Plantar Loading Characteristics During Walking in Females With and Without Patellofemoral Pain

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Background: Patellofemoral pain (PFP) is a common injury, particularly in females. Foot pronation may promote knee and hip transverse plane joint kinematics during gait thought to contribute to PFP. Greater knowledge of plantar loading characteristics in females with PFP may be valuable to provide a basis for clinical decisions regarding footwear and foot orthoses. The purpose of this study was to compare plantar loading distribution in females with and without PFP during gait.

Methods: Plantar pressure during walking was recorded from 19 females with PFP and 20 females without PFP. Contact area, peak force, and force-time integral were evaluated in ten plantar areas. Arch index was also calculated from contact area data during gait.

Results: Contact area in females with PFP was 9% smaller in the first metatarsal region ($P = .039$) and 20% smaller in the midfoot region ($P = .042$) than in females without PFP. Peak force was 31% lower in the midfoot region for females with PFP ($P = .027$) and 13% lower in the first metatarsal region ($P = .064$). Force-time integral was 18% lower in the first metatarsal region in females with PFP ($P = .024$). Females with PFP demonstrated a lower arch index (suggesting a higher arch) ($P = .028$).

Conclusions: Decreased medial forefoot loading and decreased midfoot contact suggest decreased foot pronation during gait in females with PFP relative to females without PFP. Decreased foot pronation may foster increased patellofemoral joint loading rates. These data contribute to rationale for footwear modifications to modify plantar loading characteristics in people experiencing PFP. (J Am Podiatr Med Assoc 105(1): 1-7, 2015)

Patellofemoral pain (PFP) is a common injury in young adults and adolescent athletes, particularly runners. Females seem to be more than twice as likely to develop PFP compared with males.1 Unfortunately, PFP symptoms in young adults frequently result in decreased participation in sports and recreational activities, despite attempts at rehabilitation.2 Of even more concern may be the identification of PFP as a precursor to patellofemoral osteoarthritis.3

An association between PFP and increased foot pronation has been proposed.4,5 In theory, excessive or prolonged pronation may increase tibial and femoral internal rotation during gait, resulting in decreased patellofemoral contact area and increased lateral patellofemoral joint stress.5,6 However, perhaps due to inconsistencies in foot models and limitations in methods used to examine foot kinematics, conflicting evidence exists that individuals with PFP have altered standing foot posture or motion during gait.7-10

Plantar pressure technology quantifies the magnitude and location of ground reaction forces on the plantar aspect of the foot and has been used to infer information regarding foot pronation and navicular height during gait.10,11 However, limited information exists on the plantar loading characteristics of individuals with PFP. Thijs et al12 reported that increased lateral heel and midfoot loading during gait were predictors of risk of PFP. Aliberti et al13,14 reported a “more cautious motor pattern” characterized by decreased global plantar pressure and
more medially directed support at ground contact in people with PFP during stair descent but greater medial rearfoot loading during initial heel contact and decreased medial forefoot loading during propulsion during walking. Additional study of plantar loading characteristics during walking in people with PFP may be valuable in providing a basis for clinical decisions regarding footwear and foot orthoses for this population.

Previous studies of plantar loading characteristics in individuals with PFP include both male and female participants. Anatomical variations in foot structure and stiffness may increase variability in plantar loading measurements in these studies.15,16 To date, plantar loading characteristics during walking in only females with PFP have not been reported or compared with a healthy, matched cohort. Therefore, the purpose of this study was to compare plantar loading measurements in females with and without PFP while walking. Specifically, we tested the hypothesis that females with PFP walk with less medial midfoot and forefoot force and contact area.

**Methods**

The study protocol was approved by the University of Wisconsin-La Crosse institutional review board, and all of the individuals provided informed consent before participation. Using an α level of 0.05, a β level of 0.2, and the expected variability of midfoot peak pressure data during gait, 19 participants per level of 0.2, and the expected variability of midfoot force and contact area.

Plantar loading measurements were recorded using a pedography analyzer (EMED-AT; Novel GmbH, Munich, Germany) and a capacitive pressure measurement platform that was centered flush in a level walkway. The pressure platform consisted of a 24 x 40 sensor matrix with a resolution of 2 sensors/cm². The sampling frequency was fixed at 50 Hz and began recording when first contact with the platform exceeded 10 kPa.

To control for changes in vertical ground reaction forces with gait speed, participants in this study were instructed to walk at a velocity of 1.30 m/sec (±5%) as measured by timing lights placed 1.3 m apart centered on the pressure platform. All of the participants were allowed as many practice trials as necessary to familiarize themselves with the procedure and the targeted speed before data collection.
Three trials are required to achieve good test-retest reliability for the discrete variables in this study measured during overground walking. Therefore, three trials of the dominant foot stance phase were measured on the pressure platform. The dominant foot was defined as the foot that the participant would select to kick a ball. A trial was considered acceptable when the individual achieved the targeted speed, the entire surface of the dominant foot was captured by the pressure platform, and no perceived adjustment in step length or frequency was made to aim for the pressure platform.

Gait pressure data were analyzed using a software package (Novel Multimask version 19.3.15; Novel GmbH). For each trial, the plantar loading distribution of the footprint was divided into ten regions: metatarsal head (MH) 1, MH2, MH3, MH4, MH5, hallux, second toe, toes 3 to 5, midfoot, and calcaneus (Fig. 1). These regions are determined by drawing a rectangle around the footprint in a way that its sides are parallel and perpendicular to the bisection of the angle created from lines tangent to the medial and lateral sides of the maximum pressure picture (long plantar angle). Straight lines that separate the heel and the midfoot are placed at 73% of the foot length from the toes to the heel. The boundary between the midfoot and the forefoot is defined as 45% of the foot length from the toes to the heel. The boundary between the forefoot and the toes and also between the toes is defined by taking into consideration the values of peak pressure under the toes and the gradients of pressure around these maximum values. The angles that define the metatarsal heads are given as percentages of the long plantar angle. From the medial to the lateral side of this angle, the metatarsal heads are defined as being 30%, 17%, 17%, 17%, and 19% of the long plantar angle.

In each region, three variables were calculated: peak force, force-time integral, and contact area. Repeated measurement of these discrete variables during the stance phase of gait have been reported to be consistent over time (intraclass correlation coefficient $1,5 = 0.71–0.96$). Cadence may affect plantar loading variables, resulting in significantly different ground reaction forces between groups and confounding the interpretation of regional force data. Thus, total foot contact time and peak vertical ground reaction force were also calculated for each group.

Arch index was also calculated from the pressure platform data by dividing the midfoot region contact area by the contact area of the entire foot, excluding the toes. Previous studies indicate that lower arch

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Healthy Group (n = 20)</th>
<th>PFP Group (n = 19)</th>
<th>$P$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>21.6 ± 4.5</td>
<td>21.3 ± 2.6</td>
<td>.83</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>62.1 ± 8.9</td>
<td>62.9 ± 7.7</td>
<td>.75</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.69 ± 0.9</td>
<td>1.68 ± 0.6</td>
<td>.86</td>
</tr>
<tr>
<td>Contact time (msec)</td>
<td>669 ± 58</td>
<td>688 ± 43</td>
<td>.23</td>
</tr>
<tr>
<td>Peak vertical ground reaction force (% body weight)</td>
<td>106.3 ± 7.0</td>
<td>101.7 ± 12.0</td>
<td>.12</td>
</tr>
</tbody>
</table>

Note: Data are given as mean ± SD.
Abbreviation: PFP, patellofemoral pain.

Figure 1. Graphical representation of the anatomical regions used to describe the plantar loading variables of the foot. M01 = calcaneus, M02 = midfoot, M03 = metatarsal 1, M04 = metatarsal 2, M05 = metatarsal 3, M06 = metatarsal 4, M07 = metatarsal 5, M08 = hallux, M09 = toe 2, M10 = toes 3, 4, and 5.
index values are associated with greater navicular height (correlation coefficient = 0.71) and a more vertically oriented calcaneus (correlation coefficient = 0.68) measured using plain radiographs.11,24 Excellent between-day reliability of the arch index calculated based on pressure platform measurements has been reported (intraclass correlation coefficient2,5 = 0.975).23

Between-group differences in the means of the three trials for each plantar loading variable by region were tested using three separate two-factor analyses of variance (2 [group] × 10 [plantar region]), considering the plantar regions as repeated measures. Simple main effects were analyzed for discrete plantar loading variables with significant group × region interactions. Arch index, total foot contact time, and peak vertical ground reaction force were compared between groups using independent t tests. All of the tests were performed using \( \alpha = 0.05 \). All of the statistics were calculated using a statistical software program (SPSS Inc, Chicago, Illinois).

Results

Participants in both groups were similar with respect to average age, weight, and height (Table 1). Total foot contact time and peak vertical ground reaction force were not different between groups. Significant group × region interactions were identified for contact area, peak force, and force-time integral. Analysis of simple main effects revealed that contact area for females with PFP was 9% smaller in the MH1 region (ES = 0.42; \( P = .039 \)) and 20% smaller in the midfoot region (ES = 0.49; \( P = .042 \)) compared with females without PFP (Table 2). Peak force was 31% lower in the midfoot region for females with PFP (ES = 0.45; \( P = .027 \)) and 13% lower in the MH1 region, although this difference was not statistically significant using \( \alpha = 0.05 \) (ES = 0.40; \( P = .064 \)). Finally, the force-time integral was 18% lower in the MH1 region in females with PFP (ES = 0.48; \( P = .024 \)). Differences in the arch index between groups were also observed. The mean ± SD arch index for females with PFP (0.25 ± 0.9) was lower (suggesting a higher arch) than for females without PFP (0.31 ± 0.08; ES = 0.46; \( P = .028 \)).

Discussion

The purpose of this study was to compare plantar loading characteristics during walking between females with and without PFP. The pathomechanics of PFP may be impacted by abnormal foot posture and abnormal foot pronation.10 A pronated foot (as defined by the Foot Posture Index) during standing has been found to be associated with increased midfoot and MH1 contact area and increased peak pressure under the big toe during gait.25 In the present study, females with PFP had less midfoot and MH1 contact area and peak force compared with females without PFP. As such, these regional differences in plantar loading are consistent with decreased foot pronation during walking in females with PFP. These regional differences in plantar loading may be due to increased arch stiffness, which may decrease foot mobility and shift plantar loads laterally.10-12,26 Total foot contact time and vertical ground reaction force did not differ between groups. Thus, regional differences in plantar loading are not likely owing to differences in cadence or a general decrease in ground reaction force in participants with PFP. Note that similar results were reported in the prospective study of military recruits in that greater lateral foot loading was identified in females who later developed PFP.12 These findings are also similar to those of Aliberti et al.,14 who reported decreased medial forefoot pressure during the propulsion phase of gait in a mixed sample of male and female patients with PFP. The consistency of these retrospective and prospective results suggests that individuals who develop PFP do not dramatically change plantar loading characteristics to compensate for symptoms. That is, decreased medial foot loading or increased lateral foot loading during gait may exist before and after the onset of PFP.

Females with PFP in the present study had a greater mean arch index than females without PFP. To the extent that arch index represents arch height, these findings support the conclusion that females with PFP had a greater medial arch height compared with females without PFP. However, there is some controversy regarding the value of the arch index calculated from plantar pressure data during gait as a surrogate measure of arch height. Arch index calculated from footprints during gait has been reported to correlate well with arch height measured during standing (\( r = 0.67 \)).11 This finding suggests that, at best, arch index explains 45% of the variability in arch height. A subsequent study reported a lower association between the arch index measured using plantar pressure data during gait and arch height measured during standing (\( r = 0.52 \)).27 Therefore, inferences made regarding the height of the medial longitudinal arch based on the arch index should be made with caution and the understanding that this measure explains only a
portion of the variability in arch height. Arch index has also been found to be positively correlated with fat mass percentage. However, females with and without PFP had virtually identical height and weight in this investigation.

Decreased foot mobility in females with PFP during gait could possibly contribute to patellofemoral joint symptoms. Dorsal arch height has been found to predict decreased mobility of the foot. Furthermore, in at least one previous study, individuals with PFP have been found to demonstrate 25% less foot pronation during the first 10% of the stance phase of gait. This decreased foot pronation could possibly contribute to patellofemoral joint symptoms. Dorsal arch height has been found to predict decreased mobility of the foot.28

<table>
<thead>
<tr>
<th>Foot region</th>
<th>Contact Area (cm²)</th>
<th>Peak Force (% Body Weight)</th>
<th>Force-Time Integral (% Body Weight*s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PFP Group</td>
<td>Healthy Group</td>
<td>PFP Group</td>
</tr>
<tr>
<td>Hallux</td>
<td>11.6 ± 1.8</td>
<td>11.4 ± 1.7</td>
<td>20.7 ± 7.4</td>
</tr>
<tr>
<td>Toe 2</td>
<td>4.9 ± 1.0</td>
<td>4.7 ± 0.6</td>
<td>5.1 ± 1.9</td>
</tr>
<tr>
<td>Toes 3, 4, and 5</td>
<td>9.1 ± 2.0</td>
<td>8.3 ± 2.1</td>
<td>6.4 ± 3.6</td>
</tr>
<tr>
<td>Metatarsal 1</td>
<td>12.1 ± 1.5a</td>
<td>13.3 ± 2.0</td>
<td>18.5 ± 5.3b</td>
</tr>
<tr>
<td>Metatarsal 2</td>
<td>10.2 ± 1.4</td>
<td>10.3 ± 1.4</td>
<td>22.3 ± 4.5</td>
</tr>
<tr>
<td>Metatarsal 3</td>
<td>10.9 ± 1.1</td>
<td>11.2 ± 1.3</td>
<td>21.1 ± 4.7</td>
</tr>
<tr>
<td>Metatarsal 4</td>
<td>9.4 ± 1.1</td>
<td>9.3 ± 0.9</td>
<td>13.8 ± 4.0</td>
</tr>
<tr>
<td>Metatarsal 5</td>
<td>5.6 ± 0.9</td>
<td>5.4 ± 1.0</td>
<td>5.7 ± 2.4</td>
</tr>
<tr>
<td>Midfoot</td>
<td>20.5 ± 7.4a</td>
<td>25.7 ± 8.8</td>
<td>10.2 ± 4.2a</td>
</tr>
<tr>
<td>Calcaneus</td>
<td>32.2 ± 2.8</td>
<td>32.4 ± 3.3</td>
<td>66.3 ± 8.9</td>
</tr>
</tbody>
</table>

Note: Data are given as mean ± SD.
Abbreviation: PFP, patellofemoral pain.

aP < .05.
bP = .064.

Table 2. Regional Peak Force and Force-Time Integral Values During Gait for Females with and Without PFP

Functional ambulatory activities. Aliberti et al reported that participants with PFP demonstrated a more medial plantar loading distribution during stair descent. Greater medial foot loading while descending stairs may be a consequence of the increase in ankle dorsiflexion motion required during this activity. Decreased ankle dorsiflexion flexibility has been observed in individuals with PFP and may result in compensatory calcaneal evasion or increased foot progression angle to lower their center of mass over their foot. These potential compensations for limited dorsiflexion flexibility may lead to greater medial foot loading during stair descent. Further analysis of the association between ankle dorsiflexion flexibility and PFP seems warranted to substantiate this hypothesis.

Foot mechanics during weightbearing are often interpreted in the context of a theoretical link between foot pronation and knee and hip transverse plane joint kinematics that are thought to contribute to PFP. This theory links excessive or prolonged foot pronation with accompanied tibial internal rotation and compensatory femoral internal rotation to preserve normal knee arthrokinematics occurring with flexion and extension during stance. If females with PFP truly experienced less foot pronation during gait in this study, they may have exhibited less tibial internal rotation during stance. This may have resulted in a more lateral position of the tibial tuberosity relative to the femur, more lateral quadriceps force on the patella, and greater patellofemoral joint contact pressure. Greater knee external rotation (motion of the tibia relative to

to the femur) has previously been reported in females with PFP during a variety of weightbearing activities and is consistent with these results.\textsuperscript{33} However, note that this theoretical link between foot pronation and knee and hip joint kinematics has not been consistently supported.\textsuperscript{34} Furthermore, several prospective and retrospective studies have not reported increased foot pronation or rearfoot eversion in individuals with PFP during gait\textsuperscript{35,36} or while standing.\textsuperscript{8-10} As such, the conclusion that these results may indicate a decreased magnitude of foot pronation during gait (and thus decreased tibial internal rotation) should be tested in future studies with simultaneous examination of foot kinematics and plantar pressure in females with PFP.

The present results underscore the importance of tailoring interventions for PFP to individual patient characteristics. For example, foot orthoses to minimize collapse of the medial longitudinal arch are a common intervention for PFP and may be particularly effective if a patient demonstrates increased foot mobility while weightbearing.\textsuperscript{37,38} In a recent randomized controlled trial, foot orthoses with medial arch support were associated with greater short-term improvements, but long-term improvements in pain and function were equivalent to improvements associated with physical therapy interventions and flat, cushioned inserts in patients with PFP.\textsuperscript{39} In addition, a decreased vertical loading rate was observed in people with PFP who reported decreased pain and increased tolerance for running at the conclusion of a kinematic retraining program.\textsuperscript{40,41} The results of the present study, combined with previous findings, imply that individuals with PFP who have a lower arch index (high arch) and less medially distributed plantar loading may benefit from soft foot orthoses to decrease the vertical loading rate. This rationale for cushioned orthoses may partially account for decreased pain recorded in individuals with PFP after this intervention.\textsuperscript{39}

Notable limitations of this study may exist. For example, these data are representative of young female runners with and without PFP and may not generalize well to males or sedentary individuals. In addition, decreased motion consistent with reduced foot pronation has been inferred from the plantar pressure data and not directly measured using motion analysis technology. Future studies of plantar pressure and foot kinematics in individuals with PFP are necessary to substantiate the speculation included in our interpretation of these results. Also, three separate analyses of variance were used to test for differences in plantar loading between females with and without PFP, and we did not adjust the familywise error rate to account for the effect of multiple comparisons on the type I error rate. The adjusted $\alpha$ level for this study with three tests would be 0.017. Interpretation of these results using this adjusted $\alpha$ level to account for multiple comparisons would lead to strikingly different conclusions because none of the between-group comparisons met this standard for rejection of the null hypothesis. Therefore, interpretation of these results should be made with the understanding that the familywise $\alpha$ level is higher than 0.05 (calculated to be 0.14). Finally, all foot regions are estimates of force and area that may include misplaced data from adjacent foot regions. Despite these limitations, we conclude that females with PFP experience decreased medial foot loading during gait and possess a lower arch index compared with females without PFP. Decreased foot pronation and a more rigid foot may lead to faster loading of the patellofemoral joint and symptoms associated with overuse.

Financial Disclosure: None reported.
Conflict of Interest: None reported.

References

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