Medial Compressible Forefoot Sole Elements Reduce Ankle Inversion in Lateral SSC Jumps

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Sideward movements are associated with high incidences of lateral ankle sprains. Special shoe constructions might be able to reduce these injuries during lateral movements. The purpose of this study was to investigate whether medial compressible forefoot sole elements can reduce ankle inversion in a reactive lateral movement, and to evaluate those elements’ influence on neuromuscular and mechanical adjustments in lower extremities. Foot placement and frontal plane ankle joint kinematics and kinetics were analyzed by 3-dimensional motion analysis. Electromyographic data of triceps surae, peroneus longus, and tibialis anterior were collected. This modified shoe reduced ankle inversion in comparison with a shoe with a standard sole construction. No differences in ankle inversion moments were found. With the modified shoe, foot placement occurred more internally rotated, and muscle activity of the lateral shank muscles was reduced. Hence, lateral ankle joint stability during reactive sideward movements can be improved by these compressible elements, and therefore lower lateral shank muscle activity is required. As those elements limit inversion, the strategy to control inversion angles via a high external foot rotation does not need to be used.

Keywords: shoes, ankle sprains, foot progression angle, kinematics, kinetics, EMG

Lateral movements are central components in such sports as basketball, handball, soccer, volleyball, and tennis. They occur in complex motions, such as in cuttings or in side shuffles. These lateral movements have in common that they are generally realized as a reactive stretch-shortening cycle (SSC) conducted to the side. The SSC describes a combined muscle action in which the preactivated muscle is stretched during landing, immediately followed by a concentric push-off contraction. As the lower extremity joints’ anatomy and the joints’ encompassing muscles provide less potential for stabilization in the frontal plane, these lateral SSCs are biomechanically rather difficult to control compared with sagittal plane movements.

Thus, excessive frontal plane ankle joint inversions during lateral SSC movements often result in lateral ankle sprains. Ankle sprains occur when the external inversion moments acting on the ankle joint (1) are greater than the counteracting internal eversion moments provided by the ankle joint’s encompassing muscles and ligaments, and (2) when these external inversion moments consequently cause a further rapid acceleration of inversion beyond the normal range of motion. Those injuries represent the most common peripheral joint injury. A movement analysis of ball games showed that basketball had the highest frequency of movements related to the occurrence of ankle sprains: lateral motions, rotations, jumping, and landings. Long-term analysis of American collegiate basketball also shows that approximately 1/4 of all injuries in this sport are ankle sprains.

Thus, in particular in basketball, but also in other court sports with high incidences of ankle sprains, external devices such as braces and tapes are applied to the ankle to laterally stabilize the joint and to reduce ankle joint injuries. Besides these measures, special sport shoe construction characteristics try to improve the lateral ankle joint stability. The lateral stability of a sport shoe can be defined as the ability to resist inversion. One central measurement to improve the lateral ankle joint stability in basketball is to heighten the shoe shaft to limit the ankle inversion. But so far only a few studies evaluated basketball shoe sole constructions with respect to ankle joint stability. When the influence of the shoe sole on lateral ankle joint stability is being analyzed, it needs to be considered that soles provide a greater leverage to the frontal plane ankle joint moment compared with a barefooted movement conduction. Therefore, special rearfoot sole constructions were developed to enhance lateral ankle joint stability during frontal plane movements. These constructions should reduce inversion angles and the corresponding moment leverage. Stacoff et al could, for instance, demonstrate that a rearfoot sole construction which moved laterally under loading increased the foot’s inclination and consequently reduced ankle inversion.
Also a medially banked rearfoot sole allowed a greater foot inclination during sideward landings which suggested a lower ankle inversion in comparison with a shoe with a standard sole design. But the influence of banked forefoot sole constructions on ankle stability has not been the subject of any investigations.

In addition to external mechanical ankle stabilization measurements, lateral ankle joint stability also depends on neuromuscular control. Thus, in particular the peronei oppose an ankle inversion. The function of these muscles to provide dynamic stability during lateral movements is therefore considered to be important to impede a lateral ankle sprain. Consequently, peroneal reactions to sudden inversion movements were the subject of many studies as reviewed by Menacho et al. In dynamic motor tasks, it has been observed that subjects suffering from chronic ankle instability exhibit reduced peroneus longus activity accompanied by increased ankle inversion during drop jumps. This observation leads to the assumption that peroneus longus activity might be of importance for lateral ankle joint stability during reactive lateral movements. Unfortunately, the presented studies investigating the influence of rearfoot sole modifications on lateral ankle stability did not analyze muscle activity. Hence, so far the effect of sole construction modifications on the muscular ankle joint stability during dynamic lateral movements remains unclear.

A recent study focusing on load adjustment strategies in reactive lateral SSC jumps demonstrated that a greater externally rotated foot placement marks a central strategy to shift loading from the frontal to the sagittal plane, which is less prone to acute lower extremity joint injuries. In gait analysis it could be demonstrated that an external foot rotation compared with a neutral or internally rotated foot positioning reduces ankle inversion as well as inversion moments. As foot placement influences frontal plane ankle joint mechanics, this might be an important parameter in the evaluation of footwear influence on the lower extremity motor control in reactive lateral SSC movements.

As demonstrated by Stacoff et al., shoes with rearfoot banking concepts are able to reduce ankle inversion. However, taking into account that dynamic lateral movements are generally characterized by initial medial forefoot contact, rearfoot sole constructions and their influence on ankle joint stability in reactive lateral movements should be investigated. Therefore, it was the purpose of the current study to investigate whether medial compressible forefoot sole elements reduce inversion during the landing phase of a reactive lateral movement.

We hypothesized that these sole elements would as a consequence of a lower forefoot inversion reduce ankle inversion in comparison with the reference shoe. We further hypothesized that lower ankle inversion with the shoe containing medial compressible forefoot sole elements would cause reduced lateral shank muscle activity. Our third hypothesis addressed foot placement: lower frontal plane ankle joint loading accomplished by lower ankle inversion would result in a less externally rotated foot placement with the shoe containing the modified forefoot sole. This assumption lead to the final hypothesis: the different foot placement strategy with this modified shoe will affect mediolateral ground reaction forces.

**Methods**

Twelve male basketball players (192 ± 4 cm, 87 ± 9 kg, 24 ± 3 y) who were familiar with conducting lateral movements participated in the study. They gave their written consent to participate in the approved study design, which was conducted according to the Declaration of Helsinki. All participants were free of pain on the test day and had no history of severe orthopedic or neurological disorders. They had not sustained an ankle sprain during the previous year.

Subjects performed reactive lateral SSC jumps onto a force plate. From a starting position, subjects jumped laterally with their left leg onto the force plate and back to the starting position. Landing on the force plate was performed one-legged, forefoot first, and oriented on a mark fixed perpendicular to the direction of motion onto the force plate. Subjects were instructed to jump back from the force plate to the starting position as fast as possible, to omit trunk rotations, and to keep their jumping technique consistent throughout the measurements. In pilot measurements, lateral SSC jumps proved to be a suitable approach to functionally evaluate medial forefoot sole designs on lower extremities mechanical and neuromuscular adjustments in dynamic frontal plane movements.

Two different basketball shoe sole properties (size UK 12.5) were tested in the study: (1) the reference shoe (Ref), which represented a common basketball shoe with a standard court shoe sole construction (Figure 1a). (2) The second basketball shoe (Figure 1b) was a prototype with a modified medial forefoot sole construction (modS). Besides this special medial forefoot sole element, both shoes were identical in shape, materials, and fitting. Whereas the sole of the reference shoe was exclusively made of the elastomeric material ethylene vinyl acetate, a special banking element was implemented in the medial forefoot sole of the modified shoe. This banking element consisted of soft synthetic polymer sheathing which formed in the midsole four hollow inner core chambers (Figure 1b). In contrast to the solid and therefore stiffer lateral forefoot and rearfoot sole, these hollow inner core chambers can be easily compressed under pressure. Therefore the forefoot sole of the modified shoe (478 N/mm) had a lower overall forefoot stiffness than the reference shoe (505 N/mm). Under lateral loading these medial forefoot sole elements of the modified shoe are being compressed, and hence foot inclination increases in these conditions. This banking effect is expected to reduce forefoot and consequently ankle inversion during a lateral movement.

To evaluate whether with the modified shoe frontal plane ankle joint mechanics are adjusted differently to stretch-load variation than with the reference shoe, study participants performed lateral SSC jumps with both shoes from four distances. According to Fleischmann et al., the four jumping distances were determined with respect...
to the maximum individual lateral jumping distances: Extreme distance (EXD) was set at 100%, long distance (LOD) at 85%, medium distance (MED) at 70%, and short distance (SHD) at 55% of the maximum individual lateral jumping ability.

From each of the four distances, ten lateral jumps were performed. The order of the four jumping distances as well as the order of the shoes were randomized. To exclude learning effects for each footwear condition and jumping distance, the participants could try conducting the movement until feeling comfortable before measurements started. All trials were visually controlled and repeated in the case of an incorrect movement conduction.

Ground reaction forces were measured using a force plate (OR-6-7-2000; Advanced Mechanical Technology Inc, Watertown, MA) with a sampling frequency of 1,000 Hz. Force plate (threshold 10 N) data served as the basis for calculating ankle joint moments and to determine ground contact times. A 3D-motion analysis system (Vicon V-MX, Vicon Motion Systems Ltd., Oxford, UK) consisting of 12 near-infrared cameras with a sampling frequency of 200 Hz was installed to record the kinematics of the subjects’ left leg. Retro-reflective markers (14 mm) were placed on anatomical landmarks of the pelvis and the lower left extremity—more precisely, onto the anterior superior iliac spines, the posterior iliac spines, the great trochanter, the medial and lateral epicondyles, two markers onto the tibia, and on the medial and lateral malleolus. Additional markers were externally fixed onto identical positions on the left shoe of the two tested shoe models. Three of these shoe markers were fixed onto the medial, lateral, and upper forefoot cap, and another three markers onto the medial, lateral, and posterior aspect of the lower heel cap.

Kinematic and kinetic data were analyzed using Vicon motion analysis software (Nexus 1.3, Vicon Motion Systems Ltd., Oxford, UK). Calculations were performed according to recommendations of Grood and Suntay and Wu et al. Joint moments were computed using a standard inverse dynamic approach.

For the purpose of this study, the first 25% of ground contact characterizing the early landing (early deceleration) phase were considered. Special emphasis was put to this phase because ankle sprains typically occur during deceleration shortly after touch-down. Thus, mean vertical and mediolateral ground reaction forces of the first 25% of ground contact were calculated. To investigate the influence of the shoe sole characteristics on lateral ankle joint stability, frontal plane joint mechanics were analyzed. Maximum inversion which takes place during that period of ground contact was determined. In addition, the inversion angle at touch-down and the maximum ankle inversion moment were analyzed.

Foot placement was determined by the foot progression angle. The foot progression angle describes the foot’s transversal orientation in relation to the global coordinate system. Hence, this angle characterizes the deflection of the foot’s longitudinal axis from the landing position perpendicular to the direction of motion. A negative foot progression angle has been defined as internal rotation and a positive angle as external rotation. The foot progression angle was analyzed at the moment of touchdown, to investigate possible footwear-dependent differences in the foot placement strategy initiated before ground contact. The foot progression angle at 25% of ground contact was determined to analyze foot placement after the heel was lowered to the ground.

Bipolar surface electrodes (Blue Sensor, Ambu, Balerup, Denmark) were used to record EMG activity of the shank muscles. Muscle activity of the following left shank muscles was analyzed: gastrocnemius medialis, gastrocnemius lateralis, soleus, peroneus longus, and tibialis anterior. The reference electrode was placed on the medial anterior aspect of the tibia. Skin preparation and electrode placement followed SENIAM recommendations. EMG signals were sampled at 1,000 Hz.

EMG data were processed by a LabVIEW-based (National Instruments, Austin, USA) software tool (IMAGO, University of Freiburg, Freiburg, Germany). Data were bandpass filtered (Butterworth, 2nd order, 10–500 Hz), full-wave rectified and integrated (IEMG). With respect to ankle joint stability during the landing phase, the IEMG of the shank muscles was calculated between touchdown and 60 ms of ground contact. This interval was in previous studies used to evaluate ankle inversion in lateral movements.

A two-factor analysis of variance for repeated measurements was calculated to analyze possible dependent variables’ differences between the two shoes under the four stretch-load conditions. An alpha level of 0.05 was selected to identify statistical significance.

If a main effect on a dependent variable between the two movements could be observed, differences between
the two shoes concerning this parameter were further analyzed by paired-samples t tests for each stretch-load condition. Data normal distribution was tested by the Kolmogorov-Smirnov test. Based on the low number of degrees of freedom and the interindividual dependent variable variances, the reported alpha level was used for these tests to exploratively describe the influence of the four stretch-load conditions on the two observed movements.

Statistical calculations were performed with SPSS 15.0 (SPSS Inc., Chicago, USA). Results are presented as group mean values ± standard deviation. For better readability, the results of the paired samples t tests, but not the main effect analyzed with the two-factor analysis of variance are incorporated in the graphics. The latter values are presented in the text.

Results

Mean mediolateral ground reaction forces were higher (P < 0.001) with the modified shoe than with the reference shoe (Table 1). As Table 1 also indicates, mean vertical ground reaction forces during the first 25% of ground contact did not show differences between the two shoe conditions. Contact times did not differ between the modified shoe with the medial compressible forefoot sole elements and the reference shoe.

The shoe comparison revealed significantly reduced initial inversion (P < .001) and maximum inversion (P = .002) with the modified shoe (Figure 2a,b). Figure 2c illustrates that no significant differences for the initial maximum inversion moments between the two shoes could be found.

Foot placement occurred with the modified shoe with a lower external rotation in comparison with the reference shoe. Thus, with the modified shoe the external rotation of the foot at touchdown was lower (P < .001) than with the reference shoe (Figure 3a). Also at 25% of the ground contact phase when the heel had been lowered to the ground, with the modified shoe the external rotation was lower (P < .001) than with the reference shoe (Figure 3b).

Table 1  Ground reaction forces and ground contact times for reference and modified shoes

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<thead>
<tr>
<th></th>
<th>SHD</th>
<th>P</th>
<th>LOD</th>
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<td>Mean Mediolateral GRF (N)</td>
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<tr>
<td>Ref</td>
<td>473.98 ± 90</td>
<td>541.41 ± 117</td>
<td>**</td>
<td>633.84 ± 98</td>
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<td>703.44 ± 67</td>
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<tr>
<td>modS</td>
<td>498.39 ± 100</td>
<td>570.05 ± 101</td>
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<td>666.78 ± 102</td>
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<td>756.99 ± 87</td>
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<td>Mean Vertical GRF (N)</td>
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<tr>
<td>Ref</td>
<td>932.11 ± 222</td>
<td>974.78 ± 188</td>
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<td>1080.70 ± 218</td>
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<td>1138.37 ± 31</td>
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<td>modS</td>
<td>953.92 ± 152</td>
<td>953.06 ± 167</td>
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<td>1079.88 ± 202</td>
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<td>1179.89 ± 153</td>
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<td>Ground Contact Time (s)</td>
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<tr>
<td>Ref</td>
<td>0.313 ± .04</td>
<td>0.366 ± .05</td>
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<td>0.411 ± .02</td>
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<td>0.487 ± .05</td>
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<tr>
<td>modS</td>
<td>0.323 ± .03</td>
<td>0.369 ± .04</td>
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<td>0.423 ± .04</td>
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<td>0.493 ± .07</td>
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Note. Ref = reference shoe, modS = modified shoe, SHD = short distance, MED = medium distance, LOD = long distance, EXD = extreme distance, GRF = ground reaction force. *P < .05; **P < .01; ***P < .001.
3b). The foot progression angle during ground contact of a lateral SSC jump is shown in Figure 4 for one subject. The graphic additionally illustrates the parameters inversion angle, inversion moment, and the mediolateral ground reaction force.

The shoe comparison revealed a tendency to lower muscle activities during the initial landing phase with the modified shoe (Figure 5). IEMGs were significantly reduced in the lateral shank muscles peroneus longus ($P < .021$) and gastrocnemius lateralis ($P < .007$). Figures 5b and d indicate that the differences in muscle activation tended to be smaller in the longer jumping distances than in the shorter ones. The remaining shank muscles gastrocnemius medialis, soleus and tibialis anterior did not show a significant activation difference in the shoe comparison.

**Discussion**

High ankle inversion during the initial landing phase of dynamic frontal plane movements mark a potential risk for sustaining lateral ankle sprains. Therefore, special court shoes are developed which try to reduce that injury risk. The implementation of medial compressible forefoot elements into the sole construction reduced inversion in lateral SSC jumps. In addition, muscle activity of the lateral shank muscles was lower, and foot placement occurred with a reduced external rotation with this modified shoe.

Medial compressible forefoot sole elements reduce the inversion angle at touchdown and the maximum inversion during the landing phase of lateral SSC jumps in comparison with a shoe with a standard sole construction. Incorporating medial compressible forefoot elements into shoe construction might therefore contribute to reducing the risk to sustain an ankle sprain during dynamic lateral movements. The potential to limit inversion in lateral movements by special sole designs has previously been shown for rearfoot sole modifications. In a study analyzing cuttings, it could be demonstrated that soft compressible rearfoot sole constructions minimize inversion in comparison with a harder and less compressible sole.6
In a functional shoe comparison, it is methodologically necessary to externally mount markers onto the shoes, to be able to analyze foot and ankle kinematics and kinetics. Thus, it needs to be considered that the shoe rather than the foot inversion is being measured. Shoe inversion overestimates the actual foot inversion inside the shoe, as demonstrated by Stacoff et al. This group determined shoe inversion during sideward cutting maneuvers, as well as the actual heel inversion inside the shoe, by cutting holes into the shoes and placing markers directly onto the skin. In our present study, shoe inversion was measured for both shoes using the same marker set. Therefore, the methodological constraint of measuring the shoe inversion should not limit the shoe comparison analysis. However, we cannot comment on the actual foot inversion inside the tested shoes.

Lower inversion angles with the modified shoe probably cause the lower muscle activity of the lateral shank muscles gastrocnemius lateralis and peroneus longus. Lohrer et al demonstrated that reduced ankle joint resulted in reduced peroneus longus activity. A tendency of lower muscle activity could in our study also be observed for gastrocnemius medialis and soleus. These differences were rather small, but, according to Komi et al., shoe construction differences are expected to have just small effects on EMG activation in sportive movements. The authors came to this conclusion after studying shoe sole hardness characteristics in running.

Ground contact times indicate that the modified shoe allowed performing lateral SSC jumps with the same reactivity as with the reference shoe, but less muscle activity was needed with the modified shoe to control the landing. The tendency of lower muscle activity with the modified shoe might be beneficial to movement performance as according to Nigg an optimal shoe requires reduced muscle work and therewith influences performance positively.

The modified shoe exhibited enhanced mediolateral ground reaction forces which could favor greater inversion moments. An explanation for the higher mediolateral ground reaction forces with the modified shoe can

**Figure 5** — Lower leg muscles’ IEMGs during the initial phase of contact. **Ref** = reference shoe, **modS** = modified shoe, **SHD** = short distance, **MED** = medium distance, **LOD** = long distance, **EXD** = extreme distance. (A) gastrocnemius medialis. (B) gastrocnemius lateralis. (C) soleus. (D) peroneus longus. (E) tibialis anterior. *P < .05; **P < .01.
possibly be found in the more internally rotated foot placement with this shoe. This assumption is backed by a study of Sigward and Powers. In an analysis of different cutting techniques, they reported that greater frontal ground reaction forces were associated with a lower external rotation of the foot. Also in a gait analysis investigation by Ho et al., it was shown that a greater internally rotated foot placement resulted in higher ground reaction forces, and thus in enhanced frontal plane ankle joint moments. The connection between foot placement and the ankle inversion moment could also be demonstrated by Andrews et al., who showed that increased external foot rotation correlated with reduced ankle inversion moments in gait. Based on these findings and on the fact that with the modified shoe mediolateral ground reaction forces were higher and foot placement occurred with a greater internal rotation, we would have expected higher inversion moments with this shoe. But inversion moments did not differ between the two shoes. We assume that the ability of the medial compressible forefoot sole elements to reduce the inversion angle limited the inversion moment in this shoe. And therefore, despite enhanced mediolateral ground reaction forces with this modified shoe, inversion moments did not differ between the two shoes.

The relation between inversion moments and inversion angles under different foot placement strategies showed also the previously cited investigation by Ho et al. This group found that increased inversion moments with an internally rotated foot placement were associated with higher inversion angles in comparison with an externally rotated foot placement. But in contrast to Ho et al.’s investigation, in the current study the medial compressible forefoot sole elements could reduce inversion angle. The assumption that the lower inversion angles achieved by these elements limit the inversion moment is supported by the analysis of the four stretch-load conditions: the modified shoe’s ability to reduce inversion angles seems to be limited in extreme condition in comparison with the lower jumping distances. Since mediolateral ground reaction forces were also clearly enhanced with the modified shoe in this extreme load condition, the inversion moment with the modified shoe therefore tended to be higher than with the reference shoe in this extreme condition.

Because medial compressible forefoot sole elements decrease inversion, limiting inversion does not need to be achieved by the strategy of a high external foot rotation. Hence, the safety-orientated externally rotated foot placement can be reduced, and a more internally rotated foot progression angle favoring an effective lateral push-off can be realized with the modified shoe.

To our knowledge only one other study addressed foot placement during a lateral movement in a shoe construction comparison before. In that study the foot progression angle was analyzed during shod and barefooted side-steps, but no consistent conclusion concerning foot placement could be drawn. Absolute angle values of that study are not comparable with those of the current study, as a different methodological approach was used to determine the foot progression angle. The authors reported a 1 to 2° externally rotated foot placement with a standard sole construction, whereas foot placement with a medially banked shoe led to a 2 to 3° internally rotated foot position. Although that study could just reveal tendencies concerning the foot progression angle, these results are in line with the findings of the current study. The differences between the investigation conducted by Stacoff et al. and the current study result from varying study designs and from the two different investigated lateral movements. Lateral SSC jumps are characterized by higher dynamics than side-steps; consequently, lateral SSC jumps are more difficult to control. The difficulty to control the lateral landing phase is reflected in a greater externally rotated foot placement. Therefore, the external foot rotation in lateral SSC jumps is higher than in side-steps.

The results of the current study, which are supported by the findings of Stacoff et al., allow the assumption that shoe sole constructions which limit inversion permit a more internally rotated foot placement during dynamic lateral movements. The current study suggests that with the shoe containing medial compressible forefoot sole elements a more internally rotated foot placement strategy could be anticipated, and that medial compressible forefoot sole elements might also mechanically facilitate a greater internal foot rotation during landing. The higher internally rotated foot placement with the modified shoe already at the instant of touchdown indicates a different anticipated foot placement strategy than with the reference shoe. The assumption that the modified shoe also mechanically favored a more internally rotated foot positioning by allowing a greater foot rotation after touchdown into the subsequent push-off direction is supported by the fact that the differences in foot progression angles between the two shoes are more distinct at 25% of ground contact compared with the moment of touchdown.

Acknowledgments

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References
