Effects of different shoe-lacing patterns on the biomechanics of running shoes

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Abstract
In the present study, we examined the influence of shoe lacing on foot biomechanics in running. Twenty experienced rearfoot runners ran in six different lacing conditions across a force platform at a speed of 3.3 m·s⁻¹. Foot pronation during contact, tibial acceleration, and plantar pressure distribution of the right leg were recorded. The test conditions differed in the number of laced eyelets (1, 2, 3, 6 or 7) and in lacing tightness (weak, regular or strong). The results show reduced loading rates (P < 0.05) and pronation velocities (P < 0.01) in the tightest and highest lacing conditions. The lowest peak pressures under the heel and lateral midfoot (P < 0.01) were observed in the high (seven-eyelet) lacing pattern. Regular six-eyelet cross-lacing resulted in higher loading rates (P < 0.05) and higher peak heel pressures (P < 0.01) than seven-eyelet lacing, without any significant differences in perceived comfort. The low lace shoe conditions resulted in lower impacts (P < 0.01) and lower peak pressures under metatarsal heads III and V (P < 0.01), which is probably induced by the foot sliding within the shoe. A firm foot-to-shoe coupling with higher lacing leads to a more effective use of running shoe features and is likely to reduce the risk of lower limb injury.

Keywords: Footwear, foot–shoe coupling, pronation, loading, perception

Introduction
Sport shoe research has been of major interest for more than 30 years. The main objective of scientific research has been to gain knowledge about changes in the construction and structure of sport shoes to prevent sport-specific injuries and complaints. The main purpose of running footwear is to reduce impact shocks and excessive rearfoot pronation, both of which are linked to injuries in running. Therefore, the key concepts of functional running shoes can clearly be recognized in the rear of the shoe and in its midsole constructions. Nigg and Morlock (1987) showed that a negative lateral heel flare construction reduced the pronating moment and therefore initial pronation. Running in shoes with varus wedges resulted in reduced pronation and pronation velocities (Milani, Schnabel, & Hennig, 1995). These two studies have influenced the design of running shoes on sale today. However, few studies have looked at the influence of the mechanical coupling between foot and shoe on the protective properties of the shoe (Ferrandis, Garcia, Ramiro, Hoyos, & Vera, 1994; Van Gheluwe, Kerwin, Roosen, & Tielemans, 1999; Van Gheluwe, Tielemans, & Rosen, 1995). For example, in a badly laced running shoe, the foot may slip within the shoe and so the runner may not receive the full benefit of the design features of the shoe. It can be speculated that the foot slips across the rear part of the shoe and lands in a more forward directed position within the shoe in relation to the shoe during touchdown. Van Gheluwe et al. (1995) showed that heel fit affects the eversion behaviour of the calcaneus during ground contact. A snug heel fit reduces pronation as well as the relative movement between the calcaneus and the shoe heel counter (Stacoff, Reinschmidt, & Stüssi, 1992).

The aim of the present study was to explore the effect of shoe lacing on the biomechanics of heel–toe running. Although the leading shoe manufacturers recommend special lacing techniques (e.g. for high and low arch feet), the influence of different shoe-lacing conditions on the biomechanics of the running
shoe is unclear. From the mathematical point of view, the most frequently used X-lacing is the best and strongest way to lace shoes (Polster, 2002). Sandrey and colleagues (Sandrey, Zebas, & Bast, 2001) showed that a soccer shoe with a special “anti-pronation lacing technique” was more effective in controlling rearfoot motion. Brüggemann (2006) noted that in athletic footwear construction there is substantial inter-individual variability in shoe fit because in the shoe manufacturing process a shoe last is developed on the basis of average foot morphology. Different shoe-lacing systems are one strategy to improve shoe fit and therefore shoe comfort, which is probably the most important aspect of athletic shoes. Because a good shoe fit results in a more homogeneous pressure distribution across the dorsum of the foot, greater comfort can be expected (Hagen, Hömme, Umlauf, & Hennig, 2008; Jordan, Payton, & Bartlett, 1995).

The most common running shoes are provided with six straight eyelets in line. Many running shoes have a higher seventh eyelet that is slightly shifted to the lateral side. However, most runners do not use this additional seventh eyelet. Therefore, the aim of this study was to evaluate the effect of different lacing tightness and lacing height techniques on biomechanical variables (shock attenuation and rearfoot motion) as well as on perceived shoe comfort. We hypothesized that the tighter and higher lacing techniques would lead to less rearfoot motion due to better heel counter fit. We also expected that shoe comfort would decrease as a consequence of too much lacing tightness.

Methods

Participants and lacing conditions

Twenty experienced and symptom-free male rearfoot runners (mean age 32 years, \( s = 10 \); height 1.78 m, \( s = 0.06 \); body mass 73 kg, \( s = 9 \)) participated in the study. After receiving a written summary and oral information about the test procedures, the participants were required to sign a consent form indicating voluntary participation. The protocol was approved by the Ethics Committee of the University Hospital Duisburg-Essen.

In randomized order, six shoe-lacing conditions of the right foot were investigated in a biomechanical study and in a perception test. Runners were chosen based on their match to a US size 10.5 experimental shoe (NIKE Air Pegasus), which was provided with an X-lacing, or so-called “zig-zag-lacing”. As shown in Table I, the test conditions differed in the number of pairs of eyelets used (1, 2, 3, 6 or 7) and in the tightness of the lace (weak, regular or tight).

Participants were instructed to use their preferred lace tightness according to their own perception of weak, regular, and tight conditions. This ensured that the tightness of the laces would be similar to that used by the participants in their regular running routine. In the condition “ALL7”, the laces were pulled from the outside from the sixth to the seventh homolateral eyelet, and then to the resulting loop between the sixth and seventh eyelet of the contralateral side. This lacing technique is recommended by many experienced runners and some shoe manufacturers (Figure 1d).

The test shoe (Nike Air Pegasus, US size 10.5) was scanned by using spiral computer tomography (Philips Brilliance 64, Philips Medical Imaging, Germany) to identify the areas of the cushioning elements in the rear of the shoe in the sagittal plane.

Kinetic and kinematic measurements

The participants ran in each shoe condition at a speed of 3.3 m \( \cdot \) s\(^{-1} \) across a piezoelectric force platform (Kistler 9281 B). Running speed was controlled by two photocells at equal distance in front of and behind the force platform. Only running trials within \( \pm 3\% \) of the target speed were accepted. Five successful trials were recorded in each lacing condition. Simultaneous with the recording of ground reaction forces, in-shoe pressure distribution, tibial acceleration, and rearfoot motion measurements of the right foot were performed. Seven anatomical locations of the foot (medial and lateral heel; lateral midfoot; first, third, and fifth metatarsal heads; hallux) were palpated, and piezoceramic transducers (4 \( \times \) 4 \( \times \) 2 mm; Halm, Germany) were fastened under the foot with adhesive tape. The physical properties of the piezoceramic transducers are described elsewhere (Hennig, Cavanagh, Albert, & Macmillan, 1982). To measure tibial acceleration, an Entran EGAX-F-25 miniature accelerometer was glued to the skin above the medial aspect of the tibia at a location midway between the medial malleolus and tibial plateau. The accelerometer was fastened.

### Table I. Lacing conditions.

<table>
<thead>
<tr>
<th>Code</th>
<th>Number of eyelets</th>
</tr>
</thead>
<tbody>
<tr>
<td>REG6</td>
<td>6 eyelets – regular lacing</td>
</tr>
<tr>
<td>WEAK6</td>
<td>6 eyelets – very weak lacing</td>
</tr>
<tr>
<td>TIGHT6</td>
<td>6 eyelets – very tight lacing</td>
</tr>
<tr>
<td>EYE12</td>
<td>eyelets 1 and 2</td>
</tr>
<tr>
<td>EYE135</td>
<td>eyelets 1, 3, and 5</td>
</tr>
<tr>
<td>ALL7</td>
<td>all 7 eyelets (special technique between eyelets 6 and 7)</td>
</tr>
</tbody>
</table>
by an elastic strap to improve the mechanical coupling to the underlying bone.

A lightweight half-circular metal construction with a potentiometer was fixed at the heel counter with its axis of rotation close to the height of the subtalar joint. A precision conductive plastic potentiometer (Megatron MP 10) showed an angular resolution of 0.05° and a linearity of 1%. The movable part of the goniometer was fixed at the lower leg parallel to the Achilles tendon orientation. The flexible low-mass arm of the goniometer (mass = 3.0 g) slid in a mechanical guide, which was glued to the skin and strapped around the shank with an elastic bandage. This placement ensured that the goniometer arm was at the same position on the posterior lower leg for the different shoe-lacing conditions. Rearfoot angle, as defined by the angle between rearfoot bisection and the direction of the Achilles tendon, could thus be determined by the goniometer.

After the goniometer was attached to the shoe, the participants positioned the shoes along two guiding lines on the floor. The participant adopted an upright sitting position with approximately right angles at the hip and knee joints, and their two fists placed between the medial aspects of the knees. The neutral angle of the goniometer was determined in this sitting position, and all pronation and supination measurements refer to this neutral position. The neutral angle goniometer reading was recorded as a reference value, which was substracted from all subsequent goniometer values during the following trial. Following the nomenclature of Edington and colleagues (Edington, Frederick, & Cavanagh, 1990), maximum pronation and maximum velocity of pronation were calculated from the angular values.

In the perception test, the participants compared the shoe comfort and stability in the changed lacing conditions (right shoe) against the comfort and stability of the left foot, on which they wore the reference shoe (regular lacing, REG6). The 20 runners evaluated the shoes according to “comfort” and “stability” during standing and walking on an anchored 7-point perception scale (1 = very very low; 2 = very low; 3 = low; 4 = equal; 5 = high; 6 = very high; 7 = very very high; point 4 represented regular X-lacing REG6 of the reference shoe). This protocol corresponds to that of Hennig and colleagues (Hennig, Valiant, and Liu, 1996; Milani, Hennig, & Lafontune, 1997) with a modified rating scale. At the end of the test, the participants had to provide a ranking of the shoe-lacing conditions according to their perceived comfort and stability, assigning ranks from 1 (highest comfort, highest stability) to 6 (lowest comfort, lowest stability).

Data collection and processing

The ground reaction force, axial tibial acceleration, pressure distribution, and rearfoot motion were collected simultaneously by a computer in a pre-trigger mode. The data were sampled at a rate of 1 kHz per channel with a resolution of 12 bits. A threshold of 5 N of the vertical ground reaction force
was chosen to determine the time onset of foot strike. The force and acceleration values were determined as multiples of body weight (BW) and gravitational acceleration ($g$), respectively. The maximum force rate was calculated as the highest differential quotient of adjoining vertical ground reaction force divided by the time resolution of 1 ms.

Under the seven anatomical locations, peak pressures were determined for all participants and all lacing conditions during foot contact. Using the time integral of the local forces during the stance phase, regional impulses were determined for each sensor. A relative load was calculated by dividing each regional impulse by the sum of all impulse values and expressing the value as a percentage.

Maximum pronation and pronation velocity were chosen as descriptors of rearfoot motion. Based on the convention of Edington et al. (1990), negative values represent a valgus and positive values a varus orientation of the rearfoot against neutral. Neutral was defined as a position in which the Achilles tendon angle and the rearfoot orientation were in line (Denoth, 1986).

Data analysis
After confirming normality for all measured variables by applying the Kolmogorov-Smirnov test ($P < 0.05$), a one-way repeated-measures analysis of variance (ANOVA) was used to determine the main effects of the six experimental conditions. Statistical significance was set at $P < 0.05$. Simple effects were calculated using paired Fisher LSD Student $t$-tests ($P < 0.05$).

Results

Perception questionnaire
The results of the subjective ratings show that the runners perceived moderately tight fitting running shoes as being very comfortable, which corresponds to the most favourable lacing conditions (EYE135 and WEAK6). The tightest lacing (TIGHT6) was perceived as the least comfortable, followed by the lowest and most unstable lacing condition, EYE12. The highest lacing (ALL7) was not significantly different to the normal X-Lacing (REG6) and was viewed by the participants as a comfortable lacing for distance running. The tightest (TIGHT6) and the highest (ALL7) lacings were perceived to be the most stable conditions (see Tables II and III).

Shock attenuation
The peak vertical forces show for the weakest lacing condition (EYE12) about 7.5% and 8.4% lower impacts than in REG6 and TIGHT6, respectively. In condition EYE12, peak vertical forces are significantly lower than in all 6- and 7-eyelet lacings (Figure 2). The lowest maximum vertical loading rates were observed with the highest (ALL7) and tightest (TIGHT6) lacings, which were significantly different from the lowest condition (EYE12), the weakest condition (WEAK6), and even the regular X-lacing condition (REG6) (Figure 3).

The ANOVA did not show significant differences in peak tibial accelerations, although high correlations between peak tibial acceleration and maximum loading rate were reported by Hennig and Lafortune (1991).

Rearfoot motion
The ANOVA did not identify significant differences in maximum pronation, but pronation velocities were significantly lower in the tightest (TIGHT6), the highest (ALL7), and the regular (REG6) conditions compared with the low-laced (EYE12, EYE135) and soft-laced (WEAK6) conditions. In TIGHT6, ALL7, and REG6, pronation velocities were reduced by 15–30% (Figure 4).

Plantar pressure distribution
Peak pressures beneath the lateral and medial heel showed a similar distribution. ALL7 resulted in the lowest peak heel pressures, WEAK6 in the

Table II. Results of perceived comfort and stability with changes in lacing conditions on a 7-point perception scale (group mean values and standard errors).

<table>
<thead>
<tr>
<th></th>
<th>+ EYE12</th>
<th>◇ EYE135</th>
<th>■ WEAK6</th>
<th>◆ REG6</th>
<th>▲ TIGHT6</th>
<th>◇ ALL7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comfort</td>
<td>3.4 ± 0.6</td>
<td>4.6 ± 0.3</td>
<td>4.4 ± 0.4</td>
<td>4.0 ± 0.0</td>
<td>2.00 ± 0.2</td>
<td>3.4 ± 0.2</td>
</tr>
<tr>
<td>Stability</td>
<td>1.0 ± 0.0</td>
<td>2.6 ± 0.5</td>
<td>2.1 ± 0.7</td>
<td>4.0 ± 0.0</td>
<td>5.5 ± 0.2</td>
<td>5.1 ± 0.2</td>
</tr>
</tbody>
</table>

Note: Significant differences between the lacing conditions (post-hoc $t$-tests): one symbol ($P < 0.05$), two symbols ($P < 0.01$).
Plantar pressure distribution under the lateral midfoot showed a very clear trend towards lower pressures the higher and the tighter the shoe was laced. It can be assumed that a tighter and higher lacing compresses the midfoot and induces a higher lateral arch of the foot. Lacing EYE12 resulted in the lowest peak pressures under the whole forefoot, with significantly reduced values under metatarsal heads III and V. These findings correspond to the perception of the runners who reported the foot sliding within the shoe in condition EYE12.

Discussion

The results reveal a strong influence of different shoe-lacing conditions on foot–shoe coupling in running. It can be assumed that tighter coupling due to higher (ALL7) and stronger (TIGHT6) lacing induces better use of running shoe features, such as cushioning properties. The manufacturer emphasizes that the test shoe (Nike Air Pegasus) is built with a lateral crash-pad that acts as a cushioning as well as an anti-pronation element. At the initial contact, the foot is supposed to come closer to the ground so that the pronation lever arm is reduced (Nigg & Morlock, 1987). Therefore, the tightest (TIGHT6) and the highest (ALL7) lacing conditions, which probably press the heel into the heel counter of the shoe and increase the coupling between foot and shoe, showed lower loading rates and lower peak pressures under the heel. Thus, these lacing conditions showed a better use of the running shoe cushioning features in the rear of the shoe. The results for pronation velocities underline this effect. ALL7, TIGHT6, and the regular cross lacing (REG6) showed significantly lower pronation velocities than the lower- and soft-laced conditions, which can also be explained by a better use of the crash-pad when foot–shoe coupling is increased. However, the pronation data have to be treated with caution because some participants reported slipping within the shoe in condition EYE12. The goniometer was attached to the heel counter of the shoe so that shoe to lower leg angular displacement was measured. For a well-laced shoe, the goniometer is a valid measuring device (Milani & Hennig, 2000; Milani et al., 1995), but for the softest lacing condition (EYE12) the foot slipped within the shoe and a firm coupling between heel and heel counter was not maintained. We speculate that the amount of calcaneal motion is correlated with the amount of heel counter motion in a regular laced condition. The reason for the lowest, although not statistically significant, maximum pronation values in the EYE12 condition could be that the slipping foot was deforming the shoe but not evertting the heel counter.

Originally, we hypothesized that the softer the lacing the greater the maximum pronation. Measuring pronation within shoes is still a challenge. For cinematographic measurements, it is necessary to

Table III. Results of the perception test: Ranking of the lacing conditions with respect to comfort and stability (group mean values and standard errors).

<table>
<thead>
<tr>
<th>Ranking comfort</th>
<th>Score</th>
<th>Ranking stability</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. EYE135</td>
<td>2.98 ± 0.29</td>
<td>1. TIGHT6</td>
<td>1.49 ± 0.20</td>
</tr>
<tr>
<td>2. WEAK6</td>
<td>3.11 ± 0.40</td>
<td>2. ALL7</td>
<td>1.51 ± 0.19</td>
</tr>
<tr>
<td>3. REG6</td>
<td>3.23 ± 0.41</td>
<td>3. REG6</td>
<td>1.99 ± 0.14</td>
</tr>
<tr>
<td>4. ALL7</td>
<td>4.29 ± 0.44</td>
<td>4. WEAK6</td>
<td>4.74 ± 0.25</td>
</tr>
<tr>
<td>5. EYE12</td>
<td>4.94 ± 0.62</td>
<td>5. EYE135</td>
<td>5.07 ± 0.12</td>
</tr>
<tr>
<td>6. TIGHT6</td>
<td>6.05 ± 0.28</td>
<td>6. EYE12</td>
<td>6.96 ± 0.04</td>
</tr>
</tbody>
</table>

Figure 2. Peak vertical impact forces (group mean values and standard errors) in different lacing conditions. bw = body weight.
apply reflective markers to the heel so that windows have to be cut in the heel counter of running shoes, thus changing the properties of the running shoe. Milani and Hennig (2000), who used an in-shoe goniometer device, concluded that shoe movement is slightly influenced mechanically by the in-shoe measurement. The foot is slightly elevated by the in-shoe measuring device, and adding a rigid interface for fixation of the goniometer under the heel modifies the heel cushioning characteristics. Kersting and colleagues (Kersting & Brüggemann, 2006; Kersting, Kriwet, & Brüggemann, 2006) used an in-shoe goniometer that does not seem to influence shoe movement, but the goniometer axis was located above the heel counter and therefore above the subtalar joint axis. For measuring rearfoot motion with an electrogoniometer, Milani and colleagues (Milani & Hennig, 2000; Milani et al., 1995) emphasize the importance of aligning the goniometer axis with the subtalar joint axis.

At first sight, the peak vertical forces and loading rates in EYE12 and ALL7 appear to contradict each other. In ALL7, the better foot–shoe coupling resulted in higher impact forces and lower loading rates compared with EYE12, in which the foot slipped. Due to the firm link between foot and shoe in condition ALL7, the foot was directly able to use the cushion of the shoe at touchdown, which explains the lower loading rates compared with the softer lacing conditions EYE12, EYE135, REG6, and WEAK6. If the foot slips, the contact area of the heel will shift anteriorly in relation to the shoe’s sockliner. The position of the air cushion can be seen clearly in a spiral computed tomographic scan of the right test shoe (Figure 5). The more the touchdown area of the calcaneus moves forward, the less volume of the air cushion can be used, and as a consequence loading rate increases.

Condition EYE12 was characterized by a very loose fit that was described by one participant as giving the impression of almost losing the shoe during the swing phase. Therefore, we conclude that due to the weak foot–shoe coupling, the foot and shoe contact the ground in an asynchronous manner.
First, the shoe touches the ground, followed by the heel of the runner that collides with the sole of the shoe as if wearing flip-flops. This would also mean that lacings EYE12 and ALL7 represent two very different types of heel contacts, two different impact patterns, which could explain the unexpected dynamometer results. It is also likely that the participants changed their running style to the loose shoe fit in condition EYE12. To prevent the shoe slipping from the foot in the swing phase, the participants may have increased plantar flexion of the foot and the toes – thus curling their toes. This would lower the touchdown angle of the foot, which is more typical for midfoot strikers. The modification of running style would also reduce peak vertical forces, but the impact pattern is still that of the foot falling onto the sole of the shoe already lying on the ground.

Figure 6 presents a comparison of plantar pressure distribution of EYE12, REG6, and ALL7. As mentioned above, the touchdown pattern in EYE12 results in increased loading rates in spite of decreased peak vertical forces. More vertical loading at touchdown would explain the higher peak pressures under the medial and lateral heel. The most effective foot–shoe coupling in ALL7 showed the most even pressure distribution at touchdown. Obviously, the heel can go deeper into the cushioning material of the shoe so that the crash-pad can distribute the pressure more evenly. Peak plantar pressures under the lateral midfoot become lower the higher and the tighter the shoe is laced. The pressures under the forefoot obviously increased because of foot sliding in condition EYE12. Under the forefoot, the running shoe is designed with less cushioning material, so that in ALL7 shock absorption cannot be observed as it can under the heel – peak pressures in ALL7 are increased to generate a firm counter-effort for push-off. The results of the plantar pressure distribution patterns support the interpretation that lacings EYE12 and ALL7 represent two different types of initial heel contact which have very different effects on the lower extremities.

Figure 5. Spiral computed tomographic scan of the right test shoe (Nike Air Pegasus), sagittal view. Also shown are the areas of highest volume of air cushion (solid arrow) and lowest volume of air cushion (dotted arrow).

Figure 6. Peak plantar pressures (group mean values) during running (3.3 m · s⁻¹) in lacing conditions EYE12, REG6, and ALL7.
Table IV. Biomechanical results with changes in lacing conditions (group mean values and standard errors).

<table>
<thead>
<tr>
<th></th>
<th>+ EYE12</th>
<th>◊ EYE135</th>
<th>□ WEAK6</th>
<th>• REG6</th>
<th>▲ TIGHT6</th>
<th>* ALL7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak vertical impact force (BW)</td>
<td>1.85 ± 0.19</td>
<td>1.92 ± 0.16</td>
<td>2.00 ± 0.17</td>
<td>2.02 ± 0.19</td>
<td>2.00 ± 0.17</td>
<td>1.96 ± 0.16</td>
</tr>
<tr>
<td>Maximum vertical force rate (BW · s⁻¹)</td>
<td>▲ *</td>
<td>▲ ▲ *</td>
<td>▲ ▲ *</td>
<td>▲ *</td>
<td>+ ■ ■ •</td>
<td>+ ■ •</td>
</tr>
<tr>
<td>Peak tibial acceleration (g)</td>
<td>6.1 ± 0.5</td>
<td>6.5 ± 0.4</td>
<td>6.5 ± 0.4</td>
<td>6.4 ± 0.5</td>
<td>6.4 ± 0.5</td>
<td>6.0 ± 0.4</td>
</tr>
<tr>
<td>Maximum pronation (°)</td>
<td>9.8 ± 0.7</td>
<td>10.4 ± 0.6</td>
<td>10.0 ± 0.8</td>
<td>9.9 ± 0.7</td>
<td>9.8 ± 0.7</td>
<td>10.4 ± 0.6</td>
</tr>
<tr>
<td>Maximum pronation velocity (rad · s⁻¹)</td>
<td>11.9 ± 0.8</td>
<td>11.4 ± 0.7</td>
<td>11.4 ± 0.8</td>
<td>9.7 ± 0.6</td>
<td>9.5 ± 0.6</td>
<td>9.7 ± 0.6</td>
</tr>
<tr>
<td>Peak pressure, medial heel (kPa)</td>
<td>885 ± 51</td>
<td>860 ± 58</td>
<td>927 ± 55</td>
<td>913 ± 60</td>
<td>850 ± 57</td>
<td>815 ± 54</td>
</tr>
<tr>
<td>Peak pressure, lateral midfoot (kPa)</td>
<td>168 ± 15</td>
<td>164 ± 16</td>
<td>158 ± 15</td>
<td>147 ± 13</td>
<td>131 ± 14</td>
<td>133 ± 13</td>
</tr>
<tr>
<td>Peak pressure, metatarsal head V (kPa)</td>
<td>232 ± 20</td>
<td>260 ± 20</td>
<td>251 ± 19</td>
<td>247 ± 19</td>
<td>259 ± 18</td>
<td>252 ± 18</td>
</tr>
<tr>
<td>Peak pressure, metatarsal head III (kPa)</td>
<td>318 ± 29</td>
<td>370 ± 35</td>
<td>352 ± 36</td>
<td>356 ± 35</td>
<td>340 ± 33</td>
<td>357 ± 32</td>
</tr>
<tr>
<td>Peak pressure, metatarsal head I (kPa)</td>
<td>584 ± 66</td>
<td>592 ± 53</td>
<td>608 ± 59</td>
<td>609 ± 56</td>
<td>599 ± 56</td>
<td>608 ± 58</td>
</tr>
<tr>
<td>Peak pressure, Hallux (kPa)</td>
<td>309 ± 27</td>
<td>345 ± 20</td>
<td>333 ± 24</td>
<td>331 ± 27</td>
<td>319 ± 25</td>
<td>322 ± 23</td>
</tr>
</tbody>
</table>

Note: Statistical differences between the lacing conditions (post-hoc t-tests): one symbol (P < 0.05), two symbols (P < 0.01). BW = body weight.

Conclusions

The results of this study show that foot movement in heel–toe running is influenced by the lacing pattern of the shoe. Therefore, shoe lacing has to be considered when undertaking biomechanical comparisons of running shoes.

To reduce pronation velocity and shock, runners should use highly and/or strongly laced shoes. The highest lacing condition (ALL7) was perceived by our participants to be as comfortable as the normal X-lacing condition, REG6. A higher lacing with moderate tightness results in a comfortable lacing condition that couples the foot and shoe very well. Very low- (EYE12) and very tight-laced (TIGHT6) shoes were uncomfortable and were not liked by our participants.

The perception results and the comments of the participants show that a comfortable shoe is characterized by a moderate tightness. By what amount the studied lacing conditions differed was shown by pressure distribution measurements at the dorsum of the foot (Hagen et al., 2008; Jordan et al., 1997). The leading shoe manufacturers recommend special lacing techniques for different foot types. A biomechanical examination of these recommendations with respect to different foot types is a challenge for future research.

References


