Published in final edited form as:

J Biomech. 2017 July 26; 60: 238–242. doi:10.1016/j.jbiomech.2017.06.024.

Normalized patellofemoral joint reaction force is greater in individuals with patellofemoral pain

Lucas T. Thomeer, BS, Frances T. Sheehan, PhD, and Jennifer N. Jackson, PhD

Functional and Applied Biomechanics Section, Rehabilitation Medicine Department, National Institutes of Health, Bethesda, MD, USA

Abstract

Patellofemoral pain is a disabling, highly prevalent pathology. Altered patellofemoral contact forces are theorized to contribute to this pain. Musculoskeletal modeling has been employed to better understand the etiology of patellofemoral pain. Currently, there are no data on the effective quadriceps moment arm for individuals with patellofemoral pain, forcing researchers to apply normative values when modeling such individuals. In addition, the ratio of patellofemoral reaction force to quadriceps force is often used as a surrogate for patellofemoral joint contact force, ignoring the fact that the quadriceps efficiency can vary with pathology and intervention. Thus, the purposes of this study were to: (1) quantify the effective quadriceps moment arm in individuals with patellofemoral pain and compare this value to a control cohort and (2) develop a novel methodology for quantifying the normalized patellofemoral joint reaction force *in vivo* during dynamic activities. Dynamic MR data were captured as subjects with patellofemoral pain (30F/3M) cyclically flexed their knee from 10° to 40°. Data for control subjects (29F/9M) were taken from a previous study. The moment arm data acquired across a large cohort of individuals with patellofemoral pain should help advance musculoskeletal modeling. The primary finding of this study was an increased mean normalized patellofemoral reaction force of 14.9% (maximum values at a knee angle of 10°) in individuals with patellofemoral pain. Understanding changes in the normalized patellofemoral reaction force with pathology may lead to improvements in clinical decision making, and consequently treatments, by providing a more direct measure of altered patellofemoral joint forces.

For correspondence and reprints contact: Jennifer N. Jackson, PhD, Functional and Applied Biomechanics Section, Rehabilitation Medicine National Institutes of Health Bldg 10 CRC, Rm 1-1469, 10 Center Drive MSC 1604, Bethesda, MD 20892-1604, jennifer.jackson@nih.gov, Phone: (301) 451-7554, Fax: (301) 451-7536.

All work for this study was done under protocol number 03-CC-0060, approved by the Institutional Review Board of the National Institute of Child Health and Human Development.

All authors have substantially contributed to research design acquisition, analysis and interpretation of data. All authors have contributed to drafting the paper and revising it critically. All authors have approved the final submitted manuscript.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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Keywords

Musculotendon Moment Arms; Quadriceps; Joint Mechanics; Magnetic Resonance Imaging; Musculoskeletal Modeling

INTRODUCTION

While elevated joint stress is considered integral to idiopathic patellofemoral pain (PFP) etiology, directly measuring *in vivo* joint forces and stresses currently requires invasive methodologies (Kutzner et al., 2010). Consequently, musculoskeletal models are frequently used to infer patellofemoral joint contact force and stress (Besier et al., 2009; Brechter and Powers, 2002; Steinkamp et al., 1993; Yamaguchi and Zajac, 1989). Key to the accuracy of these estimations is the fidelity of the input parameters (Hunter et al., 2009), particularly moment arms, which allow muscle force to be translated into a torque. For knee extension there is no direct relationship between quadriceps force and the tibial torque it generates, due to the dynamic fulcrum created by the patella (van Eijden et al., 1986; Yamaguchi and Zajac, 1989). Thus, the term effective quadriceps moment arm (EQma) was coined (van Eijden et al., 1986) to account for changes in the patellar tendon moment arm (PTma) and the ratio of force transferred through the patella (F_{pt}/F_q). The patellofemoral joint contact force relative to the quadriceps force (F_r/F_q) can be found as an extension of the calculations used to determine EQma. Yet, to date, there are no data regarding how PFP affects the EQma or F_r/F_q . Therefore, modeling studies evaluating patellofemoral joint reaction forces during dynamic activities in individuals with PFP have relied on static, normative values of EQma and F_r/F_q from cadaver studies (Brechter and Powers, 2002; Mostamand et al., 2010; Powers et al., 2004; Willson et al., 2014; Wirtz et al., 2012), which could produce misleading results.

Conclusions of past studies have been limited by indirectly assuming that F_r/F_q can be used as a surrogate for patellofemoral joint reaction force (F_r). The required quadriceps force for a specific task changes with the efficiency of the quadriceps (EQma), which can vary with altered patellofemoral alignment (Yamaguchi and Zajac, 1989) and surgical intervention (Edmonds and Glaser, 2015). Therefore, a new metric defining the amount of patellofemoral contact force per unit tibial torque is needed.

This study quantified EQma, F_r/F_q , PTma, and F_{pt}/F_q in individuals with chronic idiopathic PFP using dynamic magnetic resonance (MR) imaging and compared these data to measures from control subjects. In addition, a new normalized patellofemoral joint reaction force (F_r/M_{tib}) was created and compared across cohorts. This study tested these null hypotheses: EQma, F_r/F_q , PTma, F_{pt}/F_q , and F_r/M_{tib} are not different between cohorts.

METHODS

The data were collected from April 2008 – December 2014, as part of an ongoing IRB approved study. All volunteers gave informed consent. Inclusion criteria were no contraindications to entering an MR scanner, a clinical diagnosis of idiopathic PFP, a minimum pain history of six months, and no prior history of surgical intervention on the leg

being evaluated. Data were included if the subject's minimum range of motion during data collection was 10° to 40° of knee flexion. Thirty-three knees were included in the cohort with PFP (30F/3M, 22.3±11.8 years, 57.8±12.3 kg, 162.3±7.4 cm). Data for the control cohort were taken from a previous study (Im et al., 2015). Subjects in the control cohort had no history of PFP or lower leg pathology/injury/surgery. Two knees from the control cohort were deemed to be outliers and removed. The final control cohort consisted of 38 healthy knees (29F/9M, 26.7±5.7 years, 62.2±10.8 kg, 167.5±10.4 cm).

MR images for both cohorts were captured and analyzed using the same methodology (Im et al., 2015). To rule out underlying pathology, static 3D MR images were acquired and read by a radiologist. Dynamic cine-phase contrast (CPC) and dynamic multi-plane cine (MPC) MR acquisitions (Table 1) were obtained (3T, Philips Medical Systems, Best, NL) as each subject cyclically extended and flexed their knee (30 cycles/minute). The CPC acquisition captured the 3D velocity data of each pixel in a single sagittal imaging plane. These data were integrated to quantify the patellofemoral and tibiofemoral kinematics (Seisler and Sheehan, 2007; Sheehan and Mitiguy, 1999). From these kinematics, the PTma relative to the tibiofemoral instantaneous helical axis was calculated (Sheehan, 2007). The MPC images were used to manually calculate the patellar and quadriceps tendon moment arms relative to the patellofemoral center of contact, ma_p and ma_q , respectively.

The ratio of ma_q/ma_p and F_r/F_q (Figure 1A) were calculated through direct measurement on the MPC images at knee angles of 10°, 20°, 30°, and 40°. In this study, a 10° knee angle is equivalent to a 0° knee angle, when measured using the hip, knee, and ankle (Freedman and Sheehan, 2013). A knee angle was assigned to each time frame based on the CPC data integration. If the knee angle of interest was not captured in a single image, then the temporally adjacent images were analyzed to interpolate that value. To insure that the analysis used the same portion of the patella across all time frames (Shibanuma et al., 2005), the sagittal image with the largest patella was selected for each analysis. The EQma was calculated as previously published (Im et al., 2015; van Eijden et al., 1986; Yamaguchi and Zajac, 1989):

$$EQma = \frac{ma_q}{ma_p} * PTma = \frac{F_{pt}}{F_q} * PTma \quad (1)$$

The F_r/F_q ratio, as derived by van Eijden et al. (1986):

$$\frac{F_r}{F_q} = \sin(\theta + \alpha) + \left(\frac{F_{pt}}{F_q}\right) \sin(\beta - \alpha) \quad (2)$$

β = Angle of the patellar tendon relative to vertical (Figure 1B)

θ = Angle of the quadriceps tendon relative to vertical (Figure 1B)

α = Angle of the patellofemoral contact line relative to vertical (Figure 1B)

The normalized patellofemoral contact force (F_r/M_{tib}) was created for this study by combining equations (1) and (2) and solving for F_r/M_{tib} :

$$\frac{F_r}{M_{tib}} = \frac{\left(\frac{F_r}{F_q}\right) * F_q}{F_q * EQma} = \left(\frac{F_r}{F_q}\right) * \frac{1}{EQma} \quad (3)$$

A two-way analysis of variance (2×4 ANOVA, SPSS 22.0, IBM Corporation, Somers, NY) was used to assess main (cohort and knee angle) and interaction (cohort cross knee angle) effects for comparisons of PTma, F_{pt}/F_q , EQma, F_r/F_q , F_r/M_{tib} , α , β , and θ . When cohort was a main effect, Student's t-tests were used to determine the knee angles where the cohorts differed. When knee angle was a main effect, a Bonferroni post-hoc analysis was used to determine the knee angle pairings that differed. All distance measures were scaled by the ratio of the average control to the subject's epicondylar width. Student's t-tests and a Chi-squared test were used to determine any differences in demographics. A p-value < 0.05 was considered significant.

RESULTS

The cohort with PFP was younger (4.4 years, $p = 0.046$) and shorter (5.2 cm, $p = 0.017$) than the control cohort. Weight and sex were not significantly different between the cohorts.

Cohort was not a main effect for EQma or PTma, but was for F_{pt}/F_q (Figure 2). Collectively, F_{pt}/F_q was greater in the control cohort, despite not being significantly different at any individual angle. Knee angle was a main effect for F_{pt}/F_q , EQma, and PTma (Table 2). There were no interaction effects.

Cohort and knee angle were both main effects for F_r/M_{tib} and F_r/F_q (Figure 3). There were no interaction effects. F_r/M_{tib} was significantly greater in the cohort with PFP at 10°, 20°, and 30° knee angles. Collectively, F_r/F_q was greater in the cohort with PFP compared to the control cohort. F_r/M_{tib} and F_r/F_q were significantly different across all knee angle pairs (Table 2).

Cohort was a main effect for θ (quadriceps angle), but not for α or β (Figure 4). The quadriceps angle was greater in the cohort with PFP, relative to the control cohort, at all knee angles. Knee angle was a main effect for α , β , and θ (Table 2). There were no interaction effects.

DISCUSSION

The *in vivo* dynamic quadriceps moment arm data for individuals with PFP are crucial for advancing the clinical evaluation of PFP kinetics and improving models used to provide insights into the etiology of PFP. Although PTma and EQma have been used to explain knee joint musculoskeletal dynamics (Brechtel and Powers, 2002; Edmonds and Glaser, 2015; Im et al., 2015; Sheehan, 2007), their impact on patellofemoral joint reaction force is dependent on other variables. In contrast, the new normalized patellofemoral joint reaction force (F_r/M_{tib})

M_{tib}) gives direct insight into knee kinetics. The cohort with PFP experienced higher F_r/M_{tib} than control subjects, supporting the existing model for PFP. Specifically, for a task requiring the same torque application to the tibia from the quadriceps, the patellofemoral joint reaction force is higher in the cohort with PFP. This new variable may lead to improvements in clinical decision making, and consequently treatments, by providing a more direct measure of altered patellofemoral joint forces and by determining subgroups of patients who may develop PFP through different mechanisms (Sheehan et al., 2010). For instance, F_r/M_{tib} would give clinicians a quantifiable metric to evaluate the effectiveness of a specific intervention in relieving patellofemoral joint stress.

This study created a new methodology for measuring the patellofemoral contact angle (α). Previously the patellar posterior edge was used to define α (Edmonds and Glaser, 2015; van Eijden et al., 1986; Yamaguchi and Zajac, 1989). However, this study used the patellofemoral contact line. This new α is a more accurate representation of the angle of the normal force vector acting on the patella and was qualitatively different than those reported in past studies.

Compared to F_r/F_q , F_r/M_{tib} is a more effective variable for evaluating patellofemoral knee mechanics, as it is insensitive to quadriceps efficiency (EQma), which has been shown to change with altered patellofemoral alignment (Yamaguchi and Zajac, 1989) and surgical intervention (Edmonds and Glaser, 2015). In the aforementioned clinical study, one surgical technique (MPFLR) was deemed superior for stabilizing the patella, because it lowered F_r/F_q . This conclusion was based on the assumption that an increase in F_r/F_q was equivalent to an increase in patellofemoral contact force, but the surgery also caused a decrease in the EQma, implying that patients required a larger quadriceps force post-MPFLR to perform the same task. Approximating the F_r/M_{tib} for both surgeries demonstrates that they had a similar impact. Likewise, Yamaguchi and Zajac (1989) found that patella alta increased the F_r/F_q and EQma, with the latter improving knee extension efficiency and offsetting the increase in patellofemoral contact force caused by the F_r/F_q increase. F_r/M_{tib} accounts for both of these effects and is likely a more effective variable, relative to F_r/F_q , when comparing different cohorts.

Previous modeling studies assumed that EQma and F_r/F_q (as defined from static cadaver studies) were equivalent in individuals with and without PFP (Brechtel and Powers, 2002; Mostamand et al., 2010; Powers et al., 2004; Willson et al., 2014; Wirtz et al., 2012). However, the current results do not support this assumption. When studying patellofemoral stress in individuals with PFP during level walking, Brechtel and Powers (2002) found that patellofemoral stress was greater in individuals with PFP based on their smaller patellofemoral contact area. With the addition of the current data, indicating that individuals with PFP have greater normalized patellofemoral contact force, the increased patellofemoral stress found by Brechtel and Powers (2002) would be greater. Thus, prior to making assertions about patellofemoral stress in individuals with PFP, the overall effect of each modeling assumption must be better understood.

This study was not without limitations. The cohort with PFP was younger and shorter than the control cohort; the effect of size was minimized through scaling (Sheehan, 2007). All

subjects were screened to rule out osteoarthritis. Although the proportion of males was insignificantly larger in the control cohort, compared to the cohort with PFP (19.1% vs 8.3%), the study conclusions did not change when the analysis was re-run using only female subjects. In addition, MPC images were able to account for medial/lateral patellar movement, but the analysis was unable to account for any possible out-of-plane patellar rotation. Finally, the etiology of PFP is more complex than just altered patellofemoral joint reaction force. Thus, F_r/M_{tib} alone cannot account for other factors that may influence PFP.

Future work should attempt to expand this work into a 3D analysis, allowing for a greater understanding of forces causing varus/valgus moments on the patella and for the conversion of contact force into a contact pressure (Borotikar and Sheehan, 2013). This expansion to 3D should include the normalized patellofemoral joint reaction force (F_r/M_{tib}), which can serve as a useful parameter for studying knee extension kinetics.

Acknowledgments

This work was funded by the Intramural Research Program of the National Institutes of Health Clinical Center, Bethesda, MD, USA.

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Figure 1.

Example multi-plane cine (MPC) magnetic resonance (MR) image showing the manual measurements that were taken for every subject at knee angles of 10°, 20°, 30°, and 40°. **A:** The quadriceps tendon and patellar tendon moment arms (ma_q and ma_p) were defined as the shortest line between their respective tendon and the midpoint of the patellofemoral cartilage contact line (PC). The joint reaction force (F_r) acts at this point. **B:** α, β, and θ were defined as the angles between the patellofemoral cartilage contact line, the patellar tendon, and the quadriceps tendon, respectively, and the vertical.

Figure 2.

F_{pt}/F_q , PTma, and EQma values at knee angles of 10°, 20°, 30°, and 40°. The control cohort is in blue (diamonds with solid line) and the cohort with PFP is in red (squares with dashed line). Bars show one standard deviation. Cohort was a main effect for F_{pt}/F_q , but no significant findings were found at any specific knee angle.

Figure 3. F_r/F_q and F_r/M_{tib} values at knee angles of 10°, 20°, 30°, and 40°. The control cohort is in blue (diamonds with solid line) and the cohort with PFP is in red (squares with dashed line). Bars show one standard deviation. Cohort was a main effect for both F_r/F_q and F_r/M_{tib} . A star (*) indicates the knee angles where significance was found between cohorts using a Bonferroni post-hoc evaluation.

Figure 4.

Angles α , β , and θ at knee angles of 10°, 20°, 30°, and 40°. The control cohort is in blue (diamonds with solid line) and the cohort with PFP is in red (squares with dashed line). Bars show one standard deviation. Cohort was a main effect for θ . A star (*) indicates the knee angles where significance was found between cohorts using a Bonferroni post-hoc evaluation.

Table 1**Key Dynamic Imaging Parameters**

	Cine Phase Contrast (CPC)	Multi-Plane Cine (MPC)
Imaging Plane	Sagittal or Sagittal-Oblique	Sagittal or Sagittal-Oblique
Number of Slices	1	7
Number of Time Frames	24	24
Repetition Time or TR (ms)	5.0	3.2
Echo Time or TE (ms)	2.8	4.4
Flip Angle (deg)	12	20
Field of View (cm)	20 × 20	20 × 20
Slice Thickness (mm)	10	10
Matrix (pixels)	200 × 108	200 × 179
Percent Field of View	78%	78%
Image Resolution (mm)	0.78 × 0.78 × 8	0.78 × 0.78 × 6
Number of Excitations	2	1
Phase Encoding Acquisitions (# of views)	4	28
Temporal Resolution (ms)	80	90
Imaging Time	1 min 30 sec	1 min 32 sec
Motion Rate (cycles/min)	30	30
Venc	30 cm/sec	NA

Table 2**Statistical Comparisons**

Post-hoc p-values for knee angle pairings showing significant differences for PTma, EQma, and theta (θ). F_{pt}/F_q , F_r/F_q , F_r/M_{tib} , alpha (α), and beta (β) are not shown, as all comparisons were significant ($p < 0.001$). A “–” indicates significance was not reached.

Knee Angle Pairing	PTma	EQma	theta (θ)
10°–20°	$p = 0.004$	–	–
10°–30°	$p < 0.001$	$p = 0.002$	$p = 0.001$
10°–40°	$p = 0.025$	$p < 0.001$	$p < 0.001$
20°–30°	–	$p = 0.003$	–
20°–40°	–	$p < 0.001$	$p < 0.001$
30°–40°	–	$p < 0.001$	–