or more physiotherapy treatments and prevented the athlete from participating in one or more training sessions or competitive events. Injury severity was defined on the basis of time loss: an injury was considered minor if the athlete was out of training/competition for one to three days, moderate if the duration of absence was four to seven days, major if the absence lasted one to three weeks, and severe if the absence was greater than three weeks. Injury categories included the following: (a) foot/ankle/lower leg, (b) pelvis/hip/lumbar, (c) hamstrings/quadriceps, (d) knee, (e) shoulder, and (f) other. Only injuries affecting the foot/ankle/lower leg were analyzed. Absences related to illness or injuries that were unrelated to training were excluded from the analysis.

One-way analysis of variance was used to assess differences in height, sitting height, body mass, skinfold thickness, and injury incidence among the three maturation categories. A Kruskall-Wallis nonparametric test was utilized when a dependent variable failed to demonstrate a normal distribution of values. An alpha level of 0.05 was used for all statistical tests. A significantly higher incidence of foot/ankle/lower leg injuries was found for athletes who were experiencing late maturation than those who were experiencing normal and early maturation (Figure 1). Tables 1-5 present data for year-by year enrollment, maturation categories, anthropometric characteristics, injury incidence, injury distribution among body parts, and injury severity.

Discussion

LM athletes demonstrated a higher incidence of foot/ankle/lower leg injuries than EM athletes, which confirmed our hypothesis. We believe that our findings support the importance of giving consideration to maturation status for the prevention of injuries.[12-13] The period of prepubertal growth is longer for LM athletes than EM and NM athletes. The immature musculoskeletal system of LM males may be less able to cope with repetitive biomechanical stress.[14] Seven

Study 6



* $p < 0.05$ and *** $p < 0.001$ for significant difference between groups

Figure 1 Incidence of foot/ankle/lower leg injuries sustained per year per athlete according to maturity status.

to nine training sessions per week may be excessive for male athletes during a prepubertal "at-risk" maturation stage.

EM individuals progress through puberty slowly, whereas LM individuals progress more rapidly through puberty (i.e., a shorter period of pubertal growth). Because testosterone stimulates bone formation during pubertal growth, prolonged prepubertal growth and a shorter period of pubertal growth duration may be associated with a relatively lesser amount of periosteal bone formation in LM males.[15] Limb length, mass, and moment of inertia increase greatly during growth, but not in a linear manner. The relatively short pubertal growth period of LM athletes may impose sudden demands for modifications in muscle activation patterns to accommodate changing limb dynamics.[16]

There is a paucity of longitudinal data that relate injury incidence to maturation status, and the available research on soccer players has yielded inconclusive findings.[6-8] EM athletes may possess greater risk for certain types of injuries (e.g., tendinopathy, groin injury, and reinjury), but the mechanisms remain unclear. The results of this study of track and field athletes do not support the findings of previous studies of soccer players.[6-8] Because track and field is a noncontact sport, the higher injury rate for LM athletes probably relates to an inadequate adaptation to the physical demands imposed by training and competition.[17] Interpretation of differences in injury rates between different sports should be approached cautiously (e.g., comparison of injury rates for EM soccer players and EM track and field athletes), because the interaction of factors that contribute to injury occurrence in a given circumstance is often complex. Differing research methods also complicate comparison of study findings. The relationship between skeletal age offset from chronologic age and PHV age offset from chronologic age is strong ($r > 0.70$),[11] and both methods appear to classify maturation status in a consistent manner,[10] but the PHV method may not capture the true range of variation in maturation status within a cohort of adolescent athletes.

Our data confirm the predominance of foot/ankle/lower leg injuries among young track and field athletes. In an effort to prevent such injuries, we utilize the following strategies: development of an individualized stretching program for each athlete, use of customized orthotics for correction of lower extremity malalignment, running on soft surfaces, eccentric calf muscle strengthening exercises, and training with supportive running shoes rather than with spikes.

TABLE 1. ATHLETE ENROLLMENT DURING THE 3-YEAR STUDY

SEASON	Athletes Returning from the Previous Season	Athletes Enrolled at the Beginning of the Season	Athletes Leaving at the End of the Season
1		27	11
2	16	24	6
3	34	9	
Total	110 athletes		

Total enrolled = Athletes enrolled at the beginning of each season + athletes returning from the previous seasons.

TABLE 2. ANTHROPOMETRIC CHARACTERISTICS AND INJURY DATA

Groups	Number of Athletes	Height (cm)	Sitting Height (cm)	Body Mass (kg)	Skinfolds (mm)	Injury Number	Injury Incidence Rate
Beginners	23	167.9 ± 10.0	85.5 ± 6.4	52.4 ± 10.5	42.6 ± 6.8	15	0.7
Combined events and jumps	15	178.9 ± 4.6+ + +	92.7 ± 2.7+	69.2 ± 8.8+ + +	48.3 ± 10.6	8	0.5
Distance	24	166.7 ± 10.4†††	84.4 ± 6.3†	49.6 ± 9.7†††	40.1 ± 9.0	23	1.0
Sprint & hurdles	25	172.9 ± 7.1	89.1 ± 4.1	62.0 ± 7.5+,***	42.6 ± 6.6	22	0.9
Throws	23	176.7 ± 6.2+ +,***	94.5 ± 3.2+,*, #	89.1 ± 13.5+ + +,*** ,###,†††	117.2 ± 46.9+ + +,*** ,###,†††	6	0.3

Injury Incidence Rate: Injuries per player-year. Values are mean ± SD. + $p < 0.05$; + + $p < 0.01$; + + + $p < 0.001$ for differences from beginners category. † $p < 0.05$; ††† $p < 0.001$ for differences from combined events & jumps category. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ for differences from distance category. # $p < 0.05$; ### $p < 0.001$ for differences from sprint & hurdles category.

TABLE 3. INJURY TOTAL BY BODY PART

Injury Site	Total	%
Foot/ankle/lower leg	74	37.8
Pelvis/ lumbar/ hip	58	29.6
Hamstrings/ quadriceps	27	13.8
Knee	21	10.7
Shoulder	11	5.6
Others	5	2.6
Total	196	100.0

Quantity of foot/ankle/lower leg injuries compared with whole body injuries' distribution over the three seasons of the study.

TABLE 4. TYPE, SITE, AND SEVERITY OF FOOT/ANKLE/LOWER LEG INJURIES

	Ankle	Foot	Toes	Heel	Lower Leg	Calf	Achilles	Total	%
TI (Severity)	19 (18/1/0/0)	3 (3/0/0/0)	2 (2/0/0/0)	–	2 (2/0/0/0)	1 (1/0/0/0)	6 (6/0/0/0)	33	44.6
Sprain I	7 (0/2/5/0)	3 (0/2/1/0)	—	—	—	—	—	10	13.5
Tendinopathy	2 (0/0/2/0)	1 (0/0/1/0)		—	—	—	5 (0/4/1/0)	8	10.8
DOMS	—	—	—	—	—	1 (1/0/0/0)	—	1	1.4
Spasm	—	—	—	—	1 (1/0/0/0)	11 (4/6/1/0)	—	12	16.2
Contusion	1 (0/0/1/0)	1 (1/0/0/0)	—	—	—	1 (0/1/0/0)	—	3	4.1
Periostitis	—	—	—	1(0/0/1/0)	1 (1/0/0/0)	—	—	2	2.7
Other	—	2 (0/0/1/1)	—	1 (0/0/0/1)	1(0/0/0/1)	1 (0/0/0/1)	—	5	6.8
Total	29	10	2	2	5	15	11	74	100
%	39.2	13.5	2.7	2.7	6.8	20.3	14.9	100	

Trivial injuries (infraclinical injury, with poor objective findings on examination). These injuries represent complaints that required almost no loss of training time. DOMS: Delayed onset muscle soreness. Injury severity for each type and site is displayed as following: minor/moderate/major/severe.

Conclusion

We found a significantly greater foot/ankle/lower leg injury incidence rate for LM athletes, compared to those for EM and NM athletes. LM appears to be a risk factor for injury among young male track and field athletes, which should be considered when developing injury prevention strategies for such athletes.

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Original research

Reliability of a novel procedure to monitor the flexibility of lower limb muscle groups in highly-trained adolescent athletes

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ABSTRACT

Objectives: To evaluate the reliability level of an innovative method using a standardized stretch force to assess the flexibility of lower limb muscle groups in highly-trained adolescent athletes and to examine whether interchanging the examiners affects the reliability of the measures.
Design: Randomized test–retest study.
Setting and participants: In ten athletes, the flexibility of eight lower limb muscle groups was examined on two occasions on both sides and in two phases: a video capture by three distinct operators and an analysis by three distinct analysers. The reliability of the measures was assessed by the coefficient of variation (CV, 90% CI). Between-analysers and between-operators standardized differences (i.e., Cohen's *d*) were calculated.
Results: CV (%, 90% CI) were 8.3% (7.5; 9.3) for quadriceps, 3.3% (3.0; 3.7) for hamstrings, 7.2% (6.5–8.0) for adductors, 5.7% (5.1; 6.3) for gastrocnemius, 4.5% (4.0; 5.0) for soleus, 2.6% (2.3; 2.9) for hip flexors, 9.6% (8.6; 10.8) for hip medial rotators and 12.4% (12.2; 14.0) for hip lateral rotators. There was no substantial (i.e., Cohen's $d < 0.2$) difference in CV between all the possible operators/analysers combinations.
Conclusion: This method has a moderate-to-good reliability level and is examiner-independent. It may be implemented in future injury prevention programs, in order to monitor the flexibility of highly-trained adolescent athletes.

1. Introduction

While there is still no definitive consensus regarding the possible benefit of stretching on athletic performance or post-exercise muscle soreness, stretches are commonly incorporated into physical training programs (Ben & Harvey, 2010; Decoster, Cleland, Altieri, & Russell, 2007; Shrier, 2004). For instance, the development and maintenance of optimal flexibility (i.e., the necessary level of movement freedom requested for engaging a part or parts of the body in a wide range of purposeful movements) has become very popular in the past years as a mean of injury prevention (Alter, 2004). The monitoring of flexibility imbalances between agonists and antagonists muscles, or that of dominant and non-dominant sides is also regularly implemented in athletes (Corkery et al., 2007). The accuracy and the reliability of flexibility measures is therefore of primary interest for clinicians.

Today, there is a large body of literature on flexibility assessment, tightness measurement or muscle length evaluation (Alter, 2004; Kawakami, Kanehisha, & Fukunaga, 2008; Witvrouw, Danneels, Asselman, D'have, & Cambier, 2003). To assess muscle groups flexibility, several methods, using different devices, have been proposed (Ben & Harvey, 2010; Blackburn, Padua, Riemann, & Guskiewicz, 2004; Chillon et al., 2010; Folpp, Deall, Harvey, & Gwinn, 2006; Fredriksen, Dagfinrud, Jacobsen, & Maehlum, 1997; Law et al., 2009; Magnusson et al., 1997). For example, the range of motion of the joint of interest can be measured using (manual or digital) goniometers/inclinometers or a (video) camera coupled with a motion analysis software (Berryman Reese, 2002; Blackburn et al., 2004; Chillon et al., 2010). The movement can be generated either by an operator (manually or mechanically-aided) or actively by the patient himself (Folpp et al., 2006). However, the endpoint measurement is usually subjectively defined by the patient's tolerance to stretch (Law et al., 2009), which limits the accuracy of the method. Only few studies have measured the endpoint angle with the application of a standardized force (Fredriksen et al., 1997) or torque (Law et al., 2009). While eliminating any possible subjective factors, these latter procedures were demonstrated to be

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more accurate than the method involving the patients' feedback (Ben & Harvey, 2010).

In addition to accuracy, the reliability of any physiological measurement (i.e., degree of change in a particular measure when repeated on different occasions in similar conditions, as evidenced by the coefficient of variation (CV) of a measurement) is of great importance for practitioners and researchers to avoid biased interpretation when assessing changes in a marker (Hopkins & Hewson, 2001; Hopkins, Schabort, & Hawley, 2001). Half of a CV, for example, is thought to represent a minimal threshold needed to assess a meaningful difference (between-group comparisons) or change (training or rehabilitation studies), or the so-called "smallest worthwhile difference/change" (Hopkins, Hawley, & Burke, 1999). Practically, regarding flexibility assessment, knowledge of the reliability level of a procedure can allow the person in charge of the implementation of the injury prevention program to target the muscle groups that need to be stretched in priority.

Given the increasing number of adolescents involved in high level sports and the high training loads these athletes sustain, monitoring flexibility has received growing interest in the last decade. Nevertheless, to the best of our knowledge, the reliability of the methods to measure flexibility in elite adolescent athletes has not been addressed yet. Therefore the aim of this study was to evaluate the reliability of an innovative digital video analysis method to assess the flexibility of lower limb muscle groups in highly-trained adolescent athletes, i.e., the Angle at Force Standardized Endpoint (AFSE). This novel procedure is an extension of a previous method using standardized stretch force on hamstrings to several other lower limbs muscle groups (Fredriksen et al., 1997). Here, the endpoint is objectively measured (e.g., non stretch tolerance-related) and offers within- (right vs. left side of an athlete) (Law et al., 2009) and between-athletes standardization. In addition to the evaluation of the overall reliability of the procedure, we also examined whether changing the operators and/or the video analysers was likely to affect the reliability of the measures.

2. Methods

2.1. Subjects

Ten adolescent male athletes from an elite sport academy (i.e., four soccer players, three track & field athletes, one rower, one table tennis player and one taekwondo player), training around 15 h wk^{-1}, took part in this study. Mean (±SD) age, body mass, height and year from peak height velocity (PHV) (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002) were 15.3 ± 1.6 years, 65.4 ± 26.2 kg, 171.7 ± 8.8 cm and +1.5 ± 1.5 respectively. All participants were healthy and pain-free during the testing period. Participants had no history of musculoskeletal dysfunction or injuries of the lower limbs in the two months preceding testing. Prior to testing, informed consent was sought and obtained from all participants and their parents, and the study was approved by the local research ethics committee, and conformed to the recommendations of the Declaration of Helsinki. The sample size used in the present study was consistent with that used in previous reliability studies in the field (Fredriksen et al., 1997; Nussbaumer et al., 2010).

2.2. Study overview

On two occasions (3 days apart), the flexibility of the following muscle groups was tested on both sides in each athlete (Fig. 1): Adductors, hip flexors, hip medial rotators, hip lateral rotators, quadriceps, hamstrings, gastrocnemius and soleus. The first step consisted of the video capture of the lower limb in the appropriate position. Secondly, the video clips were computer-analysed to measure the angle(s) of interest (Fig. 1). Investigators who were either manipulating the patients, or analysing the video, were randomly recruited among the physiotherapists of the academy.

The 'Angle at Force Standardized Endpoint' procedure. The same procedure was repeated for each muscle group. In our study, the measurement endpoint was reflected by the angle of the joint of interest with the application of a standardized force on the distal part of the segment. The force was applied just proximal to the malleolus level for each tested muscle groups, except for the hip flexors and calf muscles. The force was applied on the anterior side of the thigh just above the patella for the hip flexors and on the heads of metatarsals at the plantar side of the foot for the gastrocnemius and soleus muscles. A specific force was defined for each muscle group using published data when available (Fredriksen et al., 1997), or empirically, i.e., using the largest force that all athletes of the academy were likely to tolerate (Ben & Harvey, 2010; Folpp et al., 2006). A hand-held dynamometer (dynamometer) (Compact force gauge, Mecmesin, Slinfold, United Kingdom) with a scale marked in 0.01-N increments was used to apply the standardized force. Since a difference in force less than 0.1-N is unlikely quantifiable, the measures were rounded at the nearest 0.1-N (Ward, Warwick, & Buccella, 2006), as shown on Fig. 2. The dynamometer was calibrated each day before each test.

Video capture of the flexibility angle measurement. As shown in Fig. 2, one pair of operators (operators) performed the video capture of the angle of interest. The first operator mobilized the lower limb using the dynamometer in order to reach the standardized stretch force. Simultaneously, the second operator recorded the movement with a digital video camera (Digital video camera recorder, DCR-SR220E, Sony corporation, Tokyo, Japan) positioned orthogonally in front of the joint rotational axis. In order to minimise parallax error, the "camera-subject" distance was defined as the furthest position allowing the largest body region representation, with the camera set at the greatest zoom value. As all the tests took place in the same laboratory with the bench located exactly at the same place, we assume that the distance between the camera and the joint was very similar for the same test (i.e., muscle group) in all subjects. As soon as the requested force (displayed on the dynamometer screen) was reached and stabilized, the first operator announced "ok" to the video recorder, who stopped the recording. Using the above-mentioned procedure, the eight muscle groups were tested as follows.

The adductors flexibility measure was performed with the athlete supine. A horizontal white line was drawn to set the longitudinal axis of the bench. The body was aligned with the white line, one leg hangs off the side of the table, and the lower limb to be tested was passively abducted with the knee in a neutral position. The dynamometer was used to further abduct the lower limb to be examined with a force of 39.2 N. The adductors measure was the angle formed between the body line and the abducted lower limb (Fig. 2.A).

The hip flexors measure was performed with the athlete supine. The pelvis was aligned with the end of the table, one lower limb was maintained by the operator in maximal flexed position towards the abdomen, and the lower limb to be tested was extended in neutral rotation. The dynamometer was used to further extend the lower limb to be examined with a force of 98.1 N. The hip flexors measure was the angle formed between the body and the extended lower limb (Fig. 2.B).

The hip medial rotators measure was performed with the athlete supine. The body was aligned with the white line, the knee and the hip were flexed to 90° and stabilized, and the lower limb to be tested was passively externally rotated at the hip. The dynamometer was then used to further externally rotate the lower limb to be examined using a force of 49.1 N. The hip medial rotators measure was the angle formed between the body line and the externally rotated lower limb (Fig. 2.C).

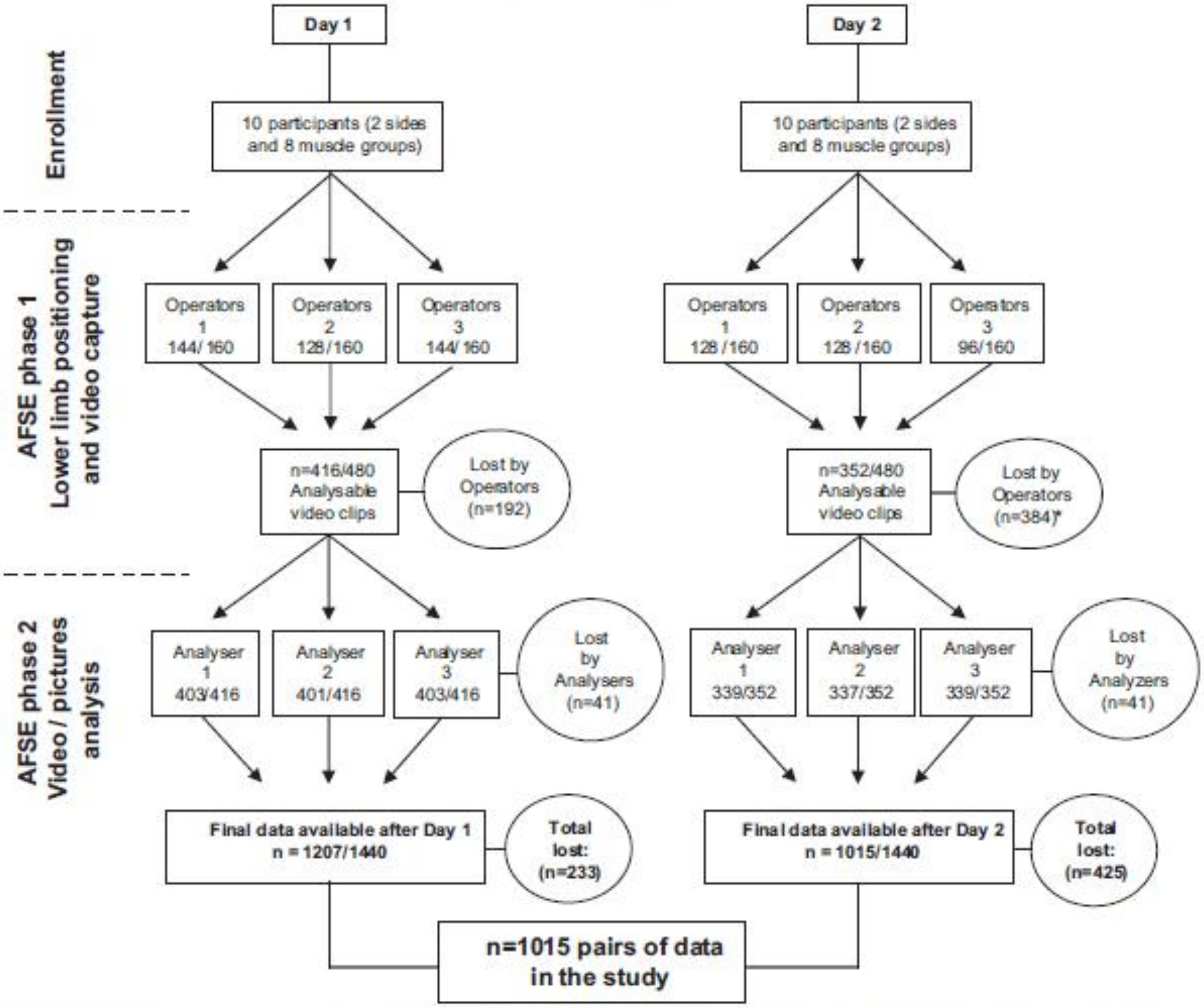

Fig. 1. Flow of participants through each stage of the study. *, Including the 192 clips removed at Day 2 due to the absence of their "twin-clips" at Day 1. Note: AFSE, Angle at Force Standardized Endpoint.

Fig. 2. Visual representation of the video capture and angle measurement for each muscle group. A, Adductors; B, Hip Flexors; C, Hip Medial Rotators; D, Hip Lateral Rotators; E, Quadriceps; F, Hamstring; G, Gastrocnemius; H, Soleus.

The hip lateral rotators measure was performed with the athlete supine. The body was aligned with the white line, the knee and the hip were flexed to 90° and stabilized, and the lower limb to be tested was passively internally rotated at the hip. The dynamometer was then used to further internally rotate the lower limb to be examined using a force of 49.1 N. The hip lateral rotators measure was the angle formed between the body line and the internally rotated lower limb (Fig. 2.D).

The quadriceps measure was performed with the athlete supine. The mid-thigh was aligned with the end of the table, one lower limb was maintained by the operator in maximal flexed position towards the abdomen and the lower limb to be tested hangs off the end of the bench in neutral rotation. The dynamometer was used to passively flex the knee to be examined with a force of 78.5 N. The quadriceps measure was the knee flexion angle (Fig. 2.E).

The hamstring measure was performed with the athlete supine. The lumbar spine was kept flat on the bench with one lower limb extended, with the other hip flexed to 90°. Keeping the hip flexed at 90°, the dynamometer was used to further extend the knee to be examined with a force of 68.7 N. The hamstring measure was the angle formed by the extended knee (Fig. 2.F). This position of the subject during the stretch manoeuvre placed tension primarily on the muscle-tendon unit without involvement of posterior capsular constraints about the knee (Magnusson et al., 1997). It is however worth mentioning that this measure does not take into account the potential effect of the gravity on the tested leg. A recent study (Guex, Fourchet, Loepelt & Millet, 2011) reported significant differences in knee angles between the aforementioned method and two alternative measures taking into account the lower leg weight.

The gastrocnemius measure was performed with the athlete prone and the knees extended. The operator manually verified a subtalar neutral position and the dynamometer was used to passively dorsiflex the ankle to be examined with a force of 147.2 N. The gastrocnemius measure was the angle formed by the dorsiflexed ankle (Fig. 2.G).

The soleus measure was performed with the athlete prone. The leg to be tested has the knee flexed to 90°. The operator manually verified a subtalar neutral position and the dynamometer was used to passively dorsiflex the ankle to be examined with a force of 147.2 N. The soleus measure was the angle formed by the dorsiflexed ankle (Fig. 2.H).

2.3. *Digital video analysis*

Following the angle measures, different groups of physiotherapists (i.e., analysers), used a digital motion analysis software (Dartfish Software, TeamPro Classroom 5.5, Fribourg, Switzerland) to measure the angle of interest. The final angles for each muscle group of each participant were expressed to the nearest 0.1°. Measurements were taken according to identifiable anatomic landmarks, avoiding the estimation of each exact joint rotational axis. The ability to zoom in on the electronic image made identification of anatomic landmarks very easy.

2.4. *Statistical analysis*

The distribution of each variable was examined using the Shapiro–Wilk normality tests and homogeneity of variance was verified with a Levene test. Data are presented as either means with 90% confidence limits (90% CL) (Hopkin, 2009). The reliability of the overall AFSE method was first assessed while analysing the standardized differences (Cohen's *d*) between the angles measured during the two testing sessions. If Cohen's $d < 0.2$ and the 90% confidence interval included zero, we considered that there was no substantial between-day difference. The spreadsheet of Hopkins (2010) was then used to determine the intraclass correlation coefficient (ICC) and the typical error of measurement (TE, s or cm), expressed as a coefficient of variation (CV, %). While a Bland & Altman test is often used in reliability studies (Nussbaumer et al., 2010; Peeler & Anderson, 2008), it was not used in the present study given its limitations to examine within-subjects variations (Hopkins, 2000; Hopkins, Marshall, Batterham, & Hanin, 2009). Additionally, it is important to acknowledge that having the best reliability does not mean a measure is the most "useful" at monitoring something valuable, as a number of physiological measures have high reliability but may not be sensitive measurement tools (Hopkins, 2000). Therefore, CV values were not interpreted as good, moderate or poor as regularly proposed. Possible reliability differences between operators, analysers and the different operators/analysers combinations were assessed by comparing the average of the 8 coefficients of variation (see below) obtained by each operators, analysers and operators/analysers combinations for each of the 8 muscle groups. The magnitude of difference between the two consecutive testing sessions or between the CV obtained for the different analysers, operators and operators/analysers combinations was expressed as standardized mean differences (Cohen's *d*). Criteria used to interpret the magnitude of the Cohen's *d* were: <0.2 trivial, 0.2–0.5 small, 0.5–0.8 moderate, >0.8 large (Hopkins & Hewson, 2001). Additionally, the chances that the angles or CV values were *greater* (i.e., greater than the smallest practically important effect, or the smallest worthwhile change (SWC) [0.2 multiplied by the between-subject standard deviation, based on Cohen's *d* principle]), *similar or smaller* than the other day (angles measures) or the other analysers, operators and operators/analysers combinations (between-staff reliability comparisons) were calculated (Cohen, 1988). Quantitative chances of substantial differences were assessed qualitatively as follows: <1%, *almost certainly not*; 1–5%, *very unlikely*; 5–25%, *unlikely*; 25–75%, *possible*; 75–95%, *likely*; 95–99, *very likely*; >99%, *almost certain*. If the chance of having *greater* or *lower* values were both >5%, the true difference was assessed as *unclear* (Hopkins et al., 2009).

3. Results

Ideally, 2880 angles could be analysed, but 425 pairs of data were lost between day 1 and day 2 (e.g., poor quality of some video clips or missing files as when operators did not perform the test for

Table 1
Measures of reliability for each lower limb muscle group.

n	Hip flexors	Hamstring	Soleus	Gastrocnemius	Adductors	Quadriceps	Hip medial rotators	Hip lateral rotators
	128	128	125	128	128	124	126	128
Endpoint angle (°)	157 (±6)	160 (±11)	59 (±10)	74 (±7)	53 (±9)	48 (±11)	53 (±15)	45 (±14)
CV (90% CL)	2.6 (2.3; 2.9)	3.3 (3.0; 3.7)	4.5 (4.0; 5.0)	5.7 (5.1; 6.3)	7.2 (6.5; 8.0)	8.3 (7.5; 9.3)	9.6 (8.6; 10.8)	12.4 (12.2; 14.0)
Difference (Cohen's d) (90% CL)	0.01 (−0.2; 0.2)	−0.06 (−0.3; 0.1)	0.01 (−0.2; 0.2)	0.10 (−0.1; 0.3)	0.05 (−0.2; 0.3)	−0.05 (−0.3; 0.2)	−0.04 (−0.2; 0.2)	−0.13 (−0.3; 0.1)
ICC (90% CL)	0.51 (0.39; 0.61)	0.80 (0.74; 0.85)	0.93 (0.90; 0.95)	0.66 (0.57; 0.73)	0.85 (0.81; 0.89)	0.86 (0.82; 0.89)	0.92 (0.89; 0.94)	0.91 (0.88; 0.93)

Mean (±SD) endpoint angle, typical error of measurement expressed as a coefficient of variation (CV, %; 90% CL), standardized between-day differences (Cohen's *d*; 90% CL) and intraclass correlation coefficient (ICC) for each lower limb muscle group.

one of the eight muscle groups). The entire flow-chart of participants including drop outs is represented in Fig. 1

3.1. *Measure of reliability for each lower limb muscle group*

Depending on the muscle group considered, we observed CV values ranging from 2.6 to 12.4% (Table 1 and Fig. 3). Table 2 presents magnitude-based differences in CV between the different muscle groups: the lower CV was observed for hip flexors, while the worse (i.e., the greater value) was noted for hip lateral rotators (Fig. 3). Between-muscle groups comparisons were substantial for all paired comparisons (all Cohen's *d* rated as large and differences at least as very likely). The associated ICC values are presented in Table 1.

3.2. *Impact of operators and/or analysers on the reliability of measurements*

Fig. 4 shows that there was no substantial difference in CV, neither between the operators, nor between-analysers (all Cohen's *d* rated as trivial and differences as unclear). As shown in Table 3, there was also no substantial difference between all the possible operators/analysers combinations (all Cohen's *d* rated as trivial and differences as unclear).

4. Discussion

The purpose of this study was to evaluate the reliability level of an innovative method to assess the flexibility of lower limbs muscle groups in highly-trained adolescent athletes, i.e., the Angle at Force Standardized Endpoint (APSE). The second aim of the study was to examine whether interchanging the operators and/or the video analysers was likely to affect the reliability of the measures. The results revealed that the coefficient of variation for the between-muscle groups' comparisons ranged from 2.6 to 12.4%, depending on the muscle group considered and there was no substantial difference between all the possible operators/analysers combinations.

4.1. *Reliability assessment*

Most previous reliability studies used the intraclass correlation coefficient (ICC) as a measure of reliability (Berryman Reese, 2002; Bolhin, Sandstrom, Angstrom, & Lindstrom, 2005).

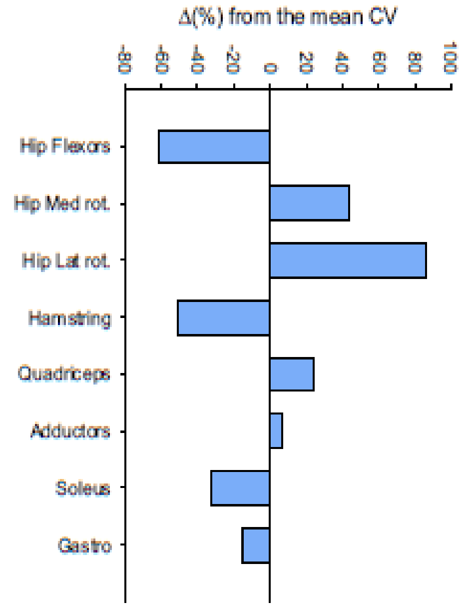

Fig. 3. Measures of reliability for each lower limb muscle group (i.e., coefficient of variation, CV) expressed as a difference (Δ, %) from the mean CV for all muscle groups. Abbreviations: Hip Med rot, Hip medial rotators; Hip Lat rot, Hip lateral rotators; Gastro, Gastrocnemius.

Table 2
Magnitude-based inferences for mean difference in CV between the different muscle groups.

	Gastro	Hamstring	Hip flexors	Hip lateral rotators	Hip medial rotators	Quadriceps	Soleus
Adductors	+1.3 (0.3; 2.3) 97/2/1	+4.6 (3.7; 5.6) 100/0/0	+5.7 (4.7; 6.7) 100/0/0	−1.7 (−2.7; −0.8) 0/1/99	−1.7 (−2.6; −0.7) 0/1/99	−1.1 (−2.1; −0.2) 2/4/94	+2.8 (1.8; 3.8) 100/0/0
Gastrocnemius	–	+2.5 (1.6; 3.5) 100/0/0	+3.7 (2.7; 4.7) 100/0/0	−2.5 (−3.5; −1.5) 0/0/100	−2.7 (−3.7; −1.7) 0/0/100	−2.3 (−3.3; −1.3) 0/0/100	+1.1 (0.1; 2.0) 93/5/2
Hamstring	–	–	+1.6 (0.6; 2.6) 99/1/0	−4.4 (−5.4; −3.4) 0/0/100	−6.2 (−7.2; −5.2) 0/0/100	−6.5 (−7.4; −5.5) 0/0/100	−1.8 (−2.8; −0.8) 0/1/99
Hip Flexors	–	–	–	−5.3 (−6.2; −4.3) 0/0/100	−7.1 (−8.1; −6.2) 0/0/100	−7.3 (−8.3; −6.4) 0/0/100	−3.1 (−4.1; −2.2) 0/0/100
Hip Lateral Rotators	–	–	–	–	+0.7 (−0.3; 1.7) 81/13/7	+1.1 (0.2; 2.1) 94/4/2	+3.4 (2.4; 4.4) 100/0/0
Hip Medial Rotators	–	–	–	–	–	+0.7 (−0.2; 1.7) 84/11/5	+4.4 (3.4; 5.4) 100/0/0
Quadriceps	–	–	–	–	–	–	+4.3 (3.3; 5.3) 100/0/0

Values represent mean standardized difference (Cohen's *d*; 90% CL) and percentage of chance of having greater/similar/lower CV value for the muscle group in the left column compared with the one on the heading row.

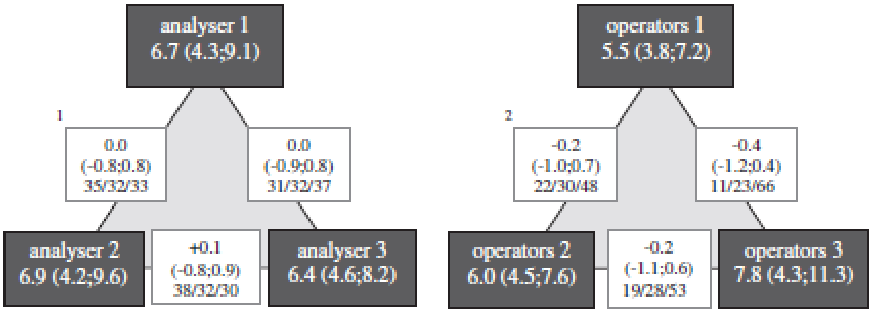

Fig. 4. Measures of reliability for each analyser or operators expressed as a coefficient of variation (CV, %; 90% CL) and impact of analysers/operators combinations. [1]Mean standardized difference (Cohen's *d*; 90% CL) and percentage of chance of having greater/similar/lower CV value for a given analyser compared with the others on its right or below (left panel). [2]Mean standardized difference (Cohen's *d*; 90% CL) and percentage of chance of having greater/similar/lower CV value or for a given operators group compared with the others on its right or below (right panel).

Nevertheless, the ICC is sample size dependent and largely affected by the heterogeneity of the between-subject measures (Weir, 2005). Moreover ICC does not provide an index of the expected trial-to-trial noise in the data, but rather reflects the ability of a test to differentiate between individuals (i.e., relative reliability, (Weir, 2005)). Since in the present study, the main objective was to examine the reliability of intra-subjects measures, ICC values were not relevant. The ICC obtained with AFSE are therefore provided for the reader's information in Table 1, but will not be discussed in the following paragraphs. Hopkins (2000) therefore proposed to use the typical error of measurement as the most appropriate measure of absolute reliability in the applied field setting. Typical error of measurement represents the noise occurring from trial-to-trial, which might confound the assessment of real changes in repeated measures (i.e., when monitoring changes in athletes).

4.2. Reliability of measurement for each lower limb muscle group

When angle measures were repeated over different days with AFSE, we observed CV values ranging from 2.6 to 12.4%. While there were substantial differences in reliability between the different muscle groups considered (Table 1 and Fig. 3), most of the CV values were within the ranges previously reported in the literature for similar muscle groups but using different methods. For example, in the present study, the CV for hamstring was 3.3%, which was consistent with the data of Fredriksen et al. (1997). Involving only 2 operators and 2 subjects, these workers reported CV ranging from 0.8% to 3.2% (Fredriksen et al., 1997). In another experiment, reliability of an isokinetic-assisted hamstrings stretching protocol yielded a CV of 5.8–6.5% (Magnusson et al., 1997). When Peeler and Anderson (2008) recently explored the flexibility of the rectus femoris with a modified Thomas test, they reported a CV value of 13%. In our study, the CV for the quadriceps was 8.3%. More recently, the reliability of several hip ranges of motion measures was assessed with an electromagnetic tracking system (Nussbaumer et al., 2010). We reported similar CV values as these authors (i.e., 7.2% for abduction and 9.6% for medial rotation in our study vs. 5.6% and 10.2%, respectively in their study).

As mentioned earlier, it is worth noting that the reliability of the measures was muscle group-dependent: the CV's for the hip rotators were 9.6% and 12.4%, while that for the hip flexors was only 2.6%. We postulate that these differences might be related to variability in standardisation for some measures. With regards to hip rotators measures, both techniques (hip at 0° or hip at 90° in flexion as we did) can be considered as equivalent in terms of reliability (Berryman Reese, 2002). This question remains however controversial, as Benell et al. (1999) or Van Dillen (2008) suggested that positioning the hip at 0° could be associated with lower CV values (due to the better stability of the thigh positioned on the bench). Such alterations could be considered in future research with AFSE. Finally, we agree that the number of athletes ($n = 10$) tested here to assess the reliability of the method could be considered as small. However, when taking into account the number of pairwise muscle comparisons, the sample size is in fact fairly large ($n = 1015$). Additionally, the fact that we found an already acceptable reliability levels suggests that increasing the sample size would not have had much greater effect on the results.

4.3. Impact of operators and/or analysers on the reliability of measurements

Our results indicated that there were no substantial differences between all the possible operators/analysers combinations (Table 3 and Fig. 4). To our knowledge, this is the first time that the potential effect of various operators/analysers combinations on flexibility measures is reported. The possibility to interchange the operators without affecting the reliability of the measures show that the AFSE method can be successfully implemented and used by any skilled physiotherapist in a team. These findings reinforce the clinical potential of this original method.

4.4. Clinical implication of AFSE

The measurements described in this paper can be easily and efficiently performed in a clinical setting. The implementation of an

Table 3
Magnitude-based inferences for mean difference in reliability between the different analysers and operators.

	Operators 1	Operators 2	Operators 1
Analyser 1	+0.3 (−0.6; 1.1) 57/27/16	+0.1 (−0.7; 0.9) 42/31/27	−0.1 (−1.0; 0.7) 24/31/45
Analyser 2	+0.3 (−0.5; 1.1) 57/27/16	+0.1 (−0.7; 0.9) 42/31/27	−0.2 (−1.0; 0.7) 23/30/47
Analyser 3	−0.2 (−1.0; 0.7) 22/30/48	+0.1 (−0.7; 0.9) 45/31/24	+0.2 (−0.6; 1.1) 54/28/18

Values represent mean standardized difference (Cohen's *d*; 90% CL) and percentage of chance of having greater/similar/lower CV value for a given analyser in the left column compared with the operators on the heading row.

objective endpoint (i.e., non stretch tolerance-related) offers within-athletes standardisation (right vs. left side of an athlete). This has a useful clinical implication for monitoring the flexibility of highly-trained adolescent athletes along the season or in targeting the optimal flexibility level (e.g., contralateral flexibility level or previous flexibility level) that an athlete must recover after an injury and before resuming full sport participation (Alter, 2004).

In addition, the use of the typical error (i.e., CV) combined with the individual flexibility measure reported for each muscle group may allow the person in charge of the stretching program to decide if there is any difference in flexibility between right and left sides for the same muscle group. Practically, AFSE may help the clinician to target more accurately the muscle groups requiring to be stretched in priority. Furthermore, as the AFSE method presents a comparable level of reliability with other aforementioned methods it has an advantage in its ease of use: the operators need only a bench, a dynamometer, a video camera and a video motion analysis software. Second, the method is not time-consuming, only 15 min in total per athlete are needed to assess the flexibility of the eight muscle groups on both sides. The operators need approximately 6 min to video capture the 16 angles, while the video analysis and the angles measures are completed in about 8–10 min.

5. Conclusions

Our study showed no substantial day-to-day differences in flexibility measures for eight lower limb muscle groups. Additionally, there was no substantial difference between all the possible operators/analysers combinations. Therefore, this method can be used to monitor the flexibility of highly-trained adolescent athletes throughout the competitive season or during the rehabilitation phase following injury. It may also be of interest to implement this method in the injury prevention programs designed for this population.

Conflict of interest

None declared.

Ethical approval

Ethics approval through our institutional review board.

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Study 7

Journal of Sport Rehabilitation

Passive Knee Extension Test to Measure Hamstring Tightness: Influence of Gravity Correction

Journal:	*Journal of Sport Rehabilitation*
Manuscript ID:	JSR-2010-0091.R2
Manuscript Type:	Article
Keywords:	hamstring, flexibility, tightness, muscle, athlete, gravity

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ABSTRACT

Context: Passive knee extension test has been shown to be a reliable method to assess the hamstring tightness. However, this method does not take into account the potential effect of the gravity on the tested leg. **Objective:** To compare original passive knee extension test with two adapted methods including the gravity effect on the lower leg. **Design:** Repeated measures. **Setting:** Laboratory. **Participants:** 20 young track and field athletes (16.6±1.6 yr; 177.6±9.2 cm; 75.9±24.8 kg) participated to the study. **Intervention:** Each subject was tested in a randomized order with three different methods: In the original one (M1), passive knee angle was measured with a standard force of 68.7 N (7 kg) applied proximal to the lateral malleolus. Second (M2) and third (M3) methods took into account the relative lower leg weight (measured respectively by hand-held dynamometer and anthropometrical table) to individualize the applied force to assess passive knee angle. **Main Outcome Measures:** Passive knee angles measured with video analysis software. **Results:** No difference in mean individualized applied force was found between M2 and M3. So we assessed passive knee angle only with M2. The mean knee angle was different between M1 and M2 (68.8±12.4 vs. 73.1±10.6, $P<0.001$). Knee angles in M1 and M2 were correlated ($r=0.93$, $P<0.001$). **Conclusions:** Differences in knee angle were found between the original passive knee extension test and a method with gravity correction. M2 is an improved version of the original method (M1) since it minimizes the effect of gravity. Therefore, we recommend using it rather than M1.

INTRODUCTION

Controversial relationships between hamstrings tightness and injury prevalence are reported in the literature.[1,2] Nevertheless, hamstrings flexibility remains one of the most common assessments performed in sports therapy. Several methods have been proposed to evaluate hamstring flexibility including: sit and reach test,[3] different modifications of the original sit and reach test,[4] active knee extension test[5] and finally passive knee extension test.[6,7] This later test is designed to minimize the associated pelvic motion; to have an objective fixed end-point; and finally to be convenient and quickly performed. The subject is supine on an examination table and the tested leg is positioned in 120°[6] or in 90°[7] of hip flexion (0° = hip in straight position). Then the knee is passively extended by applying a standardized force of 7 kg for the women and 8 kg for the men with a dynamometer located just proximal to the lateral malleolus.[6] When stabilized, the knee angle is measured with a goniometer.

This method has been shown to be reliable. In fact, no difference between the test-retest measurements (*r*=0.98) was found.[6,7] However, one may note that this method does not take into account the potential effect of the gravity on the tested leg. Indeed, the closer to the vertical, the lower the relative weight of the lower leg. As it was already shown in isokinetic testing, where the relative contribution of gravity to recorded torque values becomes increasingly larger as the active torque generation decreases,[8] it is important to correct values of passive knee extension test biased by gravitational effects in order to obtain a more accurate assessment of hamstring tightness. Therefore, the purpose of the present study was to compare an adapted method including the gravity effect on the complex "lower leg-foot" with the original passive knee extension test.

METHODS

Participants

The subjects were 20 young male track and field athletes (16.6±1.6 yr; 177.6±9.2 cm; 75.9±24.8 kg) training in a national training centre twice a day under the supervision of a coach in addition to their school time. Prior to data collection, all subjects were required to read and sign an informed consent approved by the local Institutional Review Board.

Experimental design

Each subject was tested in a randomized order with the different passive knee extension tests. Between each test, the subjects rested seated for 10 minutes.

Passive knee extension test (Method 1; M1)

Subjects were placed in the reference position: supine, the lumbar spine kept flat on the table with the controlateral leg extended and the ipsilateral hip and knee flexed to 90° (Figure 1.A). The hip was maintained in a neutral rotation position. Hamstrings muscle tightness was measured with standard protocols: a force of 68.7 N (=7 kg) was applied proximal to the lateral malleolus by the examiner using a hand-held dynamometer (Compact force gauge, Mecmesin, Slinfold, UK) to determine the passive knee angle (Figure 1.B). 0° = knee angle in the reference position and 90° = extended knee. The measurement of the angle was done with video analysis software (Dartfish Software, TeamPro, Fribourg, Switzerland).

The passive knee angle is easy to measure in adolescents since it requires them only to remain passive and relaxed. All measurements were video recorded and analyzed by the same investigator, with a good intra-tester reliability (Intra-class Coefficient [ICC (1,1)] = 0.80)

Passive knee extension test with measured lower leg weight (Method 2; M2)

Firstly, in the reference position (Figure 1.A), the hand-held dynamometer was applied on the lower leg (proximal to the lateral malleolus) to determine the weight of the lower leg at this point (WP) [N]. After that, we assessed the hamstring tightness on the same way as M1 (with the 68.7 N force) to find passive knee angle (α). To determine the applied force (F) to be added to the 68.7 N, we multiplied the cosine of alpha by the weight of the lower leg:

$$F = \text{Cos}\,\alpha \cdot WP$$

Finally we evaluated the passive knee angle with the new applied force (68.7 + F). The video analysis software was used to determine the angle for M2 (Figure 1.C).

Passive knee extension test with lower leg weight determined from anthropometrical table (Method 3; M3)

The subjects were weighted [N] and measured [m] (Holtain Limited, Crosswell, Crymych, UK). Then, the weight (W = 6.1% of body weight), length (L = 28.5% of body size) and center of mass location (from the knee: 60.6% of the length of the complex “lower leg-foot”) of the complex “lower leg-foot” were determined from the anthropometrical table.[9] To determine the lower leg weight at the dynamometer pushing place (WP_2) (proximal to the lateral malleolus) [N], we used the following formula:

$$WP_2 = [W \cdot (0.606 \cdot L)]/L$$

After that the hamstring tightness was assessed on the same way as M1 with the 68.7 N of pushing to find the alpha (α) angle. To determine the applied force (F_2) to add to this 68.7 N we used the following formula:

$$F_2 = \text{Cos}\ \alpha \cdot WP_2$$

Each subject completed M3 until this point. But, after statistical analysis (one way repeated measure analysis of variance [ANOVA] and a Tukey post-hoc test), we did not find any difference between the individualized applied force of M2 and M3 (79.4±7.6 N for both M2 and M3). So, we chose to evaluate the passive hamstring flexibility only with M2 (see discussion).

Statistical analysis

Results are presented as mean ± standard deviation (SD). Since the data were normally distributed, differences in force between the three methods were tested with an ANOVA and a Tukey post-hoc test to localize the differences between means. Differences in knee angle between M1 and M2 were tested with a paired t-test. Pearson product-moment correlations

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were used to identify significant relationships. Statistical significance was set at *P*≤0.05 (SigmaStat 11.0, Systat Software, Chicago, IL).

RESULTS

Values of force and knee angle are reported in Table 1. The one way repeated measure ANOVA showed significantly differences in the mean applied force between the three methods (F=36.86, df=2, *P*<0.001). The Tukey post-hoc test found significant differences between M2 and M1 (*P*<0.001), and between M3 and M1 (*P*<0.001), but, as mentioned in the methods, no difference was found between M2 and M3. Applied force for M2 was correlated to applied force for M3 (*r*=0.93, *P*<0.001). The mean knee angle was significantly different between M1 and M2 (t=-3.98, df=19, *P*<0.001). Knee angle for M1 was correlated to knee angle for M2 (*r*=0.93, *P*<0.001).

DISCUSSION

The present study shows significant differences in passive knee angle between M2 and M1. The choice of the applied force in the original method was empirical. It was based on the feeling of the subjects and on an unpublished, preliminary study, where it was found a linear relationship between the applied force (4-10 kg) and the knee angle.[6] To include a gravity correction, we chose to add the relative weight of the complex "lower leg-foot" to the 68.7 N of the original method. This addition can explain the difference in passive knee angle between M1 and M2, but one may argue that M2 is a more accurate method for assessing passive hamstring flexibility.

This study also shows that the mean knee angle in M2 was well correlated with the mean knee angle in M1. This result is not surprising given the repeated nature of M2 in regard with M1.

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However, as shown in table 1, since the range of knee angle is smaller with M2 than with M1, we speculated that a modified M2 (with a force added to a lower force than 68.7 N) would lead to a larger range of knee angle. This could potentially be a more discriminative method for hamstring flexibility assessment.

We did not assess the passive hamstring flexibility with M3 for the following reasons: the mean applied forces were not statistically different between M2 and M3, and were well correlated (r=0.93, P<0.001). Then, we preferred M2 to M3 for its simplicity. In fact, M2 required less calculation and was easier and quicker, which is an important aspect for physiotherapists and/or researchers. It is not surprising to find the same force values for M2 and M3. In fact, in the reference position (Figure 1.A), the passive structures of the knee (ligaments, articular capsula) and the thigh (tendons of hamstring and/or quadriceps muscles) are by a majority not in a stretch position. Then they influence to a negligible extent the relative weight of the complex "lower leg-foot" and therefore do not modify the weight obtained with M2.

Gravity correction is also an important factor when assessing population with large differences in body dimensions; for example in adolescents who various maturation status and body sizes (e.g. in this study, a distance runner was 162.2 cm tall for 41.3 kg whereas a thrower was 183.3 cm tall for 128.1 kg). One may assume that taking into account the weight of the lower leg relative to the angle would lead to a more precise and adapted measure of the hamstring flexibility.

In practice, assessing passive knee extension with M2 is more complicated than with M1 because it involves assessing twice the same measure and to calculate the cosine of alpha multiplied by the lower leg weight. But M2 is an improved version of the original method (M1) since it minimizes the effect of gravity. Therefore, we recommend using it rather than M1.

Ethical Approval: This project was reviewed and approved by the institutional research and ethics committee of Aspetar – Qatar Orthopedic and Sports Medicine Hospital

Funding: none

Conflict of Interest: none

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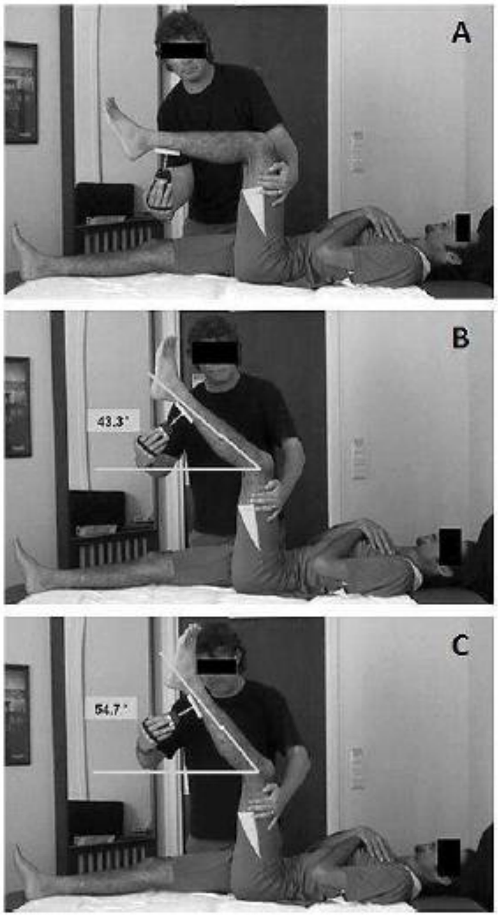

FIGURE 1. Visual representation of the video capture and angle measurement for each method. A, Reference position of the passive knee extension test. B, Method 1 – (0° = knee angle in the reference position and 90° = extended knee) for this subject, the passive knee angle is 43.3°. C, Method 2 - for this subject, the passive knee angle is 54.7°.
103x191mm (96 x 96 DPI)

		M1	M2	M3
Applied force [N]	Mean±SD	68.7±0.0	79.4±7.6 *	79.4±7.6 *
	Min	68.7	69.5	69.7
	Max	68.7	94.7	92.0
	Range	0.0	25.3	22.3
Knee angle [°]	Mean±SD	68.8±12.4	73.1±10.6 *	NT
	Min	45.8	51.9	NT
	Max	87.0	88.1	NT
	Range	41.2	36.2	NT

TABLE 1. Forces values in M1, M2 and M3 and knee angle values in M1 and M2. Abbreviation: NT, non-tested. * For significant differences with M1 ($P < 0.001$).

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COMMUNICATION BRÈVE

Électrostimulation des muscles plantaires et chute de l'os naviculaire

Plantar muscles electrostimulation and navicular drop

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MOTS CLÉS
Renforcement musculaire ;
Prévention ;
Arche médiale ;
Pronation ;
Pied

Résumé

Introduction. — Tester les effets de l'électrostimulation (EMS) pour soutenir l'arche médiale du pied (AM) chez de jeunes athlètes.

Synthèse des faits. — Pendant six semaines, huit athlètes (ES) ont ajouté trois séances d'EMS hebdomadaires à leur entraînement habituel pendant que huit athlètes (C) suivaient un entraînement normal. La chute de l'os naviculaire (CN) du pied a été mesurée avant (pré-), immédiatement après (post-) puis trois semaines après (post2-) la période d'entraînement. Entre pré- et post-, la CN a significativement été diminuée pour l'ES (8,8 ± 4,0 mm versus 5,8 ± 2,1 mm, $p < 0{,}01$) mais n'a pas été modifiée pour C (9,5 ± 3,2 mm versus 9,8 ± 3,7 mm). Entre pré- et post2-, l'effet de l'EMS a été maintenu pour l'ES.

Conclusion. — L'EMS pourrait améliorer le soutien de l'AM et ainsi prévenir les blessures liées à l'hyperpronation.

KEYWORDS
Muscles strengthening;
Injury prevention;
Medial arch;
Pronation;
Foot

Summary

Aims. — To assess electrostimulation (EMS) effects for supporting the foot medial arch in young athletes.

Methods and results. — During six weeks, eight athletes added three weekly EMS sessions to their usual training and eight athletes performed their normal practice. The navicular drop (ND) was measured before (pre-) and immediately (post-) EMS and three weeks after (post2-). Between pre- and post-, ND decreased in ES (8.8 ± 4.0 mm versus 5.8 ± 2.1 mm, $p < 0.01$) while it did not change in C (9.5 ± 3.2 mm versus 9.8 ± 3.7 mm). Between pre and post2, EMS effect remained unchanged in ES.

Conclusions. — EMS increased medial arch support, playing a role in hyperpronation related injuries prevention.

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1. Introduction

L'arche médiale du pied (AM) est soutenue par l'aponévrose plantaire, plusieurs ligaments, certains muscles extrinsèques (long fléchisseur de l'hallux, long et court fibulaires, etc.) et par des muscles intrinsèques (abducteur de l'hallux ou court fléchisseur des orteils) qui contribuent activement à l'absorption des chocs et à l'atténuation des contraintes pendant la phase d'appui [3]. Le maintien de l'AM du pied peut être évalué objectivement par le test de la chute de l'os naviculaire (CN) [1]. Une faiblesse des muscles intrinsèques du pied se traduit par l'affaissement de l'AM et conduit, soit à une situation de « pied plat flexible », soit à une hyper pronation vraie. Dans les deux cas, CN est supérieure à 10 mm (CN entre 5 mm et 9 mm est normale. CN inférieure à 5 mm est caractéristique d'un pied creux supinateur) [1]. Les pieds plats flexibles ou hyperpronateurs sont considérés à risques (aponévrosites plantaires, tendinopathies achilléennes ou fractures de fatigue des têtes des premier et deuxième métatarsiens) [6].

Aucune étude n'a évalué les effets du renforcement des muscles intrinsèques du pied sur CN par l'électrostimulation (EMS), bien que cette technique soit largement utilisée aussi bien en rééducation fonctionnelle qu'en musculation. L'hypothèse a donc été qu'un protocole de renforcement par EMS des muscles intrinsèques du pied (REMIP) appliqué à de jeunes athlètes pouvait diminuer significativement CN à court et moyen termes.

2. Matériel et méthodes

2.1. Participants

Huit athlètes d'*Academy for sports excellence* (Aspire), Centre national d'entraînement du Qatar (ES, âge : 15,8 ± 1,1 an, taille : 178,4 ± 6,2 cm, poids : 92,8 ± 13,3 kg, somme de sept plis cutanés : 123,7 ± 46,9 mm) ont effectué six semaines d'entraînement normal d'athlétisme (neuf séances par semaine) incluant le REMIP pendant les trois premières semaines, alors que huit athlètes du même centre (C, 15,6 ± 1,1 an, 176,5 ± 5,9 cm, 90,2 ± 15,0 kg, 122,7 ± 47,3 mm) servaient de groupe témoin en ne suivant qu'un entraînement normal. Chaque groupe incluait cinq sujets dont les pieds étaient normaux et trois sujets dont les pieds étaient plats et flexibles. Tous les sujets étaient volontaires pour cette étude.

2.2. Protocole

Trois séances de 15 minutes de REMIP par semaine ont été effectuées. Les athlètes en position debout recevaient les stimulations électriques émises par stimulateur Compex II (Compex SA, Ecublens, Switzerland) simultanément dans les deux pieds. Une paire d'électrodes adhésives (5 cm × 5 cm) était placée en ligne sous l'AM : la première derrière la tête du premier métatarsien et la seconde devant le tubercule médial du calcanéum [3]. Un courant alternatif a moyenne nulle (fréquence : 85 Hz, largeur d'impulsion : 400 μs, durée de contraction : quatre secondes et récupération : huit secondes) était appliqué. L'intensité du courant était augmentée régulièrement par un opérateur mais demeurait constamment sous le seuil de tolérance des sujets (Figure 1).

Figure 1 Placement des électrodes sous l'arche médiale du pied (AM).

2.3. Le test de la chute du naviculaire

L'examinateur marquait le tubercule du naviculaire avec un crayon dermographique. Puis, il enregistrait la différence de hauteur entre ce repère lorsque le sujet était assis, pied en contact avec le sol mais sans appui (articulation subtalaire maintenue en position neutre par l'examinateur) et lorsque le sujet était debout, en appui monopodal, relâché. Le résultat de cette différence constituait la chute du naviculaire. Celle-ci a été mesurée trois fois sur le pied dominant de chaque sujet et c'est la moyenne de ces valeurs qui a été enregistrée. Toutes les mesures ont été pratiquées par le même examinateur avec une variabilité interessais de 0,95 lors d'un test préliminaire sur 13 sujets. La CN a été mesurée pour ES et C avant (pré-), immédiatement après (post-) puis trois semaines après REMIP (post2-).

2.4. Blessures

L'enregistrement des blessures a utilisé un logiciel standardisé prenant en compte différents critères (type, localisation, côté, mécanisme, origine, sévérité, etc.). A été définie comme blessure, toute affection musculosquelettique donnant lieu au minimum à un traitement.

3. Résultats

Entre pre- et post-, la CN a significativement diminué pour l'ES (8,8 ± 4,0 mm versus 5,8 ± 2,1 mm, $p < 0,01$) alors qu'elle n'a pas changé significativement pour C (9,5 ± 3,2 mm versus 9,8 ± 3,7 mm). Entre pré- et post2-, l'effet de l'EMS a été maintenu pour ES (5,6 ± 3,0 mm, $p < 0,01$) alors qu'elle restait inchangée pour C (9,8 ± 3,7 mm). Finalement, après le REMIP, CN restait plus faible ($p < 0,05$) pour l'ES que pour C (5,8 ± 2,1 mm versus 9,8 ± 3,7 mm). Aussi, pour l'ES, dans les neuf mois précédant REMIP, six blessures liées à l'AM furent recensées contre aucune pour la même période après REMIP. Le nombre de blessures est resté quasi-constant pour C dans les mêmes périodes (13 contre 15).

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4. Discussion

Cette étude montre qu'une courte période de renforcement électro-induit des muscles intrinsèques de l'AM du pied provoque une diminution significative de la chute du naviculaire à court et moyen termes. Ces résultats revêtent un intérêt pratique pour la prévention des blessures. En effet, le rôle des muscles intrinsèques du pied dans le maintien actif de l'AM a déjà été rapporté, suggérant que le renforcement de ces muscles devrait être intéressant chez les sujets présentant une pronation excessive [3].

D'autres travaux ont montré les effets à court et moyen termes du renforcement des muscles du pied et de la cheville. Robbins et Hanna [5] ont rapporté un raccourcissement positif de l'AM par simple augmentation de l'activité en charge pieds nus. Toutefois, leur protocole durait quatre mois et était suivi d'un réallongement immédiat de l'arche. De même Feltner et al. [2] ont suggéré que, pendant la course, la pronation dynamique lors de la phase d'appui au sol pouvait être réduite par un programme de renforcement isocinétique (trois fois par semaines pendant huit semaines) des muscles inverseurs/éverseurs extrinsèques. Un des principaux résultats de la présente étude a été la diminution significative de CN après seulement trois semaines de REMIP (neuf séances), confirmant qu'un court programme de renforcement musculaire électro-induit avait des effets bénéfiques sur le maintien de l'AM (pied normal ou pied plat flexible). Les effets du renforcement musculaire électro-induit ont duré au moins trois semaines supplémentaires comme précédemment démontré, sur le quadriceps [4].

Les effets de REMIP sur le maintien actif de l'AM pourraient être primordiaux pour prévenir les blessures liées à l'hyperpronation (aponévrosites plantaires, tendinopathies achilléennes ou du tibial postérieur, métatarsalgies, fractures de fatigue des têtes des premier et deuxième métatarsiens, périostites...) [5,6]. Cliniquement, l'évolution des blessures enregistrées dans le groupe ES soutient cette remarque. En effet, au cours des neuf mois précédant REMIP, six blessures mettant en cause l'AM furent recensées (trois périostites, deux tendinites achilléennes et une aponévrosite plantaire) contre aucune au cours de la même période après REMIP. Comme la charge d'entraînement n'a pas varié et que le nombre des autres blessures d'hypersollicitation (impliquant les membres inférieurs et le bassin) est resté constant avant et après REMIP (13 contre 15), cela confirme les effets bénéfiques de REMIP pour la prévention des blessures liées à l'hyper pronation.

Au total, cette étude montre que le renforcement par EMS de certains muscles intrinsèques du pied induit un maintien actif de l'AM potentiellement bénéfique pour les athlètes présentant un pied plat flexible ou une pronation excessive.

5. Conflits d'intérêts

Aucun.

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Research article

Effects of combined foot/ankle electromyostimulation and resistance training on the in-shoe plantar pressure patterns during sprint in young athletes

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Abstract
Several studies have already reported that specific foot/ankle muscle reinforcement strategies induced strength and joint position sense performance enhancement. Nevertheless the effects of such protocols on sprint performance and plantar loading distribution have not been addressed yet. The objective of the study is to investigate the influence of a 5-wk foot/ankle strength training program on plantar loading characteristics during sprinting in adolescent males. Sixteen adolescent male athletes of a national training academy were randomly assigned to either a combined foot/ankle electromyostimulation and resistance training (FAST) or a control (C) group. FAST consisted of foot medial arch and extrinsic ankle muscles reinforcement exercises, whereas C maintained their usual training routine. Before and after training, in-shoe loading patterns were measured during 30-m running sprints using pressure sensitive insoles (right foot) and divided into nine regions for analysis. Although sprint times remained unchanged in both groups from pre- to post- training (3.90 ± 0.32 vs. 3.98 ± 0.46 s in FAST and 3.83 ± 0.42 vs. 3.81 ± 0.44 s in C), changes in force and pressure appeared from heel to forefoot between FAST and C. In FAST, mean pressure and force increased in the lateral heel area from pre- to post- training (67.1 ± 44.1 vs. 82.9 ± 28.6 kPa [$p = 0.06$]; 25.5 ± 17.8 vs. 34.1 ± 14.3 N [$p = 0.05$]) and did not change in the medial forefoot (151.0 ± 23.2 vs. 146.1 ± 30.0 kPa; 142.1 ± 29.4 vs. 136.0 ± 33.8; NS). Mean area increased in FAST under the lateral heel from pre- to post- (4.5 ± 1.3 vs. 5.7 ± 1.6 cm^2 [$p < 0.05$]) and remained unchanged in C (5.5 ± 2.8 vs. 5.0 ± 3.0 cm^2). FAST program induced significant promising lateral and unwanted posterior transfer of the plantar loads without affecting significantly sprinting performance.

Key words: Track and field, medial arch, reinforcement, injury prevention.

Introduction

During the ground contact phase of sprint running, a proximal-to-distal timing in the generation of peak extensor power occurs from the hip to the ankle (Johnson and Buckley, 2001). In addition to the hip and knee extensors' contribution, the foot/ankle complex plays an important part in leg stiffness regulation (Kuitunen et al., 2002; Weyand et al., 2010). Therefore, to enable efficient propulsion, the foot/ankle muscles must: 1/ be strong enough to stabilize the foot during the stance phase and therefore adjust the underlying surface (Cote et al., 2005); and 2/ allow and facilitate an efficient recoil-reuse of the elastic energy by the elastic materials (Achilles tendon, plantar fascia) (Alexander, 1992).

During the stance phase in sprinting, foot plantar pressure distribution is firstly characterized by the highest peaks under the medial and central forefoot, hallux and toes. This was shown in our recent comparison in plantar patterns between training shoes and racing spikes in young sprinters where we found a globally higher load under forefoot and toes with significantly more marked maximum force and mean pressure when wearing spikes (Fourchet et al., 2007). Eils et al. (2004) reported similar results regarding 1st and 2nd ray relative loads in subjects performing sprint when wearing soccer shoes and regardless of the surface. The findings of Queen et al. (2007) also confirmed these results with a significant higher force time integral under the medial forefoot area during the acceleration phase of sprinting when compared with other tasks such as side cuts or crossover cuts. Nevertheless, it is also known that during sprinting, the loads under the midfoot are higher than during low speed running or walking (Hennig and Milani, 1995). At the same time, forces must be much faster attenuated: in roughly one-third the time as compared to walking (Novachek, 1998). This suggests a considerable collapsing of the longitudinal arch of the foot due to the high forces acting on the foot (Alexander, 1992). A strong active support (in addition to the action of the passive structures) is needed in order to control this flattening. The muscles involved in this process are not only the extrinsic foot/ankle muscles (*e.g.* Gastrocnemius and soleus, posterior tibialis (Kitaoka et al., 1997), flexor hallucis longus, peroneus longus and brevis), but also the intrinsic foot muscles at the medial longitudinal arch (MLA) level (*e.g.* abductor hallucis and flexor digitorum brevis) (Ferris et al., 1995; Fiolkowski et al., 2003; Johnson and Buckley, 2001; Mann, 1981; Sherman, 1999). Thus weakness or fatigue of the aforementioned muscles may lead to a higher risk of injury due to overload under certain foot regions: heads of first, second and third metatarsal bones in relation with triceps surae failure (Weist et al., 2004) or MLA in relation with MLA muscles or posterior tibialis deficiency (Fiolkowski et al., 2003; Kitaoka et al., 1997). This relative overload mechanism might lead to stress reaction injuries (e.g. plantar fasciitis, first and second metatarsal stress fractures, metatarsalgia, posterior tibialis tendonitis, or shin splints) (Cornwall and McPoil, 1999; Cote et al., 2005; Robbins and Hanna, 1987). Foot and ankle problems have been reported as the second most common musculoskeletal problem in prebubertal and circumpubertal athletes next to acute injury (Stanish, 1995).

Other studies have already reported that specific foot/ankle muscle strengthening induced performance enhancement in terms of strength (Feltner et al., 1994)

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and joint position sense (Docherty et al., 1998). Recent results also showed that neuromuscular electromyostimulation reinforcement (NMES) of MLA muscles may decrease the navicular drop (Fourchet et al., 2009) and induced a lateral displacement of anterior maximal pressure point of the stimulated foot (e.g. inversion) in standing position (Gaillet et al., 2004). To our knowledge, only these two former studies used NMES of the intrinsic foot muscles despite that NMES is now widely used for strength training or rehabilitation of lower limbs muscles in athletes (Maffiuletti, 2010; Paillard, 2008).

It was demonstrated that an NMES long-term program was not systematically needed in order to obtain substantial effect on muscle fibres and that a limited dose of NMES may be sufficient for inducing significant changes on muscles strength, i.e. a short-term NMES program (3 sessions per week during 3 weeks) on knee extensors significantly enhanced isokinetic strength (Brocherie et al., 2005) and 12 sessions of approximately 12 min of NMES on ankle plantar flexors and knee extensors enhanced the jumping performance (Malatesta et al., 2003). In addition, Gaillet et al. (2004) reported that a single 20 min NMES session of the abductor hallucis muscle in the foot induced immediate specific changes in baropodogram indices, some of which persisted 2 months later. Finally, it was important to assess the efficiency of a protocol usable in the "real world" with young athletes. Therefore the aim of this study was to evaluate the effects of a brief foot/ankle strength training (FAST) program combining NMES of the MLA short intrinsic muscles and resistance strength training of the foot/ankle extrinsic muscles on sprint performance and on related plantar loading characteristics in teenage athletes.

Methods

Design

The study was carried out in a national training centre in Middle-East and consisted of a randomized clinical trial involving young track and field athletes.

Participants

A total of sixteen adolescent male athletes from a national sports institute were tested. All the subjects volunteered to participate in the study and signed an informed consent form. The study, which was approved by the local research ethics committee, conformed to the recommendations of the Declaration of Helsinki. During the 5 weeks experimental period, the athletes were instructed to continue their regular athletics training as they had done for the 6 months prior to commencement of the study. Briefly, every subject had been training in the Track and Field academy program on a regular basis, defined as averaging at least 9 sessions per week. No subject withdrew because of injury or adverse experiences. Participants were randomly assigned to either the treatment (FAST; age: 14.9 ± 1.9 yr, stature: 1.64 ± 0.09 m, body weight: 50.1 ± 10.5 kg) or a control (C; age: 15.5 ± 1.4 yr, stature: 1.65 ± 0.07 m, body weight: 53.4 ± 12.1 kg) group with eight subjects in each group (Figure 1). FAST consisted of foot medial arch and extrinsic ankle muscles reinforcement exercises, whereas C maintained their usual training routine (Figure 1).

Experimental protocol

Plantar pressure parameters were measured during 60 m full sprint in C and FAST groups, one week before (Pre) and immediately after (Post) the five week foot/ankle reinforcement program (within the 2 days following the end of the FAST program).

Training

In addition to their regular athletics training, experimental subjects were assigned a regimen of strength training; i.e. combined NEMS and resistance training for 5 weeks which consisted of foot medial arch and extrinsic ankle muscles reinforcement exercises (Figure 1).

NEMS: NEMS was performed at the beginning of certain athletics training sessions with each subject adopting a standing isometric position with both feet on the ground and the hands on the wall in front of him. This position, 0° to 20° ankle dorsiflexion, avoids the "back fall" and the cramps during the electrically induced contraction.

One portable stimulator (Compex 2, Medicompex SA, Ecublens, Switzerland) was used to deliver NEMS (15 min; 75 EMS contractions completed during each training session; rise time = 0.25 s and descending time = 0.75 s). For the soleus, two self-adhesive electrodes were placed under the medial and lateral muscle bellies of the gastrocnemius while two electrodes were placed behind the head of the first metatarsal of both legs for the medial arch muscles.

In order to maximize muscle tension without accompanying detrimental effects on fatigue onset, biphasic symmetric regular-wave pulsed currents (85 Hz) lasting 400 µs were delivered (Maffiuletti 2010, Papaiordanidou et al., 2010). Each 4-s steady tetanic stimulation was followed by pause lasting 8-s, during which subjects were submaximally stimulated at 4 Hz on the soleus muscle and the medial arch muscles. Subjects were consistently asked to increase the current amplitude within each training session and between sessions to attain the highest tolerable level without discomfort. For each subject and for each of the NEMS session, the average current amplitude was recorded. Table 1 displays the progression of NMES intensity during the 5 weeks of FAST protocol. Each athlete of the FAST group performed an average of 8.8 ± 1.0 NMES sessions throughout the 5 weeks as illustrated in Figure 1.

Table 1. Progression of NMES intensity (mean ± SD) (individual) and elastic resistance (pre-defined and standardized for the whole group) in FAST sessions.

	NMES intensity progression (mA)	Elastic tubing-aided exercices progression (kg)
Week 1	41 (4)	5.7
Week 2	55 (6)	6.8
Week 3	68 (7)	6.8
Week 4	74 (5)	7.9
Week 5	79 (3)	7.9

Abbreviations: NMES, Neuromuscular electromyostimulation; FAST, Foot/Ankle strength training.

Resistance training: Each session of the resistance

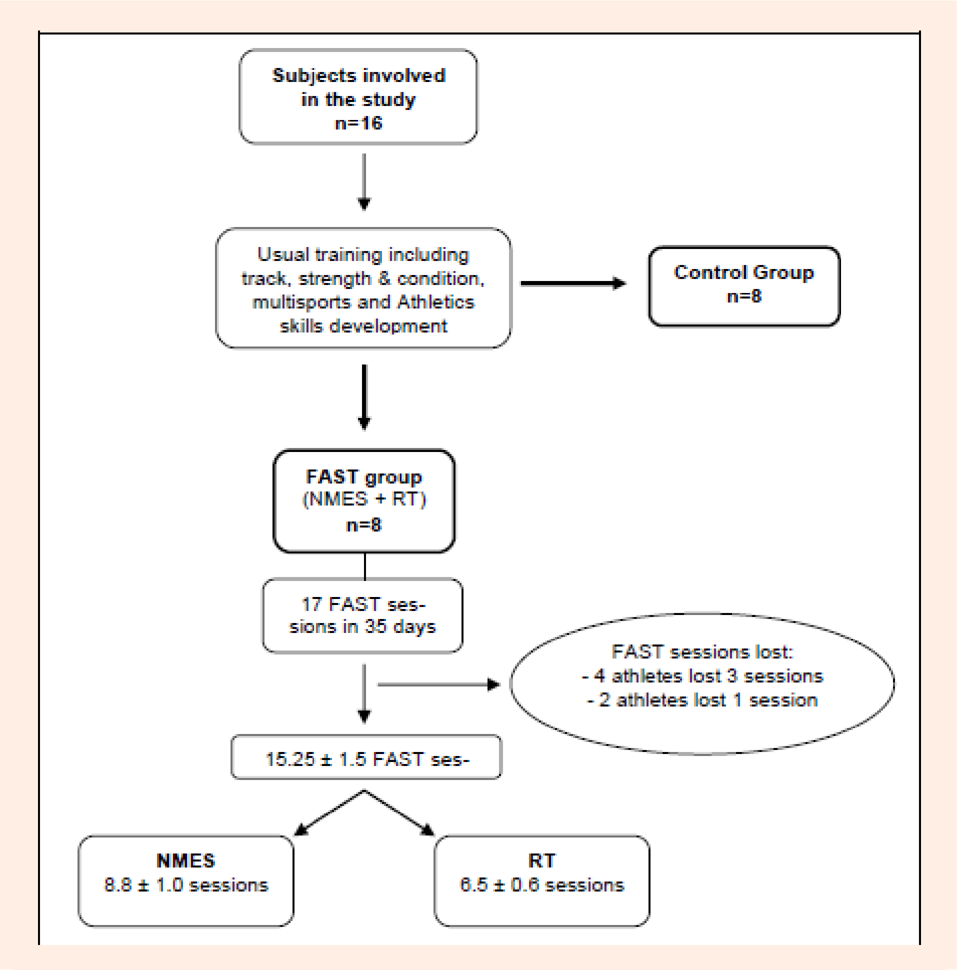

Figure 1. Illustration of the training procedure for both FAST and control groups. During the experimental procedure, both groups performed their usual training (9 sessions a week). In addition, the FAST group underwent a 5-week electromyostimulation (NMES) and resistance training (RT).

training protocol (RT) lasted 25 min and started with a standardized warm-up lasting 10 min including ergometer bicycle and rope skipping. This was implemented in the normal strength and conditioning sessions.

The six different exercises and the volume that were implemented are displayed in Table 2. Each athlete of the FAST group performed an average of 6.5 ± 0.6 RT sessions throughout the 5 weeks as illustrated in Figure 1. One or two of these six exercises were randomly implemented in the daily training program. One RT session was considered completed as soon as the six exercises have been performed within one week or less. Inversion and eversion exercises consisted of concentric and eccentric contractions using elastic tubing (Thera- Band Tubing Resistive Exerciser, The Hygenic Corporation, Akron, OH). Resistance progression is illustrated in Table 1. In accordance with the information provided by the manufacturer, 5.7 kg, 6.8 kg and 7.9 kg are equivalent to 150%, 200% and 250% of the black colored elastic tubing elongation, respectively). Lost training sessions due to athletes' absence are reported in Figure 1.

Plantar pressure data and sprint testing

Instrumentation: Insole plantar pressure distribution was

Table 2. Resistance exercises protocol used in foot/ankle strength training group (FAST).

Exercise	Resistance	Sets	Repetitions	Volume
Inversion	Elastic band	3	10	30
Eversion	Elastic band	3	10	30
Double leg toe raises	Body-weight	3	10	30
Single leg toe lowers	Body-weight	3	10	30
Horizontal calf jumps	Body-weight	2	10	20
Vertical calf jumps	Body-weight	2	10	20

recorded using the X-Pedar Mobile System (Novel GmbH, Munich, Germany). Each pressure insole consisted of a 2-mm-thick array of 99 capacitive pressure sensors. Before commencement of data collection, the insoles were calibrated according to the manufacturer's guidelines. This involved loading the insoles to a range of known pressure values, which resulted in an individual calibration curve for all sensors within the shoe (TruBlu Calibration, Novel GmbH, Munich, Germany). The insoles were placed in the right participant's spikes shoe between the foot/sock and sock liner. All the participants wore the same type spikes shoes, provided by the institution at the beginning of the season. The data logger for data storage was in a harness on the chest of the participant. Plantar pressures were sampled at 100 Hz via Bluetooth technology. Excellent reliability has been reported for this device (Hurkmans et al., 2006).

After a warm-up, the subjects performed three maximal 60 m sprints on a synthetic indoor athletics track, starting in a standing position. All the tests took place at the same indoor track. Sprint time for the last 30 m was measured with a dual-beam timing gate system (Speed Light, Swift Performance Equipment, Lismore, Australia) with simultaneous plantar pressure data collection. Sprints were also videotaped in order to define the corresponding right foot steps during the last 30 m and to assess the stride frequency. Stride frequency was calculated by dividing the stride count (i.e. number of steps of the last 30m over the fastest sprint) by the sprint time (i.e. sprint performance in the last 30m over the fastest sprint).

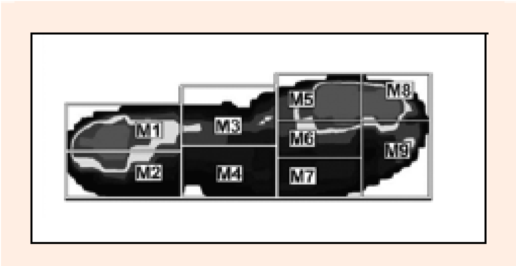

Figure 2. Regions of interest at the foot were masked to the size of the Pedar insole (Groupmask Evaluation, Novel GmbH, Munich, Germany). The regions consisted of the following: M1 medial heel, M2 lateral heel, M3 medial midfoot, M4 lateral midfoot, M5 medial forefoot, M6 central forefoot, M7 lateral forefoot, M8 hallux and M9 lesser toes.

Data analysis: The fastest sprint was chosen for the analysis of the sprint times and foot loading patterns. All the right foot contacts during the last 30 m of the fastest sprint were averaged for further analysis. A regional analysis of each foot was performed utilizing nine separate "masks" or areas of the foot; *i.e.* medial and lateral heel, medial and lateral mid-foot, medial, central and lateral forefoot, hallux and lesser toes (Groupmask Evaluation, Novel GmbH, Munich, Germany) (Figure 2). The following parameters were determined for the whole foot and the nine selected regions; maximum (MF) and mean force (mF), peak (PP) and mean pressure (mP) (e.g. the maximum mean pressure output from the novel software), ground contact times (CT) and mean area (mA). In addition, the relative load in each foot region (RL%) was calculated as the force time integral (area under the force curve) in each individual region divided by the force time integral for the total plantar foot surface (Eils et al., 2004). Analyses were performed with the appropriate software (Novel Win, Novel GmbH, Munich, Germany).

Concurrently, the arch index, defined as the area under the midfoot area divided by sum of the areas under the forefoot, midfoot, and heel regions (Nagel et al., 2008) was calculated in order to assess potential foot shape variations. The arch index calculated from dynamic foot prints has been reported as an accurate measure in non-obese subjects when measured both statically and dynamically (Taisa Filippin et al., 2008).

Statistical analysis

Mean (SD) values were calculated for all variables of interest. An independent samples *t*-test was used to examine the differences in plantar loading parameters for the whole foot. A three-way repeated measures ANOVA was performed with training mode (treatment *vs.* control group), condition (pre- *vs.* post-tests) and foot regions (masks one to nine) as the repeated factors and the foot loading parameters designated as dependent variables. This analysis revealed the global effect of training mode, the global effect of condition, the global effect of foot region and the interaction between training mode, Pre- and Post- conditions and foot regions. When significant main effects were observed, Tukey post hoc analyses were used to identify differences among means. The statistical analyses were performed using SigmaStat software (Jandel Corporation, San Rafael, CA). Statistical significance was accepted at $p < 0.05$.

Results

Sprint times remained unchanged between Pre- and Post-: 3.90 ± 0.32 vs. 3.98 ± 0.46 s in FAST and 3.83 ± 0.42 vs. 3.81 ± 0.44 s in C. No significant interaction was observed in sprint times and contact times. Moreover, no significant correlation was found between the pre- and post-training differences in sprint times and contact times for both groups.

No significant changes were observed both for contact times (122.6 ± 10.1 vs. 146.8 ± 41.4 ms and 122.4 ± 21.5 vs. 124.8 ± 21.7 ms, in FAST and C respectively), and stride frequency (3.96 ± 0.30 vs. 3.89 ± 0.31 strides.s^{-1} and 4.04 ± 0.33 vs. 4.12 ± 0.28 strides.s^{-1}, in FAST and C respectively).

Pre- and post- plantar pressure parameters for each foot region for C and FAST are presented in Table 3. Regarding the whole foot, there was no statistically significant difference in foot plantar parameters significant interactions ($p < 0.05$) between C and FAST were found in MF, PP, mP, mF, mA and RL% (Table 4).

The changes in force and pressure from heel to forefoot were different between FAST and C: In FAST, mP (Figure 3) and mF (Figure 4) increased in heel, i.e. M2 (67.1 ± 44.1 vs. 82.9 ± 28.6 kPa [$p = 0.06$]; 25.5 ± 17.8 vs. 34.1 ± 14.3 N [$p = 0.05$]) and did not change in forefoot, i.e. M6 (151.0 ± 23.2 vs. 146.1 ± 30.0 kPa;

Table 3. Foot loading parameters for each foot region before (Pre) and after (Post) the foot/ankle strength training in Control and experimental (FAST) groups. Values are means (±SD).

Group	Measure	Foot regions								
		Medial heel	Lateral heel	Medial midfoot	Lateral midfoot	Medial forefoot	Central forefoot	Lateral forefoot	Hallux	Lesser toes
Maximum force (N)										
Control	Pre	157 (134)	129 (107)	155 (118)	251 (106)	235 (80)	239 (82)	242 (85)	240 (79)	302 (96)
	Post	114 (77)	112 (96)	146 (69)	263 (92)	282 (103)	296 (98)	241 (91)	255 (101)	297 (83)
FAST	Pre	98 (86)	115 (92)	122 (48)	263 (42)	252 (101)	219 (40)	221 (58)	259 (56)	273 (54)
	Post	135 (77)	147 (71)	135 (44)	272 (69)	233 (96)	214 (48)	216 (71)	247 (61)	276 (48) *†
Peak pressure (kPa)										
Control	Pre	98 (53)	112 (61)	117 (46)	215 (91)	290 (119)	276 (111)	274 (87)	368 (100)	325 (100)
	Post	86 (45)	93 (55)	157 (53)	225 (83)	314 (92)	295 (74)	258 (73)	377 (150)	294 (74)
FAST	Pre	90 (60)	96 (56)	119 (31)	202 (50)	290 (112)	224 (46)	228 (56)	379 (99)	254 (51)
	Post	107 (49)	120 (42)	127 (36)	205 (79)	278 (98)	220 (52)	217 (75)	336 (101)	240 (55) ‡
Mean pressure (kPa)										
Control	Pre	68 (37)	79 (44)	64 (24)	108 (42)	191 (63)	167 (47)	173 (52)	220 (62)	164 (40)
	Post	57 (29)	65 (40)	66 (18)	110 (32)	219 (68)	203 (60)	170 (56)	237 (87)	157 (33)
FAST	Pre	60 (36)	67 (44)	55 (10)	100 (16)	200 (69)	151 (23)	154 (37)	238 (53)	142 (28)
	Post	70 (30)	83 (29)	58 (13)	102 (20)	186 (64)	146 (30)	148 (42)	225 (60)	145 (29) ‡†
Mean force (N)										
Control	Pre	38 (33)	31 (22)	50 (37)	113 (51)	144 (50)	146 (53)	142 (56)	139 (49)	195 (65)
	Post	29 (16)	26 (20)	53 (34)	113 (48)	162 (64)	177 (63)	147 (65)	150 (70)	195 (60)
FAST	Pre	25 (20)	26 (18)	42 (17)	112 (16)	157 (68)	142 (29)	133 (27)	152 (44)	182 (46) ‡
	Post	33 (20)	34 (14)	46 (17)	113 (22)	143 (63)	136 (34)	127 (37)	145 (48)	177 (39)
Mean area (cm^2)										
Control	Pre	6 (4)	5 (3)	9 (5)	15 (4)	11 (2)	12 (2)	12 (3)	9 (1)	16 (2)
	Post	6 (3)	5 (3)	10 (5)	14 (4)	11 (2)	13 (2)	12 (3)	9 (1)	17 (2)
FAST	Pre	5 (2)	5 (1)	10 (3)	16 (2)	12 (2)	13 (1)	13 (1)	10 (1)	17 (2)
	Post	6 (2)	6 (2)	10 (2)	15 (1)	11 (1)	13 (1)	12 (2)	10 (1)	17 (2) ‡
Relative load (%)										
Control	Pre	4 (2)	3 (3)	5 (3)	11 (4)	15 (3)	14 (2)	14 (2)	14 (3)	20 (5)
	Post	3 (2)	3 (2)	5 (3)	11 (4)	16 (4)	17 (2)	13 (4)	14 (4)	19 (4)
FAST	Pre	3 (3)	3 (2)	4 (1)	12 (3)	16 (4)	15 (2)	14 (3)	16 (2)	19 (3)
	Post	4 (3)	4 (2)	5 (2)	12 (3)	15 (4)	14 (2)	13 (3)	15 (3)	18 (2) †

*, † and ‡ $p < 0.05$ for region 5, 6 and 2 respectively. Abbreviations: FAST, Foot/Ankle strength training; Pre, one week before FAST protocol; Post, immediately after FAST protocol

Table 4. Foot loading parameters for the whole foot.

Group	Pre	Post	Change (%)
Maximum force (N)			
Control	1544 (587)	1634 (488)	5.8
FAST	1417 (238)	1401 (266)	-1.1
Peak pressure (kPa)			
Control	379 (98)	398 (134)	5.0
FAST	396 (93)	362 (92)	-8.6
Mean pressure (kPa)			
Control	137 (30)	150 (32)	9.7
FAST	134 (24)	131 (25)	-2.5
Mean force (N)			
Control	1000 (318)	1054 (304)	5.4
FAST	972 (167)	955 (177)	-1.8
Mean area (cm^2)			
Control	97 (23)	98 (18)	1.2
FAST	99 (11)	99 (6)	0.0

FAST, Foot/Ankle strength training; Pre, one week before FAST protocol; Post, immediately after FAST protocol

142.1 ± 29.4 vs. 136.0 ± 33.8 N). Mean area increased in FAST under the lateral heel between Pre- and Post-tests (4.5 ± 1.3 vs. 5.7 ± 1.6 cm^2 [$p < 0.05$]) and remained unchanged in C (5.5 ± 2.8 vs. 5.0 ± 3.0 cm^2). No additional changes were observed in other foot areas for plantar parameters after FAST.

Finally, arch index remained unchanged between Pre- and Post-: 0.40 ± 0.03 vs. 0.39 ± 0.02 in FAST and 0.39 ± 0.03 vs. 0.39 ± 0.03 in C.

Discussion

The aim of this study was to evaluate the effects of a brief foot/ankle muscles strength training program (FAST) including NMES on performance and the plantar loading distribution during sprinting in young athletes. It was found that such a program over a short period induced significant changes in in-shoe plantar pressure and forces patterns without any change in sprinting performance. Overall, FAST induced both varus (i.e. lateral shift) and posterior effects that are contradictory in term of running mechanics. Previous studies have reported that FAST lead to notable change in foot muscles' strength, foot structure, or running mechanics (Docherty et al., 1998; Feltner et al., 1994). In the present study, FAST displayed strong varus and posterior effects, as shown by the changes observed in lateral heel (for mean force, peak pressure, mean pressure and mean area) and medial forefoot (for maximum force, mean pressure and relative load).

Lateral shift

As suggested previously (Eils et al., 2004; Queen et al., 2007), one of the main characteristics of sprint biomechanics in terms of plantar loading patterns is the load

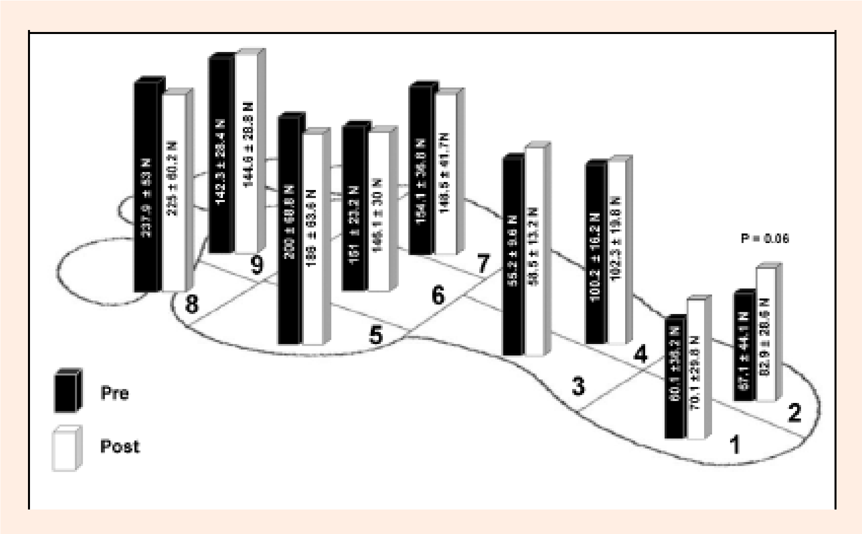

Figure 3. Mean and standard deviation mean pressure (kPa) during sprinting in each of the nine areas of interest for experimental group before and after foot/ankle strength training (FAST). Abbreviations: Pre, before foot/ankle strength training; Post, immediately after foot/ankle strength training.

under the 1st and 2nd ray, the hallux and the lateral toe. It has been previously noted that the intrinsic musculature in the plantar aspect of the foot has a role in supporting the MLA in stance (Fiolkowski et al., 2003); and even the fatigue of these muscles led to an increase in pronation (Headlee et al., 2007).

In the present study, we reported a shift of the load from the medial and central forefoot to the lateral part of the heel after FAST protocol; i.e. the reinforcement of the MLA and extrinsic ankle muscles induced the transfer of a part of the plantar loads from the medial and central forefoot to a more lateral part of the foot. The first component of this load transfer is the lateral shift which can be considered as a beneficial decrease of pronation. Similar results have been reported regarding counterbalancing the effects of overpronation. Feltner et al. (1994) suggested that one strategy to decrease pronation in runners is to use the inversion muscles at the ankle during the early part of the support phase. In the present study, FAST included strengthening of *posterior tibialis* and *flexor hallucis longus* that may have contributed to a more inverted foot position during the swing phase, at the contact and to the loads lateral excursion at the stance phase. The present results also confirmed the findings mentioned in two recent studies and reporting respectively a significant decrease of the navicular drop (Fourchet et al.,

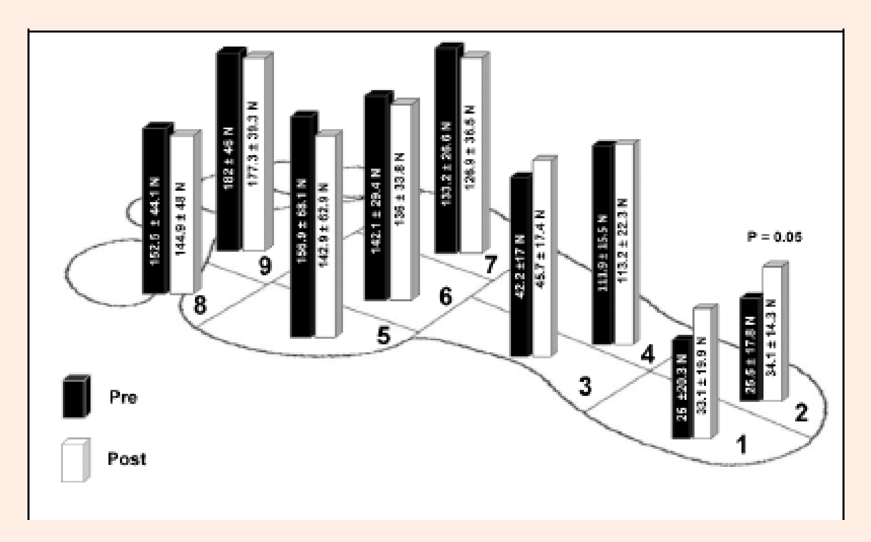

Figure 4. Mean and standard deviation mean force (N) during sprinting in each of the nine areas of interest for experimental group before and after foot/ankle strength training (FAST). Abbreviations: Pre, before foot/ankle strength training; Post, immediately after foot/ankle strength training.

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2009) and a lateral displacement of anterior maximal pressure point of the stimulated foot (e.g. inversion) in standing position (Gaillet et al., 2004), following MLA muscles strengthening by NMES exclusively. Similarly, the reinforcement of the MLA of the foot by NMES has possibly contributed to dampen force and pressure under the medial and central forefoot. Interestingly, it was shown by Robbins and Hanna (1987) that MLA strengthening via intrinsic musculature activation allows the foot to act as a dynamic impact dampening structure. One may suggest therefore that after the FAST protocol the MLA was shortened due to the increased intrinsic foot muscles tone, induced by NMES. This would induce the reported lateralization and the probable ability of the foot to act as a more efficient dynamic dampening structure (Headlee et al., 2007; Robbins and Hanna, 1987).

Posterior shift

The second shift component of the FAST protocol is an unwanted posterior transfer of the load that is likely to be detrimental for the running efficiency. It is known that a posterior load transfer during the stance phase is not biomechanically appropriate, because it may lead to higher decreases in horizontal and vertical velocities during the braking phase (Novachek, 1998; Stacoff et al., 1991). In sprint running, plantar flexors are the main muscles involved in the task of halting the negative (downward) vertical velocity of the body through eccentric contraction (Mann, 1981). Furthermore, in accordance with the degree of flexion of the knee, the soleus is the main muscle involved in this dissipation phase (Novachek, 1998). It may be assumed that the NMES reinforcement of the soleus was responsible for the posterior shift: this isometric strengthening (even though performed in a 0° to 20° ankle dorsiflexed position) possibly increased muscle fiber tightness. This could significantly decrease the muscle's stretch response, affecting the subsequent activation of the stretch reflex and then compromising force production or stability during movement (Cronin et al., 2008). This hypothesis is also supported by the normally accepted role of plantar flexors as active agonists in controlling forward toppling of centre of gravity in the standing position (e.g. when the foot is constrained on the ground) (Di Giulio et al., 2009): In the present program, the soleus muscle might have over-controlled the forward shift of the shank over the ankle at the stance phase and then consequently increased rear foot loading. In addition, there were no changes in the arch index values between pre- and post-training. This finding seems to confirm that the posterior effect of FAST protocol is not in relation with a MLA structure modification.

One limitation of the present study could be the lack of homogeneity in terms of sprint performance within the group (and thus large SDs), which might have induced non-significant changes with training. Nevertheless it is worth mentioning that several studies in the literature reported similar variability in sprint performances (Babault et al., 2007; Gains et al., 2010). Despite the performances not being statistically different, from a practical point of view a change of 0.08 s is not negligible in 30m sprint running. The observed trend of increased running and ground contact times (although not statistically significant) after FAST protocol is interesting but cannot be explained by the present data (no correlation was found between the pre- and post-training differences in sprint times and contact times neither in FAST nor in C). Similarly, ground contact times did not change significantly but we noticed a non negligible extension of this parameter in FAST group after the protocol. However, as the sprint times did not change clearly, it is difficult to conclude whether the increase of the ground contact times is detrimental or not. Finally, as the FAST group displayed an increase in sprint times which didn't achieve significance, it might be worthwhile repeating this experiment with larger groups to determine if this finding is significant.

Given the importance of the braking phase on sprint biomechanics (Ciacci et al., 2009) and the detrimental effect of heel contact on the kinetic and therefore mechanical cost, one may conclude that the current foot strength training protocol is likely to be detrimental for the running mechanics. However we suggest that the observed effect of lesser load on the metatarsal heads might be useful for reducing the stress fracture risks in runners considered 'at-risk' of this injury. As a whole, from running performance point of view, modification of the training protocol may be needed to avoid the possible decline in running performance (i.e. by excluding additional soleus reinforcement via NMES in order to avoid the observed posterior shift).

Injury prevention

Further kinematic and kinetic analyses are required for detailing the subsequent changes in running biomechanics induced by FAST and some components of this protocol may be of interest in preventing injuries. The effect of FAST on the dampening characteristics of the MLA are likely to be similar to the ones shown previously to protect the medial forefoot and mid-foot by using foot orthoses or tapes (Vicenzino et al., 2005). These findings could be of interest in terms of injuries prevention; i.e. for reducing the effects of overpronation characterized by a flattening of the MLA and a hyper mobile midfoot (Cote et al., 2005; Fourchet et al., 2009). Overpronation is an important risk factor for many injuries like plantar fasciitis, Achilles tendonitis, 1st and 2nd metatarsals stress fracture, metatarsalgia, shin splint, posterior tibialis tendonitis and femoro-patellar syndrome (Burne et al., 2004; Weist et al., 2004).

Conclusion

The aim of this study was to evaluate the effects of a brief foot/ankle strength training program on sprint performance and on related plantar loading characteristics in teenage athletes. The results showed no significant pre- to post- changes in sprint performance but revealed initially a lateral transfer and secondly a posterior unwanted transfer of the plantar loads after FAST protocol. Finally, it would be of interest to assess some adjustment to the present protocol in order to avoid the observed posterior shift and a possible decline in running performance. The

FAST protocol involving intrinsic and extrinsic foot/ankle muscles may appear to be of interest for some at-risk groups such as flexible flat foot morphology, subjects with high navicular drop, or overpronators.

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Key points

- We have evaluated the effects of a foot/ankle strength training program on sprint performance and on related plantar loading characteristics in teenage athletes, and this have not been examined previously.
- Our results showed no significant pre- to post-changes in sprint performance.
- This study revealed initially a lateral transfer and secondly a posterior transfer of the plantar loads after the foot/ankle strength training program.

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Study 10

Part 4. General integration and perspectives

The target of this thesis work was to contribute to enhance the understanding of the injury prevention at foot-ankle level in adolescent track and field athletes. This was performed through three approaches: (i) the examination of running-related risk factors (i.e. fatigue, shoes and running velocity), (ii) the epidemiological analysis of three seasons of foot-ankle injuries and their potential relations with the maturation and (iii) the design and implementation of foot-ankle injury prevention strategies on the field. The contributions of the present work to the field of foot-ankle injury prevention are summarised in the figure 4.1

4.1 Examination of running-related risk factors

4.1.1 Running-related fatigue alters foot-ankle mechanics

Study 1: Effects of a long hilly run on plantar and dorsal flexor force and fatigability

Even if this experimentation was performed on adults, it was thought that it may contribute to the present work, due to its topic (effects of running-induced fatigue) and the focused anatomical site (ankle plantar and dorsal flexors). This study revealed that, in adults, a significant isometric strength loss was only detected for the ankle plantar flexors after a 5-h hilly run and was partly due to low-frequency fatigue. Previous studies have demonstrated that PF was subjected to fatigue after a prolonged level running.[110, 317] Our results confirm previous studies on ultra-marathons and suggest that the prolonged running induced central fatigue in PF.[224, 253] It was assumed that the lower neuromuscular fatigue in dorsal flexor than plantar flexor may stem from lower mechanical stress to dorsal flexor, as the participants ran a much longer duration for uphill than downhill, which lead to an increased percentage of stride spent in stance and enhanced plantar flexor muscular loading. The main interests of this study were to take place in a natural environment and close to competitive conditions and to impose a hilly terrain on the runners, while there were some limitations in the experimentation such as the relatively small population sample size and the fact that the participants were adults. Interesting perspectives may be however proposed in terms of injury prevention following this experiment, such as to focus on plantar flexor strengthening in order to prevent up-hill running-related fatigue and not to consider the dorsal flexor tendons overuse injuries as providing from fatigue but most likely from mechanical friction/irritation when passing under the extensors retinaculum.

Study 2: Impact of high intensity running on plantar flexor fatigability and plantar pressure distribution

This study highlighted three main findings regarding the fatigue-related adaptations of adolescents following an intense exhaustive running trial.

- The plantar flexors displayed a reduced resistance to fatigue (over 50 contractions) in fatigued state while the dorsal flexors did not, confirming the predominance of fatigue at the posterior lower leg muscles found in the study 1 during a long run. These results would be similar if calculated over the 30 first contractions only, as recommended by Bosquet et al.[32] These changes affecting only PF are in line with previous studies in adults where PF were subjected to fatigue after prolonged[317] or shorter (i.e. 13 min) level running.[364] This imbalance between plantar and dorsal flexors may compromise the protective action of these muscles to the lower leg and result in overuse injury risk.[256]
- The important role of the MLA in the foot force transmission process and as a load absorbing structure in fatigued state was also emphasized in this study. This pinpointed the close and reciprocal interaction between plantar flexors and MLA: a compliant MLA (resulting in hyperpronation) may deteriorate the quality of force transmission through the foot at the stance phase (resulting in early plantar flexor fatigue onset), as suggested by previous authors,[182, 326] while the decreased plantar-flexor activity during fatigue may result in an increased loading under the MLA (due to a decreased supinatory action of these muscles).[364]
- The whole foot contact times increase when running in a fatigued state, due to a large increase in contact times under the central forefoot and the lesser toes. This may result from altered stretch-shortening-cycle, as previously reported in the literature.[152, 260] It was suggested that this fatigue-induced adaptation formed a part of a global process (together with a trend of force reduction at the forefoot when fatigued) tending to decrease the foot/ankle propulsive capacity (limiting the performance) but preventing the metatarsal heads from excessive loading.

Overall the findings of the present study emphasized the considerable role of the MLA for ensuring a proper stance phase and to avoid the risk of subsequent hyperpronation. This has further consequences in terms of prevention strategies regarding numerous lower extremity injuries (i.e. metatarsal stress injuries or medial tibial stress syndrome). Practically, implementing strengthening exercises of the intrinsic foot musculature in order to reinforce the MLA and to facilitate its load absorbing role at the stance phase, especially in a fatigued state, appears to be of interest. Electromyostimulation reinforcement of the MLA intrinsic muscles may be a promising technique in this matter, even though this type of reinforcement must be applied carefully in immature adolescent athletes.

Study 3: Changes in lower limb and foot mechanics induced by an exhaustive run on treadmill

Stride and spring mass model parameters changes are very interesting indicators of running mechanics alterations. In this study, the tested adolescent middle distance runners showed fatigue-related adaptations which were different as those frequently reported in adults.

- Differently from adult, stride frequency and stride length remained unchanged during the exhaustive run, confirming that adolescent runners do not or cannot adapt their stride parameters in fatigued state, in opposition to their adult counterparts.[81, 165, 301]
- The second major specificity of the adolescent distance runners was the constant vertical stiffness associated with a leg stiffness decrease and, above all, the increase of the peak vertical force in fatigued state. This conflicted with most of severe intensity running studies, where adults decreased their peak vertical force and stride frequency in order to reduce the impact forces and protect their lower limbs musculoskeletal structures.[75, 127, 324] It seems that adolescent runners' fatigue-induced adaptations concentrated on force production at stance phase, whereas adults tend to decrease their peak vertical force and stride frequency in order to reduce the impact forces and protect their lower limbs musculoskeletal structures.

- It is known that foot mobility magnitude measurement is highly predictive of dynamic foot posture during running.[235, 236] It has been found in the present study that the foot mobility was not affected by the running-induced fatigue. This contradicted the results of Headlee et al. where 3 plantar intrinsic foot muscles fatigue was specifically provoked.[154] Interestingly, it appeared that higher MLA stiffness and resistance to fatigue can (i) contribute to preserve the quality of the force transmission at the foot level and (ii) adequately play its role in the shock absorbing function of the foot by increasing and controlling the contact area at foot stance. These findings confirmed those of former studies, where authors emphasized that high fatigue resistance of the midfoot was linked to a better control of the plantar loading with fatigue.[208, 364]

It may therefore be appropriate to prescribe exercises soliciting the medial arch and aiming to increase stiffness and better absorption of impacts while running, in order to prevent overload and hyperpronation. In this view, barefoot intense running, midfoot-strike running sessions or sprints on soft surface (grass) might be specially relevant in adolescent runners.

In summary of this section regarding the alterations of foot-ankle mechanics due to running-related fatigue, it can be postulated that:

- Plantar flexor muscles are more affected by running-induced fatigue than dorsal flexor in adults (long hilly run) and in adolescent middle distance runners (intense exhaustive run). This imbalance between plantar flexors and dorsal flexors may compromise the protective action of these muscles to the lower leg and the foot.
- Adolescent runners displayed specific mechanical adaptations (i.e. constant stride frequency and length and increased peak vertical force) while running in fatigued state, that are considered as potentially harmful because increasing the foot-ankle and lower leg loads. This may be compensated by an adaptation of the roll-over process including longer contact time under the forefoot and the lesser toes and reduced force under the forefoot tending, conversely, to decrease the foot/ankle

propulsive capacity (limiting the performance) but preventing the metatarsal heads from excessive loading in fatigued state.

- The foot MLA stiffness and the plantar flexors' strength and fatigue resistance contribute in a large extent to the quality of force transmission and shock absorption through the foot.

Consequently strengthening exercises targeting the MLA support muscles and the ankle plantar flexors should be implemented in adolescent athletes.

4.1.2 Effect of shoe type on plantar pressure distribution while sprinting (Study 4)

This study demonstrated that wearing spikes shoes increases plantar loading under midfoot and forefoot during sprint running, when compared to running shoes. More specifically, due to the decrease in overall contact area and the simultaneous increase in force and pressure under the 1st and the 2nd metatarsal heads, higher loads are applied on medial and central forefoot. These findings provide the track and field community with additional data regarding the different foot plantar patterns while wearing shoes or spikes; this is further information following the findings of Stacoff et al. regarding torsion and rearfoot motion while running with spikes or shoes.[335] As wearing spikes may contribute to the mechanism of some foot overuse injuries (i.e. medial metatarsalgia or stress fractures of the 1st or 2nd metatarsal), it is proposed to recommend to the coaches a moderate use of this type of shoes for adolescent athletes in training.

4.1.3 Effect of running velocity on plantar pressure distribution (Study 5)

In line with the well-known biomechanical features,[63, 162, 188] it has been found in this study that the force and the pressure under the foot are much higher and the contact time lower while running than while jogging. It appeared however of higher interest to pay special attention to the higher relative loads under the medial forefoot while jogging, especially in order to inform/educate the middle distance coaches regarding this issue. It is thought that the potential harmful effect of high jogging mileage (i.e.

repeated micro trauma under the heads of the first three metatarsals) may be widely underestimated in the coaches' community. Some jogging sessions may be therefore implemented on a compliant surface as natural grass, in order to reduce the plantar pressure under the forefoot at that pace.

Take home message

- ✓ Strengthening ankle plantar flexors, especially in order to reinforce fatigue resistance, must be promoted in foot-ankle injury prevention programmes for adolescent athletes.
- ✓ The structures supporting the medial arch of the foot (e.g. triceps + intrinsic muscles) should be more frequently reinforced in adolescent athletes strengthening programmes:
  - Natural stimulation: grass running, midfoot-strike running, barefoot running…
  - Specific and local strengthening: calf + abductor hallucis & digitorum flexor brevis etc…
  - Electro-stimulation of intrinsic foot muscles → increased foot medial arch stiffness^{+++}
- ✓ Spikes shoes use and mileage at low velocity must be limited in young athletes in order to prevent metatarsal heads overload.

4.2 Foot-ankle injuries and maturation in adolescent athletes (Study 6)

The main aim of this study was to examine the foot-ankle injuries in track and field adolescent athletes because, to date, the epidemiology in this specific population was widely underestimated and underreported in the literature. To the best of our knowledge, the relationships between injury and maturation have moreover never been explored in youth track and field.

The results of this study:

- Confirmed that the foot-ankle /lower leg site was the most frequently affected one by injuries in youth track and field, in line with the findings of previous studies.[266, 291, 376]
- Revealed that late-maturing athletes demonstrated a higher incidence of foot/ankle/lower leg injuries than early maturers, even if the relationships between injury occurrence and maturation are still controversial and request further researches.[98]
- Confirmed that in track and field, injury prevention strategies should consider maturity status.

As in most of the epidemiological studies focusing on adolescents and maturation, several limitations must be noted in the present study. Some of these limitations have already been cited in the *data collection* section.

- The reporting system used for the study was based on existing reporting systems designed for adult population. This explains the absence of specific growth-related injury terms (even if these injuries or complaints were frequently recorded, but classified as “others” or “trivial injury”).
- Dealing with adolescent athletes is not easy. They may sustain very specific injuries and they may also suffer from symptoms that are frequently referred pains due to growth–related injuries. Some of these symptoms may have been misdiagnosed by the medical staff.
- Evidence regarding maturation is still very controversial and none of the available methods is perfect. The potential weaknesses of the method based on

anthropometrical measurements have already been detailed in the review of literature section of this thesis.

Take home message

✓ Accurate injury reporting systems must be widely implemented in youth track and field.

✓ The incidence of foot/ankle injury in adolescent athletes is high.

✓ There are considerable biological age differences in adolescent with similar chronological age.

✓ There may be a potential higher risk of foot/ankle overuse injuries in late mature athletes?

4.3 Injury prevention strategies design and implementation

4.3.1 Design and validation of a novel method for assessing adolescent flexibility (studies 7 and 8)

Despite the lack of consensus regarding the possible benefit of stretching on athletic performance or post-exercise muscle soreness, the monitoring of flexibility imbalances is regularly implemented in athletes' screening. While the topic of flexibility assessment is not directly connected to foot-ankle injury prevention, it is worth noting that excessive stiffness of the triceps suralis has been widely considered as a potential risk factor of Sever's disease occurrence.[46,47] The first step of a successful prevention programme is to use valid methods when assessing a risk factor.[243] The accuracy and the reliability of flexibility measures is therefore of primary interest for clinicians. To date, no method has been shown to be specifically reliable in adolescent athletes. The flexibility assessment method designed and validated in the study 7 is not only fast and convenient but also accurate due to the video analysis and the computer-aided angle measurement it encompasses. This method has a good level of day-to-day reliability, in line with most of the CV values previously reported in the literature for similar muscle groups.[98, 114, 214, 296] Even more important, there were no substantial differences between all the possible operators or video analysers combinations. In other words, the possibility to interchange the operators without affecting the reliability of the measures shows that this method can be successfully implemented and used by any physiotherapist in a team. These findings reinforce the clinical potential of this original method which should be used now when assessing the flexibility of young athletes.

For the record, the sole bias found with this procedure so far was regarding the hamstring flexibility measurement, which does not take into consideration the gravity effect. While this is not directly related to the topic of this thesis, it is worth noting that a second experiment (study 8) has therefore been conducted. It compared two alternative methods of hamstring flexibility measurement, including gravity correction. It was found that both alternative methods resulted in similar results which were significantly different from the results using the initial method, but closely correlated with each other. It was then concluded that any of the both alternative methods should replace the initial one in future protocols assessing the hamstring flexibility in young athletes.

4.3.2 Effects of foot-ankle strengthening training on medial arch stiffness and foot plantar pressure distribution (studies 9 and 10)

After having hypothesized that MLA compliance was usually associated with hyperpronation and then considered as a potential risk factor of injury in adolescent athletes, some prevention strategies should be designed and the subsequent countermeasures implemented. The last two studies of this work therefore deal with MLA and calf muscles strengthening. It was decided to perform a static assessment of a specific MLA reinforcement training in participants with normal and flexible flat feet (hyperpronators) on one hand and to perform a dynamic assessment of a varied foot-ankle strengthening training in participants with normal feet. Both experiments showed significant changes after the interventions and the following conclusions were proposed:

- Six weeks of NMES reinforcement of the MLA intrinsic muscles (three times a week) results in short and mid-term (3 weeks) increase of the MLA stiffness in participants with normal or flexible flat feet. This is thought to help preventing these participants from hyperpronation-related injuries. These findings pointed in the same direction as those of previous studies about the MLA.[111, 154, 308]

- Five weeks of varied foot-ankle reinforcement (~ three times a week)
  - Did not change the sprint running performance,
  - Resulted in lateral shift (“supinating”) of the foot plantar pressure distribution.
  - Resulted in posterior shift of the foot plantar pressure distribution.

This second strengthening programme was thought to have some potential positive effect in order to:

(i) unload the MLA and then help to prevent hyperpronation (constitutional or fatigue-induced), as it was previously suggested by several authors,[107, 121]

(ii) unload the 1st and 2nd heads of metatarsals and then help to prevent medial and central forefoot metatarsalgia.

This protocol however induced a detrimental posterior shift of the plantar pressure parameters at the stance phase, which is not compatible with sprint running. It is known that a posterior load transfer during the stance phase is not biomechanically appropriate, because it may lead to higher decreases in horizontal and vertical velocities during the braking phase.[280, 335] As this posterior effect was attributed to the calf NMES strengthening part of the programme (in accordance with the role of plantar flexors as active agonists in controlling forward toppling of centre of gravity in the standing position),[76] it has been proposed to skip this part of the training in further implementations.

Take home message

- ✓ Foot-ankle strengthening in adolescent athletes may prevent over pronation.
- ✓ In order to increase the active medial arch support, it is advised to use electro-stimulation for reinforcing the foot intrinsic muscles.
- ✓ It is not recommended to use electro-stimulation reinforcement on calf muscles for young sprinters.
- ✓ The innovative, reliable and efficient method for assessing flexibility proposed in this thesis can be used in young athletes.

In conclusion, the present studies have provided the researchers and the clinicians with some answers regarding foot-ankle injury prevention. It appears however that a lot of work remains “to be done” in this field. Some of the perspectives following the present thesis are summarized here after:

- Epidemiology of injuries in track and field adolescent athletes: To organize a group of consensus under the umbrella of the French Athletics Federation in order to propose a final statement regarding adolescent injuries prevention and management. This should be facilitated by the very close relationships, for several years, with Dr Frederic Depiesse (Head of the Medical Department at the French Athletics Federation and IAAF Medical Board member) and Dr Pascal Edouard (who published several articles about the injuries in the French track and field community). It may be of high interest to propose the same procedure to the Qatar Association of Athletics Federations or to the National Sports Medicine Programme.
- Flexibility and growth-related injuries: To use the reliable flexibility assessment method in order to assess whether muscle tightness may have an influence on apophysitis occurrence in adolescent athletes.
- Effect of a long-term stretching program: To use the reliable flexibility assessment method in order to assess the effect of a long-term stretching program on the lower limb flexibility of adolescent athletes.
- Medial arch stiffness: to assess the effect of NMES strengthening of the MLA on running economy and fatigue-related plantar pressure distribution changes in adult distance runners.
- Injury risk factors and prevention strategies assessment: To identify the main injury risk factors in other groups and circumstances; i.e. during a “several days” ultra-marathon competition, in order to implement some injury prevention countermeasures and to assess in real time the complaints/injuries onset of the runners.

Conclusion générale et perspectives

Le but de cette thèse était de contribuer à l'amélioration de la prévention des blessures du pied et de la cheville chez les jeunes athlètes. Ceci fut réalisé au travers de trois approches : (i) L'étude de facteurs de risques liés à la course à pied (fatigue, chaussage et allure de course), (ii) l'étude épidémiologique sur trois saisons des blessures du pied et de la cheville ainsi que leurs possibles relations avec la maturation et (iii) la conception et la mise en œuvre sur le terrain de stratégies de prévention des blessures du pied et de la cheville. La contribution de ce travail aux connaissances déjà existantes dans le domaine de la prévention des blessures du pied et de la cheville est illustrée à la figure 4.1.

1. Etude des facteurs de risques liés à la course à pied.

1.1. La fatigue induite par la course à pied altère la mécanique du complexe pied-cheville.

Etude 1 : *Les effets d'une course longue vallonnée sur la force et la fatigabilité des muscles fléchisseurs plantaires et dorsaux de la cheville.*

Même si cette experimentation a été conduite sur une population d'adules, il est apparu qu'elle pouvait trouver sa place dans ce travail eût égard à son sujet (la fatigue au niveau du complexe pied-cheville en course à pied). Cette étude a révélé que chez les adultes une perte significative de force isométrique touchait seulement les fléchisseurs plantaires de la cheville après une course vallonnée de 5 heures et que cette diminution était partiellement due à une fatigue de basse fréquence. De précédentes études ont montré que les fléchisseurs plantaires étaient sujets à la fatigue après des épreuves de course longues et à plat.[110,317] Les résultats de cette étude confirment ceux d'études précédentes sur l'ultra-marathon et suggèrent que la course de longue durée induit une fatigue des fléchisseurs plantaires de type central.[224,253] Il a été proposé que la moindre fatigue des fléchisseurs dorsaux pouvait provenir d'un stress mécanique inferieur de ces muscles, en raison de la durée plus longue de course passée en montée ce qui induit un pourcentage de foulée supérieur en appui et donc une charge de travail supérieure des fléchisseurs plantaires.

Les principaux intérêts de cette étude furent de se dérouler dans un environnement naturel proche des conditions de la compétition et d'imposer un terrain vallonné aux coureurs. Cependant la taille relativement faible de l'échantillon de participants et le fait que ceux-ci soient des adultes furent considérés comme des limites de cette expérimentation. D'intéressantes perspectives furent néanmoins proposées en terme de prévention des blessures comme d'insister sur le renforcement des fléchisseurs plantaires pour prévenir la survenus de la fatigue inhérente à la course en côte et de ne pas considérer la ténosynovite/tendinopathie des releveurs du pied comme une conséquence de la fatigue mais plutôt comme le résultat de la friction mécanique des tendons sous le réticulum des extenseurs.

Etude 2 : Impact de la course à intensité élevée sur la fatigabilité des fléchisseurs plantaires et la répartition des pressions plantaires.

Cette étude a mis en exergue trois résultats principaux relatifs à l'adaptation à la fatigue des adolescents, à la suite d'une épreuve de course à pied intense jusqu'à l'épuisement.

- Les fléchisseurs plantaires ont montré une résistance à la fatigue réduite en état de fatigue, contrairement aux fléchisseurs dorsaux ; ceci confirmant la prédominance de la fatigue au niveau des muscles de la loge postérieure de la jambe, déjà repérée au cours d'une course longue dans l'étude 1. Ces résultats se sont avérés similaires si le calcul était effectué sur 30 répétitions et non 50, comme conseillé par Bosquet et al.[32] Ces changements n'affectant que les fléchisseurs plantaires sont en accord avec les résultats d'études antérieures consacrées à la fatigue des fléchisseurs plantaires chez les adultes sur courtes ou longues distances.[317,364] Ce déséquilibre entre fléchisseurs plantaires et dorsaux de la cheville pourrait compromettre le rôle protecteur de ces muscles et conduire à un risque accru de pathologies de surmenage.
- Le rôle majeur de l'arche médiale du pied (AM) dans les processus de transmission de la force et d'absorption des contraintes en état de fatigue a également été souligné dans cette étude. Ceci a permis de mettre l'accent sur les interactions entre les fléchisseurs plantaires et l'AM : Une AM trop déformable (ou « compliante »), favorisant donc l'hyperpronation, pourrait détériorer la qualité de la transmission des forces au niveau du « levier-pied » au cours de la phase d'appui (provoquant une

survenue prématurée de la fatigue des fléchisseurs plantaires). A l'inverse, la diminution de l'activité des fléchisseurs plantaires à la fatigue semble conduire à une surcharge de l'AM (sans doute due, entre autre, à une baisse de l'action supinatrice de ces muscles).

- Le temps de contact de l'ensemble du pied a augmenté lors de la course en état de fatigue et ce à cause d'une forte augmentation de de ce paramètre sous l'avant-pied central et les orteils. Cela semble provenir d'une dégradation du cycle étirement-raccourcissement. Il est probable que cette adaptation à la fatigue participe d'un processus plus global (en adéquation avec une tendance à la diminution de la force sous l'avant-pied en état de fatigue) tendant à réduire la capacité propulsive du complexe pied-cheville (limitant la performance) mais protégeant les têtes des métatarsiens d'une surcharge excessive. Au total, les résultats de cette étude ont mis en évidence le rôle majeur de l'AM afin d'assurer une phase d'appui efficace et d'éviter le risque d'hyperpronation. Ceci induit plusieurs implications en terme de prévention des blessures des membres inférieurs (comme les pathologies de surmenage des métatarsiens ou les périostites tibiales). Pratiquement, la mise en œuvre d'exercices de renforcement des muscles intrinsèques du pied dans le but d'améliorer le soutien actif de l'AM semble être prometteuse. Ce renforcement faciliterait l'absorption des contraintes au niveau de l'AM lors de la phase d'appui, en particulier en état de fatigue. Le renforcement par électrostimulation des muscles de l'AM apparait comme une technique de choix à cet égard, bien que ce type de stimulation doive être employé avec précaution chez les adolescents encore non matures.

Etude 3 : *Changements induits au niveau de la mécanique du pied et du membre inférieur par une épreuve de course jusqu'à l'épuisement sur tapis roulant.*

Les variations de foulée et de raideur mécanique (système masse-ressort) sont des indicateurs très fiables des changements qui affectent la mécanique de la course à pied. Dans cette étude, les jeunes coureurs de demi-fond testés ont démontré des adaptations liées à la fatigue différentes de celles fréquemment rapportées chez les adultes.

- La fréquence et la longueur de foulée sont restées constantes au cours de l'épreuve de course jusqu'à l'épuisement, démontrant que les jeunes coureurs n'adaptaient pas ces paramètres en état de fatigue, contrairement à leurs homologues adultes.
- La seconde spécificité majeure des jeunes coureurs de demi-fond fut leur raideur verticale constante associée à une diminution de la raideur du membre inférieur et surtout à une augmentation de la force verticale de réaction du sol en état de fatigue. Ceci est opposition avec les résultats rapportes sur des études chez les adultes à haute intensité, où les sujets montrèrent une diminution de la force verticale et de la fréquence, sans doute dans le but de réduire les forces d'impact au sol et de protéger structures musculo-squelettiques des membres inférieurs.[75, 127,] Il semble donc que les adaptations à la fatigue des jeunes coureurs se focalisent sur la production de force pendant la phase d'appui, alors que les adultes tendent à diminuer leur force verticale de réaction au sol et leur fréquence de foulée, dans le but de réduire les impacts et de protéger les structures musculo-squelettiques de leurs membres inférieurs.
- Il a été démontré par le passé que la mesure de l'ampleur de mobilité du pied était hautement prédictive du positionnement dynamique du pied pendant la course. L'étude 3 révèle que la mobilité du pied n'a pas été affectée par la fatigue liée à la course. De façon intéressante, il semble qu'une importante raideur et une bonne résistance à la fatigue de l'AM puissent (i) contribuer à préserver la qualité de la transmission de la force par le levier-pied et (ii) permettre à cette structure (AM) de remplir au mieux son rôle d'absorbeur des chocs au niveau du pied, en augmentant/contrôlant la surface de contact du pied au sol pendant l'appui. Ces résultats confirment ceux de plusieurs études antérieures chez les adultes, dans lesquelles les auteurs rapportaient qu'une résistance à la fatigue élevée au niveau du medio-pied était liée à un meilleur contrôle des charges plantaires.[208,364]
- Il apparait donc approprié de prescrire aux coureurs des exercices sollicitant l'AM et visant à augmenter sa raideur pour améliorer l'absorption des contraintes pendant la course; ceci dans le but de prévenir les risques de surcharge et d'hyperpronation. A cet égard, des séances de courses rapides pieds nus, de course avec attaque du sol par

le medio-pied ou de sprints sur des surfaces souples (pelouse) pourraient être particulièrement utiles chez les jeunes coureurs.

En conclusion de cette partie consacrée aux changements de la mécanique du complexe pied-cheville dus à la fatigue, il peut être proposé que :

- Les fléchisseurs plantaires de la cheville sont davantage affectés par la fatigue liée à la course que les fléchisseurs dorsaux chez les adultes (course longue) et chez les jeunes coureurs de demi-fond (course intense jusqu'à l'épuisement). Ce déséquilibre entre fléchisseurs plantaires et dorsaux pourrait compromettre l'action protectrice de ces muscles sur la jambe et le pied.
- Les coureurs adolescents ont démontré des adaptations mécaniques spécifiques (fréquence et longueur de foulée constantes et augmentation de la force verticale de réaction du sol) lors de la course en état de fatigue ; ces adaptations pouvant être considérées comme potentiellement dangereuses car elles augmentent les contraintes sur le pied, la cheville et la jambe. Cela pourrait être compensé par une adaptation de la phase de déroulé du pied, à savoir un temps de contact plus long sous l'avant-pied et les orteils ainsi qu'une force réduite sous l'avant-pied ; ce qui tendrait à diminuer la capacité de propulsion du complexe pied-cheville (limitant la performance) mais protégerait dans le même temps les têtes de métatarsiens d'une contrainte excessive en état de fatigue.
- La raideur de l'AM, ainsi que la force et la résistance à la fatigue des fléchisseurs plantaires contribuent dans une large mesure à la qualité de la transmission de la force et à l'absorption des chocs au niveau du pied.

Par voie de conséquence, des exercices de renforcement des fléchisseurs plantaires et des muscles soutenant l'AM devraient être mis en place chez les jeunes athlètes.

1.2. Influence de la chaussure sur la répartition des pressions plantaires en sprint (étude 4).

Cette étude a démontré que porter des chaussures à pointes au lieu de chaussures de sport type « training » augmentait les contraintes plantaires sous le medio-pied et l'avant-pied en sprint. Plus spécifiquement, en raison de la diminution globale de la surface de contact au sol cumulée à l'augmentation de la force et de la pression sous les têtes des premier et deuxième métatarsiens, des contraintes supérieures sont appliquées au niveau médial et central de l'avant-pied lors du sprint « en pointes ». Ces résultats permettent de fournir à la communauté des entraineurs des données supplémentaires quant aux pressions plantaires en chaussures ou en « pointes »; ceci venant en complément des informations fournies par Stacoff et al. à propos de la torsion et du mouvement de l'arrière-pied lors de la course en chaussures ou en pointes.[335] Comme le fait de porter des chaussures à pointes pourrait contribuer à la survenue de certaines pathologies de surmenage du pied (métatarsalgies médiales, fractures de fatigue des premier et deuxième métatarsiens), il est recommandé aux entraineurs de faire un usage modéré de ce type de chaussures chez les jeunes athlètes à l'entrainement.

1.3. Influence de l'allure de course sur la distribution des pressions plantaires (étude 5).

En accord avec les principes biomécaniques bien connus, il a été démontré dans cette étude que la force et la pression enregistrées sous le pied sont plus importantes et le temps de contact moins long pendant la course à allure rapide que pendant le jogging. Il est apparu d'autre part encore plus intéressant de constater que la charge relative sous la partie médiale de l'avant-pied était plus élevée pendant le jogging que pendant la course rapide ; ce qui doit être rapporté aux entraineurs de demi-fond et de fond. Il est fort probable que les dangers d'un kilométrage élevé en jogging (répétitions de micro-traumatismes sous les têtes des trois premiers métatarsiens) soient largement méconnus dans la communauté des entraineurs. C'est pourquoi certaines séances de jogging ou sorties longues doivent se faire sur terrain souple (pelouse, sous-bois) avec pour objectif de réduire les pressions plantaires sous l'avant-pied à cette allure.

Ce qu’il faut retenir

✓ Le renforcement musculaire des fléchisseurs plantaires de cheville, notamment dans le but de résister à la fatigue, devrait être largement intégré dans les programmes de prévention de blessures destinés aux jeunes athlètes.

✓ Renforcer les structures actives de maintien de l’arche médiale du pied (triceps sural et muscles intrinsèques) semble indiqué chez les jeunes athlètes :

- Entrainement naturel : course sur l’herbe, course en attaquant le sol avec le medio-pied, course pieds nus…
- Renforcement local et spécifique : mollet + abductor hallucis & flexor digitorum brevis etc…
- Electrostimulation des muscles intrinsèques du pied en vue d’augmenter la raideur de l’arche médiale du pied.

✓ L’usage des chaussures à pointes et le kilométrage à allure lente doivent être limités chez les jeunes athlètes afin d’éviter la surcharge des métatarsiens.

2. Les blessures du pied et de la cheville et la maturation chez les jeunes athlètes (étude 6).

Le principal but de cette étude était d’examiner les blessures du pied et de la cheville chez les adolescents pratiquant l’athlétisme, car jusqu’à maintenant, l’épidémiologie des blessures dans cette population spécifique a été largement sous-référencée et sous-estimée. A notre connaissance, les relations entre blessures et maturation n’ont de plus jamais été étudiées en athlétisme. Les résultats de cette étude :

- ont confirmé que la région anatomique regroupant le pied, la cheville et le segment jambier était la plus touchée par les blessures en athlétisme.
- ont révélé que les athlètes à maturité tardive avaient un taux de blessure plus élevé au niveau du pied, de la cheville et de la jambe que les autres athlètes.
- ont confirmé qu’en athlétisme, la prévention des blessures devait tenir compte du niveau de croissance.

Comme dans la plupart des études épidémiologiques s’intéressant aux adolescents et à la maturation, plusieurs limites doivent être relevées dans la présente étude. Certaines de ces limites ont déjà été cités dans la partie *data collection* de ce travail.

- Le système d’encodage des blessures utilisé dans cette étude était basé sur des systèmes déjà existants, élaborés pour une population adulte. Ceci explique l’absence de termes spécifiques décrivant les pathologies de croissance (même si ces blessures ont été enregistrées, elles furent classées dans les catégories « autres » ou « blessures mineures »).
- Rapporter les blessures touchant des adolescents n’est pas aisé. Ils peuvent en effet contracter des blessures très spécifiques, mais ils souffrent aussi fréquemment de symptômes relatifs à des douleurs projetées consécutives à des pathologies de croissance. Certains de ces symptômes ont pu être parfois mal interprétés ou diagnostiqués par le staff médical.
- L’évidence scientifique à propos de la maturation est encore controversée et aucune des méthodes de mesure actuelle de l’âge biologique/squelettique n’est parfaite. Les faiblesses potentielles de la méthode basée sur les mesures anthropométriques ont déjà été détaillées dans la revue de littérature de cette thèse.

Ce qu’il faut retenir

- ✓ Des systèmes précis d’enregistrement des blessures doivent être mis en place chez les jeunes en athlétisme.
- ✓ L’incidence des blessures affectant le pied et la cheville est élevée chez les jeunes athlètes.
- ✓ Les différences d’âge biologique sont considérables entre adolescents de même âge chronologique.
- ✓ Les athlètes à maturité tardive pourraient encourir un risque de blessure de surmenage plus élevé au niveau du complexe pied-cheville.

3. Conception et mise en œuvre des stratégies de prévention des blessures.

3.1. Conception et validation d'une méthode innovante de mesure de la souplesse chez les adolescents (études 7 et 8).

Malgré le manque de consensus autour du possible bénéfice des étirements pour la performance sportive ou le traitement des douleurs musculaires post-exercice, un examen de la souplesse est régulièrement conduit lors du bilan de pré-saison ou du suivi longitudinal d'un sportif. Bien que le thème de la mesure de la souplesse ne soit pas directement lié à la prévention des blessures au niveau du complexe pied-cheville, il est important de noter qu'une raideur excessive du triceps sural a été largement rapportée comme possible facteur de risque de la Maladie de Sever.[46,47] La première étape d'un programme de prévention efficace est d'utiliser une méthode fiable pour quantifier le facteur de risque choisi. La précision et la reproductibilité des mesures de la souplesse sont donc de première importance. Jusqu'à présent, aucune méthode n'a été démontrée comme spécifiquement fiable chez les jeunes athlètes. La méthode de mesure de la souplesse conçue et réalisée pour l'étude 7 est non seulement pratique mais aussi fiable en raison de l'analyse vidéo et de la mesure d'angle assistée par ordinateur qu'elle comporte, comme en attestent les valeurs des coefficients de variation très proches de ceux publiés par le passé.[98,114,214,296] De plus cette méthode n'a pas montré de différences substantielles entre les différentes combinaisons d'opérateurs et d'analyseurs vidéo. En d'autre terme, la possibilité de changer d'opérateur/analyseur sans affecter la fiabilité des mesures montre que cette méthode peut être mise en place avec succès et utilisée quel(le) que soit le (la) thérapeute. Ces résultats renforcent le potentiel clinique de cette méthode originale qui devrait être désormais employée pour l'évaluation de la souplesse des jeunes sportifs.

Le seul biais important retrouvé dans cette procédure concernait la mesure de la souplesse des ischio-jambiers, dont la position ne prenait pas en compte l'action de la gravité. C'est pourquoi une seconde étude a été menée (étude 8). Elle comparait deux autres méthodes de mesure de la souplesse des ischio-jambiers, incluant la prise en compte de la gravité. Il a été trouvé que les deux méthodes proposées conduisaient à des résultats très similaires et fortement corrélés entre eux, mais significativement différents des résultats de la méthode initiale. Il fut donc conclu que l'une ou l'autre des deux méthodes alternatives devait remplacer la méthode initiale dans les futurs protocoles mesurant la souplesse des ischio-jambiers chez de jeunes sportifs.

3.2. Les effets du renforcement des muscles du pied et de la cheville sur la raideur de l'arche médiale et la répartition des pressions plantaires (études 9 et 10).

Apres avoir émis l'hypothèse que la souplesse/compliance de l'arche médiale du pied (AM) était habituellement associée à une hyperpronation (et donc considérée comme un facteur de risque chez les jeunes athlètes), des stratégies de prévention devaient être conçues et des contre-mesures mises en œuvre. Les deux dernières études de ce travail traitaient donc du renforcement des muscles du mollet et de l'AM. D'abord, une évaluation statique des effets du renforcement spécifique de l'AM fut conduite chez de jeunes athlètes à pieds normaux ou « plats flexibles » (hyper pronateurs). D'autre part, une évaluation dynamique des effets sur l'appui d'un protocole varié de renforcement du pied et de la cheville fut menée chez de jeunes athlètes à pieds normaux (neutres).

Les deux expérimentations ont montré des changements significatifs après interventions et les conclusions suivantes ont pu être proposées :

- Six semaines de renforcement par électro stimulation des muscles intrinsèques de l'AM (à raison de trois séances par semaine) ont conduit à court terme (fin du protocole) et à moyen terme (trois semaines après la fin du protocole) à une augmentation de la raideur de l'AM chez les jeunes athlètes à pieds normaux ou plats flexibles. Ces résultats confirment des données déjà publiées chez les adultes à propos de l'arche médiale du pied.[111,154,308] Ce programme peut donc être considéré comme permettant de prévenir les blessures liées à l'hyper pronation.
- Cinq semaines d'un programme de renforcement combiné des muscles du pied et de la cheville (en moyenne trois fois par semaine) :
  - n'ont pas changé les performances en sprint des athlètes testés
  - ont provoqué un déplacement vers l'extérieur (supinateur) des pressions plantaires
  - ont provoqué un déplacement postérieur des pressions plantaires.

Ce second protocole de renforcement a été considéré comme ayant des effets positifs pour (i) diminuer la charge sous l'AM et ainsi atténuer/prévenir l'hyperpronation (structurelle ou induite par la fatigue), comme cela a été proposé par certains auteurs[107,121] et (ii) décharger les première et deuxième têtes de métatarsiens et donc prévenir les métatarsalgies médiales et centrales de l'avant-pied. Ce programme a néanmoins induit un déplacement postérieur néfaste des pressions plantaires durant la phase d'appui, ce qui est incompatible avec la course de sprint. It is known that a posterior load transfer during the stance phase is not biomechanically appropriate, because it may lead to higher decreases in horizontal and vertical velocities during the braking phase En effet, un transfert postérieur des contraintes pendant la phase d'appui n'est pas approprié biomécaniquement, parce que conduisant à une diminution trop importante des vitesses verticale et horizontale pendant la phase d'absorption.[280,335] Etant donné que ce déplacement postérieur fut attribué au renforcement des muscles du mollet par électrostimulation (en rapport avec le rôle des fléchisseurs plantaires dans le contrôle de la bascule vers l'avant du centre de gravité en position debout)[76], cette partie du protocole devrait être supprimée au cours des futures applications de celui-ci.

Ce qu'il faut retenir

- ✓ Le renforcement du complexe pied-cheville chez les jeunes athlètes semble pouvoir prévenir l'hyperpronation.
- ✓ En vue d'augmenter le maintien actif de l'arche médiale du pied, il peut être conseillé d'utiliser l'électrostimulation pour renforcer les muscles intrinsèques du pied.
- ✓ Il n'est pas recommandé d'utiliser le renforcement des muscles du mollet par électrostimulation chez les jeunes sprinteurs.
- ✓ La méthode innovante, fiable et rapide de mesure de la souplesse présentée dans ce travail peut être utilisée chez les jeunes sportifs.

En conclusion, les études présentées ont fourni aux cliniciens comme aux chercheurs certaines réponses à propos de la prévention des blessures du pied et de la cheville. Il semble toutefois qu'un gros travail reste à accomplir dans ce domaine. Quelques perspectives et projets s'inscrivant dans la continuité de cette thèse sont succinctement résumés ci-après :

- *Epidémiologie des blessures chez les adolescents en athlétisme*

  Organiser un groupe d'experts sous la houlette de la Fédération Française d'Athlétisme, dans le but de proposer un consensus sur la prévention et la prise en charge des blessures chez les adolescents. Cela devrait être facilité par les relations très étroites entretenues depuis de nombreuses années avec le docteur Frédéric Depiesse (Médecin Fédéral National) et le docteur Pascal Edouard (auteur de plusieurs articles de référence sur les blessures des athlètes français). Il pourrait être aussi très intéressant de proposer une démarche similaire à la Fédération Qatarienne d'Athlétisme ou au Programme National de Médecine du Sport du Qatar.

- *Souplesse et blessures liées à la croissance*

  Utiliser la méthode de mesure de la souplesse présentée dans les études 7 et 8 afin de déterminer si le manque d'extensibilité musculaire pourrait avoir une influence sur la survenue d'apophysites de croissance chez les jeunes sportifs.

- *Effet d'un programme d'étirements de longue durée*

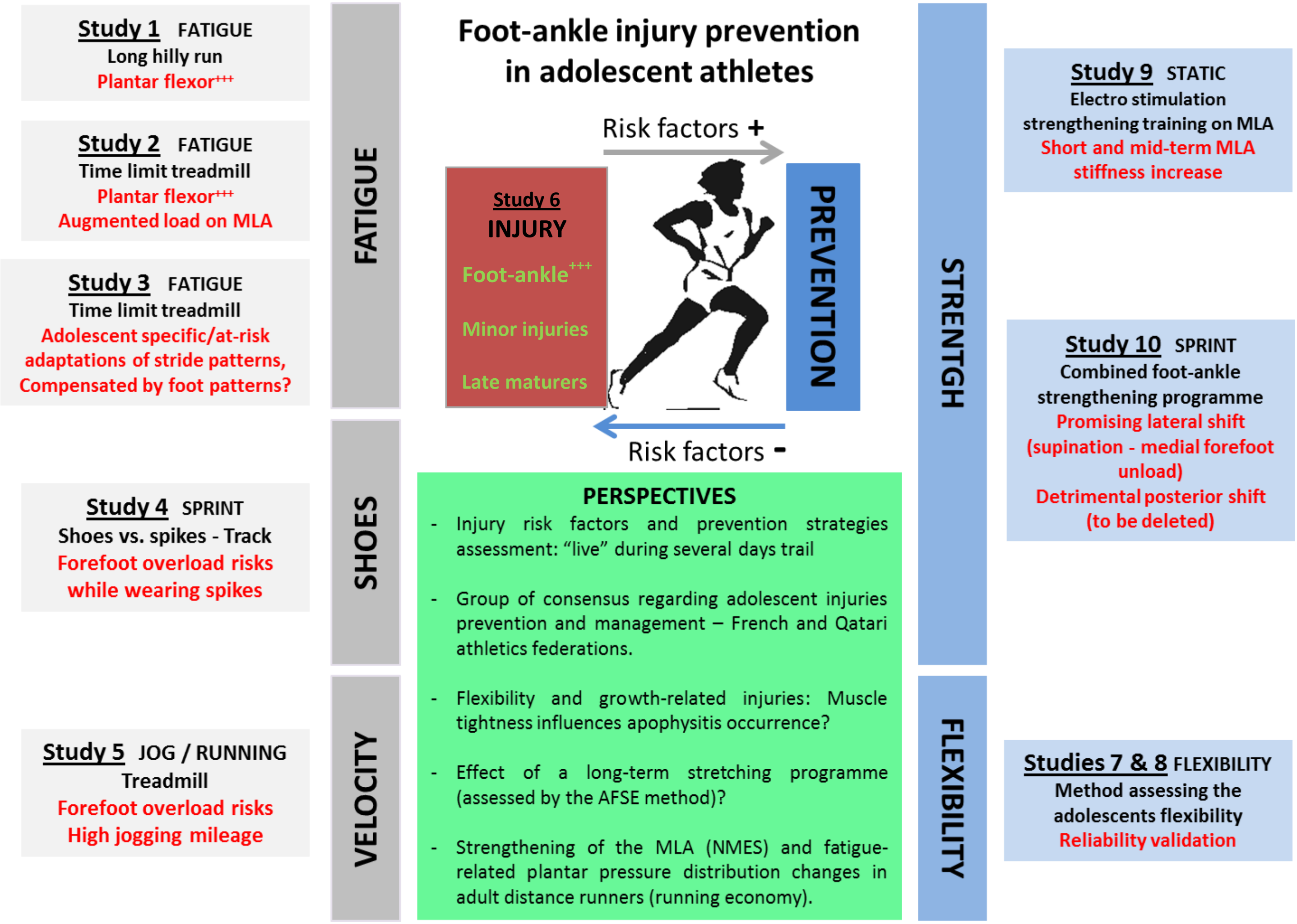
  Utiliser la méthode présentée dans les études 7 et 8 afin de quantifier les effets d'un programme d'étirement de longue durée sur la souplesse des muscles des membres inférieurs chez de jeunes sportifs.

- *Raideur de l'arche médiale du pied*

  Evaluer les effets d'un programme de renforcement musculaire par électro stimulation sur l'économie de course et les changements de répartition des pressions plantaires liés à la fatigue chez des coureurs adultes.

- *Facteurs de risque et évaluation de stratégies de prévention*

  Identifier les principaux facteurs de risque de blessures dans différents groupes d'athlètes et différentes circonstances : par exemple, au cours d'une course de type ultra marathon sur plusieurs jours, dans le but de mettre en place des contre-mesures de prévention des blessures et d'évaluer en temps réel les doléances et les pathologies des coureurs.



Foot-ankle injury prevention in adolescent athletes

Study 1 FATIGUE
Long hilly run
Plantar flexor^{+++}

Study 2 FATIGUE
Time limit treadmill
Plantar flexor^{+++}
Augmented load on MLA

Study 3 FATIGUE
Time limit treadmill
Adolescent specific/at-risk adaptations of stride patterns,
Compensated by foot patterns?

Study 4 SPRINT
Shoes vs. spikes - Track
Forefoot overload risks while wearing spikes

Study 5 JOG / RUNNING
Treadmill
Forefoot overload risks
High jogging mileage

FATIGUE

SHOES

VELOCITY

Risk factors +

Study 6
INJURY
Foot-ankle^{+++}
Minor injuries
Late maturers

PREVENTION

Risk factors -

PERSPECTIVES

- Injury risk factors and prevention strategies assessment: "live" during several days trail
- Group of consensus regarding adolescent injuries prevention and management – French and Qatari athletics federations.
- Flexibility and growth-related injuries: Muscle tightness influences apophysitis occurrence?
- Effect of a long-term stretching programme (assessed by the AFSE method)?
- Strengthening of the MLA (NMES) and fatigue-related plantar pressure distribution changes in adult distance runners (running economy).

STRENTGH

FLEXIBILITY

Study 9 STATIC
Electro stimulation strengthening training on MLA
Short and mid-term MLA stiffness increase

Study 10 SPRINT
Combined foot-ankle strengthening programme
Promising lateral shift (supination - medial forefoot unload)
Detrimental posterior shift (to be deleted)

Studies 7 & 8 FLEXIBILITY
Method assessing the adolescents flexibility
Reliability validation

Figure 4.1: Contribution and perspectives of the studies arising from this work for foot-ankle injury prevention in adolescent athletes
MLA: medial longitudinal arch, Jog: jogging, AFSE: angle at force standardized endpoint, NMES: neuromuscular electro stimulation

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Abstract

The aim of this work was to examine the foot-ankle injury prevention in adolescent athletes through three approaches: the running-related foot-ankle injury risk factors, the epidemiology of foot-ankle injuries and the implementation of prevention strategies.

The approach dealing with the running-related foot-ankle injury risk factors aimed to determine (i) how running-induced fatigue may affect the force and the fatigability of the ankle plantar and dorsal flexor muscles, the foot plantar pressure distribution, the running mechanics and the medial arch stiffness, (ii) how the shoe wear (spikes or running shoes) may affect the plantar load distribution while sprinting and (iii) how running velocity may alter the plantar load distribution. The approach related to epidemiology of foot-ankle injuries aimed at collecting and analysing, over three seasons, the foot-ankle injuries sustained by highly-trained adolescent athletes and their potential relations with the maturity status of these athletes. The approach presenting some prevention strategies implementations aimed firstly to design and validate a convenient and reliable flexibility measurement method. The second purpose of this approach was to assess on the field the effects of a neuromuscular electromyostimulation strengthening protocol on the foot medial arch stiffness and the effects of a combined foot-ankle strengthening training on the foot plantar pressure distribution and the performance while sprinting.

The first approach (risk factors) revealed three main alterations of foot-ankle mechanics due to running-induced fatigue that could be considered as injury risk factors. Firstly, ankle plantar flexor muscles are affected by running-induced fatigue whereas dorsal flexors are not. This imbalance between plantar flexors and dorsal flexors may compromise the protective action of these muscles to the lower leg and the foot. Secondly, adolescent runners displayed specific mechanical adaptations while running in fatigued state, that are considered as potentially harmful because increasing the foot-ankle and lower leg loads. These potentially detrimental adaptations appeared to be possibly compensated by an adaptation of the roll-over process preventing the

metatarsal heads from excessive loading in fatigued state. Thirdly, foot medial arch stiffness and the plantar flexor strength and fatigue resistance may contribute in a large extent to the quality of force transmission and shock absorption through the foot.

Regarding the shoe wear, it was found that wearing spikes shoes increased plantar loading under medial and central forefoot during sprint running, when compared to running shoes, which is a risk factor of metatarsalgia. Regarding the running pace, higher relative loads under the medial forefoot were found while jogging, which is potentially harmful for the heads of the first three metatarsals. This must be communicated to the coaches' community in order to avoid high mileage at jogging pace in adolescent athletes.

The second approach (injury and maturation) confirmed that the foot-ankle /lower leg site was the most frequently affected one by injuries in youth track and field. As it was found that late-maturing athletes demonstrated a higher incidence of foot/ankle/lower leg injuries than early and normal maturers, it was concluded that in track and field, injury prevention strategies should consider maturity status.

The third approach (prevention design and implementation) revealed that the flexibility assessment method designed and validated in this work was convenient and accurate due to the video analysis and the computer-aided angle measurement it encompassed. The two experiments dealing with foot and ankle muscles reinforcement showed that (i) electromyostimulation strengthening was efficient in order to increase the stiffness of the foot medial arch muscles and then prevent from hyperpronation and (ii) varied foot-ankle reinforcement may result in a positive unload of the medial and central forefoot, but electromyostimulation strengthening of the *soleus* should be avoided because it may affect the sprinting foot patterns and the sprint performance.

Résumé

L'objectif de ce travail était d'examiner la prévention des blessures du complexe pied-cheville chez les athlètes adolescents au travers de trois approches: les facteurs de risque de blessure du complexe pied-cheville liés à la course, l'épidémiologie des blessures du complexe pied-cheville et la mise en œuvre de stratégies de prévention.

L'approche relative aux facteurs de risque de blessure du complexe pied-cheville liés à la course avait pour objectif de déterminer (i) comment la fatigue induite par la course pouvait affecter la force et la fatigabilité des fléchisseurs plantaires et dorsaux de la cheville, la répartition des pressions plantaires, la mécanique de la course et la raideur de l'arche médiale, (ii) comment le chaussage (chaussures à pointes ou "runnings") pouvait affecter la répartition des pressions plantaires en sprint et enfin (iii) comment l'allure de course pouvait influencer la répartition des pressions plantaires.

L'approche relative à l'épidémiologie des blessures du complexe pied-cheville avait pour objectif de recueillir et d'analyser, sur trois saisons, les blessures subies au niveau du complexe pied-cheville par de jeunes athlètes très entrainés et leurs relations potentielles avec le niveau de maturité de ces athlètes. L'approche présentant la mise en œuvre de certaines stratégies de prévention avait pour but d'abord de concevoir puis de valider une méthode pratique et fiable pour mesurer la souplesse. Le second objectif de cette approche était d'évaluer sur le terrain les effets d'un protocole de renforcement musculaire par électrostimulation sur la raideur de l'arche médiale du pied puis les effets d'un programme de renforcement musculaire combiné sur la répartition des pressions plantaires et la performance en sprint.

La première approche (facteurs de risque) a révélé trois grandes modifications de la mécanique du complexe pied-cheville causées par la fatigue liée à la course et qui pourraient être considérées comme des facteurs de risque.

Premièrement, les fléchisseurs plantaires de la cheville sont touchés par la fatigue liée à la course alors que les fléchisseurs dorsaux ne le sont pas. Ce déséquilibre pourrait compromettre le rôle protecteur de ces muscles au niveau de la jambe et du pied. Deuxièmement, les jeunes coureurs ont démontré des adaptations mécaniques

spécifiques lors de la course en état de fatigue et celles-ci sont considérées comme potentiellement dangereuses en cela qu'elles augmentent la charge sur la jambe et le complexe pied-cheville. Ces adaptations potentiellement préjudiciables apparaissent cependant comme pouvant être compensées par une adaptation du déroulé du pied préservant les têtes des métatarsiens de charges excessives en état de fatigue. Troisièmement, la raideur de l'arche médiale du pied ainsi que la force et la résistance à la fatigue des fléchisseurs plantaires pourrait contribuer dans une large mesure à la qualité de la transmission de force et de l'absorption des chocs par le pied.

En ce qui concerne le chaussage, il résulte que porter des chaussures a pointes et non des "runnings" augmente les contraintes sous l'avant-pied médial et central en sprint, ce qui est un facteur de risque de métatarsalgie. Concernant l'allure de course, des contraintes relatives supérieures ont été retrouvées sous l'avant-pied médial à allure plus lente (jogging), ce qui se révèle potentiellement dangereux pour les têtes de métatarsiens. Ceci doit être communiqué à la communauté des entraineurs d'athlétisme dans le but d'éviter un kilométrage trop élevé à allure lente chez les jeunes athlètes.

La seconde approche (blessure et maturation) a confirmé la région formée par la jambe, la cheville et le pied était la plus fréquemment touchée par les blessures chez les jeunes athlètes. Comme il a aussi été retrouvé que les athlètes à maturité tardive souffraient davantage de blessures au niveau de la jambe, de la cheville et du pied que leurs homologues à maturité normale ou précoce, il a été conclu qu'en athlétisme la prévention des blessures devait tenir compte du niveau de maturité.

La troisième approche (conception et mise en œuvre de la prévention) a révélé que la méthode d'évaluation de la souplesse conçue et validée dans ce travail était pratique et fiable, en raison du recours à l'analyse vidéo et de la mesure des angles assistée par ordinateur qu'elle contient. Les expériences relatives au renforcement des muscles du pied et de la cheville ont montré que (i) le renforcement par électrostimulation était efficace pour augmenter la raideur des muscles de l'arche médiale du pied et ainsi préserver de l'hyperpronation et (ii) le renforcement combiné du complexe pied-cheville pourrait générer une décharge bénéfique de l'avant-pied médial et latéral, mais le renforcement par électrostimulation du soléaire devrait être évité parce qu'il pourrait altérer les appuis et la performance en sprint.