Pressure Distributions on the Plantar Surface of the Foot During the Javelin Throw

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The aim of this study was to compare the plantar pressures and forces recorded from both feet of two groups of javelin throwers of different performance levels, in order to investigate differences between skill levels. The study was carried out using an EMED insole system on a Tartan javelin runway at the University of Innsbruck, Austria. Most of the differences (at \( p < .01 \)) between the two groups were found in the two foot contacts during the delivery stride. Higher maximum total forces (forces on the whole foot) and maximum pressures were recorded for the more skilled or club throwers during the right foot contact at the beginning of this stride. For the left foot landing before release, the club throwers exhibited higher overall maximum forces and overall pressures (the largest forces and pressures recorded on any of the different foot regions) than the novices. The differences between the groups in the medial forefoot region contributed significantly to this result.

It has been claimed that the study of the plantar pressure distribution on athletes' feet has the potential to optimize technique, improve footwear, and reduce foot injuries (Schaff, Kirsch, Frey, & Mehnerl, 1987) as well as improve modeling of the forces in the foot (Morlock & Nigg, 1991). Despite these claims, few studies have quantified plantar pressures involved in track-and-field athletic techniques, and most of these have been in running. For example, Cavanagh and Rogers (1985) reported mean values for maximum pressure of 868 kPa for a group of 10 rearfoot strikers running barefoot at 3.8 m \( \cdot \) s\(^{-1} \) on a soft runway. The maximum pressures all occurred in the rearfoot, whereas the greatest impulse was recorded in the forefoot.

Nicol (1977) used a capacitive mat, which later developed into the EMED system (Novel gmbh, Munich), to study the plantar pressures during the triple
jump, using one athlete. For the hop takeoff, he recorded a maximum pressure of 380 kPa under the middle of the ball of the foot; for the landing from the hop into takeoff for the step, a maximum pressure of 700 kPa was recorded under the heel about 20 ms after first ground contact. Milani and Hennig (1990) used 8 (running) or 10 (jumping) insole piezoceramic transducers at defined anatomical landmarks. Their results suggest maximum pressures in excess of 1 MPa for running and 2 MPa for triple jumping, but they gave no specific values.

Some pilot studies on the plantar pressure distributions in the throwing events in track-and-field athletics have been reported by Bartlett, Müller, Raschner, and Brunner (1991, 1992a, 1992b), who used an EMED insole to measure plantar pressures during discus and javelin throwing and shot putting. The results indicated that the EMED insole gave insights into the forces on the foot that were difficult to discern from video observation. Despite the limited number of subjects, with only three throws analyzed for one thrower in each activity, there was evidence of intrathrower variability in plantar pressure patterns for experienced but nonelite throwers.

The validity of the overall vertical forces measured by an EMED insole in such dynamic activities was also addressed by Bartlett et al. (1992b). They compared the results from the insole with those recorded simultaneously on a Kistler Model 9281B force platform sampling at 200 Hz. The results for javelin throwing showed very similar force patterns for both measurement techniques. Differences in the times of occurrence of the peaks and troughs of the force patterns (about 15 ms) could barely be discerned from the graphical representation of the results. The mean discrepancies in force at these peaks and troughs were not larger than 170 N. The differences were probably due mainly to the different sampling rates and the summing of forces from 85 individual transducers in the insole, each of which has a threshold of 2 N. The evaluation of the results obtained with the EMED insoles as reported by Bartlett et al. (1992b) suggested the system to be suitable for force and pressure measurement during throwing events.

Several studies have compared the kinematics of the javelin throwing action between skill levels (refer to Bartlett & Best, 1988). However, apart from the limited studies of Bartlett et al. (1991, 1992a), there is a dearth of literature reporting the pressures and forces acting on the thrower and influencing the thrower's movements. Yet it is possible that differences exist in these pressures and forces between skill levels. Such differences may influence the consistency of throwing patterns and results and also the predisposition to injury.

The aim of this study was to compare the plantar pressures and forces recorded for two groups of javelin throwers of different performance levels, in order to establish differences between skill levels for several plantar pressure and force variables.

### Methodology

#### Experimental Procedures

The study reported here was carried out on a Tartan javelin runway at the University of Innsbruck from April to May 1992. The 2 mm thick EMED insoles consisted of 85 homogeneously distributed capacitive sensors, one per 2 cm².
The maximum sampling rate for each sensor was 100 Hz if only one insole was sampled, or 40 Hz if a pair of insoles was sampled.

The EMED insoles were zeroed and calibrated in the laboratory prior to commencing trials. Calibration up to 700 kPa was performed individually for each sensor and was carried out three times for each insole. Calibrations were performed on a pneumatic rig at pressures of 20, 40, 80, 100, and 150 kPa and in 100 kPa increments from 200 to 700 kPa. The sensitivity of the EMED system was adjusted so that no more than 2% of the sensors saturated beyond a pressure of 600 kPa.

It had been the original intention of the study to use two groups of eight javelin throwers, with six trials for each thrower. One group represented novices and the second group club standard throwers. Four trials were intended to sample the left and the right foot separately at 100 Hz and the remaining two trials to sample both feet at the same time at 40 Hz. All of the throwers but one were right-handed; the results for the left-handed thrower have been treated as if he were right-handed (by transposing the results from the right and left feet).

The use of a group of elite throwers was rejected for two reasons: first, the logistic difficulties of assembling such a group of throwers in Innsbruck for testing, and second, a suspicion based on the results of Bartlett et al. (1992b) that throwers of such high standard would be more likely to impose damaging forces on the insoles. In practice, even the club standard throwers, who mostly wore javelin shoes with spikes, damaged the insoles. This resulted in limiting the data acquisition to only two throws per foot for five throwers in each group with over 80% of the trials sampled at 100 Hz and the others at 40 Hz.

The insole was carefully positioned on the plantar surface of one or both of the thrower's feet after spraying with an antibacterial spray, which also helped to fix the insole to the foot. The sock was then placed over the insole, and the thrower put on his preferred shoes. The signal leads were taped to the thrower's leg and then passed through his shorts to the waistband memory/control unit. No thrower reported any inconvenience or discomfort from wearing the equipment. The EMED was activated when the athlete was ready to throw, and data were recorded until well after javelin release. Each throw was also filmed with two stationary, gen-locked Panasonic video cameras mounted with their optical axes at about 95° to each other.

Each thrower was allowed as many habituation and warm-up throws as he felt necessary to become accustomed to the equipment and the experimental setting. A throw was considered successful when it was performed in accordance with the event rules, when no problems were experienced with the EMED system, and when the athlete was satisfied with his technical performance.

After each successful throw, the athlete returned to the room housing the EMED system (about 30 m from the test area) to download the onboard memory data to an AT386 computer. This also allowed sufficient time between throws to minimize the possibility of fatigue. The recorded data were examined for any indications of insole damage, and if no damage was found, individual step files were made for the following foot contact phases: left foot contact at the start of the crossover stride (LF1), right foot contact at the start of the delivery stride (RF1), final left foot contact prior to release (LF2), and first right foot contact at recovery (RF2). Data analysis was performed for two trials of each foot and thrower. In the few cases where more trials were available, the two farthest
Figure 1 — Mask regions superimposed upon a maximum pressure picture.

throws were chosen. A standard foot mask was used (Figure 1) comprising eight plantar areas: lateral and medial rearfoot, lateral and medial midfoot, the lateral forefoot from the fifth to the second metatarsal, the first metatarsal region (medial forefoot), the fifth to second toes, and the hallux.

Statistical Methods

Careful consideration was given to the use of parametric or nonparametric statistics. Although the size of each group (sample) was only five, which might be considered small and thus might necessitate the use of nonparametric statistics, there is no clearly agreed distinction between a large and a small sample. Furthermore, it has been proposed that if samples are random and of equal size, as was the case here, small sample sizes have little effect on the relationships between variables (Boneau, 1960). The robust nature of ANOVA procedures allows the violation of assumptions regarding the data while still retaining a valid, and more powerful and flexible, statistical test (Popham, 1967; Popham & Sirotnik, 1973). The assumption of homogeneity of variance was not violated by the data in this study.

As this study was aimed at examining the effects of two independent variables (skill level and foot region) on a number of dependent variables mentioned below, a two-factor (Group × Region) ANOVA with repeated measures on the second factor was used. This was preferred to the use of individual t tests to reduce the likelihood of increasing familywise error rate (Popham, 1967). Post hoc Scheffé tests, preferred to Tukey as the more conservative of the two and therefore less likely to lead to Type I errors on any given comparison, were carried out where necessary to detect significant interaction effects.

The following parameters were subjected to this analysis:

- The mean maximum pressure (MP) over two trials in the different mask regions (M1–8)
• The mean time of occurrence of the maximum pressures (TMP) in the different mask regions
• The mean pressure–time integrals (PTI) over two trials in the different mask regions

Also, based on the above statistical rationale, the effect of one independent variable (skill level) on the following dependent variables was examined using a one-factor ANOVA for independent samples:

• Overall maximum plantar pressure (OMP)
• Time at which overall maximum plantar pressure occurred (OTMP)
• Overall maximum pressure–time integral (OPTI)
• Overall maximum force (OMF)
• Time at which overall maximum force occurred (OTMF)
• Maximum total force on the foot (MTF)
• Time at which maximum total force on the foot occurred (TMTF)
• Position of center of pressure (a) at landing as a percentage of total foot length, (b) at landing as a percentage of total foot width, (c) at takeoff as a percentage of total foot length, and (d) at takeoff as a percentage of total foot width

*Overall* is used here to refer to the largest value recorded or the time at which it occurred in any one of the eight mask regions, and *total* refers to the summation of all the mask regions.

The Bonferroni technique (e.g., Thomas & Nelson, 1990) proposes a reduction of the alpha or significance level to reduce the chance of a Type I error in the familywise error rate. In this case the level of significance for each independent comparison should become .05 divided by the total number of comparisons, here 14 (Howell, 1992). To prevent an excessive loss of statistical power and a too high Type II error rate, the alpha level per comparison was set to .01. This would give an upper limit on the familywise Type I error rate of .13, which would be reached only if the different variables compared were completely independent (Thomas & Nelson, 1990). Although this was not a strict application of the Bonferroni technique, we considered it to be acceptable in this case, especially as we share the view that the assessment of a particular alpha value for significance is, to some extent, a matter of opinion (e.g., Franks & Huck, 1986).

### Results

Table 1 presents all the differences and interactions found to be significant at the .01 level or, if outside the set alpha level, at least less than .05. For comparison purposes between the different foot strikes, Figures 2 and 3 show the pressure–time graphs for the four different strikes in one trial by a novice and by a club thrower, respectively.

For the mean MP over two trials in the different mask regions (M1–8), statistically significant differences ($p < .01$) between the two groups were found for the two foot strikes in the delivery stride (RF1 and LF2) with greater maximum pressures for the club throwers. The mean maximum pressure was also greater ($p < .05$: outside the set alpha level) for the club throwers for the first foot strike.
Table 1 Summary of Results

<table>
<thead>
<tr>
<th>Foot strike</th>
<th>Variable</th>
<th>p</th>
<th>Finding</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF1</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF1</td>
<td>MP (kPa)</td>
<td>&lt;.01</td>
<td>Difference between groups: $c = 320 \pm 65$, $n = 189 \pm 22$, $F(1, 8) = 18.9$.</td>
</tr>
<tr>
<td></td>
<td>OTMP (%ST)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 26.5 \pm 16.1$, $n = 51.3 \pm 17.0$, $F(1, 8) = 5.61$.</td>
</tr>
<tr>
<td></td>
<td>OMF (%BW)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 74.9 \pm 27.8$, $n = 44.8 \pm 8.1$, $F(1, 8) = 5.40$.</td>
</tr>
<tr>
<td></td>
<td>PCP (%)</td>
<td>&lt;.05</td>
<td>Difference at landing in position of center of pressure along the foot between groups: $c = 79.4 \pm 7.0$, $n = 70.8 \pm 3.9$, $F(1, 8) = 5.81$.</td>
</tr>
<tr>
<td></td>
<td>MTF (%BW)</td>
<td>&lt;.01</td>
<td>Difference between groups: $c = 262 \pm 48.2$, $n = 163 \pm 16.1$, $F(1, 8) = 18.6$.</td>
</tr>
<tr>
<td>LF2</td>
<td>MP (kPa)</td>
<td>&lt;.01</td>
<td>Difference between groups: $c = 397 \pm 62$, $n = 242 \pm 38$, $F(1, 8) = 23.0$.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;.01</td>
<td>Interaction of Region $\times$ Group found in M2.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;.05</td>
<td>Scheffé$_{.01}$ = 388. Difference between means = 447.</td>
</tr>
<tr>
<td></td>
<td>OMP (kPa)</td>
<td>&lt;.01</td>
<td>Difference between groups: $c = 833 \pm 127$, $n = 541 \pm 139$, $F(1, 8) = 12.1$.</td>
</tr>
<tr>
<td></td>
<td>OTMP (%ST)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 10.8 \pm 6.5$, $n = 29.8 \pm 13.7$, $F(1, 8) = 7.84$.</td>
</tr>
<tr>
<td></td>
<td>OMF (%BW)</td>
<td>&lt;.01</td>
<td>Difference between groups: $c = 127 \pm 31.8$, $n = 64.0 \pm 17.6$, $F(1, 8) = 15.0$.</td>
</tr>
<tr>
<td></td>
<td>MTF (%BW)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 275 \pm 60.1$, $n = 195 \pm 50.7$, $F(1, 8) = 6.04$.</td>
</tr>
<tr>
<td></td>
<td>TMTF (%ST)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 11.1 \pm 5.5$, $n = 24.6 \pm 11.3$, $F(1, 8) = 5.80$.</td>
</tr>
<tr>
<td>RF2</td>
<td>MP (kPa)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 377 \pm 87$, $n = 219 \pm 72$, $F(1, 8) = 9.85$.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;.01</td>
<td>Interaction of Region $\times$ Group found in M2.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;.05</td>
<td>Scheffé$_{.05}$ = 409. Difference between means = 420.</td>
</tr>
<tr>
<td></td>
<td>OMF (%BW)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 115 \pm 30.6$, $n = 60.7 \pm 37.5$, $F(1, 8) = 6.35$.</td>
</tr>
<tr>
<td></td>
<td>MTF (%BW)</td>
<td>&lt;.05</td>
<td>Difference between groups: $c = 337 \pm 65.2$, $n = 206 \pm 82.6$, $F(1, 8) = 7.69$.</td>
</tr>
</tbody>
</table>

*Note. $c =$ mean of club throwers $\pm$ SD; $n =$ mean of novice throwers $\pm$ SD; %BW = percentage of body weight; %ST = percentage of step (ground contact) time.*
Figure 2 — Total pressure–time graphs for the four foot strikes of one throw by a novice thrower: (a) LF1, (b) RF1, (c) LF2, (d) RF2.

in the recovery (RF2). Significant interaction effects (Region × Group) were found in M2 at the $p < .01$ level for LF2 and RF2.

A significant difference ($p < .01$) between groups was found for the overall maximum plantar pressure for LF2, with the club throwers having the greater values. Overall maximum plantar pressures occurred earlier (at the $p < .05$ level) for the club throwers for LF2 and RF1, as exemplified by Figure 4 for LF2. A significantly greater ($p < .01$) overall maximum force was found for the club throwers for LF2. Differences (at the $p < .05$ level) in overall maximum force were found between groups for the two right foot strikes, with the club throwers again having the larger values.

No differences at $p < .01$ were found for any of the center of pressure parameters, and only one difference between groups was found at the $p < .05$
level. This was for the landing at the commencement of the delivery stride (RF1), with the center of pressure further forward for the club throwers.

A significantly greater maximum total force ($p < .01$) was found for the club throwers for RF1. Differences outside the alpha level set by the investigators were found between groups for LF2 and RF2, again with larger forces for the club throwers. A difference ($p < .05$) was found between groups for the time (as a percentage of contact time) at which the maximum total force occurred for LF2, being earlier for the club throwers.

**Discussion**

No effect of skill level was found for any of the parameters measured for the left foot contact period at the start of the crossover stride. This was surprising,
because the club group approached this stride faster than the novices, and this greater speed might have been expected to lead to larger forces and pressures during ground contact. For the other three foot strikes, the maximum pressures were greater (significantly so for the right and left foot contacts during the delivery stride) for the club athletes. This had been expected, because the club athletes have a greater approach speed to control through the delivery stride and afterward during recovery, and because they more successfully convert their horizontal approach velocity to the vertical velocity of the javelin at release.

For the left foot strike at the end of the delivery stride and the first foot contact during recovery, the differences between the groups in mask M2, the medial rearfoot, were identified as contributing significantly to the above finding. The lack of identification of a specific region to account for the differences in maximum pressure for foot strike RF1 suggests that the difference between the two groups for that foot contact was caused simply by evenly distributed maximum pressures over all or most of the eight foot regions.

The maximum plantar pressures for both left foot contacts occurred in the medial metatarsal region for both groups (see Figure 5), with the novice group recording an equal maximum pressure on the hallux for LF1. For the right foot, the regions of occurrence of maximum plantar pressure were more varied both within and between the groups. The group means for the novices showed maximum pressures to occur on the hallux for both RF1 (mean 319 kPa) and RF2 (mean 288 kPa) with the club athletes having much larger maximum values in different regions: the medial metatarsal region for RF1 (mean 506 kPa) and medial rearfoot for RF2 (mean 694 kPa). This result is at variance with that of Bartlett et al. (1992a), who found the maxima to occur on the lateral rearfoot for the front foot landing before release. The reasons for this discrepancy are not clear.

Where differences were found in the time of occurrence of the overall maximum plantar pressure (RF1, LF2), the maximum pressures occurred earlier
Figure 5 — Maximum pressure picture for foot strike LF1 for (a) a club thrower and (b) a novice thrower. Arrows indicate areas where maximum pressures were recorded.

(as a percentage of total contact time) for the club group (Figure 4). Both groups had maximum pressures in the active rather than the impact part of the contact period for RF1, but for LF2 the maxima occurred during impact. This may be related to the different biomechanical functions of the two foot contacts during the delivery stride. The right foot contact at the start of the stride should still serve to drive the thrower forward, and the earlier maximum pressures for the club throwers may suggest that they initiate an earlier forward drive. The emphasis on the final front (left) foot contact is on braking and transferring horizontal momentum to vertical momentum, and the earlier occurrence of maximum pressure for the club throwers is probably due to a more vigorous landing.

There were no significant differences between groups or interaction effects for the pressure–time integrals. For all five throwers within each group and for all four foot strikes, the overall maximum pressure–time integral occurred either
in the medial metatarsal region or on the hallux. This result is, in general, also
different from that of Bartlett et al. (1992a), who found the maxima to occur on
the lateral rearfoot for the front foot landing before release, although in one of
the three throws an equally high pressure–time integral on the hallux was recorded.

The greater overall maximum force found for LF2, RF1, and RF2 (significant at \( p < .01 \) for LF2) for the club throwers bears out the earlier comments in
this section. The greater maximum total force for the contacts RF1, LF2, and
RF2 (significant at \( p < .01 \) for RF1) for the club throwers is not surprising owing
to the faster run-up speeds and more vigorous foot strikes used by this group.
The earlier occurrence of the maximum total force on the foot for LF2 for the
club group reflects the strong impact at landing for that group; in contrast, little
impact peak was evident for the novices (Figure 6).

The magnitudes of the maximum total force for the club group for the two
contacts in the delivery stride were 2.62 body weight (BW) (RF1) and 2.75 BW
(LF2). These are very much less than those reported by Deporte and van Gheluwe
(1988); they measured the ground contact forces on the front and rear feet in the
delivery stride for a group of eight Belgian elite throwers and reported vertical
impact forces of up to 9.1 times BW on the rear foot and up to 6.6 BW on the
front foot. The discrepancy between Deporte and van Gheluwe's figures and
those in this study are probably owing to several factors. First, the underestimation
of the total vertical force on the foot by the EMED insole, because of the sensor
threshold of 2 N, contributed a large part of the 170 N discrepancies in peaks
and troughs reported by Bartlett et al. (1992b). Second, the different skill levels
of the throwers in the two studies are important, as the elite throwers would have
exerted greater peak forces. Finally, Deporte and van Gheluwe (1988) used an
analogue plotter that provided a better reproduction of the high frequencies of
impact than did the 100 Hz sampling rate of the current study.

There was a general similarity between the two groups with respect to the
region of the foot where initial and final contact occurred for all contacts, except

![Figure 6](image_url)  
*Figure 6 — Typical pattern for total force on the foot for foot strike LF2 for (a) a club thrower and (b) a novice thrower.*
Figure 7 — Center of pressure paths for foot strike LF1 for two club (a, b) and two novice (c, d) throwers. F indicates first and L last contact.
for the right foot landing at commencement of the delivery stride, where the club throwers’ mean center of pressure position was more forward (79%) than for the novices (71%) at the $p < .05$ level. Although outside the alpha level we set, this might be considered further evidence of a more vigorous landing for the club than the novice group. The pattern of the center of pressure for the right foot landing at the start of the delivery stride reported by Bartlett (1982) from observations of elite throwers—initial contact on the lateral border with contact moving immediately to the heel—was not consistently evident in this study. The foot center of pressure patterns varied considerably between throwers within the two groups for all foot contacts (as shown, for example, in Figure 7).

Conclusions

The major differences ($p < .01$) between the two groups were found in the two foot contacts during the delivery stride. Higher maximum total forces and maximum pressures were recorded for the club group for the right foot contact at the beginning of this stride. For the left foot landing before release, the club throwers exhibited higher overall maximum forces and overall pressures than the novices. The differences between the groups in the medial forefoot region contributed significantly to this result.

The generalization of the findings of this study is limited by the number of trials and subjects involved, owing to the vulnerability of the EMED insoles. Therefore, further research in this area should incorporate larger numbers of trials per subject and subjects per group as well as a third, elite thrower group. This may be possible in the near future because new versions of the EMED insole use difference construction materials in order to improve the insole’s durability.

References


Acknowledgments

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