

Article

A Novel Method for Assessing Regional Tendon Stiffness and Its Significance

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Abstract: Elastography can be used to estimate the regional shear modulus of a tendon. This can advance our knowledge on the impact of patellar alignment and regional patellar tendon stiffness. This is important as patellar tendon abnormality is mainly found in the medial portion of the tendon in subjects with proximal patellar tendinopathy. This paper aims to assess the effect of patellar displacement on differential modulation on the shear modulus of the patellar tendon. Shear modulus is captured on the medial and lateral half of the patella tendon using the Aixplorer[®] ultrasound unit in conjunction with a 4–15 MHz, 50 mm linear transducer with the patellar being positioned in its resting, medio- and laterally displaced positions on 40 adults (19 females, 21 males). When the patellar is displaced laterally, the shear modulus is significantly increased at the medial half in both genders but decreased at the lateral half only in females. Conclusions: Elastography detects changes in regional tendon stiffness associated with alteration in patellar positions. The modulation on the shear modulus is gender and region specific.

Keywords: supersonic shear imaging; shear modulus; tendon stiffness; patellar positions; patellar tendon

1. Introduction

Supersonic shear imaging technology (SSI) is a relatively new technique to measure stiffness of soft tissue in real time [1,2]. It measures the shear wave velocity to estimate the shear modulus (an index of stiffness) of a selected area [3]. A recent study demonstrated that the tendon shear modulus generated from the SSI is correlated with the Young's modulus, which was computed from a material testing system. The study had good intra- and inter-rater reliability [4]. This new technique thereby enabled a non-invasive, direct and reliable measurement of tendon stiffness to be performed on a selected region of a tendon, providing a quantitative value. Assessment of regional tendon stiffness enabled a better understanding of mechanical demand/stress on selected regions of a tendon. This was particularly important in the patellar tendon. First, proximal patellar tendinopathy, a common knee problem, was found to have localized pathological changes, and the pathological changes were mainly detected in the medial portion of the tendon [5,6], therefore site-specific evaluation at the different regions of a tendon might have shed light on the regional changes in tissue elasticity.

The patellar tendon runs obliquely, outwardly and distally from the apex of the patella and inserts into the tibial tuberosity [7]. Patellar tendon strain could be affected by tension in the lateral retinaculum [8] or by the position of the patella [9]. Supporting this theory, a higher patellar tendon shear modulus has been associated with a higher vastus lateralis muscle shear modulus [10]. The vastus lateralis is one of the muscle heads of quadriceps femoris, which is attached to the base and the

superolateral border of the patella and is connected to the lateral side of the patellar tendon through the lateral retinaculum [11]. Using magnetic resonance imaging, a trend of increased patellar lateral tilt was observed in subjects with patellar tendinopathy when compared with controls [12]. In a recent study, patellar height, as measured by the Install-Salvati ratio, was significantly greater in patients with proximal patellar tendinopathy than in healthy controls [9]. Taken together, patella mal-alignment was observed in subjects with patellar tendinopathy. The mal-alignment of the patella may have contributed to changes in the distribution of strain within the patellar tendon. Such a relationship remains to be explored. Note that increases in proximal patellar tendon stiffness have been reported in athletes with patellar tendinopathy [10,13]. The present study aimed to determine whether experimental displacement of the patella would alter patellar tendon stiffness. Regional changes in tendon stiffness were estimated using ultrasound shear wave elastography. In consideration of gender effects on patellar tendon orientation [14], both female and male subjects were recruited. We hypothesized that sideways displacement of the patella from its resting position would modulate patellar tendon shear modulus, the modulation would be site specific and greater increases in the medial half would be observed with lateral patellar displacement and in the lateral half with medial patellar displacement.

2. Materials and Methods

2.1. Ethics Statement

This study was approved by the Human Subject Ethics Subcommittee of the administrating institution. The procedures of study were fully introduced to the participants, and all of them provided their informed written consent before testing.

2.2. Participants

Forty young adults were recruited from a local university and from the community. All participants were healthy individuals aged between 18 to 30 years old and adopted a sedentary lifestyle with less than 4 h of exercise per week. Participants meeting the following criteria were excluded: (1) a past history of patellofemoral pain syndrome (PFPS); (2) previous surgeries on lower extremities; (3) any injuries altering knee alignment; (4) taking muscle-relaxation drug; (5) body mass index ≥ 30 kg/m².

Demographic data on age, weight, height, exercise time per week and leg dominance was recorded. The leg dominance was defined as the leg which was used to kick a ball. Quadriceps angle (q-angle) was measured as the angle formed between a line from the anterior superior iliac spine to the midpoint of patella and a vertical line joining the midpoint of patella to the tibial tubercle [15]. Because of its potential influence on the patellar tendon tension (Figure 1), the q-angle was added as a covariate factor if it was associated with changes in tendon shear modulus.

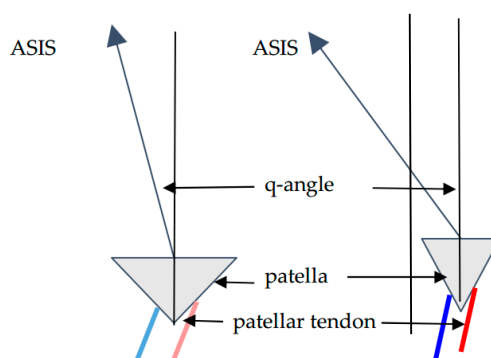


Figure 1. Relationship between the q-angle, patella and the patellar tendon. Anterior superior iliac spine and q-angle denote anterior superior iliac spine and quadriceps angle, respectively.

2.3. Procedure

Figure 2 shows the schematic flow of the study. Elastography measurement was before and after the patella was displaced from its resting position.

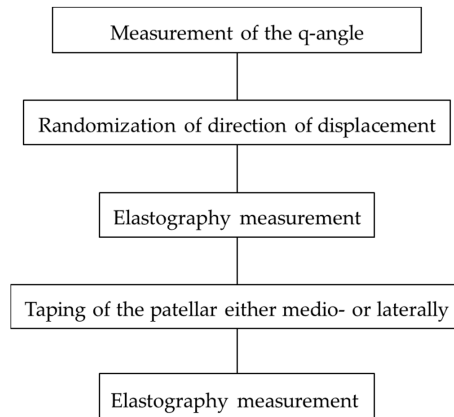


Figure 2. Schematic flow of the study.

2.3.1. Elastography Measurement

An Aixplorer[®] ultrasound unit (V4, Supersonic Imaging, Aix-en-Provence, France) in conjunction with a 50 mm linear-array transducer at 4–15 MHz and a frame rate up to 20,000 frames/s were used for assessing shear modulus of the patellar tendon.

Each participant was examined in supine, lying with the testing knees supported at 45° of flexion [16]. Prior to testing, subjects rested for 15 min [17]. The room temperature was controlled at 25 °C.

B-mode was used to locate and align the patellar tendon with the transducer placed longitudinal to the patellar tendon. The shear wave mode was then activated once a clear image was found. The musculoskeletal acquisition mode was used to measure the shear modulus of the patella tendon with the temporal averaging (persistence) and spatial smoothing set to medium and 6, respectively. The color-coded image was displayed, which indicated softer tissue in blue and stiffer in red. The range of color scale was pre-set from 0 to 600 kPa. The transducer was stationed on the skin with very light pressure on top of a generous amount of ultrasound gel for 8–12 s [10]. A total of five continuous ultrasound images were captured for off-line analysis with the patella of each knee being positioned in 2 positions; resting and displaced positions. The displaced direction (either medio- or laterally displaced) for the right knee was determined by drawing a card from an envelope. Once the position of the right knee had been determined, the left knee was taped in the opposite direction.

2.3.2. Patellar Positions

The patella was manually displaced towards the medial or lateral side from its resting position. Rigid tape (Strappal[®], 4 cm × 10 cm) was used to hold the patella in place. The taped patella was covered by a towel so the position of the patella was blinded during SSI.

2.3.3. Data Extraction

Off-line analysis was conducted. The region of interest (ROI) was defined as a square box, which was 40 mm × 40 mm, distal to the apex of the patella. A circular quantification box (Q-Box) was centered at 0.5 cm from the apex of the patellar; and its width by the medial or lateral edge of patellar tendon from a bisecting line (Figure 3). The bisecting line was drawn from the mid-point of the cross-sectional images captured at the proximal and distal end of the patellar tendon. The medial and lateral half of the patellar tendon was defined as the patellar tendon located medio- or laterally to the bisecting line. Mean values (kPa) from the five captured imaged were computed for further analysis.

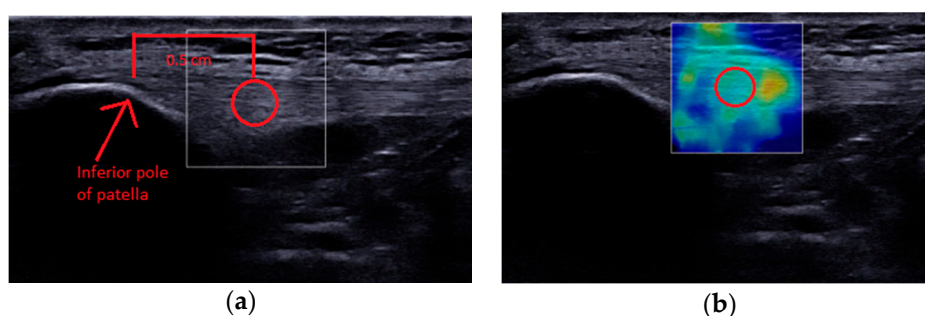


Figure 3. Representative images of a patellar tendon. (a) B-mode of the proximal patellar tendon. A 40 mm \times 40 mm square box delineated the region of interest (ROI) from the apex of the patella; (b) shear modulus mode of the same tendon. The musculoskeletal acquisition mode was used to measure the shear modulus of the patella tendon with the temporal averaging (persistence) and spatial smoothing set to medium and 6, respectively. The color-coded image is displayed, which indicates softer tissue in blue and stiffer in red. A circular circle (Q-box) was centered at 0.5 cm from the apex of patella. Mean shear elastic modulus (kPa) of circular Q-box was computed from the system.

2.3.4. Reliability Test

The procedure was repeated on four adults (eight legs) for test-retest reliability on the same day with 30 min in-between sessions.

2.3.5. Statistical Analysis

Independent *t*-tests were performed to compare the demographic data between males and females. Intraclass correlation coefficient (ICC) was performed to analyze the test-retest reliability. Percentage changes on the tendon shear modulus were computed. Correlation coefficient tests were used in assessing the relationship between percentage change in tendon shear modulus and the q-angle measured in males and females. Repeated measures ANOVA was conducted with position (resting, displaced) and side (medial, lateral half of the patellar tendon shear modulus) as within subject factors and q-angles as co-variates if significant correlations with q-angles were detected. Statistical significance was set as $p < 0.05$. All statistical analyses were performed by SPSS version 23.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Demographic Data

The age, height, weight, BMI and q-angle of participants are shown in Table 1. There were no significant differences in age and BMI between males and females ($p > 0.05$) but a significant difference was found in height, weight and q-angle between the two groups ($p = 0.001$).

Table 1. Characteristics of the participants.

Demographic	Males ($n = 21$)	Females ($n = 19$)	<i>p</i>
Age (year)	21.0 \pm 1.9	21.8 \pm 2.6	0.12
Height (cm)	173.4 \pm 6.3	161.0 \pm 5.1	0.001 *
Weight (kg)	63.4 \pm 7.5	52.3 \pm 8.1	0.001 *
Body mass index (kg/m ²)	21.1 \pm 2.1	20.1 \pm 2.3	0.056
q-angle (degrees)	16.9 \pm 3.4	20.4 \pm 3.2	0.001 *

Note: * $p < 0.05$. Data are presented as mean \pm standard deviation.

3.2. Reliability Test

Test-retest reliability of patellar tendon shear modulus indicated good reliability for the lateral half (ICC = 0.94; 95% CI = 0.75 – 0.99) and medial half (ICC = 0.81; 95% CI = 0.17 – 0.96).

3.3. Effects of q-Angle on Percentage Changes in Tendon Shear Modulus

Table 2 shows that when the patella was laterally displaced, the q-angle and the percentage changes on tendon shear modulus had were positively correlated on the lateral half ($r = 0.47, p < 0.05$) but a negative correlation with the medial half ($r = -0.48, p < 0.05$) in the female subjects. No significant association was detected when the patella was displaced towards the medial side. No significant association were observed between the two variables when the patella was displaced in in the male subjects (all $p > 0.05$).

Table 2. Correlation coefficient between the q-angle and the changes in tendon shear modulus when the patella was laterally and medially displaced from its resting position.

Patella Position	Males		Females	
	Lateral Half	Medial Half	Lateral Half	Medial Half
Laterally displaced	0.29	0.17	0.47 *	-0.48 *
Medially displaced	0.01	-0.23	0.24	-0.15

Note: * $p < 0.05$.

3.4. Effect of Laterally Displaced Patellar Position on the Shear Elastic Modulus of Patellar Tendon

Table 3 lists the shear modulus when the patella was in its resting position and taped in the laterally displaced position. In the female subjects, the tendon shear modulus significantly decreased by $4\% \pm 39\%$ ($p = 0.03$) in the lateral but significantly increased by $13\% \pm 37\%$ ($p = 0.001$) in medial half. In male subjects, a significant increase of $17\% \pm 32\%$ ($p = 0.036$) was found in the medial half of the patellar tendon. No significant change was detected in the lateral half ($p = 0.177$).

Table 3. Shear modulus of patellar tendon at its resting and displaced positions.

Patella Position	Shear modulus (KPa)		Shear modulus (KPa)	
	Males (n = 20)		Females (n = 20)	
	Lateral Half	Medial Half	Lateral Half	Medial Half
Neutral	242.1 ± 92.6	293.4 ± 85.4	281.5 ± 131.0	303.3 ± 121.8
Laterally displaced	307.9 ± 150.9	356.6 ± 147.4 *	244.3 ± 110.3 *	341.9 ± 155.1 *
Neutral	275.8 ± 104.7	341.2 ± 104.9	271.0 ± 96.8	290.7 ± 118.3
Medially displaced	280.8 ± 130.5	367.8 ± 83.4	263.3 ± 105.0	341.4 ± 140.7 *

Note: Analyses were made on patellar tendon shear modulus with the patella at its neutral and displaced positions
* $p < 0.05$.

3.5. Effect of Medially Displaced Patellar Position on the Shear Elastic Modulus of Patellar Tendon

When the patellar was taped in medially displaced position, a significant increase in the tendon shear modulus was observed in the medial half ($+24 \pm 35\%$; $p = 0.014$) with no significant change in the lateral half ($p > 0.05$) in females. No significant changes in the males were detected (Table 3, left column).

4. Discussion

Using ultrasound shear wave elastography, the present study aimed to determine the effect of patella position on regional tendon stiffness when the patella was experimentally displaced and taped from its resting position.

This was the first study exploring how patella position affects the patellar tendon shear modulus (an index of stiffness). The relationship was gender and region specific. The q-angle quantified the angle between the line of force of the quadriceps muscle and the patellar tendon. As reported in previous studies [15], we observed a greater q-angle in females than males. In addition, in the female subjects, the q-angle was positively correlated with the percentage of change in the tendon shear modulus when the patella was displaced and taped laterally. More specifically, a larger q angle was associated with a greater reduction in the tendon shear modulus on the lateral half; and a smaller increase in the shear modulus on the medial half of the patellar tendon. The male subjects exhibited a smaller q-angle, which was not correlated with the changes in tendon shear modulus when the patella was displaced. Hence, gender effects on the patellar tendon orientation may have led to tendon regional-specific adaptation and mechanical responses to patellar movement in the medio-lateral directions.

When the patella was laterally displaced, the patellar tendon became less oblique, which might have led to a reduction in tendon shear modulus. In the female subjects, a small but significant (4%) reduction in tendon shear modulus in the lateral half of the patellar tendon was detected when the patella was displaced laterally. Changes in patellar tendon obliquity would have been greater in subjects with greater q-angles. In the above paragraph, we reported the positive association between the q-angle and changes in tendon shear modulus in the lateral half of the patellar tendon. However, an increase in tendon shear modulus in the medial half in females (by 13%) and males (by 17%) was observed. The medial reticulum plays an important role as a medial stabilizer of the patella, especially at low angles and attaches onto the medial border of the patellar tendon. [18]. Increases in tension of the medial retinaculum during lateral displacement of the patella might have increased strain on the medial half of the patellar tendon. Toumi et al., 2006, noticed that the vastus medialis oblique (VMO) muscle had fibers attaching to the medial half of the patellar tendon [19]. In the present study, when the patella was taped in a laterally displaced position, increases in tension of the medial retinaculum or/and the vastus medialis oblique muscle might have led to an increase in tendon shear modulus of the medial half of the patellar tendon. Noting that the fibers of the VMO are running horizontally to the patellar tendon, its effect would be greater with the patellar tendon running vertically. Hence, subjects with smaller q-angles might have greater increases in tendon shear modulus than those with larger q-angles. The differential increase in tension at the medial and lateral half of the tendon might have induced a shear force at the interface between the medial and lateral part of the tendon. This might have had consequences for tendon health. When the patella was displaced medially, the patellar tendon became more oblique. An increase in tendon shear modulus was expected. The changes reached a statistically significant level in the medial half in female but not male subjects. The non-significant change in male subjects might have been associated with their smaller q-angles compared with female subjects. The non-significant changes in the lateral portion were unexpected. Other factors aside from the position of the patella might have had greater effects on the lateral portion of the patellar tendon stiffness when the patella was medially displaced.

Different types of equipment, from the clinically viable to more complex systems, have been developed to estimate tendon elastic properties. The material testing system is the most direct and valid method for assessing in-vitro tendon elastic properties [20,21]. However, this method cannot be applied in-vivo. Hansen et al., 2006, proposed the use of B-mode ultrasound with a dynamometer to measure the elastic properties of human patellar tendon [22]. With this approach, ultrasound imaging was used to track tendon elongation during muscle contraction, while the muscle force was estimated from the dynamometer. This method required a long acquisition time [22]. In addition, the computed stiffness reflected the stiffness of the muscle-tendon-joint complex. Direct measurement of the tendon elastic properties was made possible with ultrasound shear wave elastography [23]. The tendon shear modulus, estimated from the ultrasound shear wave elastography techniques on patellar tendon, had good intra- and inter-rater reliability [4].

In this study, the patella was manually displaced and taped at its displaced position. We did not measure the amount of displacement and assumed that the patella would stay in place. Patellar tilting caused by medio-lateral manipulation was not considered in this study. Further studies could include measurement of patellar displacement and its effects on the modulation of tendon shear modulus. Given the relatively large variability of measurements on the tendon shear modulus, a larger sample might be warranted for further study.

5. Conclusions

Using supersonic shear imaging technology, we found gender and region-specific modulation on tendon shear modulus when the patella was displaced from its resting position. More specifically, an increase in tendon shear modulus was detected in the medial half in both genders when the patella was displaced laterally and in female subjects when the patella was medially displaced. Such findings might shed light on the pathological changes detected in the proximal and medial side of the tendinopathic tendon.

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