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Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run☆

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ABSTRACT

Patellofemoral joint pain (PFP) is a common running-related injury that is more prevalent in females and thought to be associated with altered running mechanics. Changes in running mechanics have been observed following an exhaustive run but have not been analyzed relative to the sex bias for PFP. The purpose of this study was to test if females demonstrate unique changes in running mechanics associated with PFP following an exhaustive run. For this study, 18 females and 17 males ran to volitional exhaustion. Peak PFJ contact force and stress, PFJ contact force and stress loading rates, hip adduction excursion, and hip and knee joint frontal plane angular impulse were analyzed between females and males using separate 2 factor ANOVAs (2 (male/female) × 2 (before/after exhaustion)). We observed similar changes in running mechanics among males and females over the course of the exhaustive run. Specifically, greater peak PFJ contact force loading rate (5%, $P=.01$), PFJ stress loading rate (5%, $P<.01$), hip adduction excursion (1.3°, $P<.01$), hip abduction angular impulse (4%, $P<.01$), knee abduction angular impulse (5%, $P=.03$), average vertical ground reaction force loading rate (10%, $P<.01$) and step length (2.1 cm, $P=.001$) were observed during exhausted running. These small changes in suspected PFP pathomechanical factors may increase a runner's propensity for PFP. However, unique changes in female running mechanics due to exhaustion do not appear to contribute to the sex bias for PFP.

1. Introduction

Running is a popular mode of exercise across the lifespan, with nearly 30 million Americans participating regularly (2013 State of the Sport – Part II: Running Industry Report | Running USA, n.d.). Unfortunately, a high incidence of musculoskeletal injury is associated with running (Van Gent et al., 2007) and patellofemoral joint pain (PFP) is among the most common of these injuries (Lopes et al., 2012; Taunton et al., 2002). Interestingly, males and females do not appear to be at equal risk for PFP. The prevalence (Foss et al., 2014; Glaviano et al., 2015) and incidence (Boling et al., 2010) of PFP appears to be significantly higher among females.

The etiology of PFP among runners is typically associated with elevated patellofemoral joint (PFJ) kinetics. Depending on factors such as running speed, foot strike pattern and step length, the PFJ experiences peak contact forces between 4–10 body weights (Kernozek et al., 2015; Lenhart et al., 2014; Willson et al., 2015). The repetitive application of elevated forces to the patellar articular cartilage at a high rate of loading is thought to contribute to PFP by increasing patellar interosseous pressure and subchondral bone metabolic activity (Draper et al., 2012; Ho et al., 2014b). Altered lower extremity mechanics such as increased hip adduction excursion (Barton et al., 2009) and increased hip and knee abduction angular impulse (Stefanyshyn et al., 2006; Willson and Davis, 2009) have also been observed among runners with PFP and hypothesized to contribute to the etiology or exacerbation of PFJ symptoms.

The repetitive nature of running typically places the runner in an exerted state that may adversely affect lower extremity running mechanics relevant to PFP. Changes in running kinematics following a run to volitional exhaustion have been observed including increased peak hip and knee flexion (Bazett-Jones et al., 2013), increased rearfoot excursion (Dierks et al., 2010), increased knee flexion at initial contact (Derrick et al., 2002) and increased step length (Derrick et al., 2002; Gerlach et al., 2005). However, to date, the effects of running to exhaustion on PFJ kinetics have not been reported. It is also unclear whether males and females experience similar changes in running mechanics associated with PFP over the course of a run to exhaustion. Given the greater prevalence and incidence of PFP in females and the tendency for PFP symptoms manifest over the course of a prolonged run (Bazett-Jones et al.,

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2013; Ho et al., 2014b), it is conceivable that males and females demonstrate unique changes in PFP pathomechanical factors in response to running to exhaustion.

The purpose of the current study was to examine sex differences in the effects of an exhaustive run on running mechanics previously associated with the etiology or exacerbation of PFP. Specifically, we tested the hypotheses that an exhaustive run would lead to greater changes in peak PFJ contact force and stress, PFJ contact force and stress loading rates, hip adduction excursion, and hip and knee joint frontal plane angular impulse in females compared to males.

2. Methods

This study used a nonexperimental (cross sectional) research design where naturally-occurring differences in running mechanics previously associated with PFP among males and females in response to a run to exhaustion were evaluated. An *a priori* power analysis determined that 16 participants per group would be sufficient to detect sex × condition interaction effects with an effect size greater than .7 using $\alpha=.05$ and $\beta=.2$ (Park and Schutz, 1999). We chose to test for an effect size of this magnitude based on the effect size for the difference observed in PFJ stress between individuals with and without PFP (Farrokhi et al., 2011). The protocol for this study was approved by the university institutional review board and all participants provided their informed consent prior to participation.

We recruited 18 females (22.9 years, 1.68 m, 59.7 kg, preferred training pace 2.8 m/s, running experience 6 years) and 17 males (22.4 years, 1.80 m, 79.0 kg, preferred training pace 2.8 m/s, running experience 4 years) to participate in this study. All participants were between 18 and 35 years old and ran a minimum of 10 miles/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.

Running mechanics were recorded for males and females at the beginning and end of an exertion protocol. Prior to the exertion protocol, participants were asked to accommodate to the treadmill by walking and running at a self-selected pace for a minimum of 6 min (Matsas et al., 2000). At the conclusion of this accommodation period, subjects were prepared for standard 3D lower extremity motion analysis test procedures using 9 mm reflective markers to track motion of the pelvis, femur, shank, and foot; each modeled as a rigid body.

All participants in this study ran on a treadmill instrumented with force plates (Bertec Corp, Columbus, OH) at a prescribed speed (3.5 m/s) until they reported a rating of greater than 17/20 on the Borg Rating of Perceived Exertion (RPE) scale (Borg, 1998). The RPE scale ranges from 6 to 20 where 6 corresponds to “no exertion at all” and 20 represents “maximal exertion”. During the running protocol, participants were asked to provide a RPE every two minutes. Running mechanics were recorded for 20 s following the first minute of running and again immediately after the participants reported an RPE greater than 17/20. An RPE greater than 17 has been used as criteria for exhaustion in previous similar studies (Bazett-Jones et al., 2013; Dierks et al., 2010). Participants ran at a prescribed speed (3.5 m/s) rather than a self-selected speed to control for possible confounding effects of differences in running speed between males and females on the variables of interest in this study. The stance phase for five footsteps of the dominant leg (leg used to kick a ball as far as possible) were analyzed from the data recorded at the beginning and end of the protocol.

Marker data were collected during running before and after exertion at 240 Hz using an eight camera motion capture system (Qualysis AB, Gothenburg, Sweden) positioned around the treadmill. Ground reaction forces were collected at 2400 Hz. Marker and ground reaction force data were used to calculate three-dimensional hip, knee, and ankle joint kinematics and internal joint moments (Visual 3D, C-Motion Inc, Rockville, MD). Internal joint moments were calculated using an inverse dynamics approach, normalized to each participant's height and mass, and reported in the reference frame of the distal segment for 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 and Hof, 2006; Kristianslund et al., 2012). Ground reaction force data used to identify specific gait events (initial contact, vertical impact peak, and toe off) and average vertical loading rate were digitally filtered at 50 Hz using a low pass, fourth order Butterworth recursive filter. Initial contact during the running trials was defined as the time when the vertical ground reaction force exceeded 20 N.

Discrete variables of interest from the joint kinematic and kinetic data included hip adduction excursion, and hip and knee frontal plane angular impulse. Hip adduction excursion was determined as the change in hip joint angle from initial contact with the force plate to peak hip adduction angle during stance phase. Frontal plane angular impulses for the hip and knee were calculated as the respective time integral of the frontal plane joint moment during stance phase. To facilitate interpretation of the results and comparison with previous studies, step length and average vertical ground reaction force loading rate were also determined. Average vertical loading rate was calculated between 20% and 80% of the period between initial contact and vertical impact peak (Milner et al., 2006). Impact peak was defined as the highest point preceding a decline of the vertical ground reaction force in 3 consecutive samples during the first 30% of stance phase. Average loading rate was calculated as the total change in force divided by the total change in time over this period. Finally, step length was determined as the quotient of the number of stance phases and the distance run during each 20 s collection (70 m/# stance phases).

We estimated PFJ contact force and stress during running using a previously described biomechanical model (DeVita and Hortobagyi, 2001; Willson et al., 2015). Briefly, this model uses sagittal plane hip, knee, and ankle joint angles, net moments, estimated muscle moment arms and cross sectional areas to derive hamstring, quadriceps, and gastrocnemius muscle forces. Patellofemoral joint contact force was based on the ratio of quadriceps to PFJ force as a function of knee flexion angle (Van Eijden et al., 1986) after adjusting for cocontraction of the knee flexors. The PFJ loading rate was determined by numerically differentiating the PFJ force magnitude–time curve. Patellofemoral joint stress throughout the stance phase of each footstep was estimated as the quotient of PFJ contact force and PFJ contact area. Separate sex-specific patellofemoral contact areas as a function of knee flexion angle were derived for males and females through linear interpolation of data reported by Besier et al. (2005). Dependent variables of interest using this model include peak PFJ contact force, peak PFJ stress, PFJ contact force*time impulse, PFJ stress*time impulse, peak PFJ contact force loading rate, and peak PFJ stress loading rate. Peak sagittal plane hip, knee, and ankle internal joint moments were also reported to facilitate interpretation of the PFJ variables and for comparison with previous studies. Each variable was analyzed using separate 2 factor ANOVAs (2 (male/female) × 2 (before/after exhaustion)) ($\alpha=.05$).

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