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Athletic Footwear, Leg Stiffness, and Running Kinematics

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Context: The leg acts as a linear spring during running and hopping and adapts to the stiffness of the surface, maintaining constant total stiffness of the leg-surface system. Introducing a substance (eg, footwear) may affect the stiffness of the leg in response to changes in surface stiffness.

Objective: To determine if the type of athletic footwear affects the regulation of leg stiffness in dynamic activities.

Design: Repeated-measures design.

Setting: Motion analysis laboratory.

Patients or Other Participants: Nine healthy adults (age = 28 ± 6.8 years, mass = 71.6 ± 12.9 kg) free from lower extremity injuries.

Intervention(s): Subjects hopped at 2.2 Hz on a forceplate under 3 footwear conditions (barefoot, low-cost footwear, high-cost footwear). Subjects ran on a treadmill at 2 speeds (2.23 m/s, 3.58 m/s) under the same footwear conditions.

Main Outcome Measure(s): Limb stiffness was calculated from forceplate data. Kinematic data (knee and ankle angles at initial contact and peak joint excursion after contact) were collected during running. We calculated 1-way repeated-measures (stiffness) and 2-way (speed by footwear) repeated-measures analyses of variance (running kinematics) to test the dependent variables.

Results: A significant increase in leg stiffness from the barefoot to the "cushioned" shoe condition was noted during hopping. When running shod, runners landed in more dorsiflexion but had less ankle motion than when running barefoot. No differences were seen between the types of shoes. The primary kinematic difference was identified as running speed increased: runners landed in more knee flexion. At the ankle, barefoot runners increased ankle motion to a significantly greater extent than did shod runners as speed increased.

Conclusions: Footwear influences the maintenance of stiffness in the lower extremity during hopping and joint excursion at the ankle in running. Differences in cushioning properties of the shoes tested did not appear to be significant.

Key Words: shoes, gait, hopping task

Running involves moving along the ground in a bouncing fashion.[1–5] Energy is constantly stored and returned in the musculoskeletal system[6,7] by a complex system of springs composed of muscles, tendons, ligaments, and various connective tissues of the lower extremity. This complex system of springs behaves much like a single linear spring when the entire lower extremity is modeled in the sagittal plane.[8,9] Conceptually, this model may be considered as follows: after the foot contacts the ground, joint motion at the ankle, knee, and even the hip lowers the body center of mass (CoM), representing absorption of energy and compression of the spring (Figure 1). During energy generation, the runner's limb is extending, representing recoil of the spring. Subsequently, the more complex activity of running has been modeled successfully using a simple repetitive task such as double-leg hopping.[5,10–13]

Runners encounter a wide variety of terrains with various stiffness properties and act in series with the spring-mass system of the leg. If human leg stiffness were invariant, then efficiency would greatly decrease on a more compliant surface. However, the stiffness of the leg spring varies, depending on the type of terrain with which the limb comes in contact,[14–16] in inverse proportion to the stiffness of the surface on which it is acting. The total stiffness (K_{total}) is the inverse of the sum of the inverse leg stiffness ($1/k_{leg}$) and inverse surface stiffness ($1/k_{surface}$): $1/K_{total} = 1/k_{leg} + 1/k_{surface}$.[17]

The clinical utility of this information is more obvious when we consider the work of Williams et al.[18,19] These authors showed that high-arched runners exhibited greater leg and knee stiffness than low-arched runners at similar running speeds.[18] When the runners' injury histories were examined, those with increased limb stiffness (high arched) were more likely to develop bony injuries, such as stress fractures in the tibia, and those with lower limb stiffness (low arched) were more likely to develop soft tissue injuries on the medial side of the lower extremity.[19] Additionally, the authors suggested

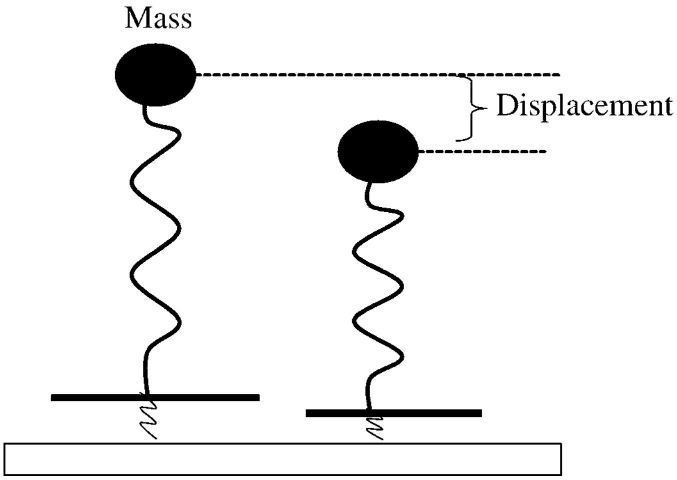

Figure 1. The conceptual model of the limb as a spring. The model represents the lower extremity during running or hopping. Compression of the spring occurs after initial contact during stance-phase absorption in running and is the result of knee flexion and ankle dorsiflexion. The point mass represents the center of mass of the body.

that decreasing lower extremity stiffness might result in decreasing the risk of future bony injury.[18] This finding is of interest to clinicians managing the training and recovery from injury of competitive and recreation athletes, because the type of footwear recommended for the athlete may affect the maintenance of limb stiffness during running.

McPoil[20] described the functions of footwear as protection of the plantar surface of the foot, provision of traction between the foot and the ground, control of motion, and attenuation of impact forces during activity. However, as footwear is introduced as a variable into the limb-surface system, the series of springs that represent the limb should adjust for the new substance in order to maintain overall system stiffness[17]: $1/K_{total} = 1/k_{leg} + 1/k_{surface} + 1/k_{shoe}$. As an example, imagine a runner with a high-arched foot. The runner may be advised to wear "cushioned" running shoes to decrease the impact forces at the foot.[20] If the cushioning in footwear attenuates impact, then overall limb stiffness may be modified during activity. However, the effect of this change in limb stiffness on ankle and knee kinematics and function is not often considered as part of this decision.

Consequently, the purpose of our study was twofold. First, we hoped to determine if the type of athletic footwear affected the maintenance of lower extremity stiffness during hopping. We chose hopping as the modeling task based on previous work validating the use of this model in human locomotion, especially in running.[11,21] We speculated that adding cushioned footwear in series with the limb would require subjects to increase limb stiffness to maintain constant limb stiffness. Specifically, we hypothesized that wearing running shoes (described as "cushioned training" shoes) would result in more limb stiffness than wearing noncushioned shoes or going barefoot. Second, we wanted to examine the effects of different types of footwear on limb kinematics during running at different speeds. Specifically, we hypothesized that subjects would reduce lower extremity joint excursion when running in "cushioned" shoes.

Shoe Properties*

	Low-Cost Shoe	High-Cost Shoe
Weight (g)	280	181
Heel cushioning	Single-density EVA	Dual-density EVA
Midsole construction	Single-density EVA	Dual-density EVA
Forefoot cushioning	Single-density EVA	EVA/rubber

*EVA indicates ethylene vinyl acetate.

METHODS

Subjects

The subjects for this study were 9 healthy adults, 6 men and 3 women (mean age of men = 28 ± 6.8 years, mean age of women = 28 ± 6.8 years; mean body mass of men = 78.9 ± 8.7 kg, mean body mass of women = 57.1 ± 2.6 kg). All participants reported that they had been free from ligamentous or bony injury in the lower extremity and lumbar spine for at least 6 months before participation and that they were in generally good physical condition and accustomed to running on treadmills. All subjects were instructed in the data collection procedures and then signed an informed consent that was approved by the university institutional review board, which also approved the study.

Instrumentation

Force data were collected from a single forceplate (Advance Mechanical Technologies, Inc, Watertown, MA) mounted to the floor of the movement analysis laboratory. Data were amplified using SGA6-4 (Advance Mechanical Technologies) amplifiers (bridge excitation = 2.5, gain = 1000) and digitally sampled at 1000 Hz using the MP150 analogue-to-digital system (Biopac Systems, Inc, Goleta, CA). Data were stored on a desktop computer and analyzed using Acqknowledge (version 3.7; Biopac Systems).

We collected sagittal-plane kinematic data at 50 Hz using a MacReflex (model 3.1b1; Qualysis, East Windsor, CT) infrared video system. The camera was placed 5 m from the treadmill and aligned so that the plane of the camera was parallel to the treadmill. The camera was leveled using the bubble level attached to the camera and set to the height of the subject's knee during quiet standing.

Procedures

We chose and purchased 2 types of footwear locally. The first pair was described by the manufacturer as "athletic joggers" and cost $10 per pair (low cost; Table). The second pair was described as "lightweight cushioned trainers for the high-mileage runner" and had a retail price of $65 (high cost). We randomly selected 2 pairs of each type of shoe for mechanical testing. Each shoe was tested at a fast loading rate (10 mm/s) and a slow loading rate (1 mm/s). The fast loading rate was meant to replicate physiologic loading, and the slow loading rate was indicative of a quasistatic environment. The shoes were mounted onto a mechanical testing machine (MTS Systems Corp, Eden Prairie, MN) and loaded in displacement control at rates of 1 mm/s and 10 mm/s to a maximum load of 2300 N, at which point the shoe was unloaded. Shoe stiffness was calculated by measuring the slope of the most linear portion of the load-displacement curve (Figure 2). Energy ab-

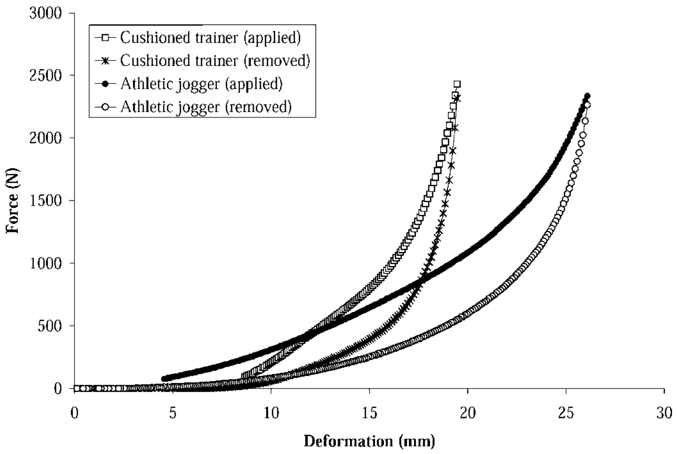

Figure 2. An example of load-displacement data from each type of shoe at the fast loading rate (10 mm/s). The superior line for each shoe represents the force-deformation curve as force was applied to the shoe; the inferior line is the response of the shoe as the force was removed. Cushioned trainer = high-cost shoe; athletic jogger = low-cost shoe.

sorbed by the shoe during mechanical testing was calculated by measuring the area under the load-displacement curve during loading.

Protocol

For data collection, subjects hopped on a forceplate at 2.2 Hz for 3 bouts of 1 minute each, separated by 1 minute of rest. The natural frequency of hopping humans is close to 2.2 Hz.[12] All subjects were given as much time as necessary to practice the task and to become accustomed to maintaining the rhythm. An electronic metronome with an audible timer maintained the rhythm. At 2.2 Hz, the interval between vertical ground reaction force peaks should be 455 milliseconds. Peak ground reaction force rates that fell with intervals within 5% (+23 milliseconds) of 455 milliseconds were considered valid data to be used for comparisons. If electric noise was detected, a band-stop filter was used at 60 Hz.

During the running trials, subjects ran at speeds of 2.23 m/s or 3.58 m/s for 5 minutes on a digitally controlled treadmill (model T55; Quinton Cardiology Systems, Inc, Bothell, WA). Three 30-second bouts (separated by 1 minute) of data were collected at each speed. Running trials were separated by 5 minutes of rest. Retroreflective markers were attached to the superior aspect of the acromion, greater trochanter, lateral condyle of the knee, head of the fibula, lateral malleolus, and fifth metatarsophalangeal joint of the foot following guidelines from the WingZ for the MacReflex motion analysis package (version 2.3; Informix Software, Inc, Lenexa, KS). Our primary interest was sagittal-plane kinematics. Therefore, we used a simple 2-dimensional model, and, subsequently, all filming was from the side to collect sagittal-plane data. Joint angles were calculated using local coordinates and the WingZ for MacReflex movement analysis software. These data were exported to the AcqKnowledge analysis program and low-pass filtered at 10 Hz.

The order of testing (hopping or treadmill) was assigned using a coin toss. Subsequent presentation of the treadmill speeds and footwear conditions was counterbalanced with a Latin square in order to control for fatigue and learning effects. Ten minutes of rest were provided between hopping and running testing.

Data Reduction

The stiffness of the leg spring can be estimated with the equation $K = F/\Delta L$, where the stiffness, K, is the result of dividing F (peak vertical ground reaction force) by ΔL (the change in displacement of the CoM),[11,22] calculated using the double integral of the peak vertical acceleration.[23]

After the primary analysis was complete, we performed an additional analysis. Time between ground contacts represents flight time and provides further insight into whether any change in limb stiffness is related to the footwear or to the prelanding velocity of the CoM.

Kinematic data were processed to provide the joint angle of the knee and ankle at initial contact and the peak knee flexion and ankle plantar-flexion angles that occurred after initial contact. The analysis allowed the ankle angle to be determined; a neutral ankle was expressed as 90°. Dorsiflexion was indicated by an increase in this value and plantar flexion as a decrease. Data were exported to the AcqKnowledge software and low-pass filtered at 10 Hz.

Statistical Analysis

A repeated-measures analysis of variance (ANOVA) was used to examine changes in limb stiffness during hopping (dependent variable), with 3 types of footwear as the within-subjects factor (barefoot, low-cost shoe, high-cost shoe). Flight times between foot contacts during hopping were analyzed (repeated-measures ANOVA) to ensure that prelanding conditions were constant among conditions.[22]

Dependent variables for statistical analyses of running were angle at initial contact and joint excursion (peak flexion angle less angle at initial contact) at both the knee and ankle. Separate 2-way, repeated-measures ANOVAs were computed. Within-subjects factors were running speed (slow and fast) and footwear (barefoot, low-cost shoe, high-cost shoe). Pairwise testing was accomplished with Bonferroni/Dunn corrections to maintain type 1 error at 5%. All statistical analyses were completed using Statview for Windows (version 5.0.1; SAS Institute, Inc, Cary, NC).

RESULTS

Shoe Properties

Load-displacement curves for the shoe mechanical testing revealed nonlinear responses to loading for all shoes. Therefore, we calculated stiffness values from the highest stiffness portion of the load-displacement curve (Figure 2). The low-cost shoe stiffness tested at the fast and slow loading rates was 426 N/mm and 358 N/mm, respectively. The high-cost shoe stiffness tested at the fast and slow loading rates was 257 N/mm and 246 N/mm, respectively. Stiffness measures were quite variable as a result of the nonlinear load-displacement response of the shoe materials. Displacement at peak load values was independent of loading rate. The average displacement at peak load for the low-cost and high-cost shoes was 11.2 ± 0.74 mm and 22.9 ± 1.66 mm, respectively. Energy absorbed by each shoe depended only on the rate at which the shoe was loaded and was unaffected by the type of shoe. Energy ab-

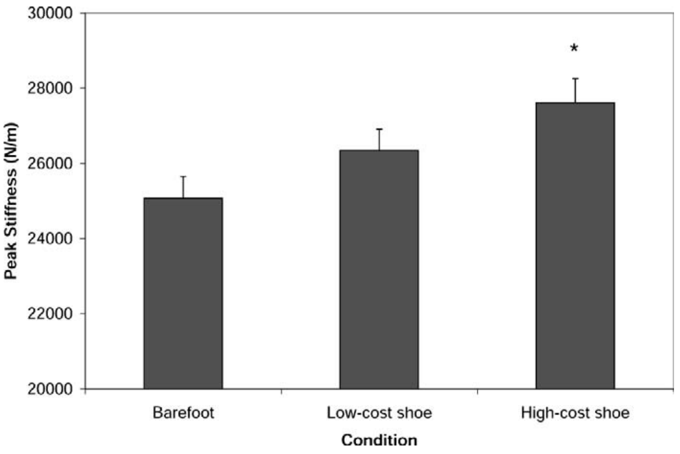

Figure 3. Peak limb stiffness during hopping. *Indicates peak limb stiffness was significantly different in the high-cost shoes versus the barefoot condition (*P* = .002).

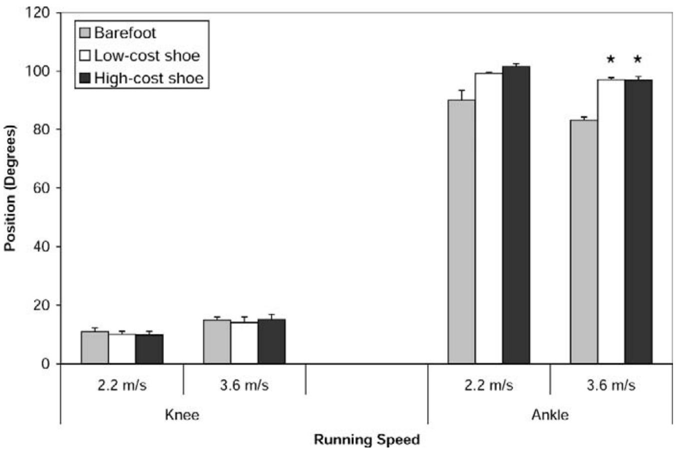

Figure 4. Joint angles at the knee and ankle at initial contact. For the ankle, range of motion is measured such that movement into dorsiflexion is indicated by an increase in the numeric value. * Indicates significantly different from the barefoot condition.

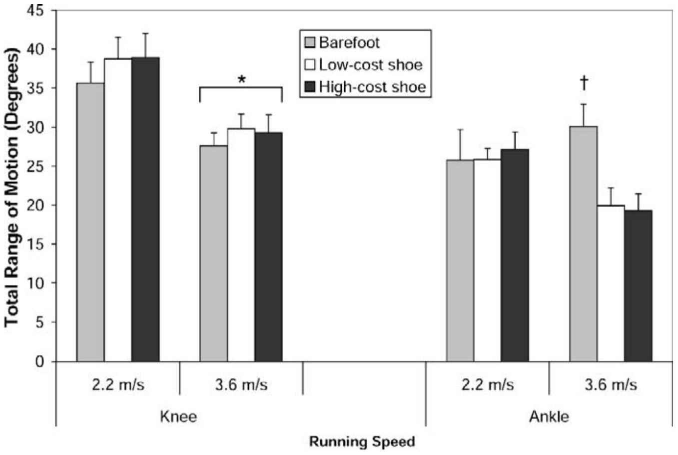

Figure 5. Excursion of each joint to peak joint angle. *Indicates main effect for running speed: less knee excursion occurred when running fast than when running slowly (*P* < .05); †, interaction effect: joint excursion was greater when running barefoot than when wearing shoes at the fast speed.

sorbed was 22.6 ± 0.28 J for the slow rate and 228.3 ± 22.56 J for the fast rate. Based on the peak stiffness measures and the average displacement at peak load, we found the high-cost shoes were less stiff than the low-cost shoes.

Limb Stiffness

No subjects reported difficulty maintaining pace with the metronome during the hopping task. Peak limb stiffness increased when the subject was wearing shoes ($F_{2,16} = 6.04$, *P* = .012, β = .1; Figure 3). Statistically, the peak stiffness with high-cost shoes was greater than noted with the barefoot condition (*P* = .002), but no statistical difference was noted between high-cost and low-cost shoes (*P* = .092) or low-cost shoes and being barefoot (*P* = .091). No statistical difference in limb stiffness between low-cost shoes and being barefoot was seen. Additionally, flight times were not different (*P* = .62) among conditions.

Running Kinematics

Joint Angles at Initial Contact. No interaction was noted between running speed and type of footwear ($F_{2,16} = 0.08$, *P* = .97, β = .94) when examining the knee angle at initial contact, nor were main effects related to the type of footwear ($F_{2,16} = 1.08$, *P* = .36, β = .70). However, a significant main effect was seen for speed ($F_{1,16} = 25.9$, *P* < .001, β = .01): subjects landed in 10° ± 0.5° of knee flexion at the slow speed and 15° ± 0.7° at the faster speed (*P* < .001; Figure 4). For the ankle, a shoe effect was significant ($F_{2,16} = 19.0$, *P* < .001, β = .01), such that subjects landed in approximately 12° more dorsiflexion when wearing either low-cost (*P* < .001) or high-cost (*P* < .001) shoes compared with the barefoot condition. No difference was noted between types of shoe (*P* = .63; Figure 4). No main effect for speed ($F_{1,16} = 3.57$, *P* = .09, β = .63) or interaction effect ($F_{2,16} = 1.64$, *P* = .23, β = .60) was demonstrated.

Joint Excursion After Initial Contact. At the knee, significant main effects were found for speed ($F_{1,16} = 6.12$, *P* = .04, β = .42) and footwear ($F_{2,16} = 4.99$, *P* = .02, β = .37) when considering range of motion to peak knee flexion after initial contact. Less excursion into knee flexion occurred when running at the faster speed (*P* = .04). Similarly, less joint excursion was evident when running barefoot than when wearing shoes (*P* = .01). No interaction was observed at the knee ($F_{2,16} = 0.64$, *P* = .80, β = .92; Figure 5). In contrast, a statistically significant interaction was noted at the ankle for the joint excursion that occurred after initial contact ($F_{2,16} = 8.33$, *P* = .003, β = .06; Figure 5), in which joint excursion increased as speed increased during barefoot running only.

DISCUSSION

We hypothesized that adding shoes to the equation for total limb stiffness would influence peak limb stiffness during hopping and would also modify the running gait. Indeed, our findings indicate that a shoe affects both limb stiffness and running kinematics. For the hopping task, mean values of limb stiffness increased during both shod conditions above values seen with the barefoot condition (Figure 3); however, only with the high-cost shoe were the values statistically different from those measured with the barefoot subject. Subjects were able to maintain hopping frequency, and times between ground contacts were not different among conditions. These data indicate that the prelanding factors were similar among conditions, allowing us to speculate that the changes in peak limb stiffness were related primarily to footwear. Human subjects adapt limb stiffness when the underlying surface stiffness properties are modified.[13,24] We speculate that the introduction of a substance of such low relative stiffness as the running shoe reduced the contact surface (shoe and treadmill) stiffness sufficiently to require our subjects to increase limb stiffness.

Runners landed in more dorsiflexion when wearing shoes than when running barefoot and then had decreased excursion into dorsiflexion as their speed increased. In comparison, a barefoot runner made initial contact in a more plantar-flexed position as the speed of running increased and moved through more ankle motion into dorsiflexion (Figure 4). The opposite was noted at the knee, with an increase in joint excursion when the subject was wearing shoes and a decrease when the subject was running barefoot. These data indicate that runners absorb the impact of initial contact at the ankle when running barefoot. In contrast, we suggest that when wearing shoes, ankle stiffness increases relative to the barefoot position; this concept is supported by the work of Stefanyshyn and Nigg,[25] who noted a significant increase in ankle joint stiffness with increases in running speed.

During running, joint excursion at the knee and ankle decreased after initial contact across all conditions as speed increased (Figure 5). This change was expected based on prior work with hopping[11,26] and running[27] that indicates increases in limb stiffness with increasing frequency of hopping and speed of running. The spring model of the limb requires the spring to lengthen and shorten. Lengthening and shortening are accomplished in the lower extremity by knee flexion and ankle dorsiflexion to shorten or compress the spring and by knee extension and ankle plantar flexion to lengthen the spring. If the spring becomes stiffer, less knee flexion and ankle dorsiflexion occur during shortening or compressing of the spring (Figure 1).

Our kinematic data are similar to those of De Wit et al,[28] who reported kinematic differences between shod and barefoot running that occur predominantly at the ankle. Runners in that study landed with a flatter foot, perhaps to decrease peak impact pressures at the heel and to minimize local pressure at the heel.[28] The sole of the foot is a highly innervated structure, second only to the palm of the hand for density of mechanoreceptors,[29] which function in the regulation of stance and balance in the foot.[30] Robbins et al[29,31–33] published extensively on the theoretic role of plantar sensation as a factor in gait. However, we recently demonstrated that ablating plantar sensation decreased leg stiffness and modified flight time values in a hopping task.[22] Therefore, we think the changes (increases) in limb stiffness observed in our current study are not primarily the result of modification of plantar sensation.

One of our initial hypotheses had been that differences in the cushioning properties of a shoe would affect overall limb stiffness. We did find differences between the more cushioned (high-cost) shoe and being barefoot, but we found no differences between the cushioned (high-cost) and less-cushioned (low-cost) shoes. Post hoc power analysis indicated that 350 subjects would be needed to find a difference between the types of shoes used in our study using limb stiffness as the dependent variable. Also, although this study had adequate power to identify an interaction at the ankle involving the type of footwear and speed of running, it lacked sufficient power to find interactions at the knee. Post hoc calculations indicated that in order to set power at 80% to find a difference in knee angle at initial contact, we would have needed 321 subjects. To find a main effect difference between types of athletic shoes would require 270 subjects. Although these numbers of subjects may reflect improved external validity of the data, given the vast number of competitive and recreational runners, we are not confident that the data would be meaningful clinically.

Furthermore, limitations exist with regard to the interpretation of the kinematic data using the 2-dimensional model we employed. Our primary interest was in examining the sagittal-plane changes in joint angle to compare the running and hopping data. Running, however, is a 3-dimensional activity and, consequently, changes in kinematics that occurred in the frontal and transverse planes during pronation at the subtalar and midtarsal joints under the different footwear conditions could not be examined. Nor could frontal-plane changes at the hip and knee be detected. We are unable to comment, for example, on whether the type of footwear influenced foot motion. Additionally, we did not model forefoot motion. Recently, Oleson et al[34] reported that the forefoot does not behave as a linear spring during running. The limb-spring model we used does not consider the forefoot as a specific part of the spring; rather, the foot is modeled as a solid segment. Nonetheless, we are confident that these data reflect real changes in limb stiffness in response to wearing athletic footwear compared with running barefoot.

Clinical Relevance

Cushioned shoes are recommended for athletes to decrease impact forces at the heel or on the feet in general.[35] Our data appear to indicate that these recommendations need to be tempered by the expectation that although direct impact forces on the heel or foot may decrease, limb stiffness may, in fact, increase. Robbins and Waked[36] suggested that advertising of athletic footwear with regard to ‘‘cushion impact’’ may be deceptive because expensive athletic shoes accounted for more than twice as many injuries as cheaper shoes in their study. Recent authors[37] tested subjects on a landing task and followed them longitudinally. Uninjured subjects had lower peak vertical ground reaction force values in the presence of similar knee-flexion ranges, indicating that they may have had less limb stiffness than subjects who were injured.[37] Thus, increased limb stiffness may be detrimental as a landing strategy. Additionally, runners with high arches had greater leg stiffness than runners with low arches.[19] Runners with greater leg stiffness had a higher incidence of bony injuries, whereas runners with lower leg stiffness experienced more soft tissue injuries in the distal extremity.[19]

CONCLUSIONS

These data support the supposition that footwear causes changes in the limb during a dynamic task such as running. Runners landed in more dorsiflexion at the ankle and had less joint excursion when shod than when barefoot. However, the effect of footwear on joint kinematics cannot be predicted based on the properties of the shoes. Thus, the specific mechanical properties of footwear cushioning may not be a primary determinant of change in kinematics during running. Our future work will examine interaction effects between foot type and footwear properties and limb stiffness.

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