Influence of step length and landing pattern on patellofemoral joint kinetics during running

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Elevated patellofemoral joint kinetics during running may contribute to patellofemoral joint symptoms. The purpose of this study was to test for independent effects of foot strike pattern and step length on patellofemoral joint kinetics while running. Effects were tested relative to individual steps and also taking into account the number of steps required to run a kilometer with each step length. Patellofemoral joint reaction force and stress were estimated in 20 participants running at their preferred speed. Participants ran using a forefoot strike and rearfoot strike pattern during three different step length conditions: preferred step length, long (+10%) step length, and short (−10%) step length. Patellofemoral kinetics was estimated using a biomechanical model of the patellofemoral joint that accounted for cocontraction of the knee flexors and extensors. We observed independent effects of foot strike pattern and step length. Patellofemoral joint kinetics per step was 10–13% less during forefoot strike conditions and 15–20% less with a shortened step length. Patellofemoral joint kinetics per kilometer decreased 12–13% using a forefoot strike pattern and 9–12% with a shortened step length. To the extent that patellofemoral joint kinetics contribute to symptoms among runners, these running modifications may be advisable for runners with patellofemoral pain.

Running is a common fitness activity that is associated with an increased risk for lower extremity injury (van Gent et al., 2007). In the United States alone, approximately 35 million people choose running as a mode of exercise and nearly half of these people run at least three times a week (National Sporting Goods Association, 2010). Patellofemoral pain (PFP) is among the most common injuries experienced by runners (Taunton et al., 2002; Lopes et al., 2012).

Patellofemoral joint kinetics such as increased patellofemoral joint reaction force (PFJRF) and patellofemoral joint stress (PFJS) may be associated with the etiology or exacerbation of patellofemoral joint symptoms. Individuals with PFP are reported to experience greater PFJS than controls during weight-bearing activities including walking (Brechtler & Powers, 2002), running (Wirtz et al., 2012), and squatting (Farrokhi et al., 2011). As such, interventions to reduce PFJRF and PFJS may benefit prevention and treatment efforts for PFP in runners.

Foot strike pattern has been investigated as a running technique modification to reduce PFJRF and PFJS. Runners who utilized a forefoot strike (FFS) were found to experience a 15% decrease in estimated peak PFJS compared with runners with a rearfoot strike (RFS) pattern (Kulmala et al., 2013). This decrease may be attributed to decreased knee eccentric joint power produced while running with a converted FFS (Williams et al., 2012). However, runners also experience greater ankle eccentric joint power (Williams et al., 2012) and Achilles tendon force (Almonroeder et al., 2013; Kulmala et al., 2013) while running with a converted FFS pattern. Because ankle plantarflexor force is partly derived from the biarticular gastrocnemius muscle, a FFS would produce greater knee flexor torque that the quadriceps must overcome to achieve a given knee extension torque during running. Previously used biomechanical models of the PFJ that do not account for cocontraction of the knee flexors during running may therefore underestimate PFJ loads while running with a FFS pattern.

Modification of step length during running may also affect patellofemoral joint kinetics. Among uninjured runners, a 10% decrease in step length was found to decrease peak PFJRF by 14% (Lenhart et al., 2014). Among runners with and without PFP, a 16% decrease in step length reduced cumulative PFJS per step by 22% and 7.5% per mile run (Willson et al., 2014). In the latter study, the estimate for cumulative PFJS was based on data from individual, nonconsecutive steps on a runway where participants were prohibited from employing the step length reduction over many consecutive gait cycles. Further, a 16% decrease in step length would impose deleterious metabolic consequences to running...
performance and likely affect long-term adherence with the step length modification (Hamill et al., 1995). As such, questions remain if a moderate step length reduction would significantly affect patellofemoral joint kinetics over a given distance.

Current best available evidence suggests both foot strike pattern and step length may influence patellofemoral joint kinetics, but questions remain from previous literature that justify further investigation of these interventions. Patellofemoral joint kinetics may also be affected by footwear (Sinclair, 2014), barefoot running (Bonacci et al., 2014), or running technique interventions to reduce impact forces (Cheung & Davis, 2011). However, interpretation of these previous findings is complicated by the fact that both step length and foot strike pattern may be simultaneously affected by these interventions. Systematic manipulation of both step length and foot strike pattern during running is necessary to determine the independent effects of these modifications on patellofemoral joint kinetics. To the extent that PFP is associated with patellofemoral joint kinetics, a greater understanding of these effects may provide a basis for decision making among healthcare professionals considering gait modification intervention options for people with this common running-related injury.

The purpose of this study was threefold. First, using a biomechanical model that accounts for knee flexor cocontraction during running, we tested for differences in patellofemoral joint kinetics between FFS and RFS techniques while controlling for step length. Second, we tested if a 10% change in step length significantly affected patellofemoral joint kinetics over a single step and over the course of a kilometer while controlling for foot strike pattern. Third, we tested if foot strike pattern and step length represented independent effects or if these modifications were dependent on the presence of the other factor.

Methods

Prior to the study, we determined that 18 participants were necessary to identify differences in PFJS per step and per kilometer with a moderate effect size (>0.6) for this repeated measures study design (α = 0.05 and β = 0.2). The expected variability of these variables was based on previous literature (Kulmala et al., 2013; Willson et al., 2014). The protocol for this study was approved by the university institutional review board and all subjects provided their informed consent prior to participation.

We recruited 20 participants [10 females (22.6 years, 1.67 m, 57.5 kg) and 10 males (22.6 years, 1.81 m, 80.7 kg)] to participate in this study. All participants were between 18 and 35 years old and ran at least twice per week for a minimum of 16 km/week. Potential participants with current lower extremity injuries or pain with general activity that restricted participation in running or recreational activities for more than 1 day over the last 2 months were excluded from participation. Subjects with a history of surgery in either lower extremity within the last 12 months were also not allowed to participate.

Subjects were prepared for three-dimensional (3D) motion analysis testing by attaching 12-mm reflective markers to the bilateral lower extremities, pelvis, and trunk. The 3D coordinates of these markers were used to track the motion of the pelvis, femur, shank, and foot, each modeled as a rigid body. Anatomical markers used to establish the segmental coordinate systems were placed over each iliac crest, greater trochanters, medial and lateral femoral condyles, medial and lateral proximal tibia, medial and lateral malleoli, the first and fifth metatarsal heads, and the tip of the shoe. The proximal end of the thigh segment was described by the ipsilateral greater trochanter marker and the calculated location of the hip joint center. The hip joint center was identified using a Newton iterative spherical fitting algorithm from data recorded during a standing trial where the instrumented leg was moved in a prescribed fashion prior to the running trials (Hicks & Richards, 2005). Following the standing calibration and hip center movement trials, anatomical markers were removed. Tracking markers, which remained in place throughout the study protocol, were positioned as a cluster of three markers on the rearfoot of the shoe, a cluster of four markers on the posterior shank, and a cluster of four markers on the lateral thigh. Tracking markers for the pelvis included bilateral anterior and posterior superior iliac spines and the L5–S1 interspace.

We analyzed running mechanics during six different combinations of foot strike pattern and step length (Fig. 1). The protocol began with at least 2 min of walking to accommodate to the treadmill. Next, preferred running velocity was determined. For this, the investigator adjusted treadmill velocity to a level representing each participant’s preferred pace during a routine training run. Participants were asked to run for 2 min at this velocity using their preferred step length and foot strike pattern. At the end of this time, running cadence was determined by counting the number of footsteps over a 30-s interval and multiplying by 2. During the next minute, participants were asked to match the step rate of an audible cue provided by a metronome set at this preferred running cadence. Running mechanics were recorded during the final 15 s of this condition. Next, participants were asked to maintain their preferred foot strike pattern but to increase or decrease step length by matching the step rate of the metronome at 10% above or below their preferred cadence, in random order. Running mechanics were recorded for 15 s following 1 min of accommodation to each step length condition. Following a brief rest period, participants were asked to adopt an alternate foot strike pattern. That is, participants who demonstrated a RFS pattern (18 participants) were asked to use a FFS pattern. Participants who demonstrated a FFS pattern were asked to use a RFS pattern. Participants who demonstrated a FFS pattern were asked to use a RFS pattern.

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Fig. 1. Experimental protocol used to measure patellofemoral joint kinetics under six different combinations of foot strike pattern and step length.
to use a RFS pattern (two participants). Participants were asked to run for 2 min with this alternate foot strike pattern to the cues provided by the metronome set at the same step rate as their preferred foot strike condition. Two minutes of practice prior to the alternate foot strike pattern/preferred step length condition was chosen in an effort to provide sufficient practice with the new strike pattern (approximately 340 steps) yet avoid fatigue of the plantarflexors. At the end of this time, running mechanics were recorded again for 15 s. Finally, participants were asked to maintain this alternate foot strike pattern but to increase or decrease step length by matching the step rate of the metronome set at 10% above or below their preferred cadence, in random order. Step length and therefore the number of steps required to run a kilometer was consistent across foot strike conditions. This control was necessary to delineate the individual effects of foot strike pattern and step length. Running velocity was also consistent for each participant across all conditions in this study. Foot strike pattern was evaluated visually during data collection and cross-validated during post-processing using the foot strike index (Cavanagh & Lafortune, 1980) to ensure the appropriate foot strike pattern was utilized during each condition. A RFS required the center of pressure at the moment of initial contact to be posterior to a point half the distance from the midpoint of the first and fifth metatarsal heads to the marker on the posterior calcaneus (Almonroeder et al., 2013). A FFS required the center of pressure to be anterior to this point. Initial contact during the running trials was defined as the time when the vertical ground reaction force exceeded 50 N. Participants successfully demonstrated each foot strike pattern during the protocol, and no data were excluded based on foot strike pattern.

Marker data in each condition were collected at 240 Hz using an eight-camera motion capture system (Qualysis AB, Gothenburg, Sweden) positioned around a treadmill instrumented with force plates collecting ground reaction forces at 2400 Hz (Bertec Corp, Columbus, Ohio, USA). Marker and ground reaction force data were used to calculate 3D hip, knee, and ankle joint kinematics and internal joint moments (Visual 3D, C-Motion Inc., Rockville, Maryland, USA). Internal joint moments were calculated using an inverse dynamics approach relative to the reference frame of the distal segment at each joint. Marker data and ground reaction force data used in inverse dynamics calculations were digitally filtered using a low pass, fourth-order Butterworth recursive filter at the same cut-off frequency (15 Hz) (Bisseling & Hof, 2006; Kristianslund et al., 2012). Ground reaction force data used to identify stance phase were digitally filtered at 50 Hz using a low pass, fourth-order Butterworth recursive filter.

Patellofemoral joint kinetics during running were derived using a modified version of a biomechanical model originally described by Salem and Powers (2001) that has been used to estimate PFJRF and stress during walking (Brechtcher & Powers, 2002), resisted squattting (Salem & Powers, 2001; Wallace et al., 2002), stair climbing (Heino Brechtcher & Powers, 2002), and running (Wirtz et al., 2012; Kulmala et al., 2013) in several previous studies. Briefly, this model uses input variables of tibiofemoral angle and net joint moment data obtained using inverse dynamics. Internal knee extension moment data during the stance phase of each footstep are then divided by the effective lever arm for the quadriceps as a function of knee flexion angle to obtain quadriceps force and ultimately, PFJRF (van Eijden et al., 1986).

A limitation of this popular patellofemoral joint model is that it does not account for cocontraction of the knee flexors during running. To account for this, hamstring and gastrocnemius force during running were estimated in the manner described by DeVita and Hortobagy (2001). Briefly, hamstring force was derived from the net hip extensor moment data based on the hamstrings and gluteus maximus cross-sectional areas (Ward et al., 2009) and muscle moment arms at the hip as a function of hip flexion angle (Nemeth & Ohlsen, 1985). Ankle plantarflexor force was determined from the net ankle plantarflexor moment and the Achilles tendon muscle moment arm as a function of ankle plantarflexion angle (Rugg et al., 1990; Spoor & van Leeuwen, 1992). The proportion of plantarflexion force attributed to the gastrocnemius was determined using the physiological cross-sectional area of the gastrocnemius relative to the soleus muscle (Ward et al., 2009). The derived hamstrings and gastrocnemius forces were then multiplied by their estimated muscle moment arms at the knee joint as a function of knee flexion angle (Visser et al., 1990; Spoor & van Leeuwen, 1992) and summed to estimate knee flexor torque during stance phase. Estimated knee flexor torque was added to the net knee extension moment derived from inverse dynamics and divided by the quadriceps knee joint moment arm as a function of knee flexion angle to derive quadriceps force adjusted for cocontraction of the knee flexor musculature. Finally, PFJRF was calculated from this adjusted quadriceps force as a function of knee flexion angle (van Eijden et al., 1986).

PFJFS was estimated using separate patellofemoral contact areas for males and females (Besier et al., 2005). In this previous study, contact area was determined at 0°, 30°, and 60° knee flexion using magnetic resonance imaging while participants supported 45% body weight on each leg. These data were linearly interpolated to provide patellofemoral contact area as a function of knee flexion angle for males and females. Instantaneous PFJRF determined with the biomechanical model above was divided by this angle and sex-specific patellofemoral contact area throughout the stance phase of each footstep to generate estimates of PFJFS during running.

Dependent variables of interest for this study included peak PFJRF and PFJFS and cumulative PFJRF and PFJFS during stance phase. Cumulative force and stress were determined by integrating the PFJRF and PFJFS time series data over each stance phase. As step length affects the number of steps required to run a given distance, we also calculated cumulative PFJRF and PFJFS per kilometer. Step length was calculated as the quotient of running velocity and step rate during each condition and used to derive the number of steps the runner would take per kilometer of distance run. The number of steps per kilometer was multiplied by the average cumulative PFJRF and PFJFS per step to determine the effect of reducing step length on cumulative PFJRF and PFJFS per kilometer run.

Variables of interest were analyzed using six separate 3 × 2 within-factor analyses of variance [3 step length (−10%, preferred, +10%) × 2 strike pattern (RFS, FFS)] and polynomial contrasts. Each dependent variable was first tested against a normal distribution using the Kolmogorov–Smirnov tests. To maintain a family-wise type I error rate of no more than 5%, we set an alpha level of 0.0083 for each test (0.05/6). Significant step length condition effects were analyzed in post-hoc tests using the least significant difference approach. Polynomial contrasts were used to identify significant linear trends across step length conditions for dependent variables with significant main effects of step length.

**Results**

All participants successfully completed each experimental condition. The preferred running speed across all participants was 2.84 m/s [standard deviation (SD) = 0.22 m/s; range: 2.5–3.5 m/s] and average step rate was 170 steps/min (SD = 9.6 steps/min; range: 152–188 steps/min). Average step length for all participants during their preferred running condition was 0.80 m (SD = 0.08 m; range: 0.32–1.2 m).

No significant step length × strike pattern interactions were identified for the six patellofemoral joint-dependent variables of interest. Significant main effects
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Table 1. Patellofemoral joint kinetics per step under different foot strike and step length conditions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Foot Strike</th>
<th>Step Length</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak PFJRF (BW)</td>
<td>RFS</td>
<td>Short (-10%)</td>
<td>Preferred</td>
</tr>
<tr>
<td></td>
<td>FFS</td>
<td>4.0 (0.7)</td>
<td>4.5 (0.9)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>3.1 (0.8)*</td>
<td>3.8 (0.7)</td>
</tr>
<tr>
<td>PFJRF impulse per step (BW × s)</td>
<td>RFS</td>
<td>0.45 (0.10)</td>
<td>0.53 (0.14)</td>
</tr>
<tr>
<td></td>
<td>FFS</td>
<td>0.38 (0.08)</td>
<td>0.46 (0.11)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>0.40 (0.09)*</td>
<td>0.49 (0.13)*</td>
</tr>
<tr>
<td>Peak PFJS (MPa)</td>
<td>RFS</td>
<td>5.1 (1.0)</td>
<td>5.9 (1.3)</td>
</tr>
<tr>
<td></td>
<td>FFS</td>
<td>4.3 (1.1)</td>
<td>5.1 (1.0)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>4.6 (1.1)*</td>
<td>5.4 (1.1)</td>
</tr>
<tr>
<td>PFJS impulse per step (MPa × s)</td>
<td>RFS</td>
<td>0.64 (0.14)</td>
<td>0.76 (0.19)</td>
</tr>
<tr>
<td></td>
<td>FFS</td>
<td>0.57 (0.13)</td>
<td>0.68 (0.16)</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>0.50 (0.13)*</td>
<td>0.61 (0.14)</td>
</tr>
</tbody>
</table>

*Significant difference from the preferred step length condition.

BW, body weights; FFS, forefoot strike; PFJRF, patellofemoral joint reaction force; PFJS, patellofemoral joint stress; RFS, rearfoot strike.

Fig. 2. Patellofemoral joint reaction force (PFJRF) per kilometer run during different foot strike and step length conditions. PFJRF per kilometer while running with a forefoot strike was significantly lower than the rearfoot strike condition across all step lengths \((P < 0.001)\). Step length changes affected PFJRF per kilometer regardless of foot strike pattern \((P < 0.001)\). No foot strike × step length interaction effect was observed \((P = 0.58)\). Error bars represent one standard error of the mean.

Fig. 3. Patellofemoral joint stress (PFJS) per kilometer run during different foot strike and step length conditions. PFJS per kilometer while running with a forefoot strike was significantly lower than the rearfoot strike condition across all step lengths \((P < 0.001)\). Step length changes affected PFJRF per kilometer regardless of foot strike pattern \((P < 0.001)\). No foot strike × step length interaction effect was observed \((P = 0.66)\). Error bars represent one standard error of the mean.

of strike pattern were present for each patellofemoral joint loading parameter. On average, across all step length conditions, participants experienced 10% decreased peak PFJRF and PFJS while running with a FFS pattern than when utilizing a RFS pattern \((P < 0.001, \text{Table } 1)\). Similarly, cumulative PFJRF and PFJS during stance and over the course of a kilometer were 13% \((P < 0.001)\) and 12% \((P < 0.001)\) less while running with a FFS pattern, respectively (Figures 2, 3).

Main effects of step length were also present for each kinetic variable. Analysis of polynomial contrasts revealed a linear trend for all variables of interest across step length conditions \((P < 0.001)\). On average, a 10% reduction in step length reduced peak PFJRF by 17% \((P < 0.001)\) and peak PFJS by 15% \((P < 0.001)\). A shorter step length also resulted in 20% less cumulative PFJRF \((P < 0.001)\) and 18% less cumulative PFJS during stance \((P < 0.001)\). Over the course of a kilometer, we estimated that participants would experience a reduction in total PFJRF and PFJS of 12% \((P = 0.001)\) and 9% \((P = 0.003)\) less with a shortened step length, respectively, despite the greater number of steps required to run this distance (Figures 2, 3). In contrast, a 10% increase in step length significantly increased patellofemoral joint kinetics. Peak PFJRF and PFJS during stance were 16% and 11% greater (both \(P < 0.001\)), while cumulative PFJRF and stress...
were 23% and 19% greater, respectively (both \( P < 0.001 \)). Likewise, despite the reduced number of steps required to run a kilometer with a longer step length, cumulative PFJRF and PFJS per kilometer increased 12% (\( P = 0.001 \)) and 8% (\( P = 0.002 \)), respectively.

**Discussion**

There were three main objectives of this study. The first objective was to test the effect of foot strike pattern on patellofemoral joint kinetics. On average, participants experienced a 10% decrease in peak PFJRF and PFJS while running with a FFS pattern. These results are generally consistent with Kulmala et al. (2013) who reported 16% lower peak PFJRF and 15% lower peak PFJS among runners utilizing a FFS pattern. The smaller difference in peak PFJRF and PFJS between foot strike conditions identified in this study may be attributed to increased gastrocnemius force (and thus knee flexor torque) during the FFS conditions (Almonroeder et al., 2013; Rooney & Derrick, 2013). Our patellofemoral joint model adds this cocontraction effect to the quadriceps force estimated from the net knee extensor moment. As PFJRF and PFJS are estimated directly from this adjusted quadriceps force, we expected smaller reductions in PFJRF and PFJS than earlier estimates based on patellofemoral joint models that do not account antagonistic knee flexor muscle forces.

There is some question whether our results can be generalized to runners who routinely run with a FFS pattern. Participants in this study were primarily RFS runners who temporarily adopted a FFS pattern as part of the experimental protocol. Rooney and Derrick (2013) reported no difference in joint contact forces, joint moments, or ankle and knee muscle force patterns between habitual RFS runners running with a FFS pattern and runners who habitually run with a FFS. Conversely, runners who temporarily adopt a FFS pattern have also been found to produce a smaller ankle plantarflexion moment than runners who routinely practice a FFS running style (Williams et al., 2000). In case of the latter finding and given that our participants were predominantly habitual rearfoot strikers, it is possible our results underestimate the gastrocnemius force experienced by runners who routinely practice a FFS running style. Future study of patellofemoral joint kinetics using methods that account for knee joint cocontraction among experienced runners with a FFS pattern appears justified.

The second objective of our study was to test if a 10% change in step length significantly affected patellofemoral joint kinetics over a single step and over the course of a kilometer. Similar to previous authors of studies using consecutive (Lenhart et al., 2014) and nonconsecutive (Willson et al., 2014) steps during running, we conclude that peak and cumulative PFJRF and PFJS per step vary directly with step length. Indeed, our results were very similar to the results of Lenhart et al. (2014) who reported a 14% decrease in peak PFJRF (current study found 17%) and 20% decrease in stance phase PFJRF impulse (current study also found 20%) while running at a self-selected speed and 10% shortened step length. This decrease in PFJRF has been attributed to decreased peak knee flexion and vasti muscle force while running with a 10% shortened step length (Lenhart et al., 2014).

Step length changes also had a direct relationship with PFJRF and PFJS per kilometer run, despite an inverse relationship with the number of steps required to run this distance. Using a series of nonconsecutive gait cycles, Willson et al. (2014) previously reported a significant reduction in PFJS per mile while running with a shortened step length. However, the runway length in this previous study prohibited participants from implementing the step length modification over several consecutive steps. Further, step length modifications greater than 10% are more likely to adversely affect running economy and therefore decrease intervention adherence (Hamill et al., 1995). As such, it is difficult to predict whether the step length intervention implemented in that study was a feasible clinical intervention. In the present study, all participants adopted and maintained the 10% step length modification while running with their preferred velocity for the duration of the condition without difficulty. However, participants were provided auditory cues as feedback throughout each measurement condition. It is not clear that step length modifications outside of the laboratory are a feasible intervention for runners. Methods to translate these methods to in-field interventions require further development and analysis.

The third purpose of this study was to test if the effect of foot strike pattern or step length varied according to the presence of the other factor. Main effects of foot strike pattern and step length were identified and linear trends were present for each patellofemoral joint kinetic variable across step length conditions. However, no foot strike pattern \( \times \) step length interactions were revealed for any variable of interest in this study. In other words, foot strike pattern and step length each influenced patellofemoral joint loading and the effect of each modification was independent of the other factor.

Analysis of the combined influence of these running modifications provides valuable insight. For example, patellofemoral joint kinetics per step was more affected by step length changes than by foot strike pattern. Relative to the preferred step length/RFS condition, decreasing step length reduced PFJS per step by 16%. Relative to this same condition, adopting a FFS decreased PFJS per step only 10%. Likewise, PFJS per step increased 20% during the long step length/RFS condition and the addition of a FFS did not entirely mitigate this increase. Changes in patellofemoral joint kinetics per kilometer, on the other hand, were larger in response to a change in strike pattern than step length. For example, relative to the preferred step length/RFS condition, PFJS per
kilo-meter decreased 7% in response to a shortened step length but decreased 10% in response to a FFS pattern. This finding is likely a consequence of the inverse association between step length and steps per kilometer. Thus, although both modifications significantly affect patellofemoral joint kinetics, adopting a FFS appears to decrease patellofemoral joint kinetics more than decreasing step length over the course of a kilometer.

The result that both foot strike pattern and step length have independent effects on patellofemoral joint kinetics has relevance for clinical practice. Among shod runners, step length differences are not routinely observed between runners utilizing a FFS and RFS pattern (Almonroeder et al., 2013; Kulmala et al., 2013; Vannatta & Kernozek, 2014; Ogueta-Alday et al., 2014). Similarly, foot inclination angle was found to change very little with a 10% step length modification during running, suggesting that step length changes do not necessarily change foot strike pattern (Heiderscheit et al., 2011). Therefore, a relationship between these running characteristics should not be assumed. It may be necessary to provide training cues specific for both foot strike pattern and step length in order to minimize patellofemoral joint kinetics among patients running in conventional footwear. However, it is important to note that, to date, no experimental studies substantiate the therapeutic value of step length or foot strike modifications for treatment of PFP. Additionally, it is important to consider that these modifications have consequences at sites beyond the patellofemoral joint. For example, adopting a FFS imposes novel stresses on the Achilles tendon that should likely be introduced in a graduated fashion to allow adaptation time for affected tissues (Almonroeder et al., 2013).

Running barefoot has been also reported to reduce PFJS. Bonacci et al. (2014) and Sinclair (2014) found runners experienced a 10–12% decrease in peak PFJS while running barefoot compared with running in conventional footwear. In these previous studies, the authors attributed reductions in PFJS to a more horizontal orientation of the foot at initial contact and a reduction in step or stride length. Participants in this study performed each condition in conventional footwear. Although running barefoot may facilitate foot strike and step length modifications (Divert et al., 2005), our results suggest it is not necessary to run barefoot to experience reductions in patellofemoral joint kinetics that are equal or greater than those previously attributed to the absence of footwear.

Participants in this study adopted the step length and foot strike modifications during the experimental conditions in this study, but runners were not asked to change their running mechanics outside of the laboratory. However, available evidence suggests runners may adopt new mechanics with appropriate training. For example, changes in step length and foot strike pattern were observed following eight practice sessions with audible feedback to reduce step length and promote a FFS pattern (Cheung & Davis, 2011). After this training, all participants (three runners with PFP) demonstrated a FFS pattern as well as subjective improvement in PFP symptoms (Cheung & Davis, 2011). Further, participants maintained a FFS pattern and subjective improvements at a 12-week follow-up visit, suggesting persistent changes in running mechanics due to training. Eight training sessions incorporating concurrent external feedback on movement performance has also been sufficient to evoke persistent changes in running mechanics among runners with PFP in other previous laboratory-based intervention studies (Willy et al., 2012). Thus, several training sessions with feedback of performance are likely necessary for runners to permanently adopt running modifications. However, it is important to note that transition to a FFS pattern imposes novel stressors to the Achilles tendon (Almonroeder et al., 2013) and metatarsals (Kernozek et al., 2014) that must be introduced gradually to avoid injury to these regions.

To date, no experimental evidence exists for a PFP treatment effect in response to these running modifications. However, a theoretical framework exists for the application of these results. Repetitive application of high joint reaction forces (Chen & Powers, 2014) with high loading rates (Lenhart et al., 2014) during running contribute to increased patellar bone metabolic activity (Draper et al., 2012), patellar water content, and symptoms of PFP (Ho et al., 2014a,b). Reduction of these stimuli may have therapeutic effects. Given the findings of this study and this previous non-experimental study results of Cheung and Davis (2011), formal testing of these running interventions to decrease symptoms of PFP with an experimental design appears warranted.

There are notable limitations of this study. For example, only runners who were currently injury free participated in this study. Similar changes in patellofemoral joint kinetics in response to step length modifications have been reported among females with and without PFP (Willson et al., 2014). However, the methodology employed in the current study is somewhat different than this previous study and generalizations of these results to runners with PFP should be made with caution. A second limitation of this study is that we estimated patellofemoral joint kinetics using a biomechanical model that did not include subject-specific muscle moment arms or patellofemoral contact areas. Additionally, transverse and frontal plane hip and knee joint rotations that might affect patellofemoral joint contact areas were not considered. We expect that errors in our patellofemoral joint kinetic estimates are consistent across conditions, limiting bias associated with repeated comparisons within subjects. Finally, it is possible that these results may be different than results obtained during over ground running, as over ground running kinetics may differ slightly from those on a treadmill. For example, decreased knee extension moment has been reported during treadmill running compared with over ground (Lee & Hidler, 2008; Riley...
et al., 2008). This would result in an underestimation of PFJRF and PFJS in our results relative to those calculated during over ground running.

We conclude from these results that foot strike pattern and step length each significantly affect patellofemoral joint kinetics. Running with a FFS pattern decreased patellofemoral joint kinetics across all step lengths compared with a RFS pattern. A 10% decrease in step length decreased patellofemoral joint kinetics per step and per kilometer while a 10% increase in step length increased patellofemoral joint kinetics per step and per kilometer, regardless of foot strike pattern. These running modifications have independent effects on patellofemoral joint kinetics and may be employed simultaneously for greatest effect. To the extent that patellofemoral joint kinetics contribute to symptoms among runners, each or both of these modifications to running technique may be advisable for people with PFP.

References


Perspective

Patellofemoral joint kinetics have been linked to the etiology and exacerbation of PFP, one of the most common running-related injuries (Farrokhi et al., 2011; Ho et al., 2014a,b). The present findings provide unique evidence for independent effects of both foot strike pattern and step length on patellofemoral joint kinetics each step during running and for each kilometer run. Although experimental evidence is lacking at this time, it is conceivable that these relatively straightforward modifications to running technique used in isolation or in combination may address underlying mechanical factors associated with this injury and improve long-term conservative PFP prevention and treatment efforts.

Key words: Patellofemoral joint stress, cadence, foot strike, running training.


