Sex differences in knee loading in recreational runners

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Short communication

Sex differences in knee loading in recreational runners

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ABSTRACT

Patellofemoral pain is the most common chronic pathology in recreational runners. Female runners are at greater risk of developing patellofemoral pain, although the exact mechanism behind this is not fully understood. This study aimed to determine whether female recreational runners exhibit distinct knee loading compared to males. Fifteen males and 15 females recreational runners underwent 3D running analysis at 4.0 m s^{-1} ± 5%. Sagittal/coronal joint moments, patellofemoral contact forces (PTF) and pressures (PCP) were compared between sexes. The results show that females exhibited significantly greater knee extension ($p < 0.008$, pη^2=0.27: males=3.04; females=3.47 N m kg^{-1}) and abduction ($p < 0.008$, pη^2=0.28: males=0.54; females=0.82 N m kg^{-1}) moments as well as PTF ($p < 0.008$, pη^2=0.29: males=3.25; females=3.84 B.W.) and PCP ($p < 0.008$, pη^2=0.26: males=7.96; females=9.27 MPa) compared to males. Given the proposed relationship between knee joint loading and patellofemoral pathology, the current investigation provides insight into the incidence of patellofemoral pain in females.

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1. Introduction

It has been shown that 19.4–79.3% of all who participate in recreational running activities will suffer from a chronic pathology over the course of one year (van Gent et al., 2007). Patellofemoral pain syndrome has been demonstrated as the most common chronic injury in runners (Taunton et al., 2003), accounting for 20–40% of all knee disorders (DeHaven and Lintner, 1986; Kannus et al., 1987). The patellofemoral joint itself involves the distal and anterior aspects of the femur, patella, and their articular surfaces (Tumia and Maffulli, 2002). The patella serves to enhance the effective moment arm of the quadriceps muscle group and reduces the mechanical effort required to extend the knee joint (Tumia and Maffulli, 2002).

Patellofemoral symptoms are defined by pain which initiates as function of the contact between the posterior aspect of the patella and distal end of the femur during dynamic activities (Besier et al., 2005). Patellofemoral pain symptoms are debilitating and may severely restrict participation in athletic activities (Selfe et al., 2013; Witvrouw et al., 2014). Patellofemoral pain has also been cited as a potential precursor to the progression of osteoarthritic symptoms in later life (Crossley, 2014; Thomas et al., 2010). A number of biomechanical mechanisms have been linked to the

etiology of patellofemoral pain. However, habitual and excessive contact stresses between the patella and femur (LaBella, 2004; Ho et al., 2012) as well as enhanced knee abduction moments (Sigward et al., 2012; Myer et al., 2015) are most strongly associated with the initiation of patellofemoral symptoms.

Female recreational runners are 2–3 times more likely to suffer from patellofemoral pain in comparison to males (Robinson and Nee, 2007; Boling et al., 2010). It has been postulated that anatomical, neuromuscular and hormonal influences contribute to the enhanced incidence of patellofemoral disorders in females (Robinson and Nee, 2007). However, the exact mechanisms behind the incidence of patellofemoral pain in female runners remain unknown. This indicates that there is a clear need to investigate the loads experienced by the patellofemoral joint in female runners in relation to males in order to gain further insight into the increased incidence of patellofemoral disorders in females.

Quantification of patellofemoral forces during dynamic activities is problematic as direct measurements of in vivo patellofemoral stresses are impractical (Mason et al., 2008). We must therefore rely on computational techniques to estimate the loads experienced by the patellofemoral joint. Early researchers examined patellofemoral forces using in vitro cadaveric models (Huberti and Hayes, 1984; Ahmed et al., 1987). Whilst these studies provided important information regarding the mechanics of the knee joint the patellofemoral joint loads could not be generalized to in vivo conditions (Powers et al., 2006). Mathematical modeling of

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the patellofemoral joint is now the most commonly utilized procedure. Approaches to modeling patellofemoral joint forces include both two-dimensional and three-dimensional (3D) techniques (Powers et al., 2006). Mathematical techniques model the patellofemoral joint as a pulley mechanism whereby the patellofemoral contact force is produced by the force generated in the quadriceps (Powers et al., 2006). In recent years musculoskeletal simulation techniques have also been developed for the quantification of lower extremity joint reactions forces. Musculoskeletal simulation uses inverse kinematics to estimate the forces required to produce dynamic movements (Delp et al., 2007).

The aim of the current investigation was to determine whether female recreational runners exhibit distinct patellofemoral loading patterns in relation to their male counterparts. The current study tests the hypothesis that females will exhibit increased knee joint loading in comparison to males.

2. Methods

2.1. Participants

Fifteen males (age 28.80 ± 4.23 years, height 1.80 ± 0.13 m and mass 79.07 ± 6.88 kg) and 15 females (age 27.67 ± 7.52 years, height 1.67 ± 0.19 m and mass 63.33 ± 10.07 kg) recreational runners took part in this investigation. Both males and females were characterized as recreational runners who trained at least 3 times per week and had a minimum of five years of distance running experience. The male group had a mean personal best 10 km time of 43 ± 5 min and the females 49 ± 4 min. Runners were all considered to exhibit a rearfoot strike pattern as they exhibited first peak in their vertical ground reaction force (GRF) time-curve (Cavanagh and Lafortune, 1980). Ethical approval was obtained from the University.

2.2. Procedure

Participants completed 10 running trials across a 22 m laboratory at 4.0 m s^{-1} $\pm 5\%$, striking an embedded force platform (Kistler instruments, Model 9281CA) which operated at 1000 Hz with their right foot. 3D marker trajectories were collected using an eight camera motion capture system at 250 Hz. Kinematic and GRF data were obtained synchronously using Qualisys track manager software (Qualisys Medical AB, Goteburg, Sweden). Participants all wore the same footwear Asics 2160, in sizes 4–10 UK sizing. As these footwear were novel to participants, they were given a 5 min period to familiarize. This involved running through the testing area without concern for striking the force platform (Sinclair et al., 2013).

The shank and thigh segments were delineated using the calibrated anatomical systems technique (Cappozzo et al., 1995). Retroreflective markers were positioned onto the medial and lateral malleoli, epicondyles of the femur and greater trochanter. Tracking clusters were positioned onto the segments. Static trials allowed the anatomical markers to be referenced in relation to the tracking clusters.

2.3. Data processing

GRF and marker data were filtered at 50 Hz and 15 Hz using a low-pass Butterworth 4th order filter and processed using Visual 3-D (C-Motion, Germantown, MD, USA). Joint kinetics were computed using Newton–Euler inverse-dynamics, allowing net knee joint moments to be calculated. To quantify joint moments segment mass, segment length, GRF and angular kinematics were utilized using the procedure previously described by Sinclair (2014). The net joint moments were normalized by dividing by body mass (N m kg^{-1}).

Knee loading was examined through extraction of peak knee extensor/abduction moments, patellofemoral contact force (PTF) and patellofemoral contact pressure (PCP). PTF was normalized by dividing the net PTF by body weight (B.W.). PTF loading rate (B.W. s^{-1}) was calculated as a function of the change in PTF from initial contact to peak force divided by the time to peak force. These variables were extracted from each of the 10 trials and the data was then averaged within subjects for statistical analysis. Knee joint kinetic curves were time normalized to stance and were ensemble averaged across subjects for graphical purposes.

PTF during running was estimated using knee flexion angle (kf) and knee extensor moment (KEM) through the biomechanical model of Ho et al. (2012). This model has been utilized previously to resolve differences in PTF and PCP in different footwear (Bonacci et al., 2013; Kulmala et al., 2013; Sinclair, 2014) and between those with and without patellofemoral pain (Heino and Powers, 2002). The model has also been shown to be sufficiently sensitive to detect differences in PTF between sexes (Sinclair and Bottoms, 2015).

The effective moment arm distance (m) of the quadriceps muscle (QM) was calculated as a function of kf using a non-linear equation, based on information presented by van Eijden et al. (1986):

$$QM = 0.00008kf^3 - 0.013kf^2 + 0.28kf + 0.046$$

The force (N) of the quadriceps (FQ) was calculated using the below formula:

$$FQ = KEM/QM$$

Net PTF (N) was estimated using the FQ and a constant (C):
$$PTF = FQ*C$$
C was described in relation to kf using a curve fitting technique based on the non-linear equation described by van Eijden et al. (1986):

$$C = (0.462 + 0.00147*kf^2 - 0.0000384*kf^2)$$
$$/(1 - 0.0162*kf + 0.000155*kf^2 - 0.000000698*kf^3)$$

PCP (MPa) was calculated using the net PTF divided by the patellofemoral contact area. The contact area was described using the Ho et al. (2012) recommendations by fitting a 2nd order polynomial curve to the data of Powers et al. (1998) showing patellofemoral contact areas at varying levels of kf.
$$PCP = PTF/contact\ area$$

2.4. Statistical analysis

Sex differences in knee kinetics were examined using independent t-tests. The alpha level was adjusted to $p \leq 0.008$ using a Bonferroni correction. Effect sizes were calculated using partial eta^2 (pη^2). The data was pre-screened for normality using a Shapiro–Wilk. Statistical procedures were conducted using SPSS v22.0.

3. Results

Table 1 and Fig. 1 present the sex differences in patellofemoral load during the stance phase of running. Although the knee kinetic curves were qualitatively similar, the results also indicate that patellofemoral kinetic parameters were significantly influenced as a function of sex.

Females exhibited significantly greater peak knee extensor moments compared to males (Fig. 1a; Table 1). Females also had

greater PTF and PTF load rate (Fig. 1b; Table 1). In addition females exhibited a significantly increased PCP (Fig. 1c; Table 1). Finally it was documented that females demonstrated a significantly increased peak knee abduction moment compared to males (Fig. 1d; Table 1).

4. Discussion

This study aimed to document sex differences in knee loading in recreational runners. This study represents the first comparative investigation to examine knee loading patterns in male and female runners and may provide insight into the increased incidence of patellofemoral disorders in female runners.

The current investigation shows that females exhibited a significantly increased knee extensor moment and patellofemoral loads compared to males. This does not support the observations of Ferber et al. (2003) who found no sex differences in knee extensor moment during running. However, it is in general agreement with previous investigations that have examined sex differences in joint kinetics during landing activities (McLean et al., 2005; Sigward et al., 2012). This finding may have clinical significance regarding the etiology of injury in females as the consensus regarding the development of patellofemoral pain is that symptoms are the function of excessive patellofemoral joint kinetics (LaBella, 2004; Ho et al., 2012).

There are several mechanisms that may serve to explain this observation. Firstly female runners have been associated with hip musculature weakness and lack of neuromuscular control at the knee joint during dynamic activities (Mizuno et al., 2001; Stefanik et al., 2011). Stearns et al. (2013) showed that weakness of the hip musculature resulted in a compensatory strategy whereby females relied more heavily on the knee extensor moment to absorb impact forces. In addition, female runners have also been shown to exhibit reduced ankle plantarflexor moments and Achilles tendon loads in comparison to males (Greenhalgh and Sinclair, 2014). An enhanced plantarflexion contribution from the ankle joint may also be a mechanism by which the loads at the knee joint are reduced in male runners. With an enhanced plantarflexion involvement the function of the knee joint as an energy absorber may be reduced in male runners, leading to a reduction in the loads experienced by the knee joint structures (Kulmala et al., 2013; Sinclair, 2014).

A further important finding from this study is that females exhibited a greater peak coronal plane abduction moment compared to males. Enhanced knee abduction moments are known to

Table 1
Patellofemoral kinetics as a function of gender.

|	Male		Female		Statistical analysis
	Mean	*SD*	*Mean*	*SD*	
Peak knee extensor moment (N m kg^{-1})	3.04	0.30	3.47	0.25	$t_{(28)}=2.88$, $p<0.008$, p$\eta^2=0.27$
Peak knee abductor moment (N m kg^{-1})	0.54	0.19	0.82	0.20	$t_{(28)}=2.92$, $p<0.008$, p$\eta^2=0.28$
PTF (B.W.)	3.25	0.46	3.84	0.45	$t_{(28)}=3.01$, $p<0.008$, p$\eta^2=0.29$
PCP (MPa)	7.96	1.30	9.27	1.36	$t_{(28)}=2.81$, $p<0.008$, p$\eta^2=0.26$
Time to peak force (ms)	0.07	0.01	0.07	0.02	$t_{(28)}=0.19$, $p>0.008$, p$\eta^2=0.02$
PTF load rate (B.W. s^{-1})	20.19	4.27	32.24	7.20	$t_{(28)}=2.74$, $p<0.008$, p$\eta^2=0.25$
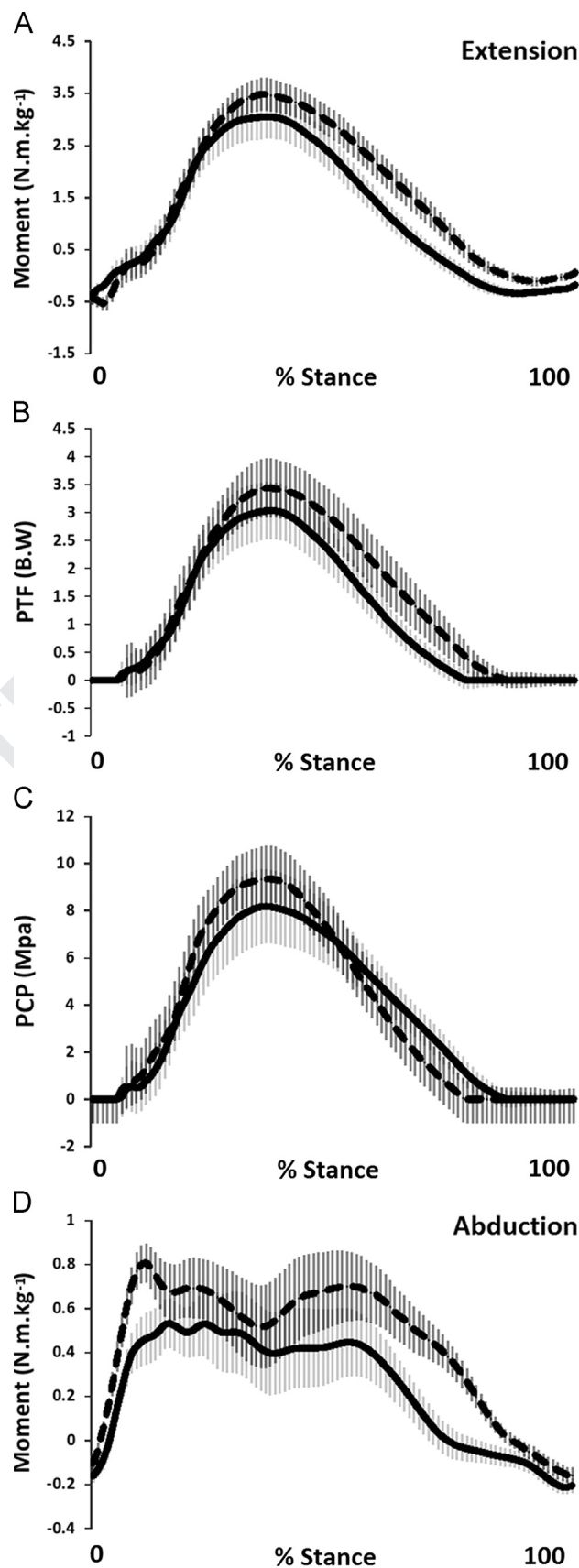
Fig. 1. Knee kinetics as a function of gender, black=male and dash=female (*a*=sagittal knee moment, *b*=PTF, *c*=PCP, and *d*=coronal knee moment) (shaded area=1SD).

correspond with increased medial compartment loading (Zhao et al., 2007) and is commonly linked to the etiology and progression of degenerative knee syndromes such as medial tibiofemoral osteoarthritis (Miyazaki et al., 2002). Furthermore, it has also been postulated that increases in coronal plane moments during running serve to enhance loading of the lateral facet of the patellofemoral joint complex and thus may further contribute to the etiology of patellofemoral pain (Myer et al., 2015; Sigward et al., 2012).

A potential drawback of the current study is that patellofemoral forces were quantified using a mathematical model. This was necessary due to the invasive nature of obtaining direct measures of patellofemoral forces. The efficacy of this algorithm has yet to be resolved in the context of its effectiveness in quantifying sex differences in knee kinetics. This model has however been utilized previously on both male and female runners (Kulmala et al., 2013; Sinclair, 2014), also to successfully resolve differences in knee loads between sexes (Sinclair and Bottoms, 2015). However future work should nonetheless seek to develop a patellofemoral model which is specific to each sex. Muscle driven simulations of joint reaction forces using inverse kinematics have improved considerably in recent years and have thus been cited as a useful tool for clinical analysis (Delp et al., 2007). Musculoskeletal simulations however do require mechanical assumptions such as constrained rotational degrees of freedom at the joints which may lead to incorrectly predicted joint kinetics. Musculoskeletal simulation methods remain relatively new however and with further work to improve their accuracy further advancements in clinical biomechanics research may be possible.

In conclusion, the observations of the current investigation show that female recreational runner's exhibit significantly greater knee loading compared to males. Given the proposed relationship between knee joint loading and patellofemoral pathology, the current investigation does appear to provide some insight into the high incidence of patellofemoral pain in females. Future analyses may seek to implement strategies aimed at reducing knee loading in female runners. In addition it may be interesting to explore the loads relative to the preferred running speeds of the two sexes rather than running at a set speed for both.

Conflict of interest statement

No conflict of interest from any author.

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