Original papers

Med Ultrason 2023, Vol. 25, no. 2, 145-152
DOI: 10.11152/mu-4193

Factors influencing the Shear Wave Elastography evaluation of the patellar tendon

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Abstract

Aim: There is no clear standardization for tendon Shear Wave Elastography (SWE), and data regarding the factors that influence the correctness of evaluation are scarce. We aimed to determine the intra- and interobserver agreement in patellar tendon SWE, and to establish the influence of various factors on elasticity values. **Materials and methods**: We recruited 37 healthy volunteers; SWE of the patellar tendon was performed by two examiners. The following factors were analyzed: probe frequency, degree of joint flexion, size of region of interest (ROI), distance of the color box from the probe footprint, utilization of coupling gel as standoff, and the effect of physical exercise on elastic modulus values. **Results:** Highest overall interobserver [k=0.767, 95%CI (0.717-0.799), p<0.001] and intraobserver agreement [k=0.920 (0.909-0.929) for examiner 1, k=0.891 (0.875-0.905) for examiner 2] was obtained with the knee in the neutral position, using the L18-5 probe. With the knee flexed at 30º and 45º, the elasticity values were higher compared to the neutral position (p<0.001). With the probe immersed in 0.25 and 0.50 cm coupling gel, the median values were lower compared to the probe placed on the skin (p=0.001, p=0.018). The ROI dimensions and the placement of the SWE box at the level of the skin or at 0.5 cm below skin did not significantly influence the elastic modulus. After physical exercise, the elasticity values decreased in the proximal and middle portion of the tendon (p=0.002, p<0.001). **Conclusion:** The best results obtained in patellar tendon SWE were with the knee in neutral position, in the proximal or middle tendon, after 10 minutes of relaxation and with the probe placed directly on the skin with minimal pressure. The size and position of ROI do not significantly influence the examination.

Keywords: Shear Wave Elastography; patellar tendon; influencing factors

Introduction

Ultrasound (US) is the imaging technique of choice in tendon evaluation [1] with very good sensitivity and specificity in detecting pathological findings, comparable to magnetic resonance imaging (MRI) [2,3]. Tendons have the property of withstanding extreme tensile forces, and their stiffness can vary with age, sex and physical activity [4-6] but also with pathology [7].

Received 20.03.2023 Accepted 24.05.2023
Med Ultrason
2023, Vol. 25, No 2, 145-152
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Shear-Wave Elastography (SWE) is an imaging technique that relies on Acoustic Radiation Impulse Force (ARFI) through which the shear waves generated propagate through the target tissue and their velocity is quantified by calculating Young's elastic modulus, expressed in kPa or m/s [8,9]. The technique proved its validity in liver, thyroid, breast, prostate pathology but also in musculoskeletal (MSK) diseases [10-12]. SWE is not without limitations. It has been proven that limited operator experience can influence elasticity values [13-15]; however, many factors that alter these values are user independent. In liver applications, for example, pathologic conditions such as elevated liver enzymes or decompensated chronic heart failure may alter the elasticity values, while others, such as the presence of ascites, make impossible the evaluation [16-18]. Patient characteristics such as high body mass index (BMI), narrow intercostal window or inability to perform proper breath hold, have also been

associated with a higher rate of failure [19-21]. Lower reproducibility has been reported for measurements deeper than 2-3 cm with linear probes, 4-5 cm with convex probes, or in superficial structures when standoff pads may be necessary [12,22-25].

Concerning MSK elastography several factors have been described as potential pitfalls: excessive transducer pressure, angle of insonation and degree of muscle or tendon contraction [7]. It was demonstrated that shear-waves propagate faster along the long axis [7,25] and higher reproducibility has been reported in studies that utilized ankle fixators for the Achilles tendon to standardize the foot position [26,27].

Although advances have been made in tendon SWE, data is still conflicting regarding the reliability of the technique for tendon measurements, with results varying between poor to excellent reliability [28]. There is still no clear standardization of the method for tendon examination and data on the various factors influencing elasticity values are still scarce. For this reason, the purpose of this study was to evaluate the reliability of SWE in evaluating the patellar tendon and to determine factors influencing shear-modulus values during acquisition (the examiner experience, the probe frequency, degree of knee flexion, ROI diameter in two different regions of the tendon, the use of coupling gel as standoff, the position of the color box in relation with the probe footprint, and the influence of physical exercise prior to examination).

Materials and methods

Between May and July of 2022, 37 healthy volunteers, ages between 18 and 40 years old, were recruited. The exclusion criteria were history of pain, knee trauma or surgery, the presence of MSK systemic inflammatory disease and recent steroid medication. A brief clinical and B-mode US examination was performed for all subjects to exclude any potential local pathology. Written consent was obtained from each of the subjects and the study was approved by the Ethics Committee of the University (Nr.100/03.05.2022).

All US and SWE examinations were performed using a SuperSonic™ MACH™ 30 machine (SuperSonic Imagine, Aix-en-Provence, France) equipped with a linear L18-5 and L20-6 hockey-stick transducers. The SWE examination was performed consecutively by two examiners with 2, respectively 7 years of MSK US experience, using a blinded protocol.

US and SWE examination

For the patellar tendon examination, the patient was asked to lie supine with the knee completely extended for 10 minutes to ensure complete relaxation.

B-Mode evaluation was made in longitudinal and transverse scan; thickness was measured in the proximal, mid, and distal portion of the tendon, length was measured from the patellar insertion to the distal insertion on the tibial tuberosity and cross-sectional area (CSA) was obtained at the point of maximum thickness. The SWE examination was first performed using the L18-5 probe followed by L20-6 (hockey-stick) probe, selecting the MSK preset. The Q-Box depth was set to 1 cm and maximum length was selected. Three measurements were done (after homogenous color map was obtained) in all situations and the mean value was used for further analysis. For intraobserver analysis the mean value of the three measurements was used for comparison. Between each of the three acquisitions, the probe was lifted from the skin. The following worksheet was used:

1) examination with the knee in neutral position, L18-5 probe – using enough gel and no pressure being applied, SWE of the proximal (0.5 cm from the insertion on the bone), middle, and distal (0.5 cm from the insertion on the bone) portions of the tendon was measured. The Q-Box was placed first below the probe footprint and then at 0.5 cm below the probe footprint. For the position of Q-Box placed below the probe footprint, 4 different sizes of ROI's were used - 4, 3, 2 and 1 mm. The probe was then immersed in 0.5 and 0.25 cm height of gel, with Q-Box placed 0.5 cm below the skin interface, and measurements were performed;

2) examination with the knee in neutral position, L20-6 probe - the diameter of the ROI was set to 2 mm and acquisitions were made at 0.5 cm, 0.2 cm from enthesis, and at the level of the fibrocartilage in the proximal and distal portions of the tendon;

3) examination with the knee flexed at 30 and 45° (by placing a foam wedge beneath the patient's knee and measuring the angle with a goniometer) - Q-Box was placed below the probe footprint and ROI was set to 2 mm. Proximal, middle, and distal portions of the tendon shear-wave were measured using the L18-5 probe;

4) examination after physical exercise – the subject was asked to perform 15 repetitions of squatting. The measurements, in neutral position, Q-Box placed below the probe, ROI of 2 mm, were realized in the 3 parts of the tendon right after the exercise and 5 minutes later, using the L18-5 probe. After 15 minutes of relaxation the second examiner performed the same worksheet (fig 1, fig 2).

The same protocol was repeated by the 2 examiners in 3 consecutive days using the same conditions as previously mentioned.

Total time of examination in one subject (both knees) was approximately 35 minutes.

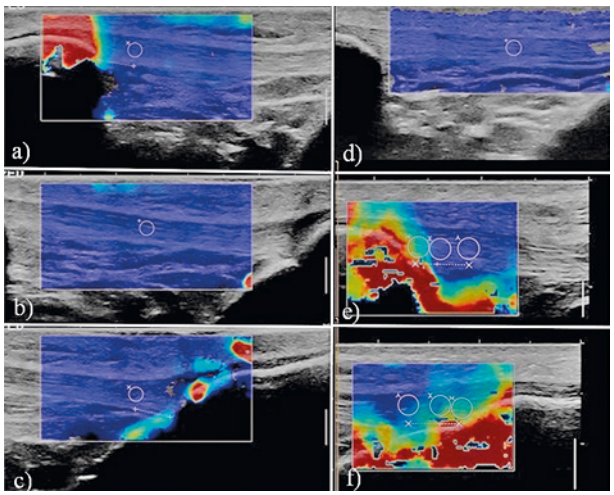

Fig 1. SWE examination of the patellar tendon with the L18-5 probe in the proximal (a), middle (b) and distal portion (c) with knee fully extended; (d) Examination of the patellar tendon with the SWE box placed just below the probe footprint. Examination with the L20-6 hockey stick probe and the proximal (e) and distal (f) portion of the tendon.

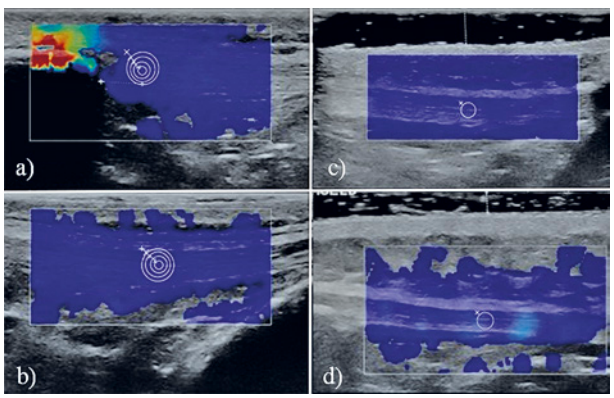

Fig 2. SWE examination of the patellar tendon with the L18-5 probe utilizing multiple overlapped ROI in the proximal (a) and middle (b) portions of the tendon. Examination of the patellar tendon with 0.50 cm (c) and 0.25 cm (d) layer of gel.

Statistical analysis

The Shapiro-Wilks test was used to assess the distribution of numerical variables. The categorical variables were presented as number and percent. The numerical variables were presented as median and interquartile range (IQR) since all the numerical variables were non-normally distributed. The differences between medians were assessed using Related Samples Wilcoxon Signed Rank Test. The inter-observer agreement was assessed by calculating the intraclass correlation coefficient (ICC) for average measures (the average of the three measurements performed in the same session by the same examiner, first session of measures was chosen for each examiner) using the Two-way mixed effects model and consistency. The intraobserver agreement was assessed by calculating ICC for average measures (three different measurements performed in three different days by each examiner) using the Two-way mixed effects model. The ICC below 0.5 was categorized as poor reliability, between 0.5 and 0.75 moderate reliability, between 0.75 and 0.9 good reliability, and above 0.9 excellent reliability [29]. A p value below 0.05 was considered significant. The statistical analysis was performed using IBM SPSS Statistics v23.

Results

In the study group 26 subjects were females (70.3%), the median age was 26 years (25.0-30.0), median BMI 22.8 kg/m^2 (20.3-24.6) and median physical activity of 2.0 (0-4.0) hours per week. B-mode US measurements of the patellar tendon are presented in table I.

Interobserver agreement

Overall interobserver agreement for the patellar tendon examination was good: ICC=0.767, 95%CI (0.717-0.799) (p<0.001) using the L18-5 probe and ICC=0.803, 95%CI (0.75-0.840) (p<0.001) using the L20-6 probe. Interobserver agreements for the patellar tendon variating with knee angle and ultrasound probe are presented in supplementary table I.

Intraobserver agreement

The overall intraobserver agreement using the L18-5 and L20-6 probes are presented in table II. Intraobserver agreements for the patellar tendon variating with knee angle and ultrasound probe are presented in supplementary table II.

Factors influencing tendon elasticity

Using L18-5 transducer, neutral position

Median elasticity values for the patellar tendon were 56.87 kPa (34.87-78.13), 53.13 kPa (38.20-84.03) and

Table I. B-mode ultrasound characteristics of the patellar tendon (N=74).

Parameter	Median (IQR)
Proximal thickness (mm)	32.5 (29.0-37.0)
Middle thickness (mm)	32.0 (28.0-35.0)
Distal thickness (mm)	33.0 (31.0-38.0)
Length (mm)	480.5 (453.0-510.0)
Area (mm^2)	79.5 (72.0-87.0)

N = Number of examined tendons; IQR = Interquartile range.

Table II. Overall intraobserver agreement for both examiners.

Examiner	L18-5	L20-6
Examiner 1	0.920 (0.909-0.929)	0.610 (0.562-0.656)
Examiner 2	0.891 (0.875-0.905)	0.679 (0.632-0.723)

63.27 kPa (40.30-96.17) at the proximal, middle and distal portions of the tendon. The difference between these medians was statistically significant (p=0.03) and the post-hoc analysis showed that the median elasticity value in distal portion was significantly higher comparing to the value obtained in the proximal (p=0.031) and the middle portion (p=0.029).

Elasticity values with ROI sizes of 4, 3, 2, respectively 1 cm near the proximal enthesis were 44.95 (34.90-71.60), 45.95 (34.50-71.90), 47.10 (35.00-73.90) and 47.40 (35.00-73.90) kPa, respectively, with no statistical significant difference (p=0.114). In the middle tendon the values were 50.55 (40.20-76.10), 52.25 (40.60-77.50), 51.40 (40.70-75.10), 52.20 (40.30-73.00) kPa, also with no statistical significant difference (p=0.705).

With the probe immersed in 0.25 and 0.50 cm thickness of gel, the medians of the elasticity values were 51.60 (37.40-60.10) kPa and 49.95 (37.50-59.80) kPa, respectively, p=0.916. Significant differences were obtained when these results were compared with those obtained with the probe in skin contact (p=0.001 and p=0.018, respectively)

No significant difference was observed (p=0.755) when comparing the values obtained during examination with the SWE box placed just below the probe footprint [51.70 kPa (40.40-72.60)] and the reference value (the value obtained in the middle portion of the tendon with the knee in complete extension and the Q-Box 0.5 below the probe footprint).

Patellar tendon elasticity after physical effort at the proximal, middle, and distal portions were 41.47 (31.83-69.47), 42.58 (37.43-62.23) kPa and 59.78 (44.90-84.50) kPa, respectively. The differences between the medians obtained after effort in the proximal and middle portion of the tendon were statistically different from the medians obtained in the relaxed condition of the tendon (p=0.002 and p<0.001, respectively), unlike the median in the distal portion of the tendon (p=0.114).

Table III. Median values of patellar tendon elasticity with 30˚ and 45˚ flexion using the L18-5 transducer.

Parameter	Median (IQR)	p-value*
30˚proximal	170.95 (140.17-207.50)	<0.001
30˚middle	166.32 (135.97-206.20)	<0.001
30˚distal	162.33 (126.63-219.77)	<0.001
40˚proximal	163.25 (122.47-204.87)	<0.001
40˚middle	144.10 (99.17-197.17)	<0.001
40˚distal	147.87 (107.50-197.53)	<0.001

*p value obtained by comparing the medians with the corresponding median calculated for the neutral position in the same portion of the patellar tendon, respectively, with the same probe.

Using L18-5 transducer,
the knee flexed at 30˚and 45˚

Median elasticity values for the patellar tendon with the knee flexed at 30˚and 45˚are presented in table III.

Using L20-6 transducer,
the knee in neutral position

Elasticity values with the L20-6 transducer in the neutral position were 104.75 kPa (68.70-135.20), 201.33 kPa (141.27-256.20) and 346.83 kPa (304.7-406.97) at 0.5, 0.2 and the level of the fibrocartilage in the proximal portion (p<0.001), and 194.98 kPa (127.40-250.43), 272.30 kPa (234.67-328.60) and 397.58 kPa (328.50-459.30) at 0.5, 0.2 and at the level of the fibrocartilage in the distal portion (p<0.001). There was a statistically significant difference between medians obtained with the same probe at the different levels and also when compared to the median obtained in the same position utilizing the L18-5 probe (p<0.001).

The median of elasticity values were slightly higher for the left tendon comparing the right tendon in all the three portions, but the differences were not statistically significant (proximal: p=0.816; middle: p=0.717; distal: p=0.545). The intraobserver agreement between the right and left tendon measurement in the neutral position were moderate for both examiners [examiner 1: ICC=0.747, 95%CI (0.632-0.827 p<0.001; examiner 2: ICC=0.738; 95%CI (0.603-0.827), p<0.001].

Discussions

In our study the highest interobserver reliability was obtained with the knee in the neutral position, at the proximal and middle levels of the tendon, using the L18-5 probe, while the lowest reliability was obtained with the L20-6 probe when measurements were made at the fibrocartilage level. Intraobserver agreement was good or excellent for both examiners in all three positions of the knee with the L18-5 probe, and markedly lower with the L20-6. The size of the ROI and position of the SWE color box did not significantly influence the examination, while immersion of the probe in gel and examination less than 10 min after physical effort, slightly influenced SWE values.

Zhang et al [30] reported excellent inter-rater reliability in patellar tendon evaluation (ICC=0.97). The value, much higher compared to our result, was obtained at the proximal insertion of the tendon with the knee in 30˚flexion. On the contrary, in our study ICC at 30˚flexion was poor (0.446) and in this position the SWE acquisition and obtaining a homogenous color map were problematic. Tas et al [31] reported good ICC interobserver values (0.71) in healthy patellar tendons with the knee flexed

at 30°. Data regarding the best position for evaluation of the patellar tendon with SWE is scarce. In the case of B-mode US, optimal examination position is with the knee flexed at 30°, as this negates anisotropy related to the concave shape of the tendon in neutral position. In the study of Hardy et al [32] SWE acquisitions were made with the knee in neutral position; however, ICC was not reported but the elasticity values were lowest with the knee in extension, compared to 30° and 90° flexion. Due to their unique compositions, tendons have the characteristic of being viscoelastic and for this reason their mechanical properties will depend on the rate of mechanical strain. At low strain rates tendons are more deformable, while during high strain rates collagen fibrils align themselves in the direction of tensile load, loss of the microscopic "crimp" pattern occurs, and the tendon becomes stiffer and less deformable in order to allow better transmission of high mechanical loads [33]. This would explain the progressive increase in elasticity with a higher degree of knee flexion, but also raises the question of the effects of mechanical strain in pathologic tendons where normal collagen fiber organization is lost and alteration of elastic modulus occurs [34].

Elasticity values obtained in our study were not consistent with those reported in other studies [30,32,35-38] and the differences in knee flexion, ultrasound equipment, and regions of the tendon in which acquisitions were made, may be the main reasons of this situation. In our study elasticity values with the knee in complete extension were used as reference as this was the knee position at which the highest reproducibility was obtained. It was demonstrated [39] that during tensile loading there is an increase in tendon stiffness. Similar to Berko et al [40], which demonstrated an increase in stiffness with passive knee flexion, we found a significant increase in stiffness when measurements were made with knee in flexion.

Variations of elasticity values with different sized ROI were small and had no statistical significance. Studies on tendon SWE have used ROI's of various sizes with variations from one small circular ROI with fixed diameter of 1 mm to a circular ROI covering the entire width of the tendon from the anterior to the posterior border [36,37,41]. This is an important finding as there is high variability of ROI dimensions between machines as some manufacturers allow preset size, while with others size is set manually by the operator. In MSK applications of SWE, influence of ROI size on elasticity values have been studied in the case of muscles [42,43]; however, for tendons data is limited.

Placement of the probe in coupling gel resulted in slightly lower and statistically significant values when compared to values obtained with the probe placed directly on the skin. This difference is possibly the result of an increase in depth to target tissue, a possible cause for decrease in elasticity due to attenuation suffered by the push pulse [44,45,46]. Using linear probes this attenuation occurs at depths >4 cm, which is not the case for the patellar tendon, except for obese subjects. Another explanation [44], could be the presence of microbubbles in the layer of gel that could further contribute to push pulse attenuation. In a study [45] that evaluated the effect of different amounts of coupling gel on shear wave velocity, it was found that interoperator reliability significantly decreased in acquisitions made in more than 20 mm of gel, possibly due to pressure applied by the coupling itself. It was our experience that using a larger layer of coupling gel, an adequate gray scale image is harder to be maintained, especially when consecutive subjects were examined, and operator fatigue could affect the overall quality of the examination.

No significant differences were obtained in elasticity when the SWE box was placed at the top of the screen as compared to the values obtained 0.5 cm below. In a phantom study [47] variability of shear wave speed when measurements were made with a larger box size was obtained; however, the position was not analyzed in this study. Position of the SWE box does not seem to influence elasticity values so long as both anterior and posterior borders of the tendon are placed within it.

Elasticity values obtained with the L20-6 hockey-stick probe were significantly higher compared to the L18-5 transducer. To our knowledge this is the first study to directly compare a hockey-stick probe to a linear high frequency probe in an in vivo setting. Various studies have addressed variability between probes [48,49] in phantom or liver applications. Obuchowicz et al [50] compared three different linear probes and obtained significant differences between the lower end frequency probe and the higher end frequency probe, the latter resulting in an increase in stiffness values. This may possibly be a result of higher attenuation suffered by a higher frequency push pulse emitted by the hockey stick probe, which may be unsuitable for measurements at depths that would be considered appropriate for a conventional linear transducer. The authors also demonstrated that using a high frequency probe resulted in less coverage of the tendon which leads to a loss of quality of the elasticity map. We found poor interobserver agreement with the hockey stick probe when measurements were made at the level of the fibrocartilage and 0.2 cm from the insertion, probably due to the bone proximity, a factor known as leading to an increase in elasticity values [51]. Nevertheless, there is a need for further

studies of the applications of SWE with hockey stick probes.

After physical exercise statistically significant lower elasticity values were obtained. This finding is contradictory to most of the knowledge regarding tendon response to physical exercise and load. It has been hypothesized that exposure to mechanical loads can lead to stimulation of tendon cells that in turn induce production of collagen, the main component responsible for increase in stiffness and load bearing capacity of the tendon [52]. A meta-analysis [53] on the adaptation of tendons to chronic exercise has shown that tendons adapt to load by increasing in stiffness. However this adaptive mechanism seems to be triggered only when exposure to exercise is of at least 12 weeks. Another systematic review [54] that focused on the immediate effects of exercise on tendons has evidenced that the immediate response of tendons to exercise is a short-term decrease in stiffness. This data is consistent with our findings and highlights the importance of tendon relaxation prior to SWE measurements.

A statistically insignificant difference between the left and right patellar tendon was found, values for the former being slightly higher. Various studies [55,56] have investigated the difference in mechanical properties of tendons in the dominant versus non-dominant sides; however, data is conflicting, most likely due to differences in populational sampling of these studies. Römer et al [57] reported a statistically significant lower stiffness on the right limb compared to the left in adolescent athletes. We believe that these differences obtained in our study could be the result of technical acquisition, the left limb being further away from the examiner, and therefore resulting in a more strenuous examining positioning, especially when taking into consideration fatigue, because both examiners began the session with the right limb and concluded with the left.

The limitations of this study include the heterogeneity of the study population regarding physical activity, as we included both sedentary and physically active subjects and the low number of subjects examined. While there was not a very strict standardization of the physical activity in our protocol, it was demonstrated that even a brief mechanical load of tendons can alter elasticity values. Acquisitions were made with the hockey stick probe; however, the protocol we included was not extensive and clearly further studies on such high frequency transducers are necessary.

Conclusion

Our results suggest that the best results in SWE examination of the patellar tendon are obtained with the knee in neutral position after a period of 10 minutes of relaxation, in the proximal and middle portions of the tendon with the probe placed directly on the skin with minimal pressure. The size of ROI and position of the SWE box did not significantly influence the examination; however, knee flexion angle and the type of transducer used resulted in altered elasticity values. While SWE is a reliable method of determining tendon elasticity, care should be taken as many factors can be a source of alteration to these values.

Conflict of interest: none

Acknowledgement: We would like to thank to Mr. George Dobre from Pondera Medical who supported our study with the US machine and gave technological advice.

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