Influence of midsole bending stiffness on joint energy and jump height performance

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ABSTRACT

STEFANYSHYN, D. J. and B. M. NIGG. Influence of midsole bending stiffness on joint energy and jump height performance. Med. Sci. Sports Exerc., Vol. 32, No. 2, pp. 471–476, 2000. Purpose: A substantial amount of rotational energy is lost at the metatarsophalangeal joint during running and jumping. We hypothesized that the lost energy could be decreased by increasing the bending stiffness of shoe midsoles. The purposes of this investigation were to determine the influence of stiff shoe midsoles on changes in lower extremity joint power during running and jumping and to determine the influence of stiff shoe midsoles on vertical jump performance. Methods: Carbon fiber plates were inserted into shoe midsoles and data were collected on five subjects during running and vertical jumping. Results: The data showed that energy generation and absorption at each of the ankle, knee, and hip joints was not influenced by the stiffness of the shoe midsole. The stiff shoes with the carbon fiber plates did not increase the amount of energy stored and reused at the metatarsophalangeal joint; however, they reduced the amount of energy lost at this joint during both running and jumping. Vertical jump height was significantly higher (average, 1.7 cm for a group of 25 subjects) while wearing the stiff shoes. Conclusions: Increasing the bending stiffness of the metatarsophalangeal joint reduced the amount of energy lost at that joint and resulted in a corresponding improvement of performance. Key Words: ATHLETIC SHOES, JOINT POWER, VERTICAL JUMP, RUNNING

Energy considerations during athletic activity have concentrated on two major strategies to improve performance: return of energy and reduction of loss of energy. Return of energy to improve athletic performance has been studied for sport surfaces and sport shoes. In general, a system must fulfill several conditions to return energy (6). It must be able to return the energy at the right time with the right frequency at the right location. Sport surfaces can be appropriately tuned to return energy. Surfaces for floor exercises in gymnastics, runways for tumbling, and tuned track and field surfaces (4,5) are successful examples of energy return by sport surfaces. Return of energy by sport shoes has been attempted several times; however, not very successfully (1,3,10). The main reasons that these attempts were unsuccessful are that materials associated with cushioning are generally not good energy return materials (7) and the location of maximum possible energy storage (the rearfoot) is not the location where effective use can be made of returned energy (6). The concept of reducing the loss of energy has anecdotally been used in certain sport shoe developments. One example is the change from a low-cut to a relatively stiff high-cut cross country skiing boot, which is expected to reduce the work for lateral stabilization of the ankle joint complex. However, the concept of reducing the loss of energy has been restricted to empirical development, and systematic theoretical attempts to use this approach cannot be found in the literature.

During athletic activities, analysis of resultant joint moments and joint power indicate that, for each joint, there are phases when energy is absorbed and phases when energy is generated. If the absorbed energy is dissipated and not stored for later reuse, one could speculate that a reduction of such energy absorption may lead to an increase in performance.

The metatarsophalangeal (MP) joint is one joint where energy is absorbed and no (or very little) energy is generated before take-off. This is because the MP joint dorsiflexes as the athletes roll onto the forefoot and does not plantarflex until after take-off (8). Because no energy is generated at this joint during stance, this energy must be either dissipated and lost or returned at a time after take-off when it will not have an influence on performance. Stiffening the shoe midsole would decrease the energy lost at the MP joint, and such a strategy may have a positive effect on performance. The MP joint absorbed an average of 24 J during one-legged vertical jumping (9). Assuming a body mass of 70 kg, this amount of energy corresponds to a difference in jump height of approximately 3.5 cm.

Consequently the purposes of this investigation were: 1) To determine the reduction in the loss of mechanical energy during running and jumping at the metatarsophalangeal joint after stiffening of this joint in an athletic shoe. 2) To determine whether stiffening the metatarsophalangeal joint influences the mechanical energy production at the ankle, knee, and hip joints during running and jumping. 3) To...
METHODS

The data collected in this investigation consisted of two parts. The first aspect was a detailed analysis of angular energetics during the stance phase for running and jumping using five subjects. The second aspect was a vertical jump test to evaluate jump height performance using 25 subjects.

Shoes. The shoes used in this investigation were commercially available running shoes (Adidas Tech Road). In each of the shoes a pocket was formed by hollowing out a 5-mm thickness of the ethyl vinyl acetate (EVA) midsole to allow insertion of different materials in the midsole (Fig. 1). Three different shoe conditions were tested: a control shoe, a shoe with a stiff midsole, and a shoe with a very stiff midsole. For the control shoe, 5 mm of the same EVA material that had been removed from the midsole was placed in the pocket. For the stiff shoe, three flat carbon fiber plates (Unicarbon, Biomechanical Composites, Camarillo, CA) that were each 1 mm thick were placed in the pocket along with a 2-mm thick insole of EVA. For the very stiff shoe, five flat carbon fiber plates (total thickness of 5 mm) were placed in the pocket. The carbon fiber plates extended nearly the entire length of the midsole and the dimensions were approximately the same as the dimensions of the insole. The different shoe conditions are described in Table 1.

The carbon fiber plates had a flexural strength of 0.77 GPa and a flexural modulus of 68.90 GPa. They were placed in the midsole such that the carbon fibers were aligned along the anterior-posterior axis. The carbon fiber material provided the necessary strength and stiffness properties while keeping the additional mass of the shoes to a minimum (Table 1). The plates were secured together with athletic tape to prevent sliding between the plates that would have resulted in frictional energy losses. The rotational stiffness of the different shoes was determined using a device consisting of a stepper motor and force transducer. The shoe was secured 8 cm from the anterior tip (corresponding to the location of the flexion line) and a load of 20 N was applied at a distance of 5 cm from the flexion line of the shoe. The movement of the stepper motor was used to quantify the deflection of the shoe, which in turn was used to determine the angular displacement of the shoe. The measured stiffness of the shoes was 0.04 N m deg⁻¹, 0.25 N m deg⁻¹ and 0.38 N m deg⁻¹ for the control, stiff, and very stiff shoes, respectively.

Angular energetics. Mechanical power production at a joint was determined by taking the product of the resultant joint moment and the joint angular velocity. Energy absorption (negative work) occurs when the resultant joint moment is opposite in direction to the joint angular velocity, such as during an eccentric contraction. Energy generation (positive work) occurs when the resultant joint moment is in the same direction as the joint angular velocity, such as during a concentric contraction. For this study, changes in joint work during running and jumping were determined on subjects while wearing shoes of three different MP stiffnesses.

Five male distance runners (mean age 32.0 ± 13.8 yr, mean mass 77.3 ± 5.1 kg, and mean height 180.6 ± 2.1 cm) volunteered for the kinetic and kinematic aspects of this study. An additional 20 male subjects (26.6 ± 5.0 yr, 72.6 ± 9.1 kg, and 179.2 ± 4.1 cm) were recruited for the second aspect of this study to determine maximal vertical jump heights. Informed written consent in agreement with The University of Calgary Ethics Committee’s policy was obtained from all subjects.

The order in which the five subjects received the shoes was randomly assigned. The subjects were given the first pair of shoes for a 1-wk period in which they were required to run in the shoes a minimum of 15 km to become accustomed to the shoes. After the 1-wk accustomization period, data were collected while the subjects ran at 4.0 ± 0.4 m s⁻¹. The running speed of the subjects was monitored with photocells placed just before and just after the force platform. Data were also collected on the subjects while performing a one-legged maximal vertical jump with a running approach. Six running trials and six jumping trials were analyzed per subject. Ten trials per movement were actually collected, however, for one subject a maximum of only six trials were usable because of technical problems.

<table>
<thead>
<tr>
<th>Shoe</th>
<th>No. of Carbon Fiber Plates</th>
<th>Carbon Fiber Thickness (mm)</th>
<th>EVA Thickness (mm)</th>
<th>Approximate Mass (g)</th>
<th>Bending Stiffness (Nm deg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>318</td>
<td>0.04</td>
</tr>
<tr>
<td>Stiff</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>370</td>
<td>0.25</td>
</tr>
<tr>
<td>Very Stiff</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>403</td>
<td>0.38</td>
</tr>
</tbody>
</table>

EVA, ethyl vinyl acetate.
Thus, for consistency, six trials was chosen as the standard number to be analyzed per subject and movement. After data collection the shoes were modified and the subjects were again required to run a minimum of 15 km over a 1-wk period to become accustomed to the second shoe condition. Running and jumping data were then collected on the subjects for the second shoe condition, then the final shoe modification was performed. The process of a 1-wk accustomization before data collection was repeated once again for the third and final shoe condition. Thus, a total of 18 running and 18 jumping trials (six trials \times three shoe conditions) were analyzed on each subject over a 3-wk period.

Kinetic data were collected with a force platform (Kistler, Winterthur, Switzerland) sampling at 1000 Hz. Kinematic data were collected simultaneously using a four video camera system (Motion Analysis Corp., Santa Rosa, CA) sampling at 200 Hz. Reflective markers (1-cm diameter) were placed on the toe, the head of the fifth metatarsal, the heel, the lateral malleolus, the lateral epicondyle, the greater trochanter, and the shoulder for kinematic data collection. Anthropometric data collected included subject height and mass as well as lengths of each of the foot, shank, and thigh segments. Inertial parameters were calculated using regression equations from Zatsiorsky and Seluyanov (12). The four video cameras were used to ensure that all of the reflective markers were visible throughout data collection. Also, because more than one camera was used, the three-dimensional coordinates of each of the markers were calculated and reviewed qualitatively to minimize two-dimensional projection errors.

A two-dimensional sagittal plane analysis was performed after smoothing both the video data (fourth-order low-pass Butterworth filter with a cutoff frequency of 8 Hz) and the force data (fourth-order low-pass Butterworth filter with a cutoff frequency of 100 Hz). Resultant joint moments were determined using inverse dynamics (2) and then used to calculate joint power by taking the product of the resultant joint moment and the joint angular velocity (11). It was assumed that the resultant joint moment at the MP joint was zero until the point of application of the ground reaction force acted distal to the joint. Work was determined by integration of the joint power curve. A concentric contraction results in positive power production and positive work or energy generation. An eccentric contraction results in negative power production and negative work or energy absorption.

A one-way repeated measures ANOVA was used to compare the change in joint energy between the different shoe conditions with a level of significance set at \( \alpha = 0.05 \).

### TABLE 2. Mean (SD) of the work performed at the metatarsophalangeal (MP), ankle, knee, and hip joints during running for each of the three shoe conditions.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Control</th>
<th>Stiff</th>
<th>Very Stiff</th>
<th>Control</th>
<th>Stiff</th>
<th>Very Stiff</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP</td>
<td>0.4 (0.2)</td>
<td>0.7 (0.3)</td>
<td>0.7 (0.4)</td>
<td>27.6 (6.4)</td>
<td>19.6* (3.0)</td>
<td>17.7* (2.5)</td>
</tr>
<tr>
<td>Ankle</td>
<td>86.9 (14.4)</td>
<td>75.7 (14.3)</td>
<td>76.1 (9.7)</td>
<td>69.5 (10.0)</td>
<td>64.1 (10.8)</td>
<td>64.2 (11.0)</td>
</tr>
<tr>
<td>Knee</td>
<td>31.0 (5.3)</td>
<td>31.1 (8.7)</td>
<td>30.7 (6.2)</td>
<td>50.1 (10.5)</td>
<td>56.3 (6.5)</td>
<td>54.9 (14.9)</td>
</tr>
<tr>
<td>Hip</td>
<td>10.9 (8.4)</td>
<td>7.2 (4.7)</td>
<td>11.0 (5.8)</td>
<td>14.0 (5.2)</td>
<td>18.4 (8.5)</td>
<td>11.4 (5.3)</td>
</tr>
</tbody>
</table>

* Indicates significantly less than control.

### Vertical Jump Height

Vertical jump heights while wearing the control and stiff (three carbon fiber plates) shoes were compared for 25 subjects. The original five subjects who participated in the angular energetics data collection and an additional 20 male subjects were recruited for this aspect of this study to determine maximal vertical jump heights.

The subjects performed three maximal effort vertical jumps per shoe that were measured using a Vertec height measurement system (Sports Imports, Columbus, OH). The Vertec is a passive mechanical reach indicator with moveable fins or blades placed at intervals of 1.27 cm (1/2 inch). All six jumps were performed in the same session and the order of the shoes was assigned randomly to the subjects to negate any learning effect. A paired \( t \)-test was used to compare the maximal jump height attained during the three jumps between the control shoe and the stiff shoe with a level of significance set at \( \alpha = 0.05 \).

**Repeatability.** To determine the repeatability of the change in joint energy calculations, repeat measurements were taken on the five subjects while running with the control shoes on a different day. Six trials were analyzed per subject. Correlation coefficients were determined for both the positive and negative work performed at each joint on the two different days. For the work variables, the mean of six trials was determined for each subject and correlation coefficients were determined (\( N = 5 \)).

The correlation coefficients for the work performed by the five subjects on two different days were 0.75, 0.54, 0.73, and 0.72 for the hip, knee, ankle, and MP joint, respectively.

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**Figure 2—**Stance phase metatarsophalangeal joint power for a typical running subject (subject 2) while wearing shoes of different stiffness. The energy absorbed at the metatarsophalangeal joint is equal to the area under the negative portion of the joint power curve.
RESULTS

Running energy. There were no significant differences in the amount of energy generated at any of the joints for the different shoe conditions (Table 2). There was also no significant difference in the amount of energy absorbed at the ankle, knee and hip for the different shoe conditions. The only significant difference ($P < 0.05$) was found in the amount of energy absorbed at the MP joint. The energy absorbed at the MP joint while wearing either the stiff shoe (19.6 J) or the very stiff shoe (17.7 J) was significantly less than while wearing the control shoe (27.6 J). Figure 2 is a plot of the MP joint power while running for one typical subject (Subject 2) while wearing the different shoes. The energy absorbed at the MP joint is equal to the area under the negative portion of the joint power curve. Figure 3 displays the differences in MP joint angle for Subject 2 while wearing the different shoes.

Vertical jumping energy. There were no significant differences in the amount of energy generated at each of the joints for the different shoe conditions (Table 3). There was also no significant difference in the amount of energy absorbed at the ankle, knee, and hip for the different shoe conditions. The only significant difference ($P < 0.05$) was found in the amount of energy absorbed at the MP joint. The energy absorbed at the MP joint while wearing either the stiff shoe (20.0 J) or the very stiff shoe (17.1 J) was significantly less than while wearing the control shoe (25.4 J). Figure 4 is a plot of the MP joint power while jumping for one typical subject (Subject 2) while wearing the different shoes. Figure 5 displays the differences in MP joint angle for Subject 2 while wearing the different shoes.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Positive Work (J)</th>
<th>Negative Work (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Stiff</td>
</tr>
<tr>
<td>MP</td>
<td>0.0 (0.0)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Ankle</td>
<td>102.7 (34.3)</td>
<td>96.3 (32.5)</td>
</tr>
<tr>
<td>Knee</td>
<td>60.6 (14.2)</td>
<td>64.0 (12.7)</td>
</tr>
<tr>
<td>Hip</td>
<td>75.4 (41.0)</td>
<td>71.5 (51.5)</td>
</tr>
</tbody>
</table>

* Indicates significantly less than control.
particular movement task. Thus, although some errors undoubtedly exist because of these factors, the magnitude of the error is difficult to quantify. However, it is expected that these errors should not affect the relative comparison between shoes.

Increased bending stiffness of the shoes lead to large decreases in MP joint dorsiflexion (Figs. 2 and 4). The result was a decrease in the amount of energy absorbed at the MP joint. While wearing the stiff shoes, the average reduction in energy lost at the MP joint across all five subjects was 5.4 J during jumping, which would correspond to an increase in jump height of 0.7 cm for an average mass of 77.3 kg. The actual average increase in jump height was 1.4 cm for the five subjects while wearing the stiff shoes. Thus it appears that on average the subjects had an increase in jump height of over twice what could be expected from the reduced negative work at the MP joint. However, Figure 5 shows that the increase in jump height for one particular subject was much greater than the rest of the subjects and much greater than would be expected from the reduced energy lost at the MP joint. The reason for the large increase in jump height for this particular subject is unknown, however, it may be a result of factors that could not be controlled such as psychological factors. The actual increase in jump height of the other four subjects was 0.8 cm which corresponds well with the expected increase of 0.7 cm. The increase in mass of the shoes (approximately 52 g for each stiff shoe and 86 g for each very stiff shoe) did not appear to influence the kinematics of the subjects or the jump height performance. The added mass of the stiff shoes would be expected to have a negative effect and result in a reduction of jump height of about 0.1 cm for the subjects in this study.

Although the average reduction in energy lost at the MP joint across all five subjects was 5.4 J during jumping, the maximum reduction was between 10 J and 15 J depending on the trial and subject. If this amount of energy (10–15 J) was saved in any one particular jump the result would be an increase in jump height of between 1.4 and 2.1 cm for an
average 73.5 kg subject. The difference in jump height between the best jumps of the two different shoe conditions was 1.7 cm for the group of 25 subjects, which corresponds well with that predicted. One point that should be noted, however, was that the highest jump for each of the five subjects was not necessarily the jump in which they had the maximal reduction in energy loss at the MP joint. This can be explained by the fact that maximal performance is not simply the result of physical factors such as mechanical energy but is rather a result of a large variety of factors that could be physical, physiological, or psychological. Additionally, the maximal vertical jump test that was performed in this study was not controlled, and it may be that differences in variables such as approach velocity may have had an influence.

The energy lost at the MP joint was decreased during running by an average of 8 J when wearing the stiff shoes and 10 J when wearing the very stiff shoes. No direct measurements of performance during running were quantified in this study. However, assuming that decreasing the amount of energy lost also has an influence on running performance, this amount of energy saved per running stride would be a saving of approximately 2% if it is assumed that 500 J are expended during each running stride of a marathon (6). Measurements of oxygen consumption with and without stiff midsoles should be performed in future studies to test this theoretical calculation.

There was no significant increase in the energy generated at the MP joint with the stiffer shoes. Even with the stiffer shoes, the MP joint remained in a dorsiflexed position at take-off and was unable to generate any energy during jumping and only a very small amount of energy during running. Thus, the shoe does not straighten until after take-off when the return of energy is too late to have an influence on performance.

There were no significant differences in the energy production and generation at the ankle, knee, and hip joints for different midsole stiffnesses. The lack of statistical significance may be largely because of the limited sample size. One trend was present for the ankle joint, which absorbed and generated less energy with the stiff shoes. This was true for both running and jumping.

Over the past 20 yr, long jump and high jump track and field shoes have progressed to shoes that have relatively stiff midsoles. The data from this investigation may help explain this natural progression to stiff shoes for performance jumping applications. In contrast, shoe manufacturers seem to be moving toward running shoes that are more flexible at the MP joint by either increasing the flexibility of the materials or modifying the structure of the midsole (e.g., incorporating flexion grooves). The authors speculate that this may not be beneficial with respect to performance and rather may be driven by comfort aspects of the recreational runner. However, running performance would need to be directly quantified as a function of shoe stiffness to either support or refute this speculation.

In conclusion, the stiffer shoes decreased the amount of energy absorbed and dissipated at the MP joint but did not affect the energy production at the other joints of the lower extremity. By reducing this lost energy it appears that average performance can be directly influenced as was seen for the jump heights of four of the five subjects. Significant increases in maximal jump height while wearing stiffer shoes (1.7 cm) correspond with maximal reductions in the energy lost. However, because of other factors playing a role in maximal performance the maximal jump height does not necessarily correspond to the jump with the maximal reduction in energy lost.

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