Published in final edited form as:
J Biomech. 2015 November 5; 48(14): 3737–3742. doi:10.1016/j.jbiomech.2015.04.003.

The Effective Quadriceps and Patellar Tendon Moment Arms Relative to the Tibiofemoral Finite Helical Axis

Hyun Soo Im, **Oren Goltzer**, and **Frances Sheehan**
Functional and Applied Biomechanics, Department of Rehabilitation Medicine, NIH, Bethesda, MD, USA

Abstract

The moment arm is a crucial parameter for understanding musculoskeletal dynamics as it defines how linear muscle force is transformed into a moment. Yet, for the quadriceps tendon this parameter cannot be directly calculated, as the patella creates a dynamic fulcrum. Thus, the effective quadriceps moment arm (EQma) was developed to define the quadriceps force to tibial moment relationship. *In vivo* data in regards to the EQma are lacking and the critical question of how patellofemoral kinematics may influence the EQma remains unresolved. Therefore, the purpose of this study was to quantify the *in vivo* EQma during a knee extension exercise in asymptomatic controls and to correlate the EQma with sagittal plane patellofemoral kinematics. While subjects (30F/10M, 26.5±5.6 years, 167.5±10.2 cm, 62.6±10.7 kg) cyclically flexed-extended their knees within the MR scanner, dynamic cine-phase contrast and cine MR images were acquired. From these data, patellofemoral kinematics, the ratio of the patellar tendon to quadriceps force, the patellar tendon moment arm, and the EQma were quantified. The EQma trended upwards (32.9–45.5mm (females) and 31.5–47.1mm (males)) as the knee angle decreased (50°–10°). The quadriceps had a mechanical advantage (ratio of patellar to quadriceps tendon forces>1.0) for knee angles ≤ 20°. The EQma did not correlate with sagittal plane patellofemoral kinematics. As this is the first study to characterize the EQma *in vivo* during dynamic volitional activity, in a large group of asymptomatic controls, it can serve as a foundation for future knee joint models and to explore how pathological conditions affect the EQma.

INTRODUCTION

The moment arm (ma) of a tendon is a crucial parameter for understanding musculoskeletal dynamics as it defines how the linear muscle force is transformed into a moment. For most tendons this is a fairly well established parameter, as it can be defined from the kinematics of the tendons' origins, insertions, and/or path. Yet, for the quadriceps this relationship is

Corresponding author: Frances T. Sheehan, PhD, National Institutes of Health, Building 10 CRC RM 1-1469, 10 Center Drive MSC 1604, Bethesda, MD 20892-1604, Tel: (301) 451-7585, fsheehan@cc.nih.gov.

Conflict of Interest:
There are no conflict of interests for any authors.

complicated by the fact that the patella serves as an intermediary, between the quadriceps and tibia, creating a dynamic fulcrum. Thus, the transfer of the quadriceps force into a moment on the tibia cannot be directly calculated. Establishing the relationship between the force in the patellar tendon and the force in the quadriceps tendon (defined by the ratio F_{pt}/F_q), allows the relationship between the quadriceps force and the moment it applies on the tibia to be calculated using the patellar tendon moment arm (PTma). The term effective quadriceps moment arm (EQma) was coined to define this derived moment arm of the quadriceps (Yamaguchi and Zajac, 1989).

Defining the EQma as it relates to patellofemoral (PF) kinematics is necessary for improving modeling studies and guiding clinical decisions. Presently, there is a lack of *in vivo* normative data in regards to the EQma. Past studies have been limited to measurements from cadavers (Grood et al., 1984) or the use of geometric models (van Eijden et al., 1986; Yamaguchi and Zajac, 1989). There are recent *in vivo* data (Ward et al., 2005), measured during static isometric quadriceps contraction, yet numerous subjects in the “control” group reported a history of anterior knee pain, thereby eliminating the normative applicability of these data. In addition, there is conflicting information regarding the relationship between the EQma and the patellar position. Yamaguchi and Zajac (1989) and Ward et al. (2005) suggest that patella alta results in an increased EQma. Conversely, patella alta in patients with cerebral palsy (CP) is assumed to weaken knee extension capacity by reducing the EQma (Lotman, 1976; Sutherland and Davids, 1993; Topoleski et al., 2000). Characterizing the relationship between the EQma and patella alta will likely impact surgical approaches to altering PF kinematics in patient groups where patella alta is prevalent. In addition, numerous dynamic knee joint models (Chinkulprasert et al.; Elias and Cosgarea, 2007; Escamilla et al., 2008; Lengsfeld et al., 1997) incorporate the ratio of F_{pt}/F_q, as published by Van Eijden et al. (1986). Yet, in reporting this value, Van Eijden and colleagues clearly stated that their results rested on the assumption of minimal quadriceps force and no strain in the patellar tendon. Thus, normative data describing the EQma during dynamic *in vivo* knee activities, requiring active quadriceps force is needed to validate findings from previous modeling studies, develop new dynamic knee joint models, and to better translate external torque measurements into estimates of quadriceps force.

Therefore, the primary purpose of this study was to quantify *in vivo* the ratio of F_{pt}/F_q, the PTma (relative to the tibiofemoral finite helical axis, (TF_IHA)), and the EQma during a dynamic knee extension task in a large population of asymptomatic male and female healthy controls. As this study contained both female and male subjects the differences between the male and female cohorts in the ratio of F_{pt}/F_q, the PTma, and the EQma were analyzed. A secondary objective was to correlate these three values to the sagittal plane PF kinematics at knee flexion angles of 10°, 20°, 30°, and 40°. Finally, the intra- and inter-rater reliability of calculating the ratio of F_{pt}/F_q was evaluated.

METHODS

Data from the control arm of an ongoing IRB approved study, collected over a six year period (3/2008–2/2014), formed the basis of the current study. A subject’s dataset was included only if all required data were available and if their range of motion extended from a minimum of 10° to 40° knee angle. Recruitment was a sample of convenience. Written informed consent was provided by all volunteers prior to participation. Any subject with contraindications to magnetic resonance (MR) imaging was not allowed to participate. Subjects with a history of lower body injury/trauma, or knee joint pathology/pain were excluded. Based on these criteria the final cohort included forty healthy volunteers (30F/10M, 26.7 ± 5.5 years, 167.7 ± 10.4 cm, 62.6 ± 10.7 kg).

Each dataset included a dynamic cine-phase contrast (CPC) MR acquisition, a dynamic multi-plane cine acquisition (MPC), and a series of high-resolution static 3D images. A radiologist read the static 3D images to rule out any underlying pathologies. For the dynamic imaging, subjects laid supine in the MR scanner (3T, Philips Medical Systems, Best, NL). Using a cushioned wedge under the knee, the hips were flexed 15–20° to maximize the knee range of motion. The leg was aligned with the central axis of the MR scanner, thus the imaging cardinal planes aligned with the anatomically defined cardinal planes. Sagittal plane CPC and MPC images were acquired for 24 time frames, as subjects performed a continuous cycle (30 cycles/min, guided by an auditory metronome) of knee flexion-extension (Behnam et al., 2011). The CPC acquisition captured a single sagittal plane, along with the 3D velocity for each pixel. The MPC data acquisition captured seven contiguous parallel sagittal planes. In addition, axial MPC data were acquired in order to establish a dynamic anatomical coordinate system (Seisler and Sheehan, 2007; Sheehan and Mitiguy, 1999). Data collection was synchronized to the movement using an optical sensor placed on the scanner bed, under the foot. Through integration of the CPC data, the 3D positions, orientations, velocities, and angular velocities of the patella, femur, and tibia were quantified. The PTma was calculated such that multiplying it by the magnitude of the patellar tendon force produced the magnitude of the moment created by that force about the point on the TF_IHA that was closest to the patellar tendon line of action (Boyd and Ronsky, 1998; Sheehan, 2007a). The TF_IHA was calculated as has been done previously (Sheehan, 2007b).

The relative moment arm of the quadriceps (EQma) was calculated such that it defined the relationship between the force within the quadriceps tendon (F_q) and the moment it generated on the tibia (M_{TF_IHA}). The quadriceps does not directly act on the tibia. Instead its force is transferred to the tibia through the patellar tendon:

$$\sum M_{\mathrm{TF\_IHA}} = PTma \times F_{pt} \quad \text{(eq. 1)}$$

M_{TF_IHA} = Moment acting on the tibia relative to the TF_ IHA

F_{pt} = Patellar tendon force

In order to define the relationship between F_q and M_{TF_IHA}, the relationship between F_{pt} and F_q was first established based on a two-dimensional force balance equation for the patella (Figure 1). Summing the moments about the PF point of contact (PC) resulted in the following equation:

$$\sum M_{PC} = (F_{pt} \times ma_p) - (F_q \times ma_q) = I \times \alpha \quad \text{(eq2)}$$

M_{PC} = Moment about PF contact point

ma_p = Patellar tendon moment arm relative to the PF contact point (Figure 2)

ma_q = Quadriceps tendon moment arm relative to the PF contact point (Figure 2)

I = Moment of inertia of the patella

α = Angular acceleration of the patella

Assuming that the moment of inertia and the angular acceleration of the patella are both small enough that their product is negligible, the above equation simplifies to:

$$\sum M_{PoC}=(F_{pt} \times ma_p) - (F_q \times ma_q)=0 \quad \text{(eq. 3)}$$

Using equation three, the relationship between the F_{pt} and F_q can be defined as:

$$F_{pt}=\frac{F_q \times ma_q}{ma_p} \quad \text{(eq. 4)}$$

Substituting equation four into equation one establishes:

$$\sum M_{TF\_IHA}=PTma \times \frac{F_q \times ma_q}{ma_p} \quad \text{(eq. 5)}$$

Rearranging equation five produces:

$$\sum M_{\mathrm{TF\_IHA}}=F_q \times \left(\frac{ma_q}{ma_p} \times PTma\right) \quad \text{(eq. 6)}$$

Thus, the EQma is defined as:

$$EQma=\frac{ma_q}{ma_p} \times PTma=\frac{Fpt}{Fq} \times PTma=Ratio \times PTma \quad \text{(eq. 7)}$$

The first step in calculating the moment arms ma_p and ma_q, relative to the patellofemoral PC, was to analyze images across five knee angles (10°, 20°, 30°, 40°, 50°) obtained from MPC data (Figure 2). Data at 50° knee angle were obtainable for nine subjects only (Table 1). As the PC was not a fixed anatomical point, ma_p and ma_q were defined based on a visual analysis of the image representing the knee angle of interest. If this exact knee angle was not captured at a single time point, then the images representing the knee angle just above and below the specific knee angle were analyzed. Interpolation was used to assess the variables at the knee angle of interest. For each knee angle analyzed, the sagittal plane image selected contained the largest patella. On the selected image, the patellofemoral PC and the direction of forces (F_{pt} and F_q) acting on the patella were identified (Figure 1). The patellofemoral PC was determined by taking the midpoint of a line drawn between the contacting surfaces of the patellar and femoral cartilage. The ma_p and ma_q were calculated by taking the perpendicular distance between the tendon's lines of action and the PC (Figure 2).

Statistics

Intraclass correlation coefficients (ICCs), using a two-way mixed effects model, were computed to evaluate intra- and inter-rater repeatability for quantifying the ratio of F_{pt}/F_q across 25 knees. The two raters were blinded to each other's measures, as well as their original measures. Due to limits in imaging time availability, the measures were re-evaluated using the same image set for each subject, but the image selected for the analysis was decided by the researcher at the time of analysis.

A two-way analysis of variance (2×4 ANOVA, *SPSS 22.0, IBM Corporation, Somers, NY*) was used to assess main and interaction effects of gender and knee angle on F_{pt}/F_q, PTma and EQma. If sex was a main effect, the knee angle where the parameters were significantly different between cohorts was investigated using a Student's t-test with a Bonferroni false discovery rate correction (Benjamini and Hochberg, 1995). If the knee angle was a main effect then a Tukey's post-hoc test was used to determine the knee angle pairs for which there were differences between the variables. Pearson's correlation coefficients were sought between all three moment arm parameters (F_{pt}/F_q, PTma, and EQma) and the sagittal plane kinematics (PF superior position and extension).

Results

The reliability of quantifying the ratio was excellent. The intra-rater reliability ICC was 0.94 and the inter-rater reliability ICC was 0.93. All data were normally distributed. The female cohort (n=30, age = 26.3±5.4 years, height = 163.6±7.6 cm, weight = 58.0±6.5kg) was significantly lighter ($p<0.001$) and shorter ($p<0.001$) relative to the male cohort (age = 27.9±6.0 years, height = 180.1±7.5 cm, weight = 76.3±8.9kg). In evaluating a size measurement specific to the knee (epicondylar width), the female cohort was smaller than the male cohort (70.5±3.4mm versus 81.0±6.0mm, $p<0.001$).

The ratio of F_{pt}/F_q was greater than 1.0 for knee angles equal to or less than 20° and below 1.0 for larger knee angles (Figure 3). As sex was not a significant factor for the ratio, the ratio was presented as an average across the entire cohort. The increase in F_{pt}/F_q as the knee extended was due primarily to a decrease in ma_p (ma_p = 25.8±1.7mm and 20.2±2.7mm at a KA=50° and 10°, respectively). A small increase in the ma_q also supported the rise in F_{pt}/F_q (ma_q = 19.4±1.7mm and 21.5±2.7mm at a KA=50° and 10°, respectively)

The PTma (Figure 4) exhibited a quadratic relationship with respect to knee angle, with a peak value of 46.5±4.0mm and 50.6± 5.0mm at 30° KA, for the female and male cohorts. Due to the rise in F_{pt}/F_q, the EQma (Figure 5) increased as the knee angle decreased (Table 1).

Sex and knee angle were both main effects for the PTma and EQma. There were no interaction effects. The post-hoc analysis revealed the PTma and EQma were larger in the male, relative to the female, cohort at 20° and 30° knee angle. The differences in EQma between knee angles existed for every knee angle pair except between 10°–20°. PTma was only different between a knee of 30° and 10°, as well as between a knee angle of 20° and 10°.

The ratio of F_{pt}/F_q demonstrated a positive correlation with the PF superior position at all knee angles evaluated, whereas the PTma demonstrated an inverse correlation with PF superior displacement (Table 2). Similar, but weaker correlations were found when both variables were associated with PF extension (KA = 10°, 20°, and 30° only). The EQma was not correlated with either the PF superior position or PF extension.

Discussion

The novel *in vivo* data acquired across a large asymptomatic control population during a dynamic extension activity requiring active quadriceps contraction fill a critical gap in our understanding of musculoskeletal dynamics. Although the PTma has been well studied (Gill and O'Connor, 1996; Herzog and Read, 1993; Imran et al., 2000; Kellis and Baltzopoulos, 1999; Tsaopoulos et al., 2006), there is minimal data for the EQma (Grood et al., 1984; van Eijden et al., 1986; Ward et al., 2005; Yamaguchi and Zajac, 1989). The EQma is much more relevant than the PTma, for understanding knee joint musculoskeletal dynamics, as it provides a direct relationship between the force in the quadriceps and the moment it produces on the tibia. This study confirms the patella's role in creating a dynamic fulcrum for the quadriceps tendon and the current data will support advances in both dynamic knee joint models and clinical evaluation of the knee joint. Although previous studies have suggested that the EQma increases with increasing patellar superior position, the current study found no direct relationship between the EQma and the sagittal plane PF kinematics.

The results from two previous studies (van Eijden et al., 1986; Yamaguchi and Zajac, 1989) and the current study suggests that the dynamic fulcrum created by the PF contact creates a mechanical advantage for the quadriceps force ($F_{pt}/F_q > 1.0$) at knee angles less than 20°. The good match between the current data and these modeling studies for the ratio F_{pt}/F_q was somewhat surprising; as the models were based on the assumption that minimal load was present in the tendons. Thus, it was anticipated that the current study would demonstrate a larger ratio due to the increased force requirements for the quadriceps. This lack of difference could be from the modeling assumptions used in the past studies. The current results align to a lesser extent with findings from Ward et al. (2005). This previous study suggested that there is only a small window around a knee angle of 20° where an advantage is created for the quadriceps force. A possible explanation for the discrepancies with the Ward et al. (2005) study is that the "control" cohort in the previous study had subjects reporting a history of PF pain, which could be indicative of an underlying difference in knee kinematics. In addition, this previous study was static, not dynamic, and the image selection for analysis was based purely on the crossing of the cruciate ligaments, which disregarded the medial-lateral patellar position within the imaging plane.

The influence of sex on the PTma and the EQma may is very likely due to the difference is size between the two cohorts, as proposed by previous research on the PTma (Sheehan, 2007a). Specifically, a positive relationship between knee size (epicondylar width) and moment arm size existed in the current population ($r=0.32$ to 0.52, $p<0.05$), which would indicate a positive relationship The small inter-subject variability, large cohort size, and the inclusion of both genders makes these data readily applicable to 3-dimensional dynamic musculoskeletal models.

Although numerous studies have reported the PTma, a direct comparison is difficult due to variations in methods across studies. Previous studies have measured the PTma two-dimensionally, as the perpendicular distance between the linear tendon force and the tibiofemoral contact point (Nisell, 1985; Yamaguchi and Zajac, 1989), relative to the geometric center of the femoral condyles (O'Brien et al., 2009), and relative to the intersection point between the cruciate ligaments (Ward et al., 2005). In addition, the TF_IHA has been used as a reference for the 3D calculation of the PTma (Krevolin et al., 2004; Sheehan, 2007a). The PTma demonstrated clear differences at the higher knee angles from our past work, which reported the PTma for an independent control cohort of 34 knees (Sheehan, 2007a). This is likely due to the 1.5T MR scanner used in the past study introducing a small amount of noise into the calculation of the tibiofemoral displacement (Appendix). The PTma matched well with the cadaver data presented by Krevolin et al. (2004), except at the smallest knee angle, which could be due to differences in the amount of tibial external rotation near full extension (“screw home” mechanism).

To date, no study has investigated the EQma *in vivo* for an asymptomatic control population. The cadaver data from Grood et al. (1984) and human subject data from Ward et al. (2005) defined the max EQma at 20° of knee flexion, which agreed with the current findings. Yamaguchi and Zajac (1989) reported a max EQma at 30°. All data indicated that after reaching its peak the EQma sharply fell in effectiveness as the angle of knee flexion increases. It is important to note that two of these past studies (Grood et al., 1984; Yamaguchi and Zajac, 1989) referenced the EQma to the tibiofemoral point of contact and the other study (Ward et al., 2005) referenced it to the crossing point of the cruciate ligaments. Although, data from past studies agree in general with the current study, past results should be applied cautiously as they do not represent *in vivo* conditions, or, as in the study by Ward et al., the results were not obtained from healthy asymptomatic individuals. Also, future studies requiring the EQma relative to a reference other than the TF_IHA, can easily use F_{pt}/F_q to calculate the EQma using the patellar tendon moment arm calculated relative to the reference of interest.

The correlation analysis did not support past conclusions that the EQma increases with increasing superior position of the patella at a specific knee angle. The two variables used to calculate the EQma had opposing relationships to patellar superior position. A superiorly positioned patella gains leverage at the PF contact point, but loses mechanical advantage with a reduced PTma. This agrees with Yamaguchi and Zajac’s findings in that as the patella moved superiorly, the F_{pt}/F_q increased, but the PTma decreased. In the work of Ward et al., all three variables (F_{pt}/F_q, PTma, and EQma) demonstrated a significant difference between the cohort with patella alta and the one without. Yet, these differences were only found for the group effect and significant differences were not found at any specific knee angles, thus the results should be interpreted cautiously. Defining the relationships between the three moment arm parameters and the sagittal plane kinematics provides further information for clinical decisions that aim to alter knee kinematics. Any intervention should consider how it will affect F_{pt}/F_q, the PTma, and the EQma. Future work should focus on evaluating these parameters in patient populations with patella alta to determine if extreme levels of alta change the relationship between the patellar sagittal plane kinematics and the EQma.

A limitation of this study is that the data collected on the 1.5Tesla GE magnet resonance (MR) imager (up until June 2005) could not be included within this study, limiting the overall cohort size. The upgrade to the 3.0Tesla Philips MR imager improved numerous aspects of image acquisition. These included, the signal-to-noise ratio, the accuracy of tracking bone motion using cine-phase contrast MR (Behnam et al., 2011), and the ability to effectively use of spatial presaturation of the blood flow from the popliteal artery (Appendix). The latter eliminated motion artifacts from the popliteal artery in the cine-phase contrast (CPC) data. This resulted in an improved calculation of PTma, which was significantly different (at knee angles greater than 16°) than the PTma derived from the previous GE data (Sheehan, 2007a). A second limitation is that the analysis was planar. Currently, the F_{pt}/F_q relationship cannot be resolved for all three dimensions, as the number of unknown forces acting on the patella exceeds the ability to analytically solve the six-degree-of-freedom equations of motion. With recent advances in determining 3D dynamic *in vivo* cartilage contact parameters using the cine-PC data (Borotikar et al., 2012), it is likely that the analysis can advance to three-dimensions in the near future. This would provide an understanding how the force produced from each quadriceps translates into moments produced on the tibia in all three cardinal planes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

We thank Sara Sadeghi for her research support. We also thank the Diagnostic Radiology Department at the NIH for their support. This research was supported by the Intramural Research Program of the NIH Clinical Center.

Bibliography

Behnam AJ, Herzka DA, Sheehan FT. Assessing the accuracy and precision of musculoskeletal motion tracking using cine-PC MRI on a 3.0T platform. J Biomech. 2011; 44:193–197. [PubMed: 20863502]

Benjamini Y, Hochberg Y. Controlling the False Discovery Rate - a Practical and Powerful Approach to Multiple Testing. J Roy Stat Soc B Met. 1995; 57:289–300.

Borotikar BS, Sipprell WH 3rd, Wible EE, Sheehan FT. A methodology to accurately quantify patellofemoral cartilage contact kinematics by combining 3D image shape registration and cine-PC MRI velocity data. J Biomech. 2012; 45:1117–1122. [PubMed: 22284428]

Boyd SK, Ronsky JL. Instantaneous moment arm determination of the cat knee. J Biomech. 1998; 31:279–283. [PubMed: 9645543]

Chinkulprasert C, Vachalathiti R, Powers CM. Patellofemoral joint forces and stress during forward step-up, lateral step-up, and forward step-down exercises. J Orthop Sports Phys Ther. 41:241–248. [PubMed: 21289449]

Elias JJ, Cosgarea AJ. Computational modeling: an alternative approach for investigating patellofemoral mechanics. Sports Med Arthrosc. 2007; 15:89–94. [PubMed: 17505324]

Escamilla RF, Zheng N, MacLeod TD, Edwards WB, Hreljac A, Fleisig GS, Wilk KE, Moorman CT 3rd, Imamura R. Patellofemoral compressive force and stress during the forward and side lunges with and without a stride. Clin Biomech (Bristol, Avon). 2008; 23:1026–1037.

Grood ES, Suntay WJ, Noyes FR, Butler DL. Biomechanics of the knee-extension exercise. Effect of cutting the anterior cruciate ligament. J Bone Joint Surg Am. 1984; 66:725–734. [PubMed: 6725319]

Krevolin JL, Pandy MG, Pearce JC. Moment arm of the patellar tendon in the human knee. J Biomech. 2004; 37:785–788. [PubMed: 15047009]

Lengsfeld M, Pressel T, Stammberger U. Lengths and lever arms of hip joint muscles: geometrical analyses using a human multibody model. Gait & Posture. 1997; 6:18–26.

Lotman DB. Knee flexion deformity and patella alta in spastic cerebral palsy. Dev Med Child Neurol. 1976; 18:315–319. [PubMed: 939346]

Nisell R. Mechanics of the knee. A study of joint and muscle load with clinical applications. Acta Orthop Scand Suppl. 1985; 216:1–42. [PubMed: 3865491]

O'Brien TD, Reeves ND, Baltzopoulos V, Jones DA, Maganaris CN. Moment arms of the knee extensor mechanism in children and adults. J Anat. 2009; 215:198–205. [PubMed: 19493189]

Seisler AR, Sheehan FT. Normative three-dimensional patellofemoral and tibiofemoral kinematics: a dynamic, in vivo study. IEEE Trans Biomed Eng. 2007; 54:1333–1341. [PubMed: 17605365]

Sheehan FT. The 3D patellar tendon moment arm: quantified in vivo during volitional activity. J Biomech. 2007a; 40:1968–1974. [PubMed: 17161841]

Sheehan FT. The finite helical axis of the knee joint (a non-invasive in vivo study using fast-PC MRI). J Biomech. 2007b; 40:1038–1047. [PubMed: 17141789]

Sheehan FT, Mitiguy P. In regards to the "ISB recommendations for standardization in the reporting of kinematic data". J Biomech. 1999; 32:1135–1136. [PubMed: 10476854]

Sutherland DH, Davids JR. Common gait abnormalities of the knee in cerebral palsy. Clin Orthop Relat Res. 1993:139–147. [PubMed: 8458127]

Topoleski TA, Kurtz CA, Grogan DP. Radiographic abnormalities and clinical symptoms associated with patella alta in ambulatory children with cerebral palsy. J Pediatr Orthop. 2000; 20:636–639. [PubMed: 11008744]

van Eijden TM, Kouwenhoven E, Verburg J, Weijs WA. A mathematical model of the patellofemoral joint. J Biomech. 1986; 19:219–229. [PubMed: 3700434]

Ward SR, Terk MR, Powers CM. Influence of patella alta on knee extensor mechanics. J Biomech. 2005; 38:2415–2422. [PubMed: 16214489]

Yamaguchi GT, Zajac FE. A planar model of the knee joint to characterize the knee extensor mechanism. J Biomech. 1989; 22:1–10. [PubMed: 2914967]

Figure 1. Patellar Free Body Diagram

Choosing the point of contact (PC) as the reference for the moment equation, set the moment arm of the contact forces to zero and eliminated them from the angular equations of motion. Assuming that angular acceleration and moment of inertia about the PC are negligible, the product of the force generated by the quadriceps (F_q) and its moment about PC is equal the product of the force in the patellar tendon (F_{pt}) and its moment about PC.

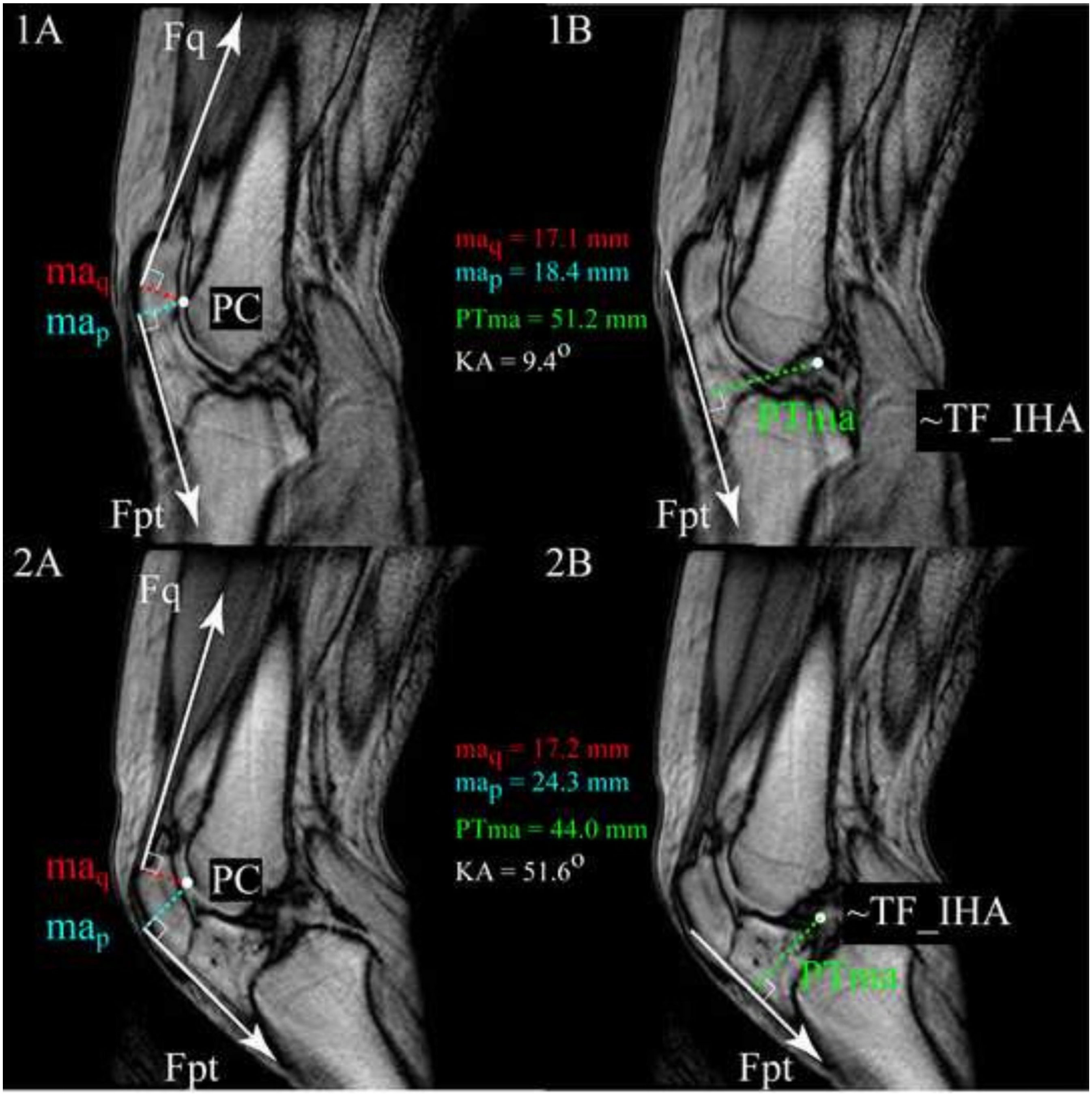

Figure 2.

Images comparing a single subject at ~10° (1A, 1B) and at ~50° (2A, 2B) of knee flexion with measurement comparisons for the ma_q (1A, 2A), ma_p (1A, 2A), and PTma (1B, 2B). The ma_q and ma_p were measured relative to the point of contact (PC) between the patellar and femoral cartilage. The PTma was measured relative to the tibiofemoral instant helical axis (TF_IHA). The ma_p increases from 10° to 50°, while the PTma decreases. The location of the TF_IHA was analytically quantified and its location is approximated in the figure.

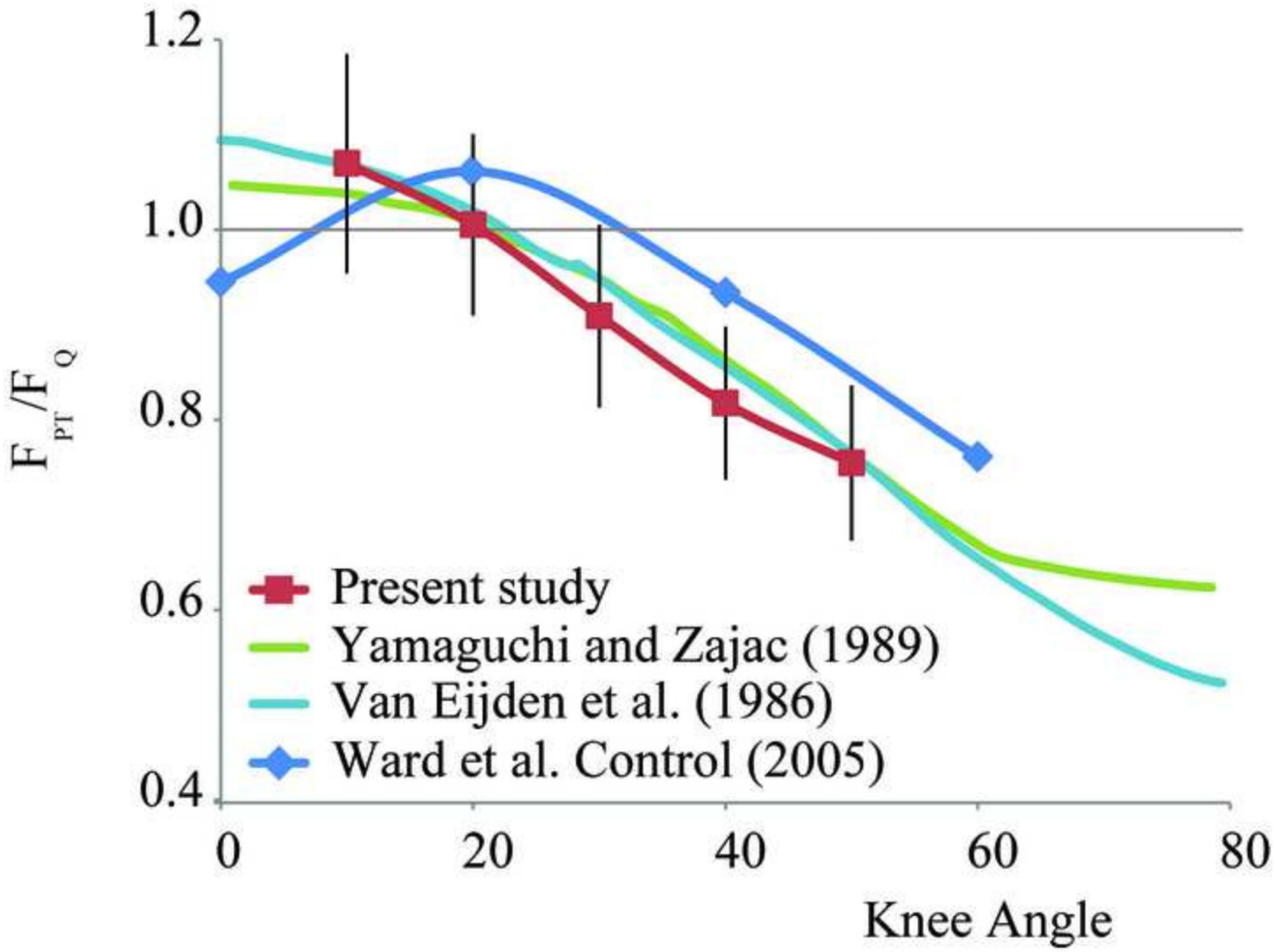

Figure 3.

Comparison of F_{pt}/F_q (ratio of the force in the patellar tendon to the force in the quadriceps tendon) from previous studies. Positive and negative one standard deviation bars included for present study only.

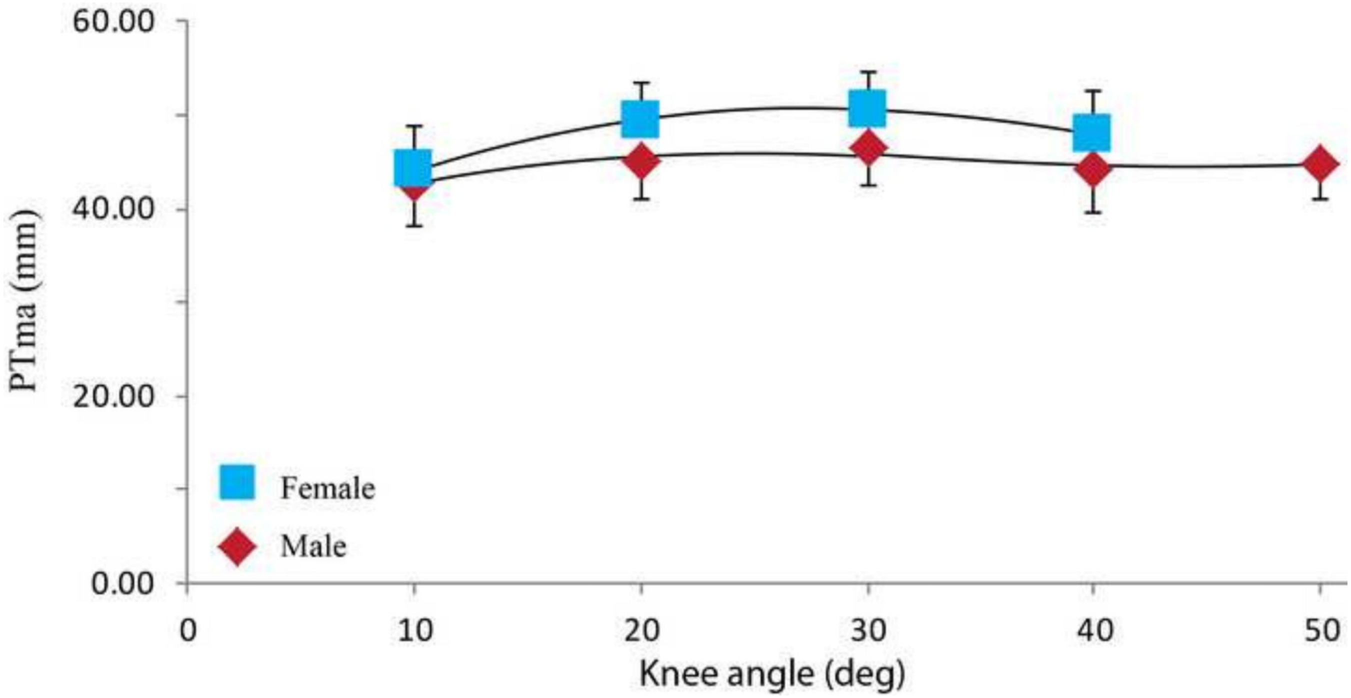

Figure 4.
The Patellar Tendon Moment Arm (PTma), relative to the tibiofemoral instantaneous helical axis. Values are provided throughout a range of active extension (10° – 50°) with one standard deviation bars.

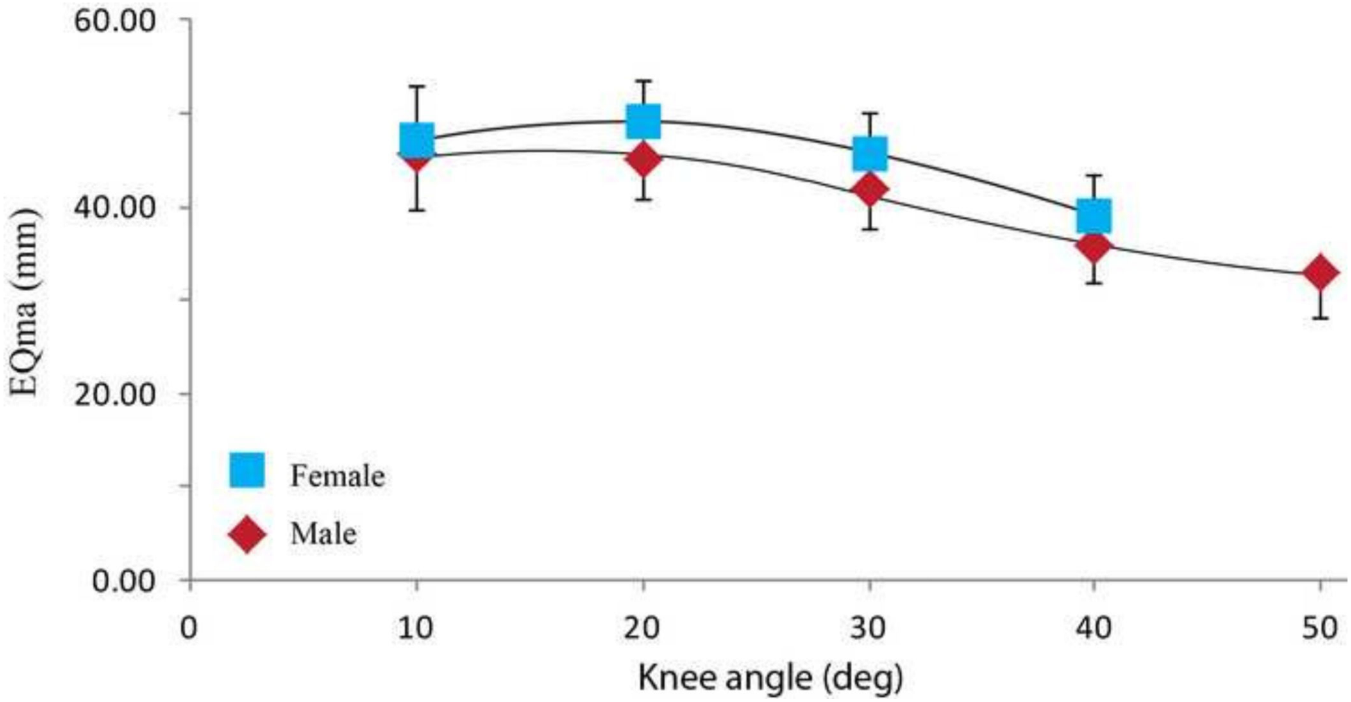

Figure 5.

The Quadriceps Effective Moment Arm (EQma), relative to the tibiofemoral instantaneous helical axis. Values are provided throughout a range of active extension (10° – 50°) with one standard deviation bars.

Table 1

PTma and EQma Values for the male and female cohort

The shaded values (with a star next to the average value) denote the parameters in which a significant different existed between the male and female cohorts. Comparisons were not completed at 50° knee angle, as data were available for only eight female subjects (age=25.8±4.7years, 57.2±7.1kg, and 160.7±9.9cm) and one males subject (22 years, 72kg, 172.7 cm).

	Females				Males			
Knee Angle (deg)	PTma (mm)		EQma (mm)		PTma (mm)		EQma (mm)	
	Ave	Ave	Ave	Ave	Ave	SD	Ave	SD
10	42.9	44.2	45.5	5.8	44.2	7.4	47.1	7.8
20	45.1*	49.4*	45.1*	4.2	49.4*	4.7	49.2*	6.2
30	46.5*	50.6*	41.8*	4.3	50.6*	5.3	45.5*	6.4
40	44.2	48.0	35.9	4.2	48.0	7.5	39.1	7.1
50	44.8	33.7	32.9	4.8	33.7	--	31.5	--

* indicates $p < 0.05$

Table 2

Correlations between moment arm parameters and patellofemoral kinematics

A) The **superior position** of the patella relative to the femoral sulcus point is associated with three moment arm variables. B) **patellofemoral extension** is associated with three moment arm variables.

A (PF SI)			
KA	**Fpt/Fq**	**Ptma**	**EQma**
10	0.38 (*p*=0.016)	−0.49 (*p*=0.001)	—
20	0.52 (*p*=0.001)	−0.38 (*p*=0.015)	—
30	0.50 (*p*=0.001)	−0.42 (*p*=0.007)	—
40	0.35 (*p*=0.026)	—	—
B (PF ext)			
KA	**Fpt/Fq**	**Ptma**	**EQma**
10	—	−0.54 (*p*<0.001)	—
20	0.35 (*p*=0.026)	−0.53 (*p*<0.001)	—
30	0.39 (*p*=0.014)	−0.39 (*p*=0.014)	—
40	—	—	—

Abberviations F_{pt}/F_q = ratio of the force in the patellar tendon to the force in the quadriceps tendon; PTma = patellar tendon moment arm relative to the tibiofemoral instantaneous helical axis; EQma = effective quadriceps moment arm; KA = knee angle; -- = no correlation existed (the p=value for these correlations ranged from 0.098 to 0.862