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Influence of patella alta on knee extensor mechanics

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Abstract

The purpose of this study was to compare the knee extensor mechanics in persons with and without patella alta. Thirteen subjects with patella alta and 14 subjects with normal patellar position participated in the study. Sagittal and axial MR images of the knee were acquired at 0°, 20°, 40°, and 60° of knee flexion. Measurements of actual moment arm, patellar ligament/quadriceps tendon force ratio, quadriceps effective moment arm, and joint reaction force/quadriceps force ratio were obtained. There were no differences between groups in terms of actual moment arm. However, subjects with patella alta had significantly larger patellar ligament/quadriceps tendon force ratios (1.04 ± 0.02 vs. 0.92 ± 0.02) and quadriceps effective moment arms (4.40 ± 0.09 vs. 4.00 ± 0.09 cm) when averaged across the range of knee flexion angles tested. There was no difference in the joint reaction force/quadriceps force ratio between groups. The observed differences in knee extensor mechanics suggest that individuals with patella alta have a more efficient knee extensor mechanism and would be expected to generate similar joint reaction forces per unit quadriceps force compared to subjects with normal patellar position. Therefore, persons with patella alta may experience less patellofemoral joint reaction force to overcome the same knee flexion moment in the range of 0°–60° of knee flexion.

Keywords: Patella alta; Patellofemoral; Patellofemoral joint reaction force

1. Introduction

Patellofemoral pain is one of the most common disorders of the knee affecting one in four persons in the general population (Levine, 1979) and as many as one in three physically active individuals (Jordaan and Schwellnus, 1994). Although the etiology of patellofemoral pain is frequently debated, a commonly proposed hypothesis is related to patellofemoral malalignment leading to elevated patellofemoral joint stress (force per unit area). This elevation in patellofemoral joint stress is believed to lead to articular cartilage degeneration (Grana and Kriegshauser, 1985; Moller et al., 1989; Steinkamp et al., 1993; Heino and Powers, 2002) and subsequent pain. Patella alta (high riding patella) is considered a predisposing factor with respect to the development of patellofemoral pain (Kujala et al., 1986). Although the association between patella alta and patellofemoral malalignment is widely accepted (Insall et al., 1972; Moller et al., 1986), research documenting the influence of patella alta on knee extensor mechanics is limited.

From a mechanical perspective the perpendicular distance from the extensor mechanism to the knee axis of rotation dictates the force required by the quadriceps mechanism to produce a given moment about the knee. The actual moment arm (M_{act}) is measured as the perpendicular distance from the tibiofemoral axis of rotation to the patellar ligament (Smidt, 1973; Nisell, 1985; van Eijden et al., 1986; Yamaguchi and Zajac, 1989). When the actual moment arm is used to estimate quadriceps force, an assumption is made that the forces in the quadriceps tendon and patellar ligament are equal in magnitude. However, the patella also pivots on the

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Nomenclature

θ	quadriceps tendon angle with respect to vertical (degrees)
α	retropatellar surface angle with respect to vertical (degrees)
β	patellar ligament angle with respect to vertical (degrees)
L_p	length of the patella (cm)
L_{pl}	length of the patellar ligament
M_{act}	actual moment arm
M_{eff}	quadriceps effective moment arm
M_{pl}	moment arm of the quadriceps tendon about the patellofemoral contact point (cm)
M_q	moment arm of the patellar ligament about the patellofemoral contact point (cm)
F_{pl}/F_q	patellar ligament force/quadriceps tendon force ratio
F_r/F_q	patellofemoral joint reaction force/quadriceps force ratio

femur producing a force differential between the patellar ligament and quadriceps tendon. Recognizing the lever action of the patella, Grood et al. (1984) described the patella ligament/quadriceps tendon force (F_{pl}/F_q) ratio. This ratio, when multiplied by the actual moment arm (M_{act}) yields the quadriceps effective moment arm (M_{eff}) which accounts for both the spacing effect and the pivoting action of the patella (Grood et al., 1984; Yamaguchi and Zajac, 1989; van Eijden et al., 1986). Once the forces in the patellar ligament and quadriceps tendon are estimated, the orientation of these structures in relation to the load-bearing surface of the patellofemoral joint can be used to compute the patellofemoral joint reaction force/quadriceps force (F_r/F_q) ratio (van Eijden et al., 1986; Yamaguchi and Zajac, 1989). This ratio characterizes the magnitude of the patellofemoral joint reaction force as a function of quadriceps force.

Evidence exists suggesting that persons with patella alta may have altered knee extensor mechanics that predispose this population to higher joint reaction forces. Using the extensor mechanism parameters described above, Yamaguchi and Zajac (1989) proposed a mathematical model of the patellofemoral joint. Experimental manipulation of this model suggested that lengthening the patellar ligament (analogous to patella alta) would increase joint reaction forces at knee flexion angles above 30°. Singerman et al. (1994) instrumented cadaveric patellofemoral joints with a six-degree-of-freedom load cell in order to measure joint reaction forces directly. This investigation noted that upon physical lengthening of the cadaveric patellar ligament, joint reaction forces were only elevated at knee flexion angles above 90°. A limitation of these studies was the fact that patella alta was simulated (i.e. not characterized in vivo) and comparisons were not made with a separate control group. Therefore, extrapolation of these results to persons with patella alta is questionable.

Using magnetic resonance imaging (MRI), the purpose of this study was to compare the knee extensor mechanics of individuals with patella alta to persons with normal patellar position. It was hypothesized that individuals with patella alta would demonstrate altered knee extensor mechanics that would predispose such individuals to elevated patellofemoral joint reaction forces.

2. Materials and methods

2.1. Subjects

Twenty-seven subjects (25 female and 2 male) between the ages of 19 and 34 participated in this study. Subject groups were similar in terms of height and weight (Table 1). Based on the procedures outlined below, 13 were determined to have patella alta and 14 had normal patellar position. Subjects were screened by physical examination to rule out the presence of tibiofemoral instability or meniscal injury. Additionally, subjects were excluded if they reported previous knee surgery or any implanted biological devices, such as pacemakers, cochlear implants, or clips which could interact with the magnetic field during imaging.

Prior to participation all subjects were informed as to the nature of the study, procedures, and risks. Each subject then signed a human subjects consent approved by the Institutional Review Board of the University of Southern California.

Table 1
Subject characteristics

	Mean ± sd	
	Control ($n = 14$)	Patella alta ($n = 13$)
Age (yrs)[a]	28 ± 4.1	25 ± 3.5
Height (cm)	164 ± 5.2	163 ± 4.8
Weight (kg)	58 ± 6.4	59 ± 9.6
Insall–Salvati index (L_{pl}/L_p)[a]	1.03 ± 0.08	1.32 ± 0.08
History of pain (n)[a]†	3	10

[a]Indicates significant differences between groups.

2.2. Instrumentation

Sagittal MR images of the knee and patellofemoral joint were obtained with a 1.5-T Signa scanner (GE Medical Systems, Milwaukee, WI). Images were obtained using a T1 weighted spin echo pulse sequence (TR 350 ms, TE 10 ms, NEX 1, FOV 20×20 cm, matrix 256×256, slice thickness 10 mm, two 5-in. receive-only coils). Acquisition time was 15 s for the scout scan and 2 min for the sagittal plane images. We selected a T1 weighted spin echo pulse sequence over faster sequences (i.e. SPGR) because it provided better signal-to-noise ratios than other sequences, and the duration of the scan was still tolerable for subjects. A slice thickness of 10 mm was chosen based on pilot data, indicating that the intersection of the cruciates could be readily obtained on a single image of this thickness.

2.3. Procedures

Subjects were placed supine on the MR gantry and secured within a custom-made non-ferromagnetic leg press apparatus (Captain Plastic, Shoreline, WA) (Fig. 1). The lower extremity of interest was placed on the footplate of the loading device and two receive-only coils were taped to the knee. Epoxy weights totaling 25% of body weight were then secured to the load carriage. Preliminary studies demonstrated that this load was sufficient to remove any slack in the knee extensor mechanism and was tolerable to patients with patellofemoral pain.

Subjects were first positioned at 0° of knee flexion and were instructed to hold this position during imaging. Once the desired knee flexion angle was achieved (determined using a standard goniometer), the knee was landmarked, a triplanar scout scan was acquired, and sagittal images of the knee were obtained. This procedure was repeated at 20°, 40°, and 60° of knee flexion. A 2 m rest was given between imaging sequences.

2.4. Data analysis

Images were magnified ($1.5\times$) and calibrated using Scion Image software (Scion Corporation, Frederick, MD). To determine the presence of patella alta, images were screened to determine which contained the maximum patellar ligament length and patellar length. Measurements of patellar ligament length were made along the posterior surface from the tibial tuberosity to the patellar apex, while measurements of patellar length were made from the apex of the patella to the most posterior superior aspect of the patellar base (Fig. 2) (Insall and Salvati, 1971). In all cases, the longest patellar ligament length and longest patellar length were used even if they were on separate images in a series, as previous research has suggested that this method produces the strongest reliability and validity with measurements obtained from lateral radiographs of the knee (Miller et al., 1996). The length of the patellar ligament was then divided by the length of the patella to yield the Insall–Salvati index (Insall and Salvati, 1971). Insall–Salvati ratios greater than or equal to 1.2 indicated the presence of patella alta, while indices between 0.80 and 1.19 identified subjects as having normal patellar position (Insall and Salvati, 1971).

The sagittal images were then screened to determine which image contained the midsection of the knee. This

Fig. 1. Custom non-ferromagnetic leg press (Captain Plastic, Shoreline, WA) used to simulate weight-bearing. A resistance of 25% body weight was used to load the knee extensor mechanism. Reprinted with Permission from Salsich GB, Ward SR, Terk MR, Powers CM. In vivo Assessment of Patellofemoral Joint Contact Area in Individuals Who Are Pain Free. *Clin Orthop* 417, 277–284, 2003.

Fig. 2. The Insall–Salvati index is computed by dividing the length of the patellar ligament (L_{pl}) by the longest diagonal length of the patella (L_p). Reprinted with Permission from Ward SR and Powers CM. The Influence of Patella Alta on Patellofemoral Joint Stress During Normal and Fast Walking. *Clin Biomech* 19(10), 1040–1047, 2004.

Fig. 3. The actual moment arm (M_{act}) is the distance from the axis of rotation (C) to the patellar ligament (A–B). Reprinted with Permission from Ward SR and Powers CM. The Influence of Patella Alta on Patellofemoral Joint Stress During Normal and Fast Walking. *Clin Biomech* 19(10), 1040–1047, 2004.

was determined by identifying the image containing the intersection of the cruciate ligaments. This image was used to measure all four indices of knee extensor mechanics according to the methods described by Yamaguchi and Zajac (1989). All images were screened for motion artifact and reacquired if present.

Actual moment arm (M_{act}) was measured as the perpendicular distance from the tibiofemoral axis of rotation, estimated at the intersection of the cruciate ligaments (O'Connor et al., 1989), to the patellar ligament (Fig. 3). The intersection of the cruciate ligaments was chosen to estimate the axis of rotation of the knee as previous literature has suggested that it produces smaller errors than using the tibiofemoral contact point when compared to the helical axis method (Baker and Ronsky, 2001).

Quadriceps moment arms (M_q) and patellar ligament moment arms (M_{pl}) were measured as the perpendicular distances from the patellofemoral contact point to the respective tendons (Fig. 4). When the patellofemoral contact point could not be identified by a single point, the line of contact between the patella and femur was bisected and the midpoint of this line was used as the axis of rotation. The force in the patellar ligament/quadriceps tendon force (F_{pl}/F_q) ratio was then computed using the following equation (Grood et al., 1984):

$$F_{pl}/F_q = M_q/M_{pl}. \quad (1)$$

Quadriceps effective moment arms were calculated using the following equation (van Eijden et al., 1986; Yamaguchi and Zajac, 1989):

$$M_{eff} = F_{pl}/F_q(M_{act}). \quad (2)$$

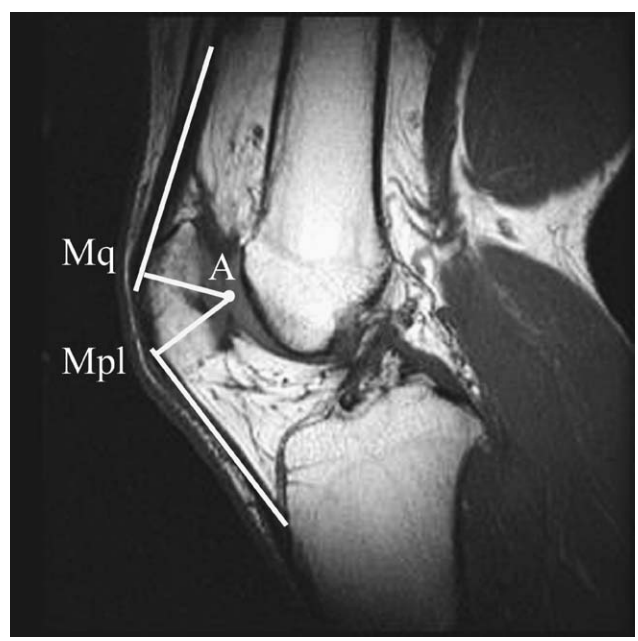

Fig. 4. The quadriceps tendon moment arm (M_q) and the patellar ligament moment arm (M_{pl}) are the perpendicular distances from the patellofemoral contact point (A) to the lines of action of their respective tendons. Reprinted with Permission from Ward SR and Powers CM. The Influence of Patella Alta on Patellofemoral Joint Stress During Normal and Fast Walking. *Clin Biomech* 19(10), 1040–1047, 2004.

Compression from the patellar ligament and quadriceps tendon forces was estimated using the angles that the quadriceps tendon (θ), retropatellar surface (α), and patellar ligament (β) formed with the vertical were measured (Fig. 5). Using the following equation, these angles and the F_{pl}/F_q ratio were used to calculate the ratio of patellofemoral joint reaction force to quadriceps force (F_r/F_q),

$$\frac{F_r}{F_q} = \frac{F_q[\sin(\theta+\alpha)] + [F_q(F_{pl/Fq})][\sin(\beta-\alpha)]}{F_q}, \quad (3)$$

where F_q is assigned a value of 1 N. This ratio represented the magnitude of the expected joint reaction force, in Newtons, per unit quadriceps force.

A custom-written macro for Scion Image (Scion Corp., Frederick, MD) was used to measure all perpendicular distances and angles. All measurements were made twice by the same investigator and averaged for statistical analysis.

2.5. Reliability analysis

Although MRI has been shown to provide valid measurements of moment arms about the knee (Arnold et al., 2000; Spoor and van Leeuwen, 1992), a reliability analysis of the measurements obtained in this study was performed on 16 subjects. Sagittal images of the knee were obtained on two separate occasions. Two measurements from each set of images were averaged and then compared to establish measurement reliability. M_{act} was the most reliable measurement (CV 4%, SEM 0.19 cm), followed by the F_{pl}/F_q ratio (CV 5%, SEM 0.05), M_{eff} (CV 6%, SEM 0.29 cm), and the F_r/F_q ratio (CV 10%, SEM 0.04).

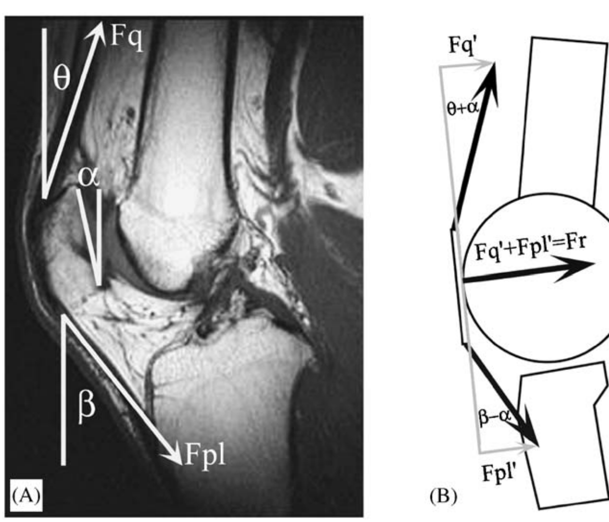

Fig. 5. (A) Measurements of the quadriceps tendon (θ), retropatellar surface (α), and patellar ligament (β) relative to the vertical. (B) These angles were used to compute the joint reaction force (black line, F_r) from the quadriceps tendon force (gray line, F_q') and the patellar ligament force (gray line, F_{pl}'). Reprinted with Permission from Ward SR and Powers CM. The Influence of Patella Alta on Patellofemoral Joint Stress During Normal and Fast Walking. *Clin Biomech* 19(10), 1040–1047, 2004.

2.6. Statistical analysis

Initial statistical analysis included the Shapiro–Wilk's and Levene's tests to screen the data for assumptions of normality and homogeneity of variances. A 2×4 (group $\times$ knee flexion angle) repeated measures analysis of variance was used to test for main effects and interactions. This analysis was repeated for each dependent variable: $M_{act}, F_{pl}/F_q$ ratio, M_{eff}, and F_r/F_q ratio. Main effects for group, and group by knee flexion angle interactions were of interest in this study. In the event of a significant interaction, post hoc Tukey's tests were used to determine where differences existed. All statistical analyses were performed using SPSS statistical software (SPSS Inc., Chicago, IL) with a significance level of $p<0.05$.

3. Results

There was no significant group effect for actual moment arm (M_{act}) and no group $\times$ knee flexion angle interaction (Fig. 6). When averaged across all knee flexion angles, M_{act} in the patella alta group was comparable to that of the control group (4.22 ± 0.05 vs. 4.33 ± 0.05 cm, respectively).

There was a significant group effect for the F_{pl}/F_q ratio and no significant group $\times$ knee flexion angle interaction (Fig. 7). When averaged across all knee flexion angles, subjects with patella alta had greater F_{pl}/F_q ratios compared to control subjects (1.04 ± 0.02 vs. 0.92 ± 0.02; $F_{1,3} = 16.59, P<0.001$). The largest difference in the F_{pl}/F_q ratio between the patella alta group and control group occurred at 60° of knee flexion (0.91 ± 0.15 vs. 0.76 ± 0.10, $P<0.05$).

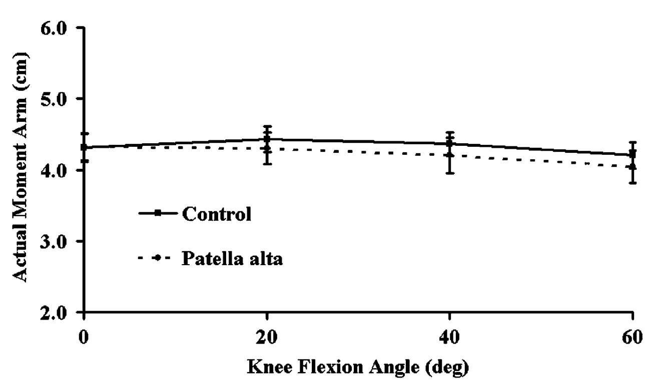

Fig. 6. Comparison of M_{act} between groups. Error bars indicate 1 standard deviation. † indicates significant differences ($p<0.05$) between groups.

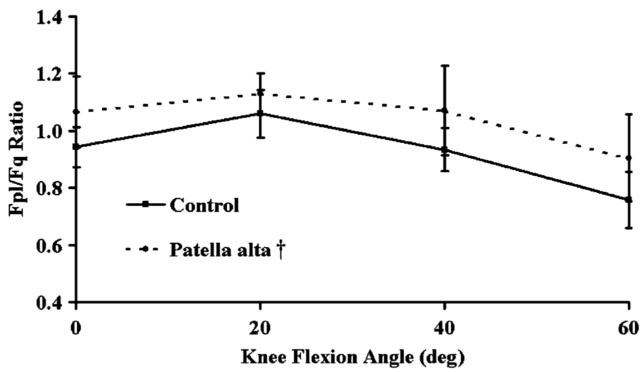

Fig. 7. Comparison of the F_{pl}/F_q ratio between groups. Error bars indicate 1 standard deviation. † indicates significant differences ($p<0.05$) between groups.

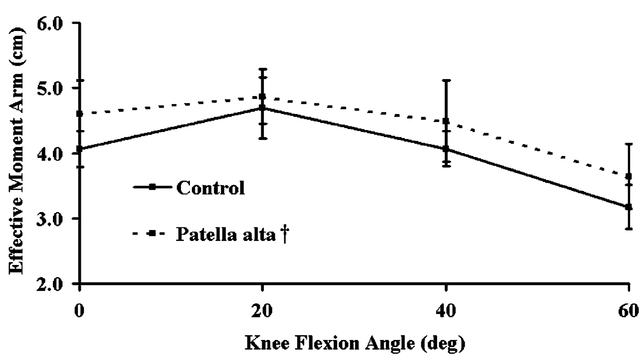

Fig. 8. Comparison of M_{eff} ratios between groups. Error bars indicate 1 standard deviation. † indicates significant differences ($p<0.05$) between groups.

There was a significant group effect for M_{eff} and no significant group × knee flexion angle interaction (Fig. 8). When averaged across all knee flexion angles, subjects with patella alta had greater M_{eff} compared to control subjects (4.40 ± 0.09 vs. 4.00 ± 0.09 cm; $F_{1,3} = 10.56, P = 0.003$). The largest difference in M_{eff} between the patella alta group and the control group occurred at 0° of knee flexion (4.60 ± 0.52 vs. 4.06 ± 0.27 cm, $P<0.05$).

There was no significant group effect for the F_r/F_q ratio and no group × knee flexion angle interaction (Fig. 9). When averaged across all knee flexion angles, the F_r/F_q ratio in the patella alta group was comparable to that of the control group (0.81 ± 0.02 vs. 0.77 ± 0.02, respectively).

4. Discussion

Contrary to our initial hypotheses, the results of this study indicated that persons with patella alta had increased mechanical efficiency of the quadriceps mechanism from 0° to 60° of knee flexion as illustrated by the increase in M_{eff} in this range. On average, the patella alta group demonstrated a 10% increase in M_{eff} across all knee flexion angles. The largest difference between groups occurred at 0° of knee flexion, where a 15% increase was observed.

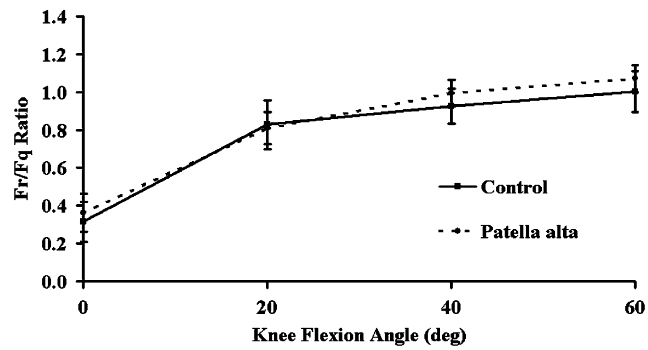

Fig. 9. Comparison of the F_r/F_q ratio between groups. Error bars indicate 1 standard deviation. † indicates significant differences ($p<0.05$) between groups.

Two factors are taken into consideration when determining $M_{eff} : M_{act}$ which accounts for the spacing effect of the patella and the F_{pl}/F_q ratio which reflects the pivoting action of the patella (Yamaguchi and Zajac, 1989). Although no group differences were observed with respect to M_{act}, the patella alta group demonstrated significantly greater F_{pl}/F_q ratios compared to control subjects, indicating a greater pivoting effect. This greater pivoting action of the patella resulted in a significantly larger M_{eff} in the patella alta group.

The finding of a greater F_{pl}/F_q ratio in persons with patella alta is consistent with previous model predictions (Yamaguchi and Zajac, 1989). Our data indicated that persons with patella alta had larger quadriceps moment arms (M_q) and smaller patellar ligament moment arms (M_{pl}) than control subjects (Fig. 10). This is not surprising given that subjects with patella alta have a higher vertical patellar position causing the patellofemoral contact point to be closer to the patellar apex. The larger M_q relative to M_{pl} would result in a greater transmission of force from the quadriceps tendon to the patellar ligament.

With respect to the F_r/F_q ratio, no statistically significant differences were observed. This result is consistent with the data of Singerman et al. (1994) who did not find increases in patellofemoral joint reaction forces in a cadaver simulation of patella alta when tested from 0–60° of knee flexion. It should be noted that these authors did report a significant increase in patellofemoral joint reaction forces with patella alta at 90°; however, this knee flexion angle was not assessed in the current investigation as the bore diameter limited knee flexion to 60° in our subjects. Yamaguchi and Zajac (1989) reported a 10% increase in the F_r/F_q ratio at 60° of knee flexion in their mathematical simulation of patella alta, which was similar to the 8% increase

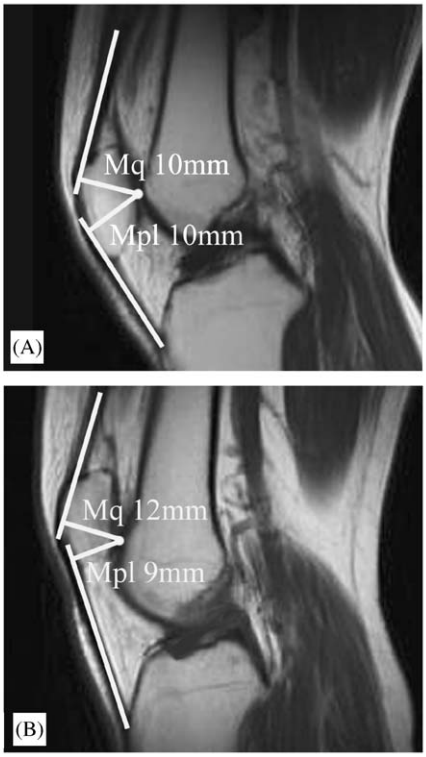

Fig. 10. Comparison of quadriceps moment arms (M_q) and patellar ligament moment arms (M_{pl}) at 20° of knee flexion. (A) A person with normal patellar position had an M_{pl} slightly equal to M_q, indicating an F_{pl}/F_q ratio of 1.0. (B) A person with patella alta had an M_{pl} smaller than M_q, indicating an F_{pl}/F_q ratio greater than 1.0.

observed in the current investigation. However, the relevance of this difference can be challenged, as statistical significance was not achieved.

An apriori power analysis power analyses ($\alpha = 0.05, \beta = 0.20\delta = 10\%, \sigma = 8\%$) based on pilot data suggested that 10 subjects per group would be needed to detect a clinically relevant difference (10%) in all four variables. However, in our non-significant findings, M_{act} had a power of 68% and the F_r/F_q ratio had a power of 51%. These values can be explained by the fact that we overestimated the effect size and underestimated the variability in our pilot data. However, we can defend them in several ways. First, the observed between-group differences in these variables were small, 5% for the F_r/F_q ratio and 3% for M_{act}, leading one to question the clinical relevance of these effect sizes. Second, M_{act} is simply one of the variables used to calculate M_{eff} and significant differences were observed in this variable. Finally, although the F_r/F_q ratio was 5% larger on average in the patella alta group, the reduction in M_{eff} was larger (9%), suggesting that any increase in the joint reaction force potential would be offset by smaller quadriceps forces for a given external moment about the knee.

The observed difference in M_{eff} suggests that individuals with patella alta have greater quadriceps leverage than subjects with normal patellar position. This indicates that persons with patella alta would need less quadriceps force to overcome the same knee flexion moment compared to those without patella alta. Given that these subjects would be expected to generate similar joint reaction forces per unit quadriceps force, subjects with patella alta may experience smaller joint reaction forces to overcome the same knee flexion moment in the range of 0°–60° of knee flexion. However, as patellofemoral joint stress is defined as force per unit area, care must be taken in assuming that reductions in joint reaction force would equate to reductions in stress. For example, recent investigations have shown that persons with patellofemoral pain have diminished patellofemoral joint contact area (Heino and Powers, 2002). Given the fact that the patella sits higher in the trochlear groove in persons with patella alta, it is not unreasonable to assume that such individuals may have similar reductions in contact area. Future research is necessary to determine if persons with patella alta demonstrate increases in patellofemoral joint stress.

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