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Increase in passive muscle tension of the quadriceps muscle heads in jumping athletes with patellar tendinopathy

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Abstract

To investigate the passive muscle tension of the quadriceps muscle heads in male athletes clinically diagnosed with patellar tendinopathy (PT) with those of healthy controls and explore the interplay between passive muscle tension and patellar tendon stiffness. Between November 2012 and December 2013, 66 male athletes (mean age of 21.1 ± 4.4 years) were examined using supersonic shear wave imaging technology. The passive tension of the vastus lateralis (VL) and rectus femoris (RF) muscles and patellar tendon stiffness were assessed. The shear elastic modulus of the VL muscle was increased by 26.5% ($P < 0.001$) in the subjects with PT when compared with the controls. Greater passive tension in the VL was associated with higher patellar tendon stiffness ($r = 0.38$; $P = 0.001$). The vastus lateralis muscle of the quadriceps shows increase in passive muscle tension in jumping athletes with patellar tendinopathy. These findings suggest that increase in muscle tension is not similar in the individual muscles of the quadriceps muscle. Traditional stretching of the whole quadriceps muscle might not be targeted to the tight muscle heads.

Patellar tendinopathy (PT) is a common and often chronic knee disorder among competitive athletes (Witvrouw et al., 2001). Its prevalence has been reported to be as high as 30% to 45% in athletes involved in jumping sports (Lian et al., 2005). Most importantly, the condition is often prolonged and causes an early cessation of an athletic career (Kettunen et al., 2002). PT is characterized with localized pain at the proximal patellar tendon during jumping and squatting activities that load the tendon (Cook et al., 2000). Overloading has thereby been suggested to be a causative factor in the development of PT (Lian et al., 1996). The risk factors of tendon overloading are considered to be multifactorial. Extrinsic factors, such as training frequency, duration, intensity (Neely, 1998) and the training surface (Torstensen et al., 1994; Lian et al., 2003) have been reported. Intrinsic factors, such as muscle strength and muscle flexibility refer to processes internal to the individual affecting tendon loading (Crossley et al., 2007).

The muscle-tendon units of the hip, knee, and ankle act to dissipate the kinetic energy on landing (Fredberg & Bolvig, 1999). The knee extensor was the primary shock absorber during landing (Decker et al., 2003), and reduced flexibility of the quadriceps muscle was found to increase the magnitude of loading on the patellar tendon, and contribute to patella tendon overload. In a 2-year prospective study, Witvrouw et al. (2001) reported that reduced flexibility in the quadriceps and hamstrings would contribute to the development of PT. van der Worp et al. (2011), based on a systematic review on reported prospective and retrospective studies, suggested that reduced flexibility of the quadriceps muscle is one of major risk factors for the development of PT. Note that all the reported studies used maximum range of passive joint motion as an indication of muscle flexibility (van der Worp et al., 2011). However, passive range of joint motion depends on tendon extensibility and joint mobility in addition to muscle flexibility. In addition, exercise induced passive muscle tension on the muscle, i.e., muscle heads of soleus verse gastrocnemius may differ (Green et al., 2012), it is important to assess passive muscle tension of individual muscles of the quadriceps muscle such that muscle-specific change can be identified in athletes with PT.

Supersonic Shear Imaging (SSI) is a technique to quantify the elasticity of a localized area of soft tissue. SSI produces elastography images based on the combination of a radiation force and an ultrafast ultrasound acquisition imaging system is capable of capturing the propagating wave in real time. Shear modulus was computed from the velocity of the propagation waves (Bercoff et al., 2004; Lacourpaille et al., 2012). Because there exists a strong linear relationship between the muscle shear modulus captured from SSI and the Young's modulus computed from Material Testing System (Eby et al., 2013), muscle shear modulus can be considered as an indirect measure of resting muscle tension. In this manner, gastrocnemius muscle elasticity by SSI was found to be associated with passive ankle joint stiffness (Chino & Takahashi, 2016). SSI thereby enables measuring of passive muscle tension of the superficial heads of the quadriceps muscle. The deep head (i.e., vastus intermedialis) could not be measured in a valid manner because of poor quality of the elasticity images on this muscle (Hug et al., 2014).

The aims of this study were to compare the muscle elasticity of the vastus lateralis (VL) and rectus femoris (RF) heads of the quadriceps muscle in athletes involving frequent jumping with and without PT; as well as to explore the interplay between muscle elasticity and patellar tendon elasticity. We hypothesized that the increase in passive muscle tension in the VL and RF muscles would be different in athletes with PT when compared with healthy controls. In addition, greater passive muscle tension would be associated with higher patellar tendon tension.

Material and methods

Subject recruitment

Thirty-six male athletes with PT were recruited from local volleyball and basketball teams whom had fulfilled the criteria of (a) between 18 and 35 years of age; (b) pain in the inferior pole of patella or the proximal part of patellar tendon aggravation during single leg squatting and jumping (Lian et al., 1996); (c) pain duration >3 months; (d) maximum intensity of pain in the previous week >3 using a visual analog scale with 0 as no pain and 10 as the worst pain; (e) Victoria Institute Sports Assessment-patella (VISA-P) score <80 (Zwerver et al., 2011); (f) no history of corticosteroid injection and surgery to the lower limb; and (g) thickening of proximal part of patellar tendon with area of hypoechoic signals (Kulig et al., 2013). Thirty age-matched subjects from the same teams with no past history of knee trauma or surgery and not having anterior knee pain or inflammation were recruited as control. Ultrasound imaging also confirmed no thickening/hypoechoic/vascularization of the proximal part of the tendon. The subjects would be physically assessed by an experienced physical therapist having 13 years of clinical experience and then received ultrasonography examination from another physical therapist with 3 years of performing ultrasonography. For subjects with bilateral PT, measurements were taken on the more painful leg (BlaBolgla et al., 2015).

Ethics statement

This study was approved by the Human Subject Ethics Subcommittee of the Department of Rehabilitation Sciences, the Hong Kong Polytechnic University. The experimental procedures were conducted in accordance with the Declaration of Helsinki. The procedures of the study were fully explained to the participants and they provided their informed written consent before testing.

Demography data

Age, weight, height, years of participation, as well as the training hour per week were captured.

Measurement

Supersonic shear wave imaging (SSI) was conducted using an Aixplorer® ultrasound unit (Supersonic Imaging, Aix-en-Provence, France) in conjunction with a 50-mm linear-array transducer at 4–15 MHz frequency to measure the muscle and tendon shear elastic modulus with similar procedures being reported from our group (Kot et al., 2012). The musculo-skeletal acquisition mode was used with the temporal averaging (persistence) and spatial smoothing set to medium and six, respectively. The elastic images were taken at 1 Hz.

Measurement of the elastic shear modulus properties of the VL and RF muscles and patellar tendon

The quadriceps muscles of interest were the VL and the RF muscles were measured. We excluded measurement of muscle stiffness on the vastus medialis (VM) muscle because our pilot study on 20 subjects did not show any trend of group difference on the VM muscle stiffness.

Subjects were examined in supine lying with 30° of knee flexion. The knee was supported on a firm towel and a custom-made ankle stabilizer to keep the leg in neutral alignment on the coronal and transverse planes. The room temperature was controlled at 25°. The scanning site for VL was located at the lower 1/3 along a line drawn from the anterior superior iliac spine (ASIS) to the lateral side of patella; and that for RF was in the mid-point from ASIS to the superior border of patella. These sites were selected with reference to the recommended placements of the electrodes for electromyographic recording of these muscles (Hermens et al., 1999). The sites were located and marked with an eye-liner pencil. The muscles were first identified using the conventional grey scale of the ultrasound unit. Once the muscles were identified, the probe was aligned and parallel to the muscles fibers (Eby et al., 2013) and the shear wave elastography mode was activated to measure the muscle shear elastic modulus. The probe was stationed on the skin with light pressure for 8–12 s (Kot et al., 2012). The muscle status was monitored by an examiner during capturing the SSI map. If the muscle contraction was detected during testing, the SSI map was discarded and another measurement was performed. The images were saved when the color in the region of interest was uniform and stored for off-line analyses. Three images were captured for each muscle.

Off-line analysis was conducted. A circle delineating the Q-box was centered on the tested muscle (Fig. 1a). The diameter of the Q-box was defined by the thickness of the muscle, which was determined by the distance between the superficial and deep muscle fasciae (Nordez & Hug, 2010).

Measurement on the elastic shear modulus of the proximal patellar tendon

B-mode was used to locate and align the patellar tendon longitudinally with the transducer. When a clear image of the patellar tendon was captured, the shear wave elastography mode was then activated. The transducer was stationed on the skin with light pressure on top of a generous amount of coupling gel, perpendicularly on the surface of the skin. The transducer was kept stationary for 8–12 s during the acquisition of the SSI map (Kot et al., 2012). A total of three images were captured for the tendon on each knee for off-line analysis. The region of interest (ROI) was first defined by a rectangular box of 13.5 mm × 12.5 mm (biggest size provided from the manufacturer) distal to the apex of the patella and with the patellar tendon located within its center part. The diameter of the Q-box was defined by the thickness of the tendon (Fig. 1b). The Off-line analysis was conducted and the procedures have been described in our recent study (Zhang et al., 2014).

Data reduction

The mean values of the Young's modulus within the Q-Box™ were computed and displayed on the computer screen. The mean muscle shear elastic moduli were calculated by dividing the Young's modulus generated from the system by three (Royer et al., 2011). The ICCs of the shear elastic modulus of the VL and RF muscles was 0.89 and 0.80, respectively (unpublished data on 30 subjects).

Statistical analysis

SPSS version 17.0 (SPSS Inc, Chicago, Illinois, USA) was used to perform the statistical analyses. Normality of the variables was assessed using the Shapiro-Wilk test. The continuous variables were expressed as the means and standard deviations. Chi-square tests were used to examine the difference in sports between the PT group and the control group. Independent t-tests were performed to compare the demographic data between players with and without PT. Paired t-tests were used for side-to-side comparisons of the variables in the controls. If no significant side-to-side differences in the variables in the controls, multivariate analysis of covariance (MANCOVA) tests would be used to compare the shear elastic modulus of the quadriceps muscles (VL and RF) between the painful side in athletes with PT and the dominant side of the controls with variables with significant group difference as covariates. Post hoc analysis using univariate analysis of covariance tests was conducted when level of significance has reached. Pearson's correlations were used to examine the relationships between the shear elastic modulus of muscle heads (VL and RF), and patellar tendon tension in volleyball and basketball players. The P values <0.05 were considered to be statistically significant.

Results

Subjects characteristics

The age, height, weight, BMI, and training intensity of the subjects in both groups are shown in Table 1. There were no significant differences in age, height, weight, and distribution of sports type ($P > 0.05$). However, significant differences were found in BMI ($P = 0.032$) and training hours per week between the two groups ($P = 0.011$) (Table 1). BMI and training hours were used as covariates for further analysis.

Side-to-side comparisons in the control group

No significant side-to-side differences in the shear elastic modulus of the VL and RF muscles of control group ($P > 0.05$) (Table 2).

VL and RF muscle stiffness between athletes with and without PT

Subjects with PT had higher shear elastic modulus of their VL muscle (by 26.5%; $P < 0.001$) than the controls (Table 3).

Relationship between shear elastic modulus of patellar tendon and the VL and RF muscles

Table 4 illustrates that the shear elastic modulus of the patellar tendon was significantly correlated with the shear elastic modulus of the VL muscle ($r = 0.38$; $P = 0.035$) in the volleyball players and basketball players ($r = 0.41$; $P = 0.016$). Hence, greater shear elastic modulus of the VL was associated with higher shear elastic modulus of the patellar tendon.

Discussion

This study aimed to compare passive muscle tension of the RF and VL muscle heads of the quadriceps muscle between basketball and volleyball players with and without PT. Findings from this study supported our hypotheses that the increase in passive muscle stiffness is different between the muscle heads, i.e., the increase was only observed in VL but not RF muscle head.

More importantly, the stiffness of the proximal patellar tendon was related to VL muscle stiffness.

The passive muscle tension of the VL muscle of the volleyball and basketball players with PT was found to be stiffer than the control group. In this study, SSI technology was used to indirectly measure the passive tension, a part of intrinsic resistance of resting muscle to stretch (Ng et al., 1998; Masi & Hannon, 2008) of the VL and RF muscles. Increased muscle stiffness was detected in the VL muscle but not in the RF muscle in subjects with PT. One of the reasons could lie in the morphology of the muscle. RF is a bi-articular muscle, whereas VL is mon-articular muscle. The impact on these two muscles during jumping and landing might be different in the jumping athletes. In this connection, Green et al. (2012) indicated that exercise-induced muscle tension is different in the muscle heads in the calf. Based on magnetic resonance elastography, Green et al. (2012) observed that the changes in magnitude and course of muscle stiffness are different between gastrocnemis and soleus muscles. Taken together, effect of exercise on muscle stiffness is specific to muscle heads within a muscle group. Increase in muscle stiffness contributes to increase in passive joint stiffness (Chino & Takahashi, 2016) and is one of the predictive factors for PT (Witvrouw et al., 2001). Nevertheless, persistent pain associated with chronic PT might modulate resting muscle stiffness related to corticospinal and neuromuscular adaptations (Rio et al., 2016). Further study is required to explain intermuscular differences within a muscle group between PT and non-PT athletes; as well as the possible influence of neuromuscular adaptations on muscle tension in athletes during the pain-free stage.

Our study also demonstrated that there is a relationship between the tension of proximal patellar tendon and the VL muscle. Note that the VL muscle is attached to the base and superolateral border of the patella and is connected to the lateral side of patellar tendon via the lateral retinaculum (Becker et al., 2010). Given this anatomic relationship, the patellar tendon and VL muscle are closely related. Tension in this muscle would induce tension on the patellar tendon. In cadaveric study, the patellar tendon tension was affected by tension in the lateral retinaculum (Powers et al., 2006). Findings from this study proved the close relationship between VL and patellar tendon tension in human. In addition, these findings suggest that releasing the VL muscle tension is recommended for the treatment of PT in volleyball and basketball players.

Passive muscle stiffness reflects the ability to resist the forceis during stretch. The ability to resist external force is determined by the various elastic tissues such as sarcolemma, endomysium, perimysium, and epimysium (Rassier et al., 1999; Winters et al., 2011). A more compliant muscle unit is capable of storing more elastic energy for subsequent jumps and a stiffer muscle unit is capable of producing fast power output (Brughelli & Cronin, 2007). Kubo et al. (1999) observed that greater elasticity at the musculo-tendinous junction of the vastus lateralis was related to higher vertical jump height. The research group later reported significant relationship between the elasticity of the Achilles tendon and the height of countermovement and drop jumps (Kubo et al., 2007). Collectively, these findings provide evidence that aponeurosis and tendon elasticity are essential for jumping performance in healthy individuals. However, athletes with PT have been shown to be better jumpers than the healthy players (Lian et al., 2003). In this consideration, there are inconsistent findings in strength loss in athletes with PT (Rio et al., 2016). Further study is warranted in assessing possible relationship between stiffness of muscle-tendon unit and jumping performance in athletes with PT.

The orientation of the US probe is essential in minimizing possible anisotropy effect, in particular, on the pathological tendon with increased bound water. For VL, the optimal transducer location was determined when several muscle fascicles could be seen without disconnection through the image. Because of the complex arrangements of RF fascicles, the transducer was placed over the lateral component of this muscle and oriented in muscle shortening direction. When measuring the patellar tendon, the US probe was oriented parallel to the deep fibers.

Limitations

There are some limitations in this study. Firstly, myoelectrical activity was not recorded to ensure that the muscles remained passive. However, similar to what was done in previous studies (Lacourpaille et al., 2013; Koo & Hug, 2015), the participant was verbally instructed to stay relaxed before each knee flexion. Secondly, the architecture and size of quadriceps muscles were not measured in this study. We noted that the mechanical output of a muscle can be affected by muscle size and architecture such as pennation angle (Timmins et al., 2016). However, muscle shear elastic modulus is not affected by its anatomical cross-sectional area (Koo & Hug, 2015) or its pennation angle (Bouillard et al., 2011). Due to limitation of the SSI, we did not investigate the stiffness of the vastus intermedialis; and only parts of the VL/RF muscles and patellar tendon stiffness were assessed by the SSI. Our findings could not be generalized to other muscles (such as vastus intermedialis or medialis); as well as other regions of the VL/RF muscles and patellar tendon. Finally, although increase in passive muscle tension was detected in players with PT, a causal relationship could not be established. A prospective study is needed to ascertain the cause and effect relationship between passive muscle tension and tendon stiffness.

Conclusions

Athletes with PT have an increase in passive muscle tension in vastus lateralis but not the rectus femoris of the quadriceps muscle and the increase in passive muscle tension of the vastus lateralis is associated with proximal patellar tendon stiffness. These findings suggest muscle-specific approach is needed in prevention and rehabilitation of PT in volleyball and basketball players.

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Table 1 Demographic data between PT and control group

Variables	PT group (n = 336)	Control group (n = 330)	P
Age (year)	22.8 ± 4.2	23.5 ± 4.6	0.504
Weight (kg)	74.1 ± 6.6	72.5 ± 8.4	0.357
Height (cm)	180.1 ± 5.9	182.0 ± 5.9	0.203
BMI (kg/m^{2})	22.9 ± 1.9	21.8 ± 2.0	0.032
Sport-specific training (h/week)	6.3 ± 3.5	8.7 ± 4.0	0.011
Sports (volleyball/basketball)	17/19	15/15	0.509
Pain duration (year)	2.6 ± 1.7		
Unilateral/bilateral PT	18/18		

Values shown are means±standard deviations; PT: patellar tendinopathy; BMI: body mass index.

Table 2 Side-to-side comparisons of shear elastic modulus of muscles in the control subjects

Variables	Dominant side	Non-dominant side	*P*
Shear elastic modulus (kPa)			
VL muscle	3.6 ± 0.5	3.6 ± 0.5	0.808
RF muscle	3.9 ± 0.9	4.0 ± 0.8	0.650

Values shown are means±standard deviations; VL: vastus lateralis; RF: rectus femoris

Table 3 Comparisons of elastic modulus of thigh muscles on the painful side of athletes with PT and dominant side of the control subjects

Variables	PT group (n = 36)	Control group (n = 330)	P
Shear elastic modulus (kPa)			
VL muscle	4.9 ± 0.9	3.6 ± 0.5	0.000
RF muscle	3.9 ± 0.6	3.9 ± 0.9	0.831

Values shown are means±SDs. VL: vastus lateralis; RF: rectus fermoris

Table 4 Correlations between patellar tendon elastic modulus and shear elastic modulus of thigh muscles of the affected leg

Variables	r	P
Volleyball players		
VL shear elastic modulus	0.38	0.035
RF shear elastic modulus	−0.12	0.503
Basketball players		
VL shear elastic modulus	0.41	0.016
RF shear elastic modulus	0.07	0.698

VL: vastus lateralis; RF: rectus fermoris.

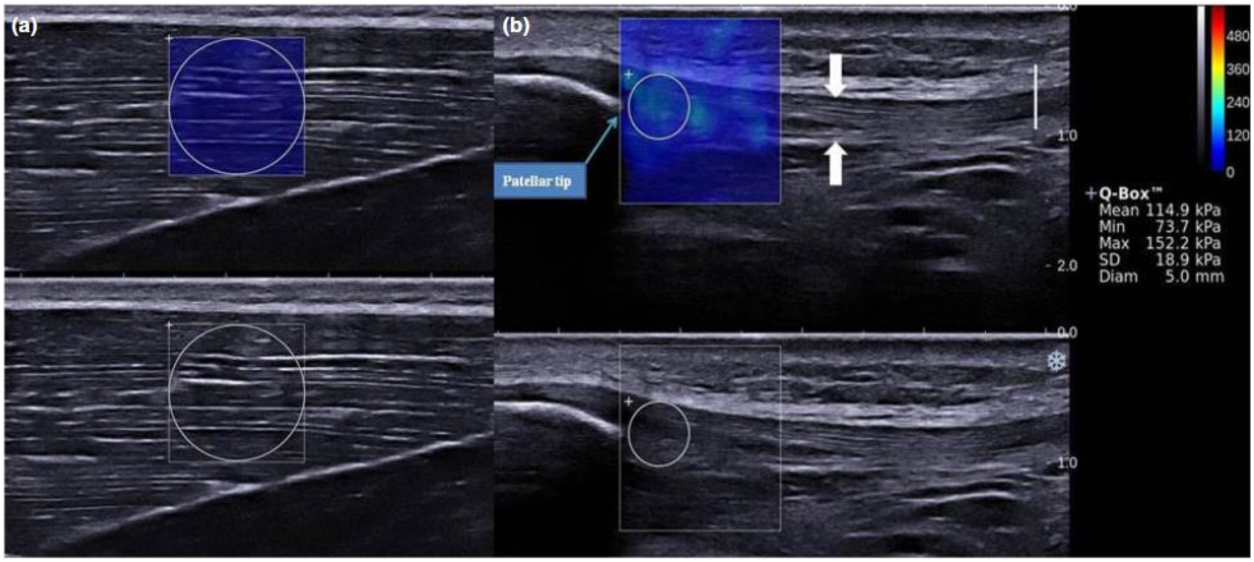

Figure 1 Upper images show color-coded box presentations of vastus lateralis muscle (a) and patellar tendon (b) on elastograph superimposed on a longitudinal grey-scale sonogram of patellar tendon and vastus lateralis muscles, with the circle representing the region of interest and its corresponding elastic modulus demonstrating under Q-Box™ on the right. Bottom images show longitudinal grey-scale sonograms of patellar tendon and vastus lateralis muscle on the identical scan planes.