

Shoe Midsole Longitudinal Bending Stiffness and Running Economy, Joint Energy, and EMG

JEAN-PIERRE R. ROY and DARREN J. STEFANYSHYN

Human Performance Laboratory, The University of Calgary, Calgary, Alberta, CANADA

ABSTRACT

ROY, J-P. R., and D. J. STEFANYSHYN. Shoe Midsole Longitudinal Bending Stiffness and Running Economy, Joint Energy, and EMG. *Med. Sci. Sports Exerc.*, Vol. 38, No. 3, pp. 562–569, 2006. **Purpose:** It has been shown that mechanical energy is dissipated at the metatarsophalangeal (MTP) joint during running and jumping. Furthermore, increasing the longitudinal bending stiffness of the midsole significantly reduced the energy dissipated at the MTP joint and increased jump performance. It was hypothesized that increasing midsole longitudinal bending stiffness would also lead to improvements in running economy. This study investigated the influence of midsole longitudinal bending stiffness on running economy (performance variable) and evaluated the local effects on joint energetics and muscular activity. **Methods:** Carbon fiber plates were inserted into running shoe midsoles and running economy, joint energy, and electromyographic (EMG) data were collected on 13 subjects. **Results:** Approximately a 1% metabolic energy savings was observed when subjects ran in a stiff midsole relative to the control midsole. Subjects with a greater body mass had a greater decrease in oxygen consumption rates in the stiff midsole relative to the control midsole condition. The stiffer midsoles showed no significant differences in energy absorption at the MTP joint compared with the control shoe. Finally, no significant changes were observed in muscular activation. **Conclusion:** Increasing midsole longitudinal bending stiffness led to improvements in running economy, yet the underlying mechanisms that can be attributed to this improvement are still not fully understood. **Key Words:** ATHLETIC SHOES, RUNNING PERFORMANCE, METATARSOPHANGEAL JOINT, BIOMECHANICS

Performance in general terms has been defined as the result of a physical activity measured in time, distance, work, or similar quantity (22). Increasing performance relies heavily on efficiently transforming chemical energy to mechanical energy at a cellular level via the musculoskeletal system. The mechanical energy produced allows the body to move during athletic activities.

When mechanical energy is considered in the increase of performance in physical activity, three major strategies have been the focus of attention: (a) optimizing the musculoskeletal system, (b) maximizing the energy returned, and (c) minimizing the energy loss or absorption (22,23). During running, optimizing the musculoskeletal system has not really been addressed although energy return has been attempted with sport shoes as well as sport

surfaces. Although surface constructions have been successful (19,20), footwear constructions have had limited success at returning substantial amounts of energy (1,18,31). The main factor to which this limited success has been attributed is the capability of cushioning materials to return energy (25). Nigg and Segesser (22) suggest that the return of energy is not an appropriate approach to improve performance in sport shoe construction and that focus should be on strategies to minimize energy loss.

Experiments done by Stefanyshyn et al. (27,30) since the mid-1990s have given particular attention to the metatarsophalangeal (MTP) joint and the manner in which this joint contributes to various movements in order to potentially address the strategy of limiting energy loss. Based on data obtained by these authors (27,30), it was shown that the bending of the forefoot or MTP joint causes a loss or dissipation of energy during running, sprinting, and jumping. The authors showed that, by increasing the midsole longitudinal bending stiffness of the shoe and reducing the range of motion of the MTP joint, one could reduce the amount of energy lost at this joint in both running and jumping.

The impact that this energy savings had on performance was quantified by measuring jump height, which increased by 1.7 cm (29). The same authors showed that increased longitudinal bending stiffness of the footwear during

Address for correspondence: Darren Stefanyshyn, Human Performance Laboratory, The University of Calgary, 2500 University Drive N.W., Calgary, Alberta, Canada T2N 1N4; E-mail: darren@kin.ucalgary.ca.

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running also led to a decrease in energy absorbed, yet performance in this case was not measured. Theoretic calculations were made based on an approximate 2% energy savings per stride for a marathon runner who expends 500 J during each stride (22), yet no concrete evidence exists to show a definite physiological advantage.

It is apparent that a gap in the literature exists on how these changes in midsole longitudinal bending stiffness, which are aimed at decreasing energy loss, affect certain movements, such as running. Although theoretic estimates have been made for running, no performance variables have been analyzed. Moreover, the underlying mechanisms linked to longitudinal bending stiffness modifications, which may lead to increases in performance, remain ambiguous.

Therefore, we conducted this study to (a) quantify the effects of increasing shoe midsole longitudinal bending stiffness on submaximal oxygen consumption rate ($\dot{V}O_{2\text{submax}}$) during steady-state submaximal running (running economy); (b) evaluate the effects that increased midsole longitudinal bending stiffness may have on joint energetics at the hip, knee, ankle, and MTP joints; and (c) determine the influence of increased midsole longitudinal bending stiffness on muscular activity in the lower extremities. It was hypothesized that (a) midsole longitudinal bending stiffness would be inversely proportional to the gross metabolic cost; (b) increased midsole longitudinal bending stiffness would decrease the negative work at the MTP joint; and (c) increased midsole longitudinal bending stiffness would decrease the total intensity of the muscular activity of the lower limbs.

METHODS

Statistical power calculations performed on three pilot subjects (Table 1) suggested that nine subjects were required for this investigation. To ensure significant results were found when they existed, this estimate was increased by approximately 50% and data were collected on a total of 13 subjects who had a mean age of 27.0 (SD 5.1) yr, a mean height of 177.1 (SD 4.4) cm, a mean mass of 73.2 (SD 5.4) kg, and a mean $\dot{V}O_{2\text{max}}$ of 57.6 (SD 5.0) mL·kg⁻¹·min⁻¹. Subjects were recruited based on shoe size (9 US), weekly mileage (minimum of 25 km·wk⁻¹), and 10-km race time (≤40 min). All subjects were characterized as heel-toe runners (rearfoot-strikers). All subjects gave their informed written consent according to the guidelines of the University of Calgary ethics committee before their participation.

Three shoe conditions were evaluated. All shoes were based on the Adidas Adistar Comp running shoe and were manufactured by Adidas-Salomon AG. The first shoe was an unmodified control shoe, which had a longitudinal

bending stiffness of 18 N·mm. The two test shoes were modified by inserting a carbon fiber plate throughout the full length of the midsole to increase the longitudinal bending stiffness of the shoe. The test shoes had a longitudinal bending stiffness of 38 N·mm (stiff) and 45 N·mm (stiffest). The longitudinal bending stiffness values of the shoes were measured at the Adidas testing facilities (Scheinfeld, Germany). A three-point bending test was performed on the complete shoe (including shoe upper). The forefoot of the shoe was placed on a frame, which had two supporting points (80 mm apart). A stamp 12 mm thick and 70 mm wide was attached to a material testing machine that measures force and displacement (Instron Corp., Canton, MA., model # 8502). The machine was set to displace the center point of the forefoot 7.5 mm vertically downward in a time of 0.1 s, at which point it returned to its original position in the same amount of time (0.1 s). This cycle was repeated 20 times, and the mean force required to displace the stamp from 5 to 6 mm was used as the longitudinal bending stiffness of the shoe (N·mm). The mass of the shoes (right shoe only) were 241.6 g (control), 236.6 g (stiff), and 240.2 g (stiffest).

Subjects performed a maximal aerobic power ($\dot{V}O_{2\text{max}}$) test using their own running shoes. The purpose of the $\dot{V}O_{2\text{max}}$ test was to determine each subject's anaerobic threshold. The anaerobic threshold for each subject was used to set the submaximal running speed to ensure that the economy tests were performed at the same speed relative to each subject's fitness level. The $\dot{V}O_{2\text{max}}$ protocol used was adapted from the PFLC protocol manual (10). All tests done on the treadmill over the course of this study used a 1% incline to compensate for the lack of air resistance (16). The treadmill velocity was increased by 0.22 m·s⁻¹ at 2-min intervals until the subject reached exhaustion or $\dot{V}O_{2\text{max}}$ criteria had been achieved (10). The measurement of $\dot{V}O_{2\text{max}}$ was calculated every 30 s using a ParvoMedics TrueMax 2400 Metabolic Cart. Gases of known concentration were used for calibration immediately before and following each test (Matheson certified calibration standard).

After the maximal aerobic power test, two adaptation sessions were performed (Table 2). The purpose of this phase was threefold: to allow the subjects to become accustomed to running with the various midsole conditions, to become familiarized with running on a treadmill, as well as to adapt to wearing $\dot{V}O_2$ data collection equipment. These sessions were done to avoid any confounding adaptation effects. During the adaptation sessions, subjects performed the same protocol as the actual economy test sessions described in the following paragraph, the only difference being that no physiological data were collected. One adaptation session was conducted per day over two successive days. The order of footwear conditions was randomly assigned for each of the two sessions. Past research has shown

TABLE 1. Pretest sample size calculation for given power, based on oxygen consumption rate variations between the test shoes and the control shoes, for three subjects tested.

| <i>N</i> | Power (β -1) | Sign. Level (α) | Two-sided | Mean of Alternate Hypothesis | Mean of the Null Hypothesis | SD | Comparison |
|----------|---------------------|--------------------------|-----------|--|-----------------------------|--|-----------------|
| 9 | 0.8 | 0.05 | X | 0.506 mL·kg ⁻¹ ·min ⁻¹ | 0 | 0.467 mL·kg ⁻¹ ·min ⁻¹ | Control – stiff |

TABLE 2. Overview of the general testing schedule for each subject.

| | Week 1 | Week 2 |
|-------|---------------------------|--------------------|
| Day 1 | Prescreening | Economy test |
| Day 2 | | |
| Day 3 | $\dot{V}O_{2\max}$ test | Economy test |
| Day 4 | Adaptation session | |
| Day 5 | Adaptation session | Biomechanical test |
| Day 6 | | |
| Day 7 | | |

Bold areas represent adaptation phase (no physiological data were collected).

that this type of adaptation period is sufficient to allow subjects to become accustomed to running on a treadmill (6) and, based on subject feedback from pilot work, was also sufficient to accommodate to the various shoe conditions.

Before the first economy test of each session, subjects ran a 10-min warm-up in their own shoes. The speed at which subjects ran was equivalent to one workload ($0.22 \text{ m}\cdot\text{s}^{-1}$) below the workload at which anaerobic threshold was achieved (determined from the $\dot{V}O_{2\max}$ test). The average speed for the 13 subjects was $3.7 \text{ m}\cdot\text{s}^{-1}$. Metabolic cost while running in the test shoes was measured using a running economy protocol that was adapted from Daniels et al. (11). A single running economy test for a given shoe condition was 6 min long; the first 4 min were to allow the athlete to reach a steady state and data from the last 2 min were used for the analysis. The only difference between the present protocol and the one used by Daniels et al. was the treadmill gradient. The present study used a 1% gradient, whereas Daniels et al. used a level gradient. A total of four economy tests were conducted during a given testing session. Shoes were assigned in a blinded, randomized fashion for the first three tests. Five-minute breaks were given between each footwear condition to change shoes and consume water, as needed. The fourth economy test, which was a repeat of the first condition tested, was conducted to determine the reliability of the test method. These four economy tests were repeated a second time 2 d later (condition assignments were rerandomized). One day of rest was given between the first and second economy testing sessions to eliminate fatigue. Williams et al. (33) found that approximately 90–98% of the total within-subject variation in economy could be accounted for in 2 and 5 d of consecutive testing, respectively. They concluded that because of the minimal improvement in precision gained by additional testing, the average of two economy sessions per subject would yield an acceptable stable measure of running economy (2 d of testing, three conditions tested each day).

The oxygen consumption values were averaged every 30 s during each 6-min run. The four average samples collected during the final 2 min of each 6-min trial were then averaged to determine steady-state oxygen consumption rates (10). O_2 consumption values were normalized to time (min) as well as to subject's body mass (kg) (10). All testing sessions were carried out at similar times of day for each subject to eliminate the potential variation in $\dot{V}O_2$ caused by circadian rhythm (26).

In a separate biomechanical testing session, subjects performed 20 running trials in each of the three footwear

conditions (total of 60 trials). Kinematic, kinetic, and electromyographic (EMG) data were simultaneously collected during each trial. Kinematic data were acquired with an eight-camera high-speed video capture system (Motion Analysis Corp., Santa Rosa, CA, Model: Eagle) sampling at 240 Hz. Kinetic data were collected using a force platform (Kistler, Winterthur, Switzerland, model # Z 4952c) sampling at 2400 Hz. Timing lights were used to ensure that subjects ran all 20 trials within 5% of the running velocity used for the economy sessions. Biomechanical data collection took place on a separate day following the $\dot{V}O_2$ measurements. This was done to avoid subjects being either physically or mentally fatigued. The shoe conditions were also presented in a blinded randomized fashion for the biomechanical testing session.

Electromyography data acquisition was done with a BioVision data acquisition system (BioVision, Wehrheim, Germany), sampling at 2400 Hz. Five lower-extremity muscles were chosen for data collection: soleus, gastrocnemius medialis, rectus femoris, vastus lateralis, and biceps femoris (long head). Each electrode had a diameter of 10 mm with an intraelectrode distance of 22 mm.

Before biomechanical data collection, subjects were given approximately 10 trials to practice running and striking the force platform with their right foot at the required running velocity (3,24). Once this task could be performed comfortably, reflective markers were placed on the right leg for kinematic data collection. Reflective markers (1.9 cm in diameter) were placed on the first and fifth metatarsal heads, the medial and lateral malleoli, the medial and lateral epicondyles, the greater trochanter, and anterior superior iliac spine. These markers indicated joint centers of rotation of the metatarsophalangeal (MTP), ankle, knee, and hip joints, respectively during standing neutral trials, and were removed for the running trials. In addition, five sets of three (separate) reflective markers arranged in a triangular fashion, but not rigidly connected to one another, were used to represent each segment above and below the joints of interest during the kinematic analysis. Five segments were used for this study: (a) forefoot (phalanges), (b) rearfoot (segment distal to malleoli and proximal to MTP), (c) shank, (d) thigh, and (e) upper body.

For the purpose of this study, three-dimensional kinematic and kinetic data were analyzed, but only the sagittal plane data are reported. Video and force data collected during overground running trials were smoothed using a fourth-order low-pass Butterworth filter. Raw video data were filtered with a cutoff frequency of 10 Hz, and force data were filtered with a cutoff frequency of 100 Hz. These cutoff frequencies are similar to those used by researchers in the past (28,30,34).

Joint moments were calculated using an inverse dynamics approach (4). The body segment parameters utilized were (a) forefoot (phalanges), (b) rearfoot (segment distal to malleoli and proximal to MTP), (c) shank, (d) thigh, and (e) upper body. Anthropometric parameters of the

segments were determined using the data from Dempster (12) and Clauser et al. (7). All calculations (kinetics and kinematics) were performed using Kintrak software (University of Calgary, Calgary, Alberta, Canada). Instantaneous joint powers were calculated by taking the instantaneous product of joint moment and angular velocity. Positive and negative work were then calculated by integrating the power-time curve. Extensor moments at the hip and knee, and plantar flexor moments at the ankle and MTP joints, were defined as positive (30,34).

The EMG data were analyzed for the stance phase of the right leg. The ground reaction forces were used to determine heel-strike and toe-off. A total of 20 steps per condition were used to calculate the means for the EMG data collected while running over ground. A fourth-order band-pass Butterworth filter was used to remove any skin movement artifacts and high-frequency noise (cutoff frequency 10–500 Hz). Root mean square (RMS) values for four different time periods of stance phase were used to compare each muscle's activation level, between each of the shoe conditions. The time windows were defined as: (a) 0–20% of stance phase (heel-strike to foot-flat), (b) 20–70% of stance phase (weight acceptance), (c) 70–100% of stance phase (propulsion phase), and (d) 0–100% of stance phase. These stance phase zones have been previously defined by Donatelli (13).

A one-way repeated-measures ANOVA was used to compare mean differences in metabolic cost ($\dot{V}O_{2\text{submax}}$), joint energy, and EMG root mean square values for all the conditions. If differences were found, a paired *t*-test was performed to evaluate which two conditions were significantly different. A Cronbach's alpha reliability coefficient was used to ensure reliable $\dot{V}O_2$ measures were being obtained for the first and fourth economy tests. For the one-way repeated-measures ANOVA, the level of significance was set at $\alpha = 0.05$, and for the reliability coefficient, the Cronbach's alpha was set at $\alpha = 0.85$.

A Pearson's correlation coefficient was used to compare variations in O_2 consumption rates between conditions with subject mass. The rationale for performing this analysis was to determine whether an athlete's mass may have been a contributing factor to the interindividual variations in metabolic energy savings between shoe conditions.

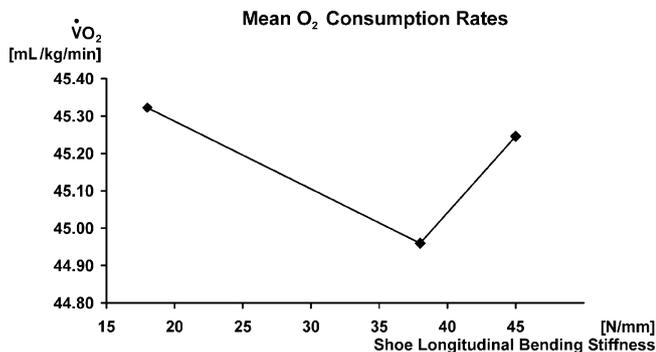


FIGURE 1—Mean $\dot{V}O_2$ values for all 13 subjects tested. Absolute values in each shoe show the U-shaped curve indicating that the stiff shoe may have been the most effective bending stiffness.

TABLE 3. Mean $\dot{V}O_2$ values ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) for each shoe condition.

| Subject | Control | Stiff | Stiffest |
|---------|---------|---------|----------|
| 1 | 41.842 | 41.536 | 42.556 |
| 2 | 49.185 | 49.079 | 49.659 |
| 3 | 42.743 | 42.092 | 42.196 |
| 4 | 47.358 | 46.706 | 46.469 |
| 5 | 42.703 | 42.047 | 42.325 |
| 6 | 47.043 | 46.440 | 46.728 |
| 7 | 47.367 | 46.839 | 47.749 |
| 8 | 46.863 | 46.997 | 46.826 |
| 9 | 48.721 | 48.454 | 48.963 |
| 10 | 43.296 | 43.808 | 43.985 |
| 11 | 38.625 | 38.541 | 38.085 |
| 12 | 46.406 | 45.059 | 45.849 |
| 13 | 47.041 | 46.878 | 46.810 |
| Mean | 45.323 | 44.960* | 45.246 |
| SD | 3.032 | 3.002 | 3.125 |

Values for both economy sessions were combined for the means listed.

* Significant difference compared with the control shoe ($P < 0.05$).

RESULTS

The mean O_2 consumption rates decreased for the stiff shoe condition (stiff: $-0.363 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) relative to the control condition (Fig. 1). The stiff shoe had significantly decreased $\dot{V}O_2$ relative to the control shoe ($P = 0.014$). Eleven of 13 subjects tested showed decreased $\dot{V}O_2$ in the stiff shoes relative to the control shoes (Table 3). A significant reliability coefficient was obtained between economy tests 1 and 4 ($\alpha > 0.85$) for all subjects on both days.

A significant negative correlation ($R^2 = 0.602$; $P = 0.002$) was found between subject mass and decrease in O_2 consumption rate when subjects ran in the stiff shoe condition (Fig. 2). A similar negative correlation was

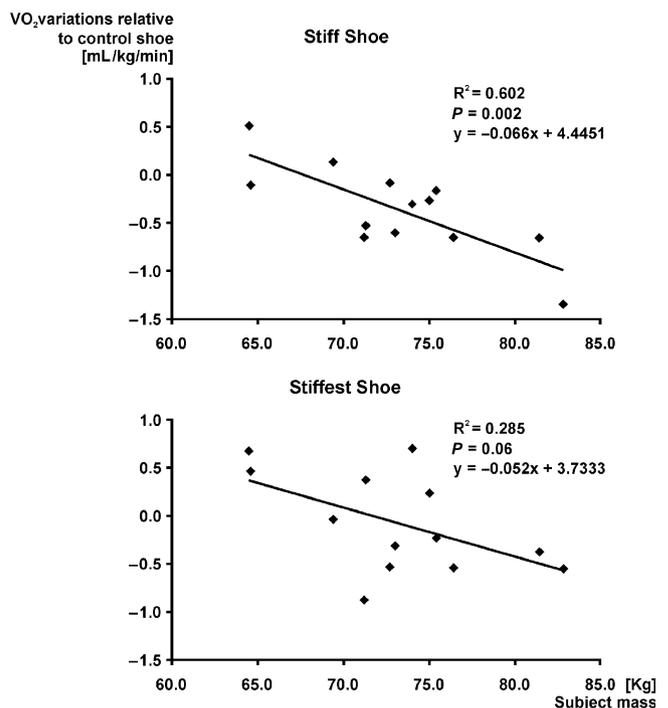


FIGURE 2—Pearson's correlation between $\dot{V}O_2$ variations and subject mass. The y-axis represents the difference in $\dot{V}O_2$ when subjects ran in the stiff and stiffest shoe conditions compared with the control condition ($N = 13$).

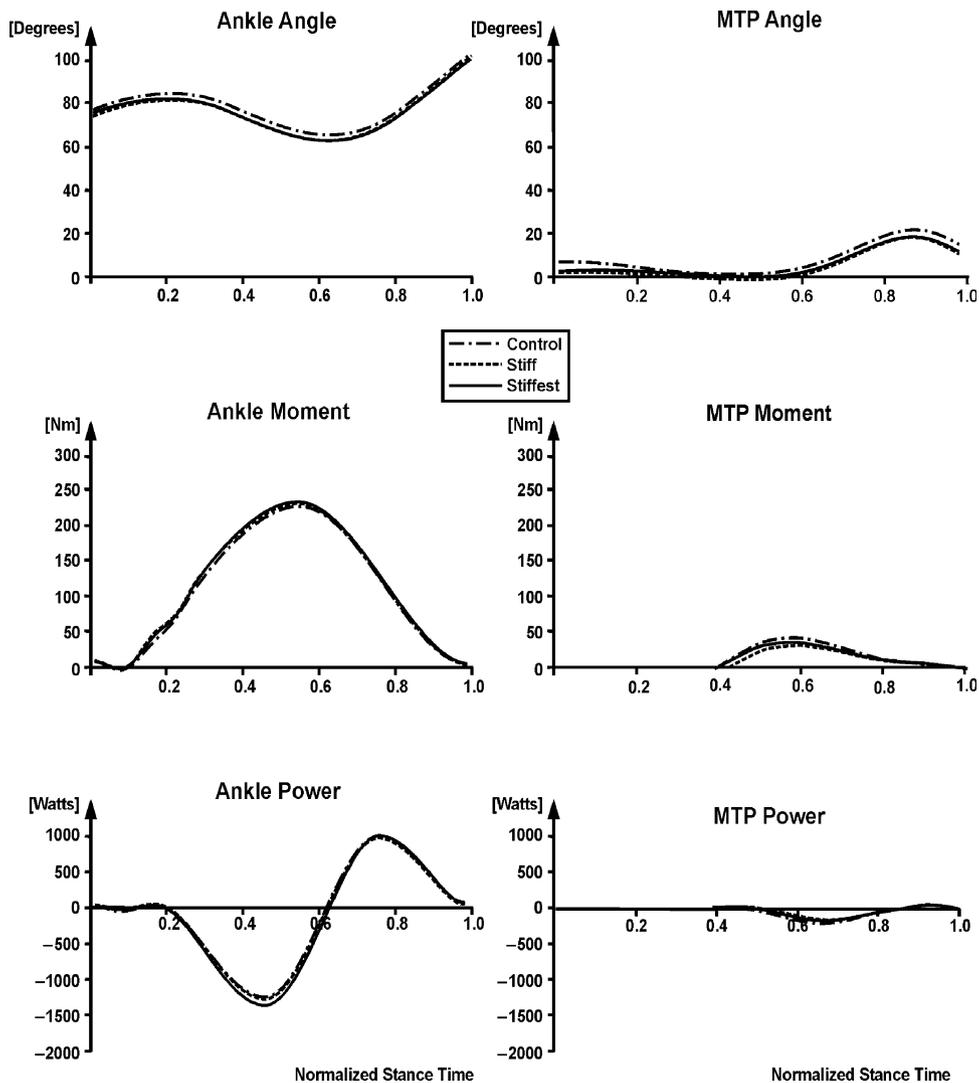


FIGURE 3—Mean angle, moment, and power curves ($N = 11$) for the ankle and metatarsophalangeal (MTP) joints during the stance phase while wearing the various shoe conditions. Time has been normalized from heel-strike (0) to toe-off (1).

found for the stiffest shoe, but it was not significant ($R^2 = 0.285$; $P = 0.06$).

The mean peak ankle moments calculated for each of the three shoe conditions showed significant differences

between all shoe conditions (control vs stiff, $P = 0.044$; control vs stiffest, $P = 0.002$; stiff vs stiffest, $P = 0.048$). The mean peak moment calculated for the control shoes was 231.3 (SD 24.7) N·m, compared with 235.9 (SD 24.7) N·m for the stiff shoes and 240.6 (SD 26.5) N·m for the stiffest shoe (Fig. 3). This was the only joint that showed significant moment differences; the MTP, knee and hip joint moments were not significantly different between conditions.

The only significant difference found for either the energy absorbed or generated at the four joints being

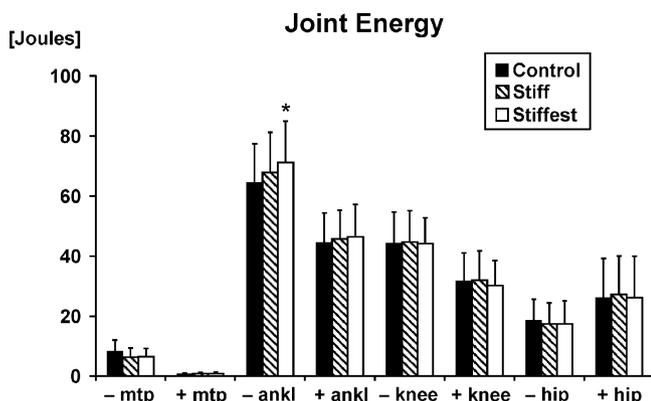


FIGURE 4—Comparison of the energy absorbed (neg) and energy generated (pos) at each of the lower-extremity joints while running in the various shoe conditions. The data presented are means for 11 subjects with standard deviation bars. * Significant difference when compared with the control shoe ($P = 0.001$).

TABLE 4. Group mean (SD) electromyographic (EMG) root mean square (RMS) values of the soleus, gastrocnemius, biceps femoris, vastus lateralis, and rectus femoris muscles for 12 subjects during overground running trials, while in the various shoe conditions.

| Muscle | EMG RMS (mV) | | |
|------------------|---------------|---------------|---------------|
| | Control | Stiff | Stiffest |
| Soleus | 0.322 (0.064) | 0.324 (0.070) | 0.318 (0.063) |
| Gastrocnemius | 0.344 (0.131) | 0.342 (0.141) | 0.324 (0.122) |
| Biceps femoris | 0.151 (0.076) | 0.170 (0.097) | 0.169 (0.086) |
| Vastus lateralis | 0.191 (0.082) | 0.190 (0.08) | 0.183 (0.077) |
| Rectus femoris | 0.113 (0.147) | 0.097 (0.121) | 0.089 (0.107) |

The RMS values represent the overall stance phase, calculated from heel-strike to toe-off.

analyzed was in the energy absorbed at the ankle (Fig. 4). The mean energy absorbed when subjects ran in the stiffest shoe condition was -71.2 (SD 13.8) J compared with -64.4 (SD 13.0) J absorbed in the control shoe ($P = 0.01$). Because of technical difficulties with standing trials for subjects 5 and 8, only 11 subjects were used for the joint energetics analysis.

No significant differences in EMG RMS values were found between any of the shoe conditions, regardless of whether an individual time window was being compared or the overall stance phase was being compared (Table 4). One of the 13 subjects had to be excluded from the EMG analysis because of technical problems with the equipment while recording.

DISCUSSION

This study was conducted to quantify the effects of shoe midsole longitudinal bending stiffness on three different variables during steady-state submaximal running: (a) oxygen consumption rate ($\dot{V}O_{2\text{submax}}$); (b) joint energetics at the hip, knee, ankle, and MTP joints; and (c) muscular activity in the lower extremities. It was hypothesized that the midsole longitudinal bending stiffness would be inversely proportional to the gross metabolic cost. This was not found to be true, because the rate of oxygen consumption ($\dot{V}O_{2\text{submax}}$) did not show a linear decrease as the shoe conditions became progressively stiffer. The second hypothesis proposed that increased midsole longitudinal bending stiffness would decrease the negative work at the MTP joint. This hypothesis was rejected because the negative work was not significantly decreased as the stiffness increased. The last hypothesis was that increased midsole longitudinal stiffness would decrease the total intensity of the muscular activity of the lower limbs. This was also rejected because no significant differences were observed in the RMS values between conditions, regardless of the time windows being compared. The oxygen consumption, kinetic, and EMG data reported in the present study were comparable to other running studies, which had similar subject inclusion criteria and running speeds (9,21,30,36).

The relationship between the $\dot{V}O_{2\text{submax}}$ and the amount of midsole longitudinal bending stiffness can be described effectively as a “U-shaped” curve (Fig. 1). This relationship suggests that an optimal longitudinal bending stiffness may exist to improve running economy. Similar results were found when investigating the influence of midsole longitudinal bending stiffness on sprint performance (27). The improvements found with the stiff shoe tested in the present study can be translated to approximately a 1% gross metabolic cost savings when running one workload ($0.22 \text{ m}\cdot\text{s}^{-1}$) below anaerobic threshold. These savings are slightly more conservative than the 2% savings approximated by Stefanyshyn and Nigg (29) with the use of mechanical energy results.

On further analysis of the individual oxygen consumption rate results (Table 3), a negative correlation was

obtained between subject mass and variations in $\dot{V}O_{2\text{submax}}$ (Fig. 2). This correlation was found while subjects ran in the stiff shoes relative to the control, suggesting that the optimal longitudinal bending stiffness may be dependent on the runner’s mass. A similar negative correlation, although not significant ($P = 0.06$), was found for the stiffest shoe condition. A larger variation was noted in oxygen consumption rate responses in the stiffest shoes relative to the control shoes for the subjects in the mass range of approximately 70–75 kg (Fig. 2). It may be that a finite range of running shoe longitudinal bending stiffness is suitable to improve running economy in a given range of athlete mass. Beyond this finite range, it may be that other factors influence a subject’s physiological response. Although mass does seem to be one of the contributing factors, individual characteristics, whether they be biomechanical, physiological, or even psychological, may also be contributing factors to running economy responses in footwear of various longitudinal bending stiffness.

The present study found no significant difference in the negative work at the MTP joint, whereas Stefanyshyn and Nigg (29) found a significant decrease when comparing their stiff and very stiff test shoes relative to their control shoe. In this study, a trend was noted toward decreased negative work (Fig. 4) as well; however, the differences were not significant ($P = 0.107$), primarily because of smaller differences between conditions. The smaller differences are likely methodological. For the purpose of sagittal plane moment calculations in the present three-dimensional study, the MTP center of rotation was chosen as the midpoint between the fifth and the first MTP marker. Stefanyshyn and Nigg (29), however, performed a two-dimensional analysis and selected the fifth MTP marker as the center of rotation. The energetics calculated at the MTP joint are sensitive to the position of the center of rotation; a 1-cm anterior shift of the joint center marker can lead to a decrease in the mean energy absorbed at the MTP joint by 27% (30). Selecting the fifth MTP as the center of rotation increases the lever arm of the ground reaction force acting on the MTP joint and, therefore, generates greater moments. The current method provided a more conservative MTP moment calculation. Other factors, such as different placements of the carbon fiber plates relative to the foot within the midsole of the shoe, as well as greater variability in MTP power between subjects (Fig. 4), may have contributed to the discrepancies as well.

The EMG data during locomotion can vary considerably between subjects (35), and this was also true for this study. As a result, no significant differences were seen in muscle activity between the different stiffness conditions. One of the limitations of this study was that muscular activation levels were only recorded for two plantar flexor muscles (medial gastrocnemius, and soleus). It is possible that other plantar flexors (i.e., lateral gastrocnemius, peroneus, plantaris, and so on) or that ankle dorsiflexors (i.e., tibialis anterior) may have been affected by midsole stiffness, but these data were not recorded.

Based on previous research (27,29), it was theorized that increased midsole longitudinal bending stiffness would reduce the energy lost at the MTP joint, thus requiring less muscle activity needed to perform the negative work, resulting in an overall improvement in running economy. Although running economy was improved, no change was seen in MTP joint energy or lower-extremity EMG. It appears that the principle of minimizing the loss of energy (22) that was successful for power activities such as sprinting and jumping (27,29) may not apply for endurance activities such as running. Rather, it is speculated that the principle of optimizing the musculoskeletal system (23) may be why the stiff shoes resulted in better running economy. This principle suggests that athletes can manipulate technique and equipment to increase performance by optimizing the contractile properties of the muscles through the force-length and force-velocity relationships.

Although no significant differences in the ankle joint kinematics were noted between the shoe conditions, some subtle changes were seen in joint positions as can be seen in Figure 3. Also a trend ($P = 0.057$) was noted toward increased dorsiflexion angular velocity in the stiff ($352.18^{\circ}\text{s}^{-1}$) and stiffest ($364.5^{\circ}\text{s}^{-1}$) shoe condition, relative to the control shoe ($350.4^{\circ}\text{s}^{-1}$). Thus, increasing the midsole longitudinal bending stiffness appears to have a slight influence on the length and the velocity of stretch of the ankle plantar flexors. Kyrolainen et al. (17) suggested, through *in vivo* force measurements of the Achilles tendon, that higher stretching velocity would generate greater peak force. These researchers based this on findings from subjects running at different speeds (3 and $5\text{ m}\cdot\text{s}^{-1}$), in which muscle tendon unit length changes were estimated using the methods of Hawkins and Hull (14). In the present study, however, speed was held constant between conditions with a slight increase in joint angular velocity, which suggests that a more complex explanation may be required. If the test shoe conditions affect the mechanical behavior of the contractile or elastic elements of the muscle tendon unit, a proper explanation would likely require a computer model of the muscle to estimate the active

state and internal muscle behavior (15). Although it was out of the scope of this investigation, perhaps with the use of a computer model, a reasonable speculation could be made on the mechanisms involved in such an outcome. Based on the results of this study, more work in this area is required because some limiting factor may exist to increasing the midsole longitudinal bending stiffness with footwear modifications; hence, the larger gross metabolic cost savings in the stiff shoe relative to the stiffest condition. Finally, caution should be taken when relating mechanical joint work to metabolic cost (5,8), because energy that may have been stored or transferred through various muscle tendon units does not necessarily incur a metabolic cost (2,32). This may have contributed to the decrease in metabolic cost shown in the stiff shoe condition compared with the control shoe, when no significant changes in net joint work were detected between the two conditions.

In conclusion, the results showed that increased midsole longitudinal bending stiffness significantly improved running economy. Based on these findings, an optimal longitudinal bending stiffness may exist for improved running economy at submaximal velocities. The mean metabolic energy savings related to midsole longitudinal bending stiffness was approximately 1%. The negative correlation between running economy variations and subject mass indicates that energy savings could be improved if shoe stiffness is regulated with a runner's mass in mind. This information may be extremely useful to athletes, coaches, and footwear manufacturers to help improve running performances, even though the underlying mechanisms linked to improved running economy may not yet be fully understood. An initial suggestion for footwear manufacturers may be to explore grading the longitudinal bending stiffness of race shoes according to size. Assuming shoe size correlates positively with runners' mass, it may be beneficial to increase the longitudinal bending stiffness of the footwear as shoe size increases, based on the results of this study.

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