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Reliability of Continuous Shear Wave Elastography in the Pathological Patellar Tendon

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Abstract:

Objectives: Patellar tendon injuries occur via various mechanisms such as overuse, or due to surgical graft harvest for anterior cruciate ligament reconstruction (ACLR). Quantified patellar tendon stiffness after injury may help guide clinical care. Continuous shear wave elastography (cSWE) allows for the assessment of viscosity and shear modulus in tendons. The reliability of the measure, however, has not been established in the patellar tendon. The purpose of this study was to investigate the inter-rater reliability, intra-rater reliability, and between day stability of cSWE in both healthy and pathological patellar tendons.

Methods: Participants with patellar tendinopathy (n = 13), history of ACLR using bone-patellar tendon-bone autograft (n = 9), and with no history of patellar tendon injury (n = 13) were recruited. cSWE was performed 4 times by multiple raters over 2 days. Intra-class correlations (ICC) and minimum detectable change ($MDC_{95\%}$) were calculated.

Results: Good to excellent between day stability were found for viscosity (ICC = 0.905, $MDC_{95\%}$ = 8.3Pa*s) and shear modulus (ICC = 0.805, $MDC_{95\%}$ = 27.4kPa). The inter-rater reliability measures, however, were not as reliable (ICC = 0.591 and 0.532).

Conclusions: cSWE is a reliable assessment tool for quantifying patellar tendon viscoelastic properties over time. It is recommended, however, that a single rater performs the measure as the inter-rater reliability was less than ideal.

Keywords: viscoelastic properties, patellar tendon, continuous shear wave elastography, anterior cruciate ligament, tendinopathy, bone-patellar tendon-bone graft

Introduction:

Patellar tendon injuries are common amongst athletes of all levels (recreational to professional) and age groups, and may become a significant burden for those who suffer such injuries [1,2]. One of the themes observed across pathological tendons, regardless of the source of injury, are morphological alterations (e.g., tendon thickening, larger cross-sectional areas, or hypoechoic regions identified on sonographic evaluations) to the tendon [3]. Tendon structure is associated with function and outcomes after injury, and may be readily assessed in a clinical setting [4–8]. Evaluating the structural changes in the injured patellar tendon may assist in identifying the underlying pathophysiology as well as guide clinical care after injury.

Patellar tendinopathy is an overuse injury of the patellar tendon typically associated with activities involving plyometrics [9,10]. Prevalence of patellar tendinopathy has been reported as high as 45% in higher level jumping athletes [2]. Tendon injury may also be of iatrogenic nature after procedures such as graft harvest of the bone-patellar tendon-bone (BPTB) autograft during anterior cruciate ligament reconstruction (ACLR) [11]. The BPTB autograft, harvested from the central third of the patellar tendon, is frequently used due to the low re-rupture rates reported in active young adults compared to alternative graft types [12,13]. The use of a BPTB autograft, however, comes with secondary impairments specific to the graft harvest site. Prolonged quadriceps weakness [14,15], a metric associated with successful outcomes after ACL surgery has been identified [16], likely because of the additional trauma to the extensor mechanism. Anterior knee pain also persists after using BPTB autografts [17,18] and rates of post-traumatic knee osteoarthritis may also be elevated [19,20]. In both populations described above, understanding the injured tendon's structure may assist in improving our knowledge on the underlying pathophysiology and assist in guiding post-injury or post-operative care to optimize outcomes.

Morphological (e.g., thickness and cross-sectional area) changes to injured tendons assessed using B-mode ultrasound and magnetic resonance imaging have been observed with time after surgery and rehabilitation in patients after tendon pathology[5,21–24]. It is also known, however, that improvements in symptoms and function can happen without morphological changes [25]. The variability and mismatch in morphological and symptom presentation along the course of rehabilitation, may in part be due to changes in the underlying viscoelastic properties (i.e., stiffness) of the tendon which may not be captured with traditional imaging modalities [7,26–29]. Assessing viscoelastic properties of the patellar tendon may provide additional knowledge beyond measuring morphology alone when identifying pathological tendons and tracking changes over time.

Methods using shear wave elastography to quantify stiffness in the musculoskeletal system have become increasing popular in recent years due to the low risk and non-invasive approach to quantify and track tissue mechanical properties [29–32]. Continuous shear wave elastography (cSWE) is an ultrasound-based method to evaluate tendon viscoelastic properties as biomarkers for injury and recovery [33]. cSWE involves measuring wave speeds of shear waves transduced through a tendon using an external actuator [34–36] to calculate two coefficients of interest in viscoelastic materials, shear modulus (kPa) and viscosity (Pa-s). The method has been validated in the Achilles tendon and demonstrated fair to excellent intra-rater reliability [37]. The reliability of cSWE in the patellar tendon, tendons with pathology (tendinopathy or graft harvest), or the inter-rater reliability of cSWE, however, has not been established. The purpose of this study was to investigate the inter-rater reliability, intra-rater reliability, and between day stability of cSWE in both healthy and pathological patellar tendons.

Materials and Methods:

Participants:

An a priori power analysis was completed using methods based on a lower acceptable limit [38]. Fourteen participants were required with two raters, a desired reliability of ICC = 0.9, lower acceptable limit of ICC = 0.6, β = 0.8, and α = 0.05. Thirteen participants with patellar tendinopathy (PT), 9 participants with a history of bone-patellar tendon-bone graft harvest for ACLR (BPTB), and 13 participants with no current or history of patellar tendon injury (Healthy) were recruited for this study (**Table 1**). Participants in the tendinopathy group all had symptomatic patellar tendinopathy confirmed by a licensed physical therapist (A.S.) at the time of data collection, and the participants in the BPTB group were included in the study regardless of patellar tendon symptoms at the time of testing. This study was approved by the institutional review board at the University of Delaware and participants provided written informed consent.

Study Design:

cSWE was performed by 4 different raters (**Table 2**) of varying levels of experience performing cSWE. Rater A, the most experienced rater, and rater B, the rater with the least amount of experience who received 2 hours of training for familiarization of the methods performed all data collections for the patellar tendinopathy group. Rater C and D performed all data collections for the healthy and BPTB group. Rater A and C were assigned as the primary rater to compare for intra-rater reliability and between day stability, while measurements from rater B and D were assigned as secondary raters used to calculate inter-rater reliability.

cSWE was performed in two sessions approximately 24 hours apart (**Figure 1)**. Participants were encouraged to avoid any strenuous exercise 24 hours prior to each test session. On day 1, the primary raters (A and C) performed 1 round of cSWE. On day 2, the primary raters performed 2 rounds of cSWE followed by the secondary raters (B and D) performing 1 round of cSWE. Between trials on day 2, participants were asked to stand up and walk a single loop around the room to reset positioning for the test, and all markings indicated on the participants' knees were removed using alcohol wipes (**Figure II**). The patellar tendon of interest (right vs. left) was determined using the surgical knee for the BPTB group, the symptomatic side (or the most symptomatic side if the participant experienced bilateral symptoms) for the tendinopathy group, and a random number generator was used to choose the side of interest in the healthy control group.

Continuous Shear Wave Elastography (cSWE):

Participants were positioned in an upright chair with both hips and knees position at 90 degrees of flexion. Both feet were strapped in a custom setup made of controlled ankle motion boots for stabilization and to limit muscle contractions and movement artifact (**Figure II**). The region of interest over the patellar tendon was marked using a marker after inspecting the patellar tendon using ultrasound imaging (**Figure II**). For the BPTB group, the region of interest was over the central third where the graft was harvested. For the tendinopathy group, the measurement was taken 1 cm distal to the inferior pole of the patella. For the healthy control group, the patellar tendon was trisected vertically, and the central third of the patellar tendon was measured. An ultrasound scanner (Ultrasonix, Vancouver, BC, Canada) with a L14-5/38 probe was used to capture raw radiofrequency data over the region of interest (6438 frames per second), while an external actuator (Minshaker Type 4810, Bruel and Kjaer, Norcross, GA, USA) was placed over the quadriceps tendon just superior to the patella to produce shear waves. The ultrasound probe was placed parallel with the longitudinal axis of the region of interest and stabilized using a 3-prong clamp (**Figure II**).

Shear waves at 11 fixed frequencies (322, 339, 358, 379, 402, 429, 460, 495, 536, 585, and 643Hz) were produced at the quadriceps tendon while the raw radiofrequency data were collected simultaneously (**Figure III**). All 11 frequencies were produced and captured independently while the knee and ultrasound probe were secured in the same position. Ultrasound data were collected for 10 ms for each of the frequencies. Three successful trials were collected during each test while the ultrasound probe was removed and repositioned between each trial to confirm proper contact and placement over the region of interest. A custom MATLAB script was used to calculate static shear modulus and viscosity using data from all 11 frequencies using the Voigt model for viscoelasticity which has been detailed in previous work[33]. The average shear modulus and viscosity of the three trials collected were calculated and reported.

Statistics:

Three separate reliability measures for both shear modulus and viscosity were calculated using intra-class correlations (ICC). *Between-day intra-rater stability (Trial 1 vs. Trial 2)* and *within-day intra-rater reliability (Trial 2 vs. Trial 3)* were calculated using a mean-rating, absolute agreement, two-way mixed effects model. *Within-day inter-rater reliability (Trial 2 vs. Trial 4)* was calculated using a mean-rating, absolute agreement, one-way random effects model [39].ICCs were calculated for the complete sample combining data from both healthy and pathological patellar tendons (n=35), and separately using the data from only the pathological patellar tendons (n=22) for comparison. The standard error of the measurement (SEM) and individual minimum detectable change ($MDC_{95\%}$) at the 95% confidence interval were calculated using ICC values obtained from the two cohorts. Group $MDC_{95\%}$ were also calculated within our sample (Group $MDC_{95\%}$ = Individual $MDC_{95\%} / \sqrt{n}$) for comparisons between the 3 groups in our study.

As a secondary purpose, one-way analysis of variance (α=0.05) was used to compare shear modulus and viscosity among the three groups (PT, BPTB, Healthy). The assumptions for normality and homogeneity were met. Pair-wise comparisons were performed for significant main effects of group. All statistics were performed using R [40].

Results:

For the complete sample, excellent between day stability was observed for viscosity (ICC = 0.905), and good between day stability was observed for shear modulus (ICC = 0.805). Good within-day intra-rater reliability was observed for both viscosity and shear modulus (ICC = 0.839 and 0.751). Moderate inter-rater reliability was observed for both viscosity and shear modulus (ICC = 0.591 and 0.532). The individual $MDC_{95\%}$ of the measures were identified to be 8.3Pa*s for viscosity, and 27.4kPa for shear modulus (**Table 3**). ICC outcomes using only the pathological patellar tendons (**Table 4**) identified similar reliability measures compared to the complete sample including healthy patellar tendons.

Main effects of group were observed for both shear modulus (F(2, 32) = 4.43, p = 0.020, η_p^2 = 0.217) and viscosity (F(2, 32) = 4.33, p = 0.022, η_p^2 = 0.213) (**Table 5**). Pairwise comparisons identified for viscosity, that the PT group presented with higher viscosity compared to both the BPTB (p = 0.013) and Healthy (p = 0.025) groups. No differences were found between the BPTB and Healthy groups (p = 0.612). For shear modulus, the PT group presented with higher shear modulus compared to the BPTB group (p = 0.007) and the difference between the Healthy group trended towards significance (p = 0.052). No differences were found between the BPTB and Healthy groups (p = 0.308).

Discussion:

The purpose of this study was to investigate the inter-rater reliability, intra-rater reliability, and between day stability of cSWE in both healthy and pathological patellar tendons. Our study findings indicate good to excellent reliability for both viscosity and shear modulus measures obtained via cSWE when repeat measures were collected by a single rater. The inter-rater reliability of the measure, however, only demonstrated moderate reliability, emphasizing the importance of a single rater performing cSWE when used in any study design.

The good to excellent reliability found in this study is comparable to what has been reported in the Achilles tendon [37]. Additionally, this study supports the reliability of using cSWE not only in healthy tendons but also in pathological tendons as comparable ICCs were observed (**Table 3 and 4)**. The comparison between groups identified that the PT group may present with higher shear modulus and viscosity compared to the 2 other groups in this study, possibly indicating the underlying source of pathology and symptoms (**Table 5**). No differences were found between the BPTB and Healthy groups, and this finding is likely due to the sampling strategy for the BPTB group which was not optimized for detecting group differences (**Table 1).** Symptoms were not a part of inclusion criteria for the BPTB group as the primary objective of the study was to establish reliability, and participants from a large range of time from surgery were included to strengthen external validity for the reliability measure in this population. A more homogeneous sample in the BPTB group such as those with symptomatic patellar tendons or those acutely after ACLR is necessary to establish clinical meaning of the mechanical properties measured using cSWE. While a larger sample size is needed to further establish group differences in tendon viscoelastic properties, our data from a limited sample provides promising insight for future use of cSWE. cSWE can be used as a reliable tool in future studies investigating long term changes in the patellar tendon over the course of treatment for patellar tendinopathy or recovery after BPTB autograft harvest for ACLR.

The relatively low inter-rater reliability compared to intra-rater reliability was an unexpected finding. While no definitive conclusions can be drawn from our data, we have identified potential sources of error that may explain this finding. The initial scanning of the patellar tendon to identify region of interest is the first likely reason. The ultrasound probe is only able to image a 1mm width region (credit card thickness), and it is likely the region selected varied between raters. The variability in alignment of the probe with the tendon fibers may also affect values recorded for shear wave speed due to tendon anisotropy. We do, however, report the average of 3 repositioned trials to limit this error, and the slight variation within the region captured is intended to capture a more representative image of each region. To improve inter-rater reliability of cSWE, an average of more than 3 trials may be necessary. Other sources of error may be from the amount of pressure applied at the ultrasound probe on the patellar tendon or the external actuator at the quadriceps tendon. Especially at the quadriceps tendon, since the rater manually held the actuator, there may have been variability in the pressure or steadiness of the hand holding the actuator resulting in slightly different shear waves transferred through the tendon. Future studies may investigate the influence of taking the average of more trials or controlling for ultrasound probe and actuator pressure and steadiness, to see if inter-rater reliability can be improved. Lastly, exercise between the 2 days of study visits were not tightly controlled due to ethical reasons, since participation in rehabilitation was a priority for the participants who were currently undergoing treatment. The participants’ activity level between study days may have influenced reliability in tendon mechanical properties.

Continuous shear wave elastography is a reliable assessment tool of the viscoelastic properties in the patellar tendon with pathology. It is recommended, however, that a single rater performs all tests, as the inter-rater reliability of the measure was found to be less reliable in this study.

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Conflict of interest:

The authors of this manuscript have no conflicts of interest to disclose.

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Table 1:

Participant demographics by group. PT = Patellar tendinopathy, BPTB = Bone-Patellar Tendon-Bone graft, Healthy = Healthy control, All = all participants combined.

Group	Sex (women:men)	Age (years)	Height (meters)	Weight (kilograms)	Symptom Duration (months [range])	Time from Surgery (months [range])
PT	4:9	31.2±9.4	1.79±0.10	80.8±17.0	33.8 [1.0 - 93.1]	-
BPTB	5:4	22.9±5.6	1.73±0.13	72.7±19.9	-	28.2 [1.6 - 91.7]
Healthy	6:7	26.2±2.4	1.76±0.09	76.0±8.4	-	-
All	15:20	27.2±7.2	1.76±0.11	76.9±15.2	-	-

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Table 2:

Clinical and ultrasound experience of each rater.

Raters	Clinical Credentials	Years since licensure	Experience with ultrasound imaging	Experience with cSWE
A	Physical Therapist	4 years	4 years	4 years
B	None	-	No experience	2 hours
C	Physical Therapist	1 year	2 years	1 year
D	Physical Therapist	12 years	2 years	1 year

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Table 3:

Reliability and minimum detectable change of the complete sample (n=35). ICC = intra-class correlation, 95%CI = 95% confidence interval, SD = standard deviation, SEM = standard error of measure, $MDC_{95\%}$ = minimum detectable change, kPa = kilopascals, Pa*s = Pascal-seconds. Highlighted in yellow = ICC and MDC relevant for assessing tendon changes over time.

	ICC	**95%CI**		**Pooled Mean**	**Pooled SD**	**SEM**	**$MDC_{95\%}$**
Shear Modulus (kPa)	**Average Measures**	**Lower**	**Upper**				**Individual**
Stability	0.805	0.657	0.890	68.2	22.4	9.9	27.4
Intra-rater	0.751	0.562	0.859	65.8	22.8	11.4	31.6
Inter-rater	0.532	0.176	0.735	67.0	21.1	14.4	40.0
Viscosity (Pa*s)							
Stability	0.905	0.833	0.946	25.3	9.7	3.0	8.3
Intra-rater	0.839	0.705	0.910	24.1	9.7	3.9	10.8
Inter-rater	0.591	0.279	0.769	25.5	9.1	5.8	16.1

Footnote:

Excellent reliability: ICC > 0.9, Good reliability: 0.75 < ICC < 0.9, Moderate reliability: 0.5 < ICC < 0.75, Poor reliability: ICC < 0.5 [39]

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Table 4:

Reliability and minimum detectable change of the pathological tendons only (i.e., PT and BPTB groups) (n=22). ICC = intra-class correlation, 95%CI = 95% confidence interval, SD = standard deviation, SEM = standard error of measure, $MDC_{95\%}$ = minimum detectable change, kPa = kilopascals, Pa*s = Pascal-seconds. Highlighted in yellow = ICC and MDC relevant for assessing tendon changes over time.

	ICC	95%CI		Pooled Mean	Pooled SD	SEM	$MDC_{95\%}$
Shear Modulus (kPa)	**Average Measures**	**Lower**	**Upper**				**Individual**
Stability	0.817	0.624	0.912	68.6	22.8	9.8	27.1
Intra-rater	0.813	0.616	0.909	68.4	22.9	9.9	27.4
Inter-rater	0.424	-0.185	0.722	65.8	20.0	15.2	42.0
Viscosity (Pa*s)							
Stability	0.933	0.863	0.968	27.3	10.4	2.7	7.4
Intra-rater	0.880	0.753	0.942	26.0	10.4	3.6	10.0
Inter-rater	0.644	0.266	0.828	26.3	9.8	5.9	16.3

Footnote:

Excellent reliability: ICC > 0.9, Good reliability: 0.75 < ICC < 0.9, Moderate reliability: 0.5 < ICC < 0.75, Poor reliability: ICC < 0.5 [39]

Table 5:

Shear modulus and Viscosity by group. PT = Patellar tendinopathy, BPTB = Bone-Patellar Tendon-Bone graft, Healthy = Healthy control, kPa = kilopascals, Pa*s = Pascal-seconds.

Group	Shear modulus (kPa)	Viscosity (Pa*s)
PT	80.3±16.4	31.3±10.5
BPTB	57.1±16.3	20.1±7.9
Healthy	65.5±22.1	22.9±8.6

Figure Legends

Figure 1:

Title: Reliability measures of interest

Description: Inter- and intra- rater reliability was assessed within the same day and between day intra-rater stability was assessed 24 hours apart.

Figure 2:

Title: cSWE set up

Description: Participants were seated with their hips and knees at 90 degrees of flexion with their lower leg stabilized in a custom boot (right). The ultrasound probe was placed on a custom clamp after the region of interest was determined, and the external actuator was placed on the quadriceps tendon above the knee held by the rater (left).

Figure 3:

Title: Shear wave propagation through the patellar tendon

Description: Shear wave speeds measured within the region of interest for the 11 frequencies were then used to calculate viscosity and shear modulus using the Voigt model[33]. The images reflect an example trial from one of the healthy patellar tendons at the 322Hz frequency.