Surface effects on ground reaction forces and lower extremity kinematics in running

SHARON J. DIXON, ANDREW C. COLLOP, and MARK E. BATT

Department of Exercise and Sport Science, University of Exeter, Exeter, EX1 2LU, UNITED KINGDOM; and School of Civil Engineering, and Sports Medicine, University of Nottingham, University Park, Nottingham, NG7 2RD, UNITED KINGDOM

ABSTRACT

DIXON, S. J., A. C. COLLOP, and M. E. BATT. Surface effects on ground reaction forces and lower extremity kinematics in running. *Med. Sci. Sports Exerc.*, Vol. 32, No. 11, pp. 1919–1926, 2000. **Introduction:** Although running surface stiffness has been associated with overuse injuries, all evidence to support this suggestion has been circumstantial. In the present study, the biomechanical response of heel-toe runners to changes in running surface has been investigated. **Methods:** Six heel-toe runners performed shod running trials over three surfaces: a conventional asphalt surface, a new rubber-modified asphalt surface, and an acrylic sports surface. The surfaces were categorised according to impact absorbing ability using standard impact test procedures (BS 7044). **Results:** The rubber-modified asphalt was found to exhibit the greatest amount of mechanical impact absorption, and the conventional asphalt the least. The comparison of peak impact force values across surfaces for the group of subjects demonstrated no significant differences in magnitude of force. However, a significant reduction in loading rate of peak impact force was detected for the rubber-modified surface compared with conventional asphalt ($P < 0.1$). Although analysis of group data revealed no significant differences in kinematic variables when running on the different surfaces, a varied response to surface manipulation among runners was demonstrated, with marked differences in initial joint angles, peak joint angles, and peak joint angular velocities being observed. **Discussion:** For some subjects, the maintenance of similar peak impact forces for different running surfaces was explained by observed kinematic adjustments. For example, when running on the surface providing the least impact absorption, an increased initial knee flexion was observed for some subjects, suggesting an increased lower extremity compliance. However, for some subjects, sagittal plane kinematic data were not sufficient for the explanation of peak impact force results. It appears that the mechanism of adaptation varies among runners, highlighting the requirement of individual subject analyses. **Key Words:** SPORTS SURFACES, IMPACT ABSORPTION, JOINT ANGLES, SHOD RUNNING

Sports participation on artificial surfaces has been associated with an increased incidence of overuse injuries (19). One suggestion for this increased injury rate has been the increased mechanical stiffness associated with these surfaces (1,22). However, all evidence to support this suggestion has been circumstantial. To better understand the association between sports surfaces and injury occurrence, knowledge of the biomechanical effect of surface variation is required.

It has typically been assumed that excessive peak impact force values are associated with the occurrence of overuse injuries and that peak impact forces are reduced when running on surfaces with increased cushioning properties. This assumption has led to the belief that the manufacture of sports surfaces providing increased cushioning will result in a reduced incidence of overuse injuries. However, peak impact forces have typically been found to be maintained at similar levels when running on surfaces with differing mechanical properties (9,18,23). In addition, similar results have been found when running shoes with different amounts of cushioning have been worn (4,14,17,20). Because the ground reaction force represents the acceleration of the total body center of gravity, it appears that this acceleration is maintained at consistent levels despite changes in the impacting interface.

It has been suggested that maintenance of similar impact forces across conditions is achieved by adjustments in running kinematics, compensating for changes in stiffness of the impact interface. For example, de Wit and de Clercq (7) described a reduced initial foot sole inclination with the ground when running barefoot compared with wearing running shoes. These authors suggested that this adjustment

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acts to increase the surface area of the foot on initial ground contact, increasing the contribution of the human heel pad to the provision of cushioning. Bobbert et al. (2) described how the variation of lower extremity geometry of the body immediately before ground contact may influence the peak impact force by adjusting the stiffness of the lower extremity during impact. For example, an increased initial knee flexion has been suggested to reduce the lower extremity stiffness, compensating for increased stiffness of the shoe/surface interface (4,10). In addition, reductions in heel impact velocity have been observed when running on a stiff concrete surface compared with a turf surface (13). However, generalized patterns of kinematic response to changes in the provision of mechanical shock-absorption by the shoe-surface interface have not been established.

The cushioning ability of sports surfaces is generally quantified using mechanical tests. These tests typically involve impacting the surface material with a specified mass, and the measurement of impact variables including peak deceleration of the impact device, peak force and surface deformation. The inability of impact tests to uniquely characterize sports surfaces has previously been highlighted by Nigg (15). However, for the purposes of the present study, impact test procedures were considered to be adequate to provide an indication of the different mechanical properties of sports surface materials.

In the present study, the mechanical impact absorbing properties of three sports surfaces were measured using a standard impact test (3). The influence of the three different surfaces on impact forces and lower extremity kinematics was investigated for shod running. It was hypothesized that variations in surface mechanical impact absorption would not influence magnitude or rate of loading of peak impact force in running, and that adjustments in lower extremity kinematics at initial ground contact would account for the similar impact force values.

METHODS

Six subjects performed heel-toe running trials along a runway of approximate length 15 meters, making left foot contact with a force plate (Kistler 9261A, Winterthur, Switzerland) situated flush with the runway. Written informed consent was obtained from each subject before data collection. All subjects were well-trained, female middle-distance runners, with mean mass 55.6 kg (SD 3.5 kg). Each subject wore a standard running shoe model (Adidas Galaxy II, Portland, Oregon, size UK 5½), provided new at the start of the testing session. Subjects initially performed practice running trials as required until they were familiar with the test conditions. A running speed of 3.3 $\text{m}\cdot\text{s}^{-1}$ was chosen and was monitored over a distance of approximately 3 m using a marker placed on the hip of the subject. Trials were accepted if a running speed of within ± 5% of that specified was attained, and left foot contact with the force plate was achieved without obvious alterations to running stride. In addition, analysis of anterior-posterior impulse during ground contact ensured that only running trials showing no marked change in horizontal velocity were included.

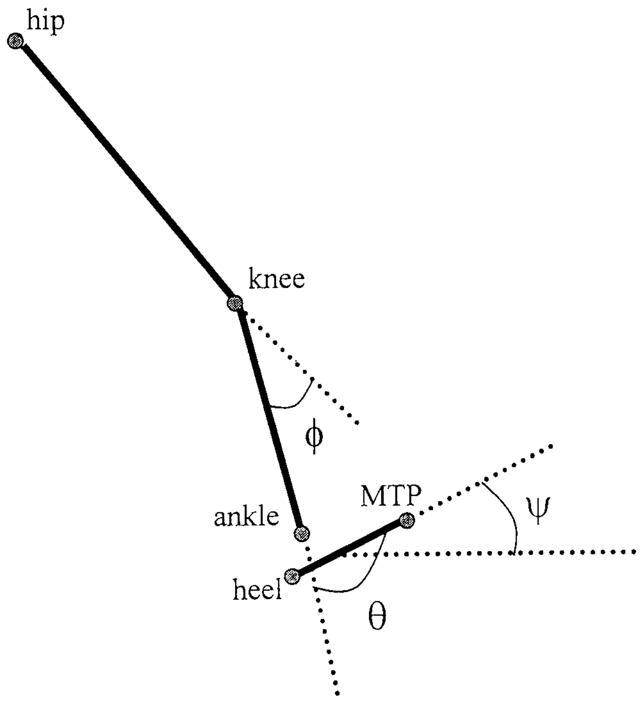

Figure 1—Conventions for foot angle (ψ), ankle angle (θ), and knee angle (ϕ). The foot angle is defined such that a negative foot angle corresponds to a positive inclination to the horizontal (as illustrated).

For each of the running trials, force plate data were collected at 800 Hz. Synchronized sagittal plane kinematic data were collected at 800 Hz using an opto-electronic unit (CODA mpx30, Charnwood Dynamics, Loughborough, UK). Active markers were placed on the left of the body at the hip, knee, ankle, and metatarsal-phalangeal (MTP) joint centers, and at a point on the heel (Fig. 1). The locations of the heel and MTP markers were chosen so that a straight line joining these two markers was parallel to the ground during standing. The start of data collection was triggered when the hip marker was in the field of view of the CODA system. Ground contact was defined as the period when the vertical ground reaction force exceeded 10 N. Along the line of movement, the horizontal field of view of the CODA system was 3 m, providing data for around two meters before force plate contact, and 1 m after contact. Adequate kinematic data were therefore available for the determination of selected initial variables immediately before contact with the force plate. The kinematic data fields immediately before ground contact were used for the determination of initial variables.

Three sports surface conditions were used to provide an approach runway and to cover the force plate. Two of the surface materials were bituminous: a conventional asphalt material and a new rubber-modified bituminous material (SARCO UK and The University of Nottingham, UK). A third test surface was a commercially available synthetic sports surface material, comprising an acrylic carpet on a thin (6 mm) prefabricated shock pad, and was provided by ETC (Holdings) Ltd., Melton Mowbray, UK. For testing, the acrylic carpet and shock pad were attached to a conventional asphalt material using a two-component polyurethane adhesive, as typically occurring in commercial applications of the surface (this surface is denoted "acrylic" in the rest of the paper). For each of the surface conditions, slabs of 25-mm thickness and dimensions 280 mm × 400 mm were placed on the surface of the force plate. In addition, a runway of the surface under study was constructed using slabs of material of the same thickness as that placed on the force plate, and dimensions 800 mm × 700 mm. An approach of approximately eight meters in length was provided before contact with the force plate. To ensure that force platform readings related only to the single foot impact required, there was a space of approximately 5 mm between the approach runway surface and the force plate.

After a full modal analysis of the force plate, vertical ground reaction force (GRF) data were filtered at 100 Hz, using a second order Butterworth low-pass digital zero phase filter. The magnitude and time of occurrence of the peak impact force were determined using the vertical ground reaction force (GRF) data and were used to calculate the average loading rate during impact.

Sagittal plane joint angles were defined as illustrated in Figure 1. The foot angle was defined as the angle between the foot segment and the horizontal, such that a positive inclination (contribution to ankle dorsiflexion) provided an angle with a negative sign. Initial ankle and knee angles were calculated using the data field immediately before ground contact. Peak ankle dorsiflexion and peak knee flexion angles were also determined. The peak joint angular velocities, occurring during the first 50% of the stance phase, were calculated by numerically differentiating the filtered joint angle data. The vertical velocity of the heel marker was determined immediately before impact using a similar procedure.

The results of a pilot study indicated that 10 running trials provided stable peak impact force data. Each subject therefore performed 10 successful running trials on each of the three surfaces, with the order of conditions randomized between subjects. Subjects were not informed of specific differences between the test surfaces. Force and kinematic variables were calculated for each running trial. Using the mean values obtained over 10 running trials to represent the value for each subject-surface combination, group mean values were calculated for each variable. An ANOVA with repeated measures was used to compare the group mean values for each of the selected biomechanical variables for the three surface conditions. Pilot study results with 10 running trials were used in a power analysis of peak impact force data, indicating that, for a desired effect size of 1.0 and a significance level of 0.05, a power value of 56% was obtained. For a significance level of 0.1, this power value was increased to 70%. These findings were used to justify the use of a significance level of 0.1. The conventional asphalt surface was used as a baseline condition from which to graphically compare the individual subject results obtained for the rubber-modified surface and the acrylic surface.

TABLE 1. Peak deceleration, time of occurrence and average deceleration rate for the three running surfaces: conventional asphalt, rubber-modified asphalt, and acrylic.

	Asphalt	Acrylic	Modified
Peak deceleration (g)	300	105	55
Time of occurrence (ms)	1	3	4
Average deceleration rate ($g \cdot ms^{-1}$)	300	35	13.8

The mechanical impact absorption provided by each of the three surfaces was determined using an impact rig adhering to British Standard 7044 for playing surfaces (3). The test procedure involved the release of a 6.8-kg spherical head form to impact with the test surface. Peak deceleration of the impact device during impact was determined using an accelerometer mounted on the head form (sampling frequency 10 kHz) and was presented in multiples of gravity (peak g). For the present study, peak g was determined for each test surface using a drop height of 10 cm, corresponding to an impact velocity of approximately 1.4 $m \cdot s^{-1}$ (corresponding with typical heel impact velocities in running). The time of occurrence of peak g relative to initial surface contact and the average rate of deceleration were also determined for each surface impact.

RESULTS

Table 1 provides the impact test results (BS 7044) of peak impact deceleration, time of occurrence of peak deceleration, and average rate of deceleration for each of the three surfaces. For the rubber modified asphalt surface compared with the conventional asphalt surface, it can be seen that the peak deceleration has reduced by a factor of approximately 6 and the time of occurrence of this peak has increased by a factor of approximately 4. The corresponding factor for the acrylic surface compared with the conventional asphalt surface is approximately 3 for both the magnitude and time of occurrence of the peak deceleration. It can also be seen from Table 1 that the average rate of deceleration has reduced by a factor of approximately 22 for the rubber-modified surface compared with the conventional asphalt surface. The corresponding factor for the acrylic surface compared with the conventional asphalt surface is approximately 9. These results clearly show that, under the conditions of the impact test (BS 7044), the rubber-modified asphalt surface has markedly greater impact absorbing properties than the conventional asphalt surface. The acrylic surface provides more impact absorption than the conventional asphalt surface and less impact absorption than the rubber-modified asphalt surface.

Table 2 provides the peak impact force and average loading rate of impact force for each running subject, for the three surface conditions. Also provided are group means and standard deviations. Analysis of group data for peak impact force indicated that there were no significant differences between the three surface conditions ($P < 0.1$). Figure 2 illustrates the differences in peak impact force with surface variation for the individual subjects, highlighting differences in individual subject response.

TABLE 2. GRF data for each running surface: peak impact force in bodyweights (BW) and average loading rate in BW per second; standard deviations are provided in parenthesis.

	Peak Impact Force (BW)			Average Loading Rate ($BW \cdot s^{-1}$)		
Subjects	**Asphalt**	**Acrylic**	**Modified**	**Asphalt**	**Acrylic**	**Modified**
Subject 1	1.73	1.47	1.68	47.7	42.1	42.5
	(0.12)	(0.21)	(0.18)	(5.8)	(7.4)	(5.7)
Subject 2	1.65	1.71	1.56	52.9	56.6	51.9
	(0.19)	(0.08)	(0.23)	(7.8)	(6.9)	(9.7)
Subject 3	1.31	1.59	1.53	42.9	43.7	37.2
	(0.25)	(0.17)	(0.25)	(7.9)	(7.8)	(9.4)
Subject 4	1.68	1.66	1.64	56.6	52.4	49.3
	(0.19)	(0.09)	(0.06)	(11.8)	(7.0)	(5.8)
Subject 5	1.51	1.49	1.61	45.7	46.4	47.8
	(0.10)	(0.10)	(0.21)	(4.1)	(6.2)	(9.8)
Subject 6	1.73	1.79	1.44	62.3	56.7	57.4
	(0.16)	(0.11)	(0.15)	(4.6)	(6.4)	(5.5)
Group mean	1.60	1.62	1.58	51.4	49.7	47.7*
	(0.16)	(0.13)	(0.09)	(7.3)	(6.5)	(7.1)

* Significant group difference from the conventional asphalt condition ($P < 0.1$).

For the average loading rate of impact force, group analysis revealed a significant reduction for the rubber-modified surface compared with the conventional asphalt surface ($P < 0.1$, Table 2). Figure 3 provides the individual subject results, illustrating that loading rate is reduced for the rubber-modified surface compared with the conventional asphalt for all but subject 5.

For each running surface, mean values and standard deviations for initial and peak joint angles are provided in Table 3, for the group data and for the individual subjects. Changes in joint angles for each individual subject when running on the rubber-modified asphalt surface and the acrylic surface compared with the conventional asphalt are presented in Figures 4 and 5. Analysis of group data revealed that there were no significant differences in joint angles across the three surface conditions. Individual subject results indicated that, compared with running on the conventional asphalt surface, the acrylic and the rubber-modified surfaces resulted in both increases and decreases in the initial ankle and initial knee angles across subjects. Initial heel velocities were found to be unchanged by the changes in surface ($P < 0.1$).

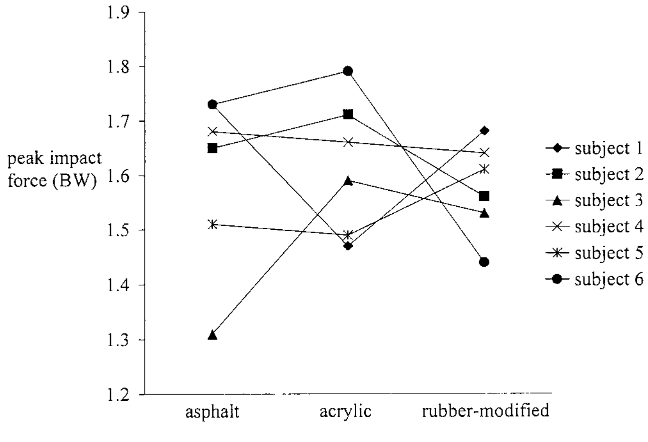

Figure 2—Mean peak impact force over 10 trials for each of the six subjects, for the asphalt surface, the acrylic surface, and the rubber-modified surface.

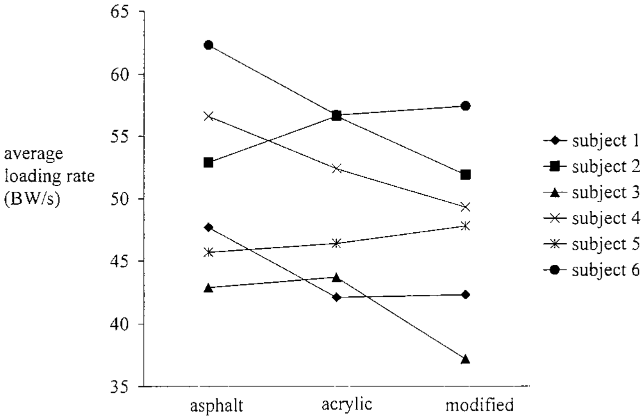

Figure 3—Mean loading rate of impact force over 10 trials for the six subjects, for the asphalt surface, the acrylic surface, and the rubber-modified surface.

Although no statistical significance was detected in the group peak angle data, the acrylic surface and the rubber-modified surface resulted in a trend for the peak ankle and knee angles to be increased compared with running on the conventional asphalt surface. Individual subject results highlight that typically the angle increases were greater for the rubber-modified surface than for the acrylic surface (Figs. 4 and 5). The trend for increased peak joint angles indicates an increased ankle dorsiflexion and an increased knee flexion with increased shock-absorption provision by the contact surface. For the rubber-modified surface, one subject (subject 5) demonstrated conflicting peak angle responses to the remaining subjects, with marked reductions in peak ankle and peak knee angles compared with the conventional asphalt surface.

Group and individual subject mean values and standard deviations for peak joint angular velocities are provided in Table 4, for each running surface. Changes in angular velocities with surface variation for each individual subject are illustrated in Figure 6 and Figure 7. Compared with the conventional asphalt surface, the acrylic surface and the rubber-modified asphalt surface resulted in both increases and decreases in peak ankle plantarflexion velocity and peak knee flexion velocity. Individual subject results indicate that the peak ankle dorsiflexion velocity showed a trend to be increased for both the acrylic surface and the rubber-modified surface compared with the conventional asphalt (Figs. 6 and 7).

DISCUSSION

The drop test results have demonstrated that there is a clear mechanical difference in the impact absorbing ability of the three sports surfaces used in the present study. Compared with the conventional asphalt surface, the acrylic material resulted in a reduction in the peak g value. A further reduction in the peak g has been demonstrated for the rubber-modified asphalt surface. In addition, the observed increase in impact time for the acrylic surface and the rubber-modified surface compared with the conventional

TABLE 3. Joint angles (°) for the conventional asphalt surface, acrylic surface and the modified asphalt surface; standard deviations are provided in parenthesis.

	Initial Ankle Angle (°)			Initial Knee Angle (°)			Peak Ankle Angle (°)			Peak Knee Angle (°)		
Subjects	**Asph.**	**Acry.**	**Mod.**	**Asph.**	**Acry.**	**Mod.**	**Asph.**	**Acry.**	**Mod.**	**Asph.**	**Acry.**	**Mod.**
Subject 1	105.8 (1.9)	102.6 (1.2)	104.1 (1.6)	19.2 (2.7)	21.3 (2.4)	18.2 (2.9)	120.9 (1.1)	120.9 (1.5)	121.0 (1.8)	49.1 (1.2)	50.0 (1.4)	49.2 (1.6)
Subject 2	101.1 (2.6)	101.3 (1.5)	99.6 (2.6)	12.5 (2.3)	15.3 (2.3)	14.2 (2.0)	117.4 (1.7)	117.5 (1.7)	118.7 (1.5)	40.9 1.6)	41.0 (1.9)	41.8 (1.7)
Subject 3	103.7 (2.4)	103.0 (2.0)	104.2 (2.2)	20.1 (3.0)	20.4 (2.9)	21.0 (3.1)	120.5 (1.3)	120.0 (1.4)	121.7 (0.9)	48.9 (2.1)	49.9 (1.3)	50.5 (1.6)
Subjet 4	102.3 (3.7)	108.1 (3.1)	109.0 (2.1)	27.6 (4.8)	25.3 (3.6)	27.7 (4.3)	116.3 (1.7)	117.5 (1.6)	119.9 (1.2)	48.4 (2.1)	50.0 (1.2)	51.9 (1.2)
Subject 5	97.1 (1.4)	95.5 (0.8)	97.2 (1.0)	12.2 (1.7)	11.9 (2.6)	10.1 (1.2)	117.4 (1.1)	116.9 (1.0)	116.3 (1.4)	44.6 (1.0)	44.8 (0.7)	43.8 (1.3)
Subject 6	99.3 (2.1)	100.6 (0.8)	96.6 (2.5)	16.0 (1.2)	14.7 (1.7)	16.7 (1.4)	118.1 (1.7)	118.6 (0.6)	118.5 (1.5)	46.8 (1.4)	47.4 (0.9)	47.0 (1.5)
Group	101.6 (3.1)	101.9 (4.1)	101.8 (4.8)	17.9 (5.8)	18.2 (5.0)	17.9 (5.9)	118.4 (1.8)	118.6 (1.6)	119.4 (1.9)	46.5 (3.2)	47.2 (3.7)	47.4 (3.9)

asphalt surface also highlights the different cushioning abilities of the test surfaces. If the impact conditions were consistent across running surfaces, then a difference in the peak impact force during running would be expected.

The initial hypothesis that the peak impact forces would be similar for the different running surfaces has only been partially supported. Despite the increased mechanical impact absorption provided by the acrylic surface and the rubber-modified surface, compared with the conventional asphalt, the peak impact forces were typically not influenced by the change in surface. This finding is in agreement with much previously published data using running shoes (4,14,17) or surfaces (18,23) to manipulate mechanical shock-absorption. However, visual examination of individual subject data has highlighted marked changes in peak impact force for some subjects. The finding that average rate of loading of impact force is significantly reduced for the rubber-modified surface compared with the conventional asphalt supports previous findings that rate of loading may be a better indicator of cushioning ability than peak impact force (6).

The factors previously identified as influencing the magnitude of impact force include: impact velocity, contact area between the impacting surface and the foot, joint angles at initial impact, motion of the segment centers of masses particularly the foot, preactivation of muscles, and surface stiffness (5). For all subjects, differences have been demonstrated in the initial joint angles for the acrylic surface and the rubber-modified surface compared with the conventional asphalt surface. However, despite the common running style and similar training status of the subjects, different responses have been observed across subjects. The presence of differences in initial angles suggests that subjects have adjusted their kinematics in response to the surface variation, but the varied response highlights the large number of combinations of adjustment available to the runner. Although the angle changes appear relatively small (ranging from less than one degree to seven degrees), the resulting influence on the moment arm of ground reaction force and the moment arm of tendons and ligaments could have a marked influence on the loads experienced by lower extremity structures. The subtle changes observed in joint

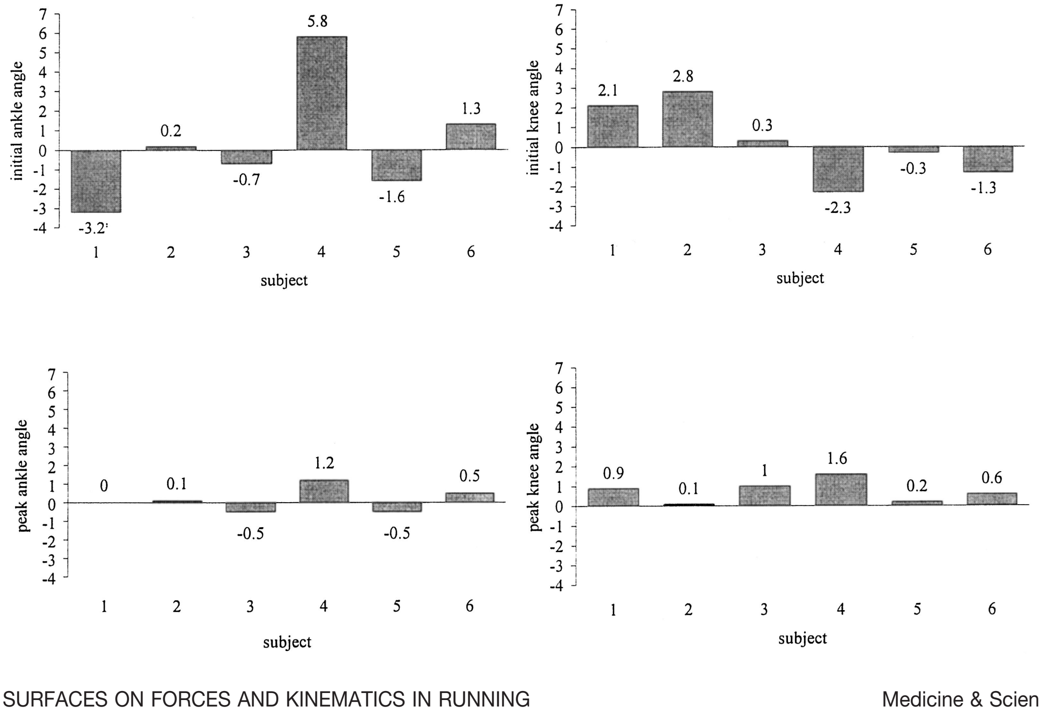

Figure 4—Initial ankle angle, initial knee angle, peak ankle angle, and peak knee angle for the acrylic surface compared with the conventional asphalt surface (degrees). (Note: A reduction in ankle angle indicates a reduced ankle dorsiflexion).

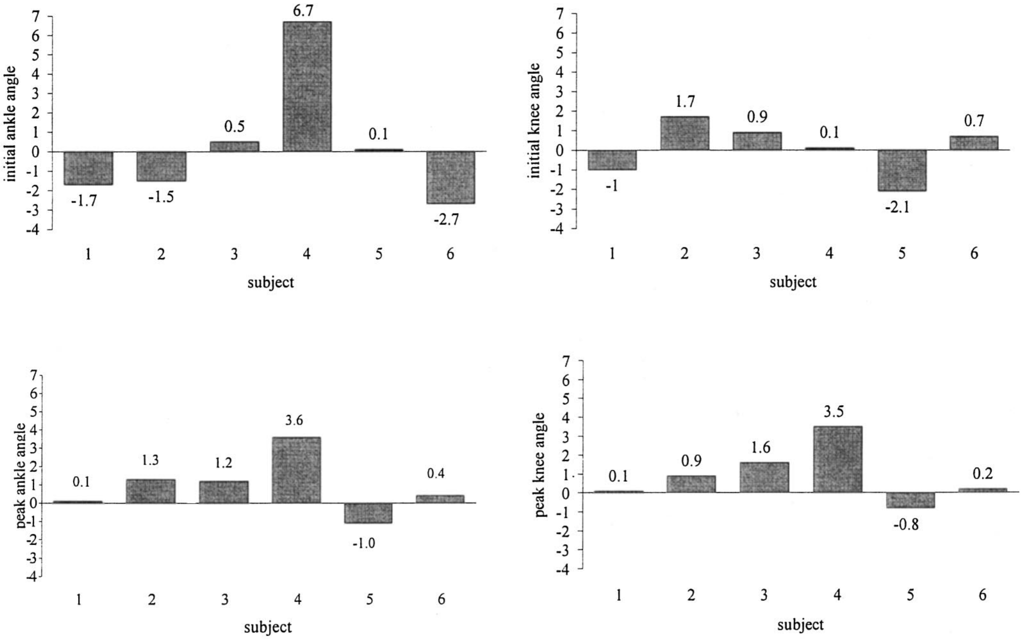

Figure 5—Initial ankle angle, initial knee angle, peak ankle angle, and peak knee angle for the rubber-modified surface compared with the conventional asphalt surface (degrees). (Note: A reduction in ankle angle indicates a reduced ankle dorsiflexion).

angles may also alter the coupling between lower extremity segments, possibly influencing the susceptibility to injury (11,12).

In support of the hypothesis that consistent peak impact force results will be explained by changes in impact kinematics, the peak impact force results can be explained for some subjects. For example, subject 6 showed a greater initial knee flexion, accompanied by negligible change in peak impact force, for the conventional asphalt surface compared with the acrylic surface. It is suggested that the greater initial knee flexion for the asphalt surface is a compensatory adjustment contributing to an increased compliance of the lower extremity at impact for this mechanically less compliant surface. For this same subject, running on the rubber-modified surface compared with conventional asphalt produced consistent initial knee angles, while a reduced peak impact force was observed on the rubber-modified surface. It is suggested that the similar lower extremity compliance when running on these two running surfaces has resulted in the more compliant running surface producing a reduced peak impact force for this subject.

A similar argument can be presented to explain the results for subject 5. This subject was the only one not to exhibit a reduced rate of loading of peak impact force when running on the rubber-modified surface compared with the conventional asphalt surface. Subject 5 was also the only subject to show a reduction in peak ankle dorsiflexion and peak knee flexion for the rubber-modified surface compared with the conventional surface. It is suggested that the greater joint flexion when running on the less compliant conventional surface indicates that joint movements have contributed to providing cushioning of the impact force, resulting in similar loading rates despite differences in surface compliance.

The suggestion that kinematic adjustments before ground contact can account for the similar peak impact forces observed for different subjects is attractive, but many of the observed peak impact force results cannot be explained in this way. For example, subject 3 has been found to exhibit

TABLE 4. Foot segment and ankle and knee joint angular velocities for the conventional asphalt, acrylic surface, and the modified asphalt surface (radians per second); standard deviations are provided in parenthesis.

	Peak Foot Angular Velocity (radians·s^{-1})			Peak Ankle Plantarflexion Velocity (radians·s^{-1})			Peak Ankle Dorsiflexion Velocity (radians·s^{-1})			Peak Knee Flexion Velocity (radians·s^{-1})		
Subjects	**Asph.**	**Acry.**	**Mod.**	**Asph.**	**Acry.**	**Mod.**	**Asph.**	**Acry.**	**Mod.**	**Asph.**	**Acry.**	**Mod.**
Subject 1	16.2	14.8	15.2	11.6	10.7	10.5	9.2	10.0	9.8	12.2	11.7	12.4
	(1.4)	(1.0)	(1.5)	(1.3)	(1.0)	(1.5)	(0.7)	(0.7)	(1.1)	(1.0)	(1.7)	(1.5)
Subject 2	13.6	13.1	12.8	7.6	7.1	7.0	7.9	8.1	8.4	10.2	9.4	10.0
	(1.5)	(1.3)	(1.0)	(1.9)	(1.5)	(1.5)	(0.2)	(0.5)	(0.6)	(1.3)	(1.0)	(1.0)
Subject 3	13.6	13.0	12.4	7.8	7.3	6.7	7.9	7.8	7.7	10.2	10.1	9.5
	(1.5)	(1.0)	(1.0)	(1.5)	(1.2)	(1.2)	(0.4)	(0.5)	(0.4)	(1.2)	(1.4)	(1.6)
Subject 4	11.9	13.3	13.0	6.9	9.6	8.5	6.7	7.4	7.7	8.0	10.2	9.6
	(1.1)	(1.2)	(1.1)	(1.6)	(1.8)	(1.8)	(1.5)	(0.9)	(0.5)	(1.7)	(1.1)	(1.3)
Subject 5	10.8	11.7	11.4	5.5	6.4	6.1	8.4	10.2	8.3	12.1	12.3	12.3
	(0.9)	(1.1)	(0.8)	(1.3)	(1.0)	(1.1)	(0.4)	(2.1)	(0.5)	(1.1)	(0.7)	(0.9)
Subject 6	14.0	14.7	12.5	9.0	9.6	7.5	8.6	9.4	11.7	11.3	13.0	10.6
	(0.7)	(0.8)	(0.7)	(0.9)	(0.7)	(0.8)	(0.9)	(0.9)	(2.9)	(1.3)	(1.2)	(0.6)
Group	13.4	13.4	12.9	8.1	8.5	7.7	8.1	8.8	8.9	10.77	11.1	10.7
	(1.9)	(1.2)	(1.3)	(2.1)	(1.7)	(1.6)	(0.8)	(1.2)	(1.6)	(1.6)	(1.4)	(1.3)

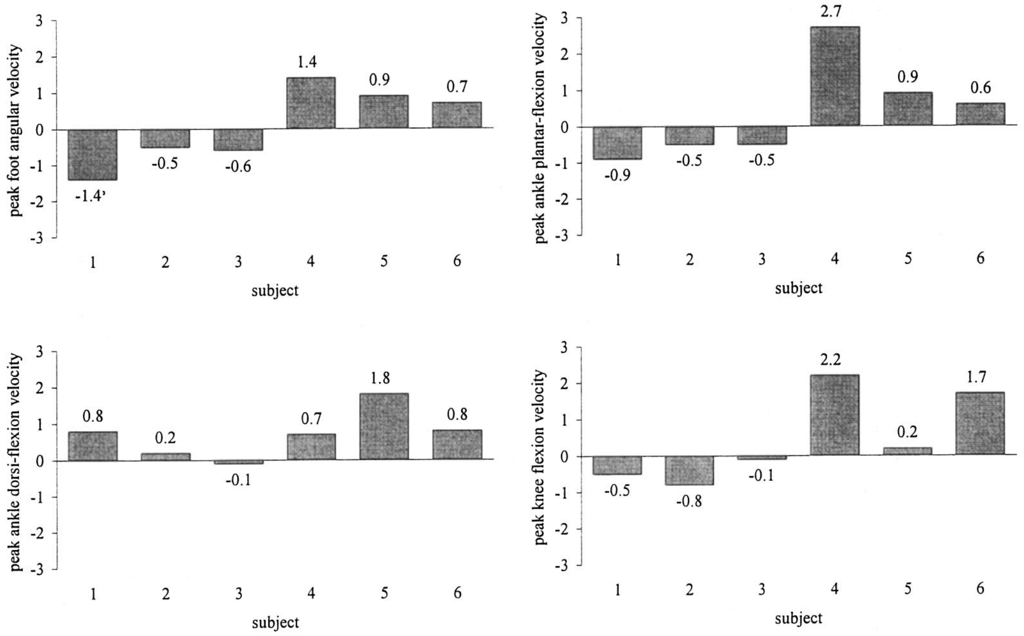

Figure 6—Peak foot angular velocity, peak ankle plantarflexion velocity, peak ankle dorsiflexion velocity, and peak knee flexion velocity for the acrylic surface compared with the conventional asphalt surface (radians·s^{-1}).

similar peak impact force values for all surface conditions, with negligible changes in initial knee angle. There appears to be some other mechanism(s) by which peak impact forces are regulated. An additional variable that has been suggested to contribute to the cushioning of impact in running is rearfoot pronation (21). Measurement of rearfoot motion in future studies may therefore explain the ground reaction force results for some subjects. Of the factors listed by Denoth (5) as influencing peak impact force values, the muscle activity immediately before impact is also a variable that has not been measured in the present study. It has been speculated by Nigg (16) that running on different surfaces influences the activity of lower-extremity muscle groups due to different damping requirements on different surfaces. It is suggested that, in addition to initial joint angles, changes in initial muscle activity may also affect initial joint stiffness, influencing the resulting peak impact force values. This suggestion may account for the presently unexplained peak impact force results, but clearly requires investigation.

The initial conditions monitored in the present study provide an indication of subject adjustments to different surface conditions, whereas the peak joint angles and angular velocities are influenced by these adjustments. A trend has been demonstrated for the peak ankle dorsiflexion velocity to be increased, and peak ankle dorsiflexion and knee flexion angles to be increased for the surfaces providing increased mechanical cushioning. Interestingly, these trends across subjects occur despite the differences observed between subjects in initial joint angles. It is evident that subject kinematics immediately following ground contact are influenced by more than just the initial joint angles.

In contrast to the findings of the present study, an earlier study has indicated that the kinematic response of barefoot runners to surface variation can explain observed peak

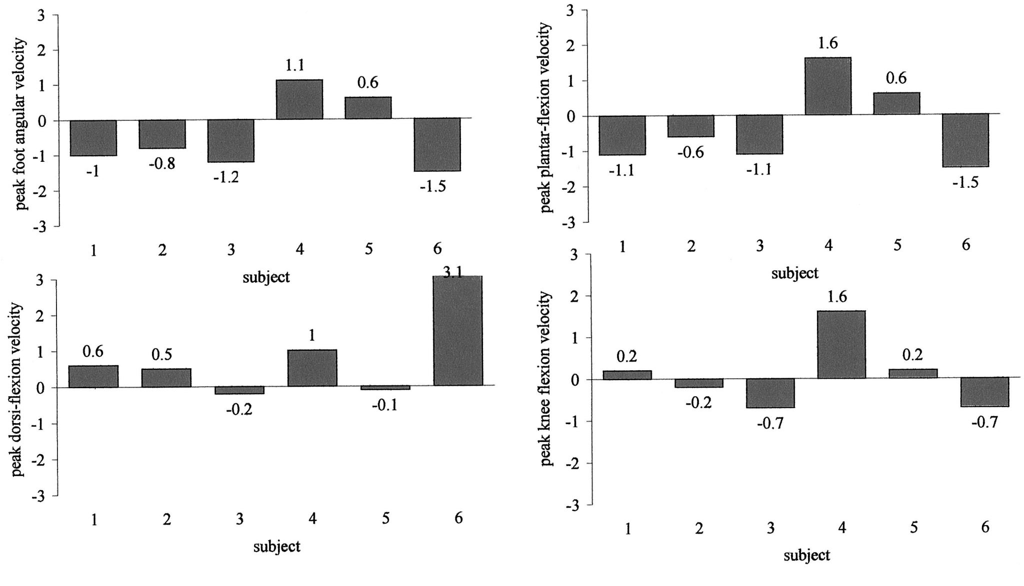

Figure 7—Peak foot angular velocity, peak ankle plantarflexion velocity, peak ankle dorsiflexion velocity, and peak knee flexion velocity for the rubber-modified surface compared with the conventional asphalt surface (radians·s^{-1}).

impact force results for all subjects studied, with initial heel velocity found to be most influential (8). It is suggested that the different results observed in the present study may be due to the wearing of running shoes. The earlier barefoot study allowed the controlled variation of cushioning provided by the impacting interface, providing an insight into human behavior. The use of shoes in the present study has provided a more realistic running condition and highlights the interaction between shoe and surface effects. It is recommended that future studies quantify the combined mechanical impact absorbing properties of the study shoe and surface.

The implication of the study results for the occurrence of overuse injuries appears complex. It is clearly not possible with present knowledge to generalize about the effects of sports surfaces on lower extremity kinematics. Thus, although certain biomechanical characteristics are believed to predispose to the occurrence of specific overuse injuries, it is not possible to identify surface conditions most likely to cause injury occurrence. The current findings would suggest that in depth individual biomechanical assessment is required for the identification of desirable shoe/surface combinations.

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Address for correspondence: Dr. Sharon J. Dixon, Department of Exercise and Sport Science, University of Exeter University, Exeter University, Exeter EX1 2LU, United Kingdom; E-mail: s.j.dixon@exeter.ac.uk.

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