IJSPT INTERNATIONAL JOURNAL OF SPORTS PHYSICAL THERAPY

Jacobson L, Vannatta CN, Schuman C, Kernozek TW. An Updated Model Does Not Reveal Sex Differences in Patellofemoral Joint Stress during Running. *IJSPT*. 2022;17(7):1290-1297.

Original Research

An Updated Model Does Not Reveal Sex Differences in Patellofemoral Joint Stress during Running

Laura Jacobson[1], C. Nathan Vannatta[2] [a], Catherine Schuman[1], Thomas W. Kernozek[3]

[1] Family Medicine, Gundersen Health System, [2] Department of Sports Physical Therapy, Gundersen Health System; La Crosse Institute for Movement Science, University of Wisconsin – La Crosse, [3] La Crosse Institute for Movement Science, University of Wisconsin – La Crosse; Department of Health Professions, University of Wisconsin - La Crosse

Keywords: knee, kinetics, patellofemoral pain, biomechanics

https://doi.org/10.26603/001c.39608

International Journal of Sports Physical Therapy

Vol. 17, Issue 7, 2022

Background

Structure-specific loading may have implications in understanding the mechanisms of running related injury. As females demonstrate a prevalence of patellofemoral pain twice that of males, this may indicate differences in patellofemoral loads between males and females. Previous works investigating differences in patellofemoral joint stress have shown conflicting results, but the models employed have not used estimates of muscle forces or sex specific contact areas.

Hypothesis/Purpose

The aim of this study was to examine sex differences in patellofemoral joint stress using an updated model to include estimates of quadriceps muscle force and sex-specific patellofemoral contact area.

Study Design

Descriptive Laboratory Study

Methods

Forty-five healthy recreational runners ran at a controlled speed down a 20-meter runway. Kinetic and kinematic data were utilized to estimate muscle forces using static optimization. Quadriceps muscle force was utilized with sex-specific patellofemoral joint contact area in a two-dimensional patellofemoral joint model to estimate patellofemoral joint stress. Multivariate tests were utilized to detect sex differences in patellofemoral loading and hip and knee kinematics.

Results

No differences were found between sexes in measures of patellofemoral loading or quadriceps force. Females displayed a reduced knee extension moment and greater hip adduction and internal rotation than males.

Conclusion

The inclusion of static optimization to estimate quadriceps muscle force and sex-specific contact area of the patellofemoral joint did not reveal sex differences in patellofemoral joint stress, but differences in non-sagittal plane hip motion were detected. Therefore, two-dimensional patellofemoral models may not fully characterize differences in patellofemoral joint stress between males and females. Three-dimensional

---

[a] **Corresponding author:**
C. Nathan Vannatta, PT, DPT, SCS
Department of Sports Physical Therapy
Mail Stop: NC1-002 3111 Gundersen Drive
Onalaska, WI 54650
Phone: 608.775.8986 Email: cnvannat@gundersenhealth.org

patellofemoral models may be necessary to determine if sex differences in patellofemoral joint stress exist.

Level of Evidence

3b

INTRODUCTION

Structure-specific loading has become of interest, especially pertaining to overuse running injuries.[1,2] This premise seeks to understand how elements of running biomechanics, such as different kinematic and kinetic features of running, may lead to stresses on tissues that predispose those structures to injury.[2] This has implications to understanding common running injuries such as patellofemoral pain (PFP). Patellofemoral pain has been reported as the most common running related injury accounting for 16.5% of all injuries presenting to a running clinic.[3] More recently, a systematic review and meta-analysis has estimated an incidence rate of 1080.5/1000 person-years in amateur runners.[4] As increased patellofemoral joint stress (PFJS), patellofemoral bone stress, and cartilage strain have been implicated in PFP and certain running kinematics and kinetics may increase structure-specific loading (i.e. PFJS), understanding differences in structure-specific loading between sexes may be relevant to the development of this common injury.[5–7]

As PFP is two times more prevalent in females,[8] it has been proposed that females may demonstrate increased PFJS leading to greater structure-specific load. Although the theoretical link is clear, studies investigating sex differences in PFJS have shown mixed findings.[9–11] Almonroeder & Benson[9] reported males had greater PFJS and patellofemoral joint reaction force (PFJRF) during running, while there were no differences between sexes in knee extension moments or knee flexion. Sinclair & Selfe[10] reported females had greater patellofemoral contact force, PFJS, and peak knee extension moment compared to males, while Willson et al.[11] did not demonstrate sex differences in PFJS, PFJRF, or knee extensor moment.

To understand these discrepancies, important differences should be noted in the musculoskeletal modeling approaches employed. First, two studies[9,10] utilized estimates of PFJS based on inverse dynamics methods that calculate joint stress directly using the knee extension moment. This may not account for any potential muscle co-contraction. Therefore, inverse dynamics approaches alone may lead to underestimation of PFJS.[12]

Willson et al.[11] adjusted their model to account for the force of the knee flexors but how this method compares to other approaches estimating quadriceps force is unknown. Static optimization based methods used to estimate muscle forces yield different values of PFJS compared with inverse dynamic approaches.[12] Therefore, estimates of PFJS from musculoskeletal models utilizing muscle forces may provide a more robust estimate of quadriceps loading for estimates of PFJS.

Methods used to estimate patellofemoral joint contact area (PFJCA) is another factor that may explain the different findings associated with PFJS based on sex. Almonroeder & Benson used *in vivo* measurements in females obtained via MRI to estimate PFJCA despite testing a mixed sex sample.[9] Willson et al.[11] used similar data that were sex-specific while Sinclair & Selfe[10] used data from cadaveric, non-sex specific samples. As PFJCA differences have been reported between sexes,[13] it seems imperative to utilize sex-specific contact areas in attempts to elucidate differences in PFJS.

Table 1. Demographic factors reported as means (SD).

	Females	Males
Age (yrs)	21.8 (1.5)	21.1 (2.2)
Height (cm)	167.6 (6.4)	179.1 (8.2)
Mass (kg)	62.0 (8.1)	74.6 (10.3)
Tegner Scale	6 (5-7)	6 (5-9)

Tegner scale is reported as the median (range).

A combination of utilizing quadriceps muscle force estimates from static optimization and sex-specific PFJCA may help to clarify inconsistencies reported in previous studies examining sex differences in PFJS, lead to further understanding of tissue stresses imposed on the patellofemoral joint during running, and help guide future research.

The purpose of this study was to examine sex differences in patellofemoral joint stress using an updated model to include estimates of quadriceps muscle force and sex-specific patellofemoral contact area. It was hypothesized that females would demonstrate increased PFJS when quadriceps muscle force and sex-specific contact area were considered.

METHODS

PARTICIPANTS

Using the peak patellofemoral joint stress differences from Willson et al.,[11] an alpha = 0.05, a correlation between scores of 0.5 to determine a power of 0.8, a sample size of 18 subjects was calculated. Twenty-four healthy females and 21 males participated (Table 1). Inclusion criteria: self-reported running routine of greater than 16 km/week, rearfoot strike pattern (first ground contact made with the heel) while running, score of ⩾5 on the Tegner scale, and no reported injuries limiting regular running participation within the prior 12 months. Exclusion criteria: pregnancy, reported cardiovascular pathology, and surgery to either lower extremity within the prior 12 months. All subjects provided informed consent approved by the Institutional Review Board at the university.

PROTOCOL

A static trial was completed to calibrate the musculoskeletal model. Then after a minimum of three practice running trials, participants ran down a 20-m runway using their typical rearfoot running pattern. Pattern was verified using the foot strike index where the center of pressure at ground contact was located in the rear third.[14]

Speed was restricted to a range of 3.52-3.89 m/s using photocells interfaced with a digital clock. Range was chosen to ensure comparable running speeds were present between groups. Running pattern was observed and no targeting of the force plate was allowed. A minimum of five successful right leg trials were completed.

INSTRUMENTATION

Prior to running, participants were prepped for motion analysis. Forty-seven retroreflective markers were applied to each participant's skin, tight fitted clothing, or footwear as previously described.[15] Markers were left in place during data collection and data were captured at 180 Hz via 15 Motion Analysis cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) surrounding the runway. Ground reaction forces were collected with a force platform (Model 4080, Bertec Corporation, Columbus, OH, USA) flush with the runway. Analog data were sampled at 1800 Hz. Both analog data from force platforms and kinematic data were processed through a low-pass Butterworth filter at 12 Hz.

DATA PROCESSING

The Human Body Model (HBM, Motek Medical, Amsterdam, Netherlands) was used to calculate muscle forces using a 44 degree of freedom (DOF) musculoskeletal model with 16 rigid segments.[16] The hip joint was treated as a ball-in-socket joint based on Bell et al.[17] The knee joint was modeled as a single DOF hinge where any tibio-femoral translations and non-sagittal rotations were constrained as a function of knee flexion. Limb segments and inertial characteristics were sex-specific.[18] From estimates of hip joint center from the standing neutral trial and estimates of the of sacroiliac joint center,[19] the HBM creates pelvic geometry for each participant.

Eighty-six muscles were modeled in the lower extremities where the muscle insertion points and wrapping points were from Delp.[20] A kinematic solver within HBM used global optimization to determine skeletal model kinematics.[21,22] Joint moments were then obtained from equations of motion and estimated by minimizing a static cost function where the sum of squared muscle activations is related to maximum muscle strengths at each time step.[20] A recurrent neural network was used to solve the static optimization problem.[23]

The muscle forces from the HBM were then used to quantify the total quadriceps force (QF) by summing the muscle forces of the rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius. PFJS is calculated by dividing PFJRF by the PFJCA. To determine the PFJRF, a conversion factor (*k*) was estimated from Brechter & Powers[24]:

$$k(\mathrm{x}) = \frac{(4.62\mathrm{e}^{-01} + 1.47\mathrm{e}^{-03}\mathrm{x} - 3.84\mathrm{e}^{-05}\mathrm{x}^2)}{(1 - 1.62\mathrm{e}^{-02}\mathrm{x} + 1.55\mathrm{e}^{-04}\mathrm{x}^2 - 6.98\mathrm{e}^{-07}\mathrm{x}^3)}$$

where x is the knee joint angle in the sagittal plane. This represented the portion of the quadriceps force acting directly on the patellofemoral joint. Both knee angle and the orientation of the quadriceps muscle affect force imposed on the patellofemoral joint. Therefore,

$$\mathrm{PFJRF}(\mathrm{x}) = k(\mathrm{x}) \times \mathrm{QF}(\mathrm{x}).$$

Sex-specific PFJCA was calculated as a function of knee angle using the data reported from Besier et al.[13] to formulate predictive equations:

$$\text{Females: } \mathrm{PFJCA}(\mathrm{x}) = 191.336 + 5.479\mathrm{x}$$
$$\text{Males: } \mathrm{PFJCA}(\mathrm{x}) = 311.3227 + 5.732\mathrm{x}$$

PFJS was then calculated as follows:

$$\mathrm{PFJS}(\mathrm{x}) = \mathrm{PFJRF}(\mathrm{x})/\mathrm{PFJCA}(\mathrm{x})$$

DATA ANALYSIS

A multivariate analysis of variance (MANOVA) was used to examine any sex differences in peak PFJS, PFJRF, QF, knee extensor moment, peak knee flexion, peak hip adduction, and internal rotation during the stance phase of running (α=0.05). Follow up univariate tests were performed to assess sex differences in these same kinetic and kinematic data. A Bonferonni correction was employed. Statistical calculations were performed in SPSS 24.0 (IBM, Armonk, NY, USA). Effect sizes were calculated using partial eta squared (η^2) where a small effect size was considered as η^2<0.06, a medium effect size 0.06⩽ η^2 <0.14, and a large effect size η^2 ⩾0.14.

RESULTS

Multivariate differences were shown on sex (Wilk's lambda = 0.456; *p* =0.000). From follow up univariate tests, there were no differences between the sexes in peak PFJS (Figure 1), PFJRF, QF, or knee flexion angle shown during running (Table 2). Females showed 11.7% less knee extensor moment compared to males (p = 0.049). Effect sizes for peak PJFS, PFJRF, QF and knee flexion angle were small while a medium effect size was present for knee extensor moment (Table 2).

Follow up univariate tests showed hip adduction (Figure 2A) and internal rotation (Figure 2B) were different between sexes. Females demonstrated 111% greater peak value for hip internal rotation (absolute difference: 3.62°). Females also demonstrated 48.5% greater hip adduction (absolute difference: 4.80°) than males. A large effect size was present for hip adduction and medium effect size was present for hip internal rotation (Table 2).

DISCUSSION

The aim of this study was to examine sex-related differences in patellofemoral joint loads. Even with static optimization and sex-specific contact areas, no differences in PFJS, PFJRF, or QF were shown between sexes during running. However, females demonstrated less knee exten-

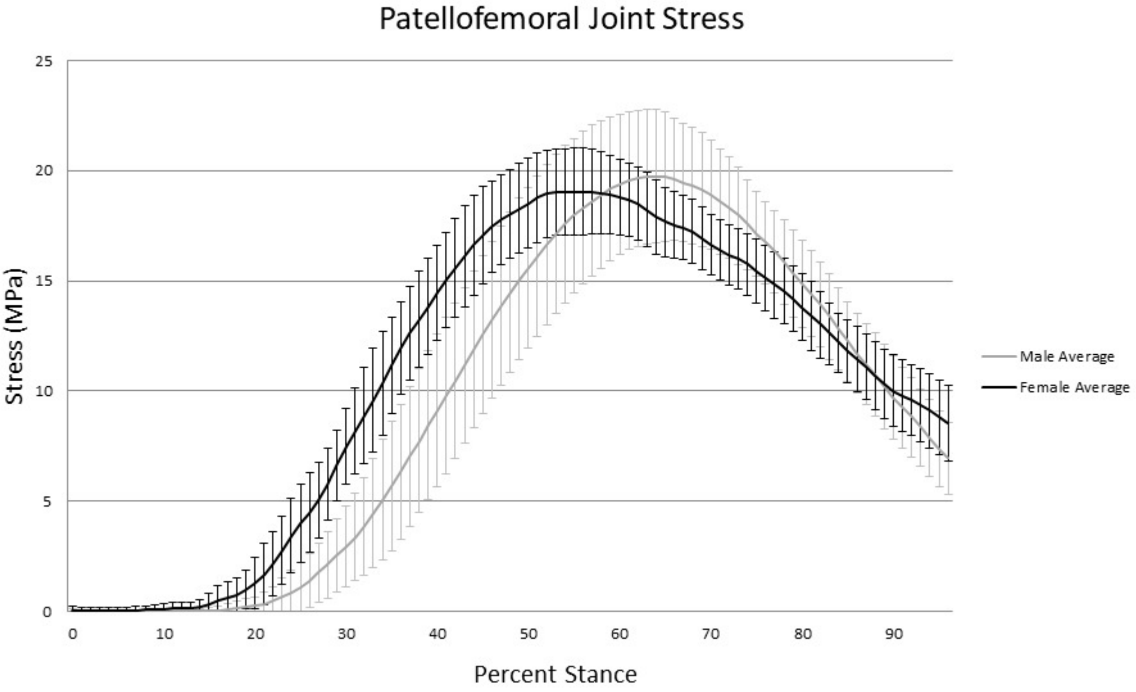

Figure 1. Ensemble average of patellofemoral joint stress over the stance phase of running.

Table 2. Peak values of selected variables.

	Females	Males	*p* value	Effect Size (η^2)
PFJS (MPa)	9.20 (1.65)	9.32 (2.22)	0.829	0.001
PFJRF (BW)	6.89 (1.22)	7.24 (1.52)	0.391	0.017
QF (BW)	7.82 (1.17)	8.28 (1.50)	0.249	0.031
Knee extensor moment (N•m/kg)	0.869 (0.136)	0.984 (0.239)	**0.049**	0.087
Knee flexion (degrees)	48.4 (5.00)	46.6 (5.20)	0.244	0.031
Hip adduction (degrees)	14.7 (4.07)	9.90 (4.20)	**0.000**	0.259
Hip internal rotation (degrees)	6.89 (5.71)	3.26 (5.28)	**0.034**	0.101

Values are presented as group averages with standard deviations. Bold type indicates statistically significant differences.

sion moment and greater transverse and frontal plane hip motion than males. The presence of a sex difference in knee extension moment and lack of a sex difference between QF may indicate that the use of muscle force estimates could be important in describing sex differences in PFJS. Further, as hip motion may affect loads at the patellofemoral joint,[25,26] more comprehensive models of the patellofemoral joint may be needed to account for these motions. Since muscle force estimates to derive PFJRF and sex-specific contact areas did not detect sex differences in PFJS, a consideration of frontal and transverse plane contributions to PFJCA in conjunction with muscle force estimates may be necessary to detect such differences. Further characterization of PFJS with the use of 3D patellofemoral joint models may be a necessary step in understanding structure-specific load based on sex.

Results were contrary to what was hypothesized. This study and previous work on sex differences in patellofemoral joint loading have had inconsistent findings.[9–11] Several aspects of approaches used within previous models could have contributed to these inconsistencies that attempts were made to account for in the current investigation. This was an attempt to build on previous efforts by improving on the available 2D models to see if inclusion of muscle forces and a sex-specific PFJ model could support the hypothesis that females demonstrate greater PFJS. Yet, even with these additions, no differences in peak PFJS were detected. Based on a qualitative assessment of the average ensemble PFJS time series data, it appears that males had a later peak in PFJS during stance (65% of stance vs. 57% of stance). However, in both males and females, peak QF seemed to occur at nearly the same time as peak PFJS during stance (65% and 60%, respectively) whereas knee flexion occurred only slightly later in stance for males (69% of stance) but a larger difference in the timing of peaks was seen in females (peak knee flexion occurred at 67% of stance in females). This may depict that males are displaying a peak PFJS and QF closer to the time of peak knee flexion where PFJCA is increased as the knee is more flexed. Therefore, this might indicate that males may be

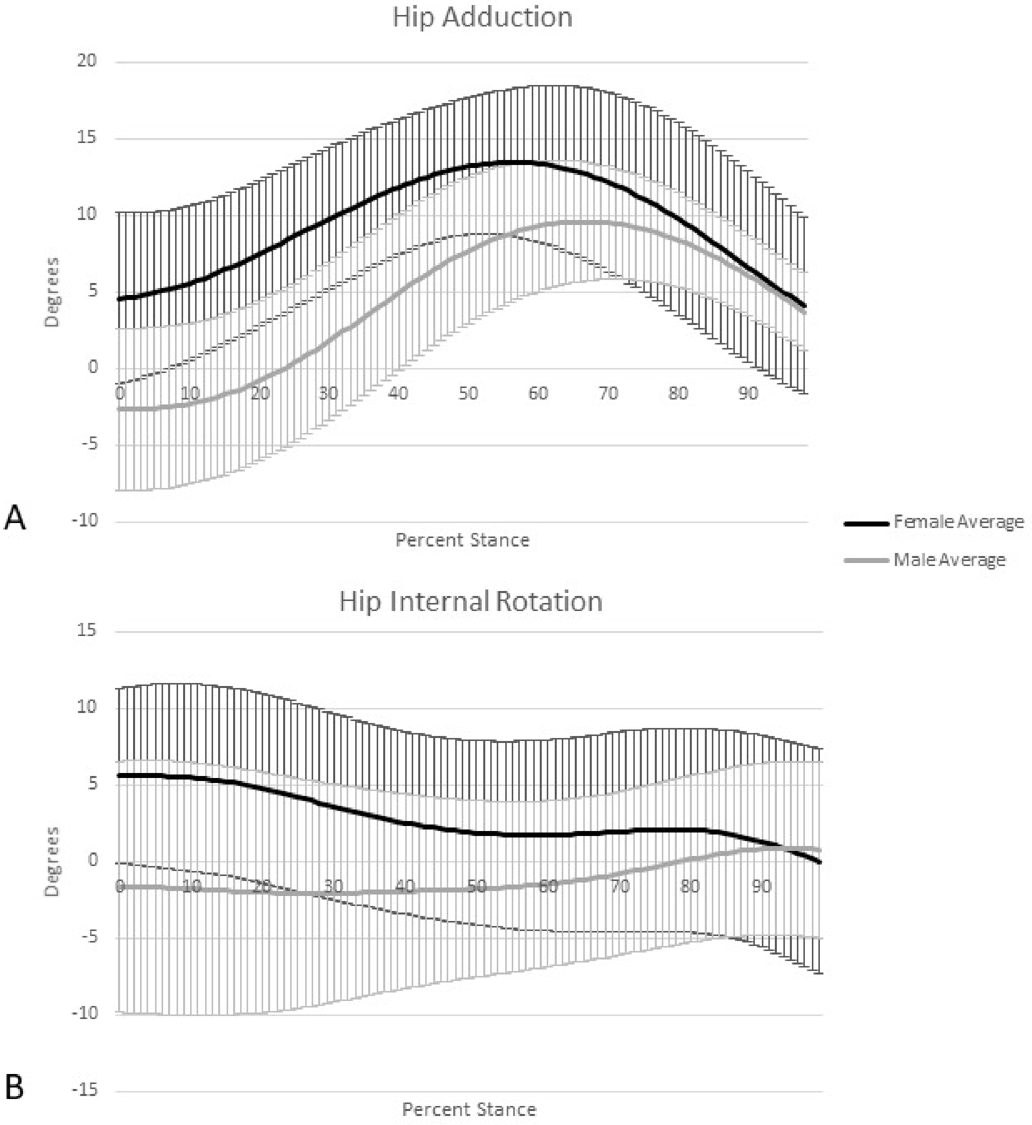

Figure 2. Ensemble averages of hip adduction (A) and hip internal rotation (B) over the stance phase of running.

demonstrating peak QF during stance when the knee is in a more desirable position to distribute these patellofemoral contact forces across the patellofemoral joint. However, this hypothesis needs further examination. In addition, the lack of differences in peak patellofemoral forces shown here may indicate that 2D models may be insufficient to fully characterize PFJS based on sex.

Estimates of PFJS from static optimization are higher as inverse dynamics does not account for co-contraction of muscles crossing the same joint.[12] In the present study, peak knee extension moment during stance was similar to previous studies.[9,11] In previous work, Almonroeder et al.[9] reported females had 12.9% less knee extension moment than males, whereas Sinclair & Selfe[10] reported females demonstrating 14.1% greater knee extension moment than males, and Willson et al.[11] reported no differences between sexes. Differences may be related to how individuals co-contract their knee flexors and extensors to control knee motion during running. These results from the current study showed differences between sexes in knee extension moment, but not in QF. This may indicate differences between sexes in the muscle force production of the knee flexors during stance may affect the net knee moment. Consideration of muscle forces from static optimization may be an important in portraying PFJS.

As PFJS is the quotient of PFJRF and PFJCA, differences in either of these can also explain study differences. Despite sex-specific estimates of PFJCA, no differences in PFJS between males and females was identified. However, consistent with previous studies,[9,27,28] peak hip adduction and internal rotation during the stance phase of running were greater in females. Although statistical differences were detected in non-sagittal plane hip motions, the meaningfulness of these small differences is uncertain. However, the reported differences appear consistent with previously reported literature where females display more non-sagittal hip motion during running than males.[27–30]

Hip positioning has been demonstrated as impacting PFJCA and, thus, measures of PFJS in individuals with and without PFP.[25,26] This occurs as frontal and transverse plane rotations at the hip can position the femur and the patella in a way that the location and contact area is either increased or decreased. Liao & Powers[26] reported that the location and magnitude of peak patella cartilage stress did not differ between runners with and without PFP. These authors did find, however, that tibiofemoral rotations in both the transverse and frontal planes explained 45% and 26% of the variance in patellar cartilage stress, respectively. Further, when investigating the isolated role of tibial and femoral rotations on patellar cartilage stress, it has been reported that increased femoral internal rotation of 4°, 6°, 8°, and 10° yielded increases in patellar cartilage stress ranging from 41-77%.[25] Similarly, increases in 10° of femur adduction produced increases in patellar cartilage stress of 43%.[25]

Therefore, even small changes in femoral rotation may have a notable impact on PFJS. Since there was nearly a 4-5° difference shown between males and females in both femoral internal rotation and adduction, it is likely that these differences in hip kinematics here would have influenced the magnitude of PFJS in participants. As the model used in this study did not utilize frontal or transverse plane knee motion to determine PFJS, sex differences in patellofemoral joint loads may have gone undetected. Therefore, the lack of observed differences between sexes even with quadriceps muscle force estimates supports the notion that if sex differences in PFJS exist it may be related to differences in frontal and transverse plane kinematics at the patellofemoral joint. If contributions from the frontal and transverse planes can be characterized and quantified, this may assist clinicians in assessing when increased hip motion may be a contributing factor to a patient's presentation. Further research characterizing the effects of femoral orientation on patellofemoral joint loads by sex in running appears warranted.

Despite the attempts to build on the work of previous authors, several limitations to the approach used should be noted. First, the patellofemoral model was limited to two-dimensions and was incapable of capturing frontal and transverse plane motions. This was largely due to the limitations of the musculoskeletal model constraining the knee to one degree of freedom. However, this model attempted to build upon previous work using 2D models by including muscle force estimates and sex-specific 2D estimates of PFJCA in the model. Next, all musculoskeletal models utilize numerous anatomical assumptions to yield estimates of muscle force. As these do not necessarily reflect the anatomy of the included participants, there is an amount of error inherent to this approach. Therefore, the degree to which these estimates reflect the actual physiological loads is still questionable and therefore may not fully reflect the true patellofemoral joint loading present. Thirdly, running speed was controlled for all participants to assist with comparisons between groups. As joint kinematics and muscle forces change with running speed,[31,32] the patellofemoral joint loading estimated here may not reflect the loads regularly imposed on the individual participants during their typical training runs. Additionally, only rearfoot strike runners were examined as forefoot striking appears to alter patellofemoral joint stress.[15,33] To what extent sex differences in PFJS is present in those who employ a non-rearfoot strike pattern is unknown. Because only healthy runners were investigated, these findings may not be applicable to injured runners. Finally, differences in running experience were not accounted for. As aspects of running mechanics can differ with greater experience,[34] how these results may differ in novice versus experienced runners is uncertain.

CONCLUSION

The results of the current study indicate that there was no difference between sexes in PFJS during the stance phase of running despite the use of quadriceps muscle force and sex-specific contact area estimates in a 2D patellofemoral joint model. Differences were noted between sexes in knee extension moment yet not in quadriceps force. This indicates that the methods employed to estimate PFJRF should be considered when comparing modeling approaches utilized. Further, peak hip adduction and internal rotation angles during running were greater in females compared to males. Since quadriceps muscle force estimates did not reveal sex differences in PFJS, it is plausible that, if these differences exist, they may be related to frontal and transverse plane kinematics. Utilization of 3D models that incorporate transverse and frontal plane kinematics of the patellofemoral joint in conjunction with estimates of quadriceps muscle force may be necessary to characterize potential differences in PFJS between sexes and may help clinicians identify risk factors for PFP.

……

DECLARATIONS OF INTEREST

The authors have no financial conflicts of interest to declare.

Submitted: April 26, 2022 CST, Accepted: July 24, 2022 CST

REFERENCES

1. Bertelsen ML, Hulme A, Petersen J, et al. A framework for the etiology of running-related injuries. *Scand J Med Sci Sports*. 2017;27(11):1170-1180. doi:10.1111/sms.12883

2. Nielsen RO, Bertelsen ML, Møller M, et al. Training load and structure-specific load: applications for sport injury causality and data analyses. *Br J Sports Med*. 2018;52(16):1016-1017. doi:10.1136/bjsports-2017-097838

3. Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med*. 2002;36(2):95-101. doi:10.1136/bjsm.36.2.95

4. Smith BE, Selfe J, Thacker D, et al. Incidence and prevalence of patellofemoral pain: A systematic review and meta-analysis. *PLoS One*. 2018;13(1):e0190892. doi:10.1371/journal.pone.0190892

5. Ho KY, Keyak JH, Powers CM. Comparison of patella bone strain between females with and without patellofemoral pain: A finite element analysis study. *J Biomech*. 2014;47(1):230-236. doi:10.1016/j.jbiomech.2013.09.010

6. Liao TC, Keyak JH, Powers CM. Runners with patellofemoral pain exhibit greater peak patella cartilage stress compared with pain-free runners. *J Appl Biomech*. 2018;34(4):298-305. doi:10.1123/jab.2017-0229

7. Farrokhi S, Keyak JH, Powers CM. Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: A finite element analysis study. *Osteoarthr Cartil*. 2011;19(3):287-294. doi:10.1016/j.joca.2010.12.001

8. Boling M, Padua D, Marshall S, Guskiewicz K, Pyne S, Beutler A. Gender differences in the incidence and prevalence of patellofemoral pain syndrome. *Scand J Med Sci Sports*. 2010;20(5):725-730. doi:10.1111/j.1600-0838.2009.00996.x

9. Almonroeder TG, Benson LC. Sex differences in lower extremity kinematics and patellofemoral kinetics during running. *J Sports Sci*. 2017;35(16):1575-1581. doi:10.1080/02640414.2016.1225972

10. Sinclair J, Selfe J. Sex differences in knee loading in recreational runners. *J Biomech*. 2015;48(10):2171-2175. doi:10.1016/j.jbiomech.2015.05.016

11. Willson JD, Loss JR, Willy RW, Meardon SA. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech*. 2015;48(15):4155-4159. doi:10.1016/j.jbiomech.2015.10.021

12. Kernozek TW, Vannatta CN, van den Bogert AJ. Comparison of two methods of determining patellofemoral joint stress during dynamic activities. *Gait Posture*. 2015;42(2):218-222. doi:10.1016/j.gaitpost.2015.05.017

13. Besier TF, Draper CE, Gold GE, Beaupré GS, Delp SL. Patellofemoral joint contact area increases with knee flexion and weight-bearing. *J Orthop Res*. 2005;23(2):345-350. doi:10.1016/j.orthres.2004.08.003

14. Cavanagh PR, Lafortune MA. Ground reaction forces in distance running. *J Biomech*. 1980;13(5):397-406. doi:10.1016/0021-9290(80)90033-0

15. Vannatta CN, Kernozek TW. Patellofemoral joint stress during running with alterations in foot strike pattern. *Med Sci Sports Exerc*. 2015;47(5):1001-1008. doi:10.1249/mss.0000000000000503

16. Van Den Bogert AJ, Geijtenbeek T, Even-Zohar O, Steenbrink F, Hardin EC. A real-time system for biomechanical analysis of human movement and muscle function. *Med Biol Eng Comput*. 2013;51(10):1069-1077. doi:10.1007/s11517-013-1076-z

17. Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech*. 1990;23(6):617-621. doi:10.1016/0021-9290(90)90054-7

18. De Leva P. Adjustments to zatsiorsky-seluyanov's segment inertia parameters. *J Biomech*. 1996;29(9):1223-1230. doi:10.1016/0021-9290(95)00178-6

19. Reynolds H, Snow C, Young J. *Spatial Geometry of the Human Pelvis*. Oklahoma City; 1982.

20. Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM. An Interactive Graphics-Based Model of the Lower Extremity to Study Orthopaedic Surgical Procedures. *IEEE Trans Biomed Eng*. 1990;37(8):757-767. doi:10.1109/10.102791

21. Lu TW, O'Connor JJ. Bone position estimation from skin marker co-ordinates using global optimisation with joint constraints. *J Biomech*. 1999;32(2):129-134. doi:10.1016/s0021-9290(98)00158-4

22. Press WH, Teukolsky S a, Vetterling WT, Flannery BP. *Numerical Recipes 3rd Edition: The Art of Scientific Computing*.; 2007. doi:10.1137/1031025

23. Xia Y, Feng G. An improved neural network for convex quadratic optimization with application to real-time beamforming. *Neurocomputing*. 2005;64:359-374. doi:10.1016/j.neucom.2004.11.009

24. Brechter JH, Powers CM. Patellofemoral stress during walking in persons with and without patellofemoral pain. *Med Sci Sports Exerc*. 2002;34(10):1582-1593. doi:10.1097/00005768-200210000-00009

25. Liao TC, Yin L, Powers CM. The influence of isolated femur and tibia rotations on patella cartilage stress: a sensitivity analysis. *Clin Biomech*. 2018;54:125-131. doi:10.1016/j.clinbiomech.2018.03.003

26. Liao TC, Powers CM. Tibiofemoral kinematics in the transverse and frontal planes influence the location and magnitude of peak patella cartilage stress: An investigation of runners with and without patellofemoral pain. *Clin Biomech*. 2019;62:72-78. doi:10.1016/j.clinbiomech.2019.01.003

27. Chumanov ES, Wall-Scheffler C, Heiderscheit BC. Gender differences in walking and running on level and inclined surfaces. *Clin Biomech*. 2008;23(10):1260-1268. doi:10.1016/j.clinbiomech.2008.07.011

28. Ferber R, Davis IM, Williams DS III. Gender differences in lower extremity mechanics during running. *Clin Biomech*. 2003;18(4):350-357. doi:10.1016/s0268-0033(03)00025-1

29. Willson JD, Petrowitz I, Butler RJ, Kernozek TW. Male and female gluteal muscle activity and lower extremity kinematics during running. *Clin Biomech*. 2012;27(10):1052-1057. doi:10.1016/j.clinbiomech.2012.08.008

30. Phinyomark A, Hettinga BA, Osis ST, Ferber R. Gender and age-related differences in bilateral lower extremity mechanics during treadmill running. *PLoS One*. 2014;9(8):e105246. doi:10.1371/journal.pone.0105246

31. Schache AG, Blanch PD, Dorn TW, Brown NAT, Rosemond D, Pandy MG. Effect of running speed on lower limb joint kinetics. *Med Sci Sports Exerc*. 2011;43(7):1260-1271. doi:10.1249/mss.0b013e3182084929

32. Dorn TW, Schache AG, Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol*. 2012;215(11):1944-1956. doi:10.1242/jeb.064527

33. Kulmala JP, Avela J, Pasanen K, Parkkari J. Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers. *Med Sci Sports Exerc*. 2013;45(12):2306-2313. doi:10.1249/mss.0b013e31829efcf7

34. Hafer JF, Peacock J, Zernicke RF, Agresta CE. Segment Coordination Variability Differs by Years of Running Experience. *Med Sci Sports Exerc*. 2019;51(7):1438-1443. doi:10.1249/mss.0000000000001913