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Shear wave elastography of the healing human patellar tendon following ACL reconstruction☆

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ABSTRACT

Purpose: Anterior cruciate ligament (ACL) ruptures are common and are frequently reconstructed using a patellar tendon (PT) autograft. Unfortunately, the time course of PT healing after ACL reconstruction is not particularly well understood. Thus, the primary objective of this study was to use shear wave elastography (SWE) to evaluate the extent to which shear wave speed (SWS) is associated with time after ACL reconstruction.
Methods: Longitudinal SWE images were acquired from lateral, central, and medial regions of the PT from two groups: 30 patients who had undergone ACL reconstruction with a PT autograft within the preceding 40 months, and 30 age-matched asymptomatic control subjects. SWE images were acquired at 20° and 90° of passive flexion from both knees. In each subject group, statistical analyses assessed changes in mean SWS with time post-surgery, as well as differences in mean SWS between PT regions and limbs.
Results: In the ACL reconstruction patients, mean SWS increased with time post-surgery in the lateral region of the involved knee ($p = 0.025$) and decreased with time post-surgery in the central region of the contralateral knee ($p = 0.022$).
Conclusion: The findings suggest that there is an association between the mechanical properties of the PT and time post-surgery in both the involved and contralateral limbs after ACL reconstruction. These changes are likely due to maturation of the donor site tissue and changes in gait/loading patterns following ACL rupture and reconstruction.
Level of evidence: Level II — Prospective Cohort.

1. Introduction

Anterior cruciate ligament (ACL) ruptures are common, with approximately 175,000 surgical reconstructions performed in the United States each year [1]. Reconstructing the ACL with a patellar tendon autograft is a common surgical approach, whereby the surgeon harvests the central third of the patient's patellar tendon and uses this tissue to replace the ruptured ACL. This approach generally results in acceptable clinical outcomes ([2,3]), but complications at the donor site (e.g., patellar tendon rupture [4,5] or

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patellar fracture [6]) that occur when mechanical forces exceed the structural properties of the healing patellar tendon tissue can contribute to long-term knee pain and functional deficits. Unfortunately, no technique currently exists for quantitatively assessing patellar tendon healing, and therefore relatively little is known about the time course of patellar tendon healing after ACL reconstruction. Consequently, clinicians base recommendations for post-surgical rehabilitation and activity levels on subjective assessments of pain and function (e.g., strength, ROM) without any direct knowledge of the inherent mechanical and functional capacity of the healing patellar tendon.

Previous efforts aimed at assessing patellar tendon healing after ACL reconstruction have utilized radiographs [7], conventional ultrasound imaging [1,8,9], MRI [10,11], and pain/function questionnaires [1,11,12] on human patients. Patellar tendon healing has also been assessed via mechanical and histological analysis of healing tissue in animal models [13]. Unfortunately, there are limitations with each of these approaches. Clinical imaging modalities such as MRI and ultrasound are ideal for assessing the presence or absence of tissue in a patellar tendon defect, but these conventional imaging techniques provide only a qualitative assessment of tissue properties. In contrast, animal studies afford the opportunity for quantitative assessments of repair tissue strength and composition, but these experimental approaches are impractical for human studies.

As an alternative approach which may overcome many of these limitations, ultrasound shear wave elastography (SWE) is being used increasingly to estimate in vivo soft tissue elasticity [14]. SWE has been used extensively for breast and liver imaging [15–18], and has been used to estimate the in vivo mechanical properties of tendons and muscles [19–22]. One recent study demonstrated shear wave speed (SWS) was significantly correlated with the tendon elastic modulus, stress and strength measures, thus indicating potential for quantitatively assessing the mechanical integrity of pre-operative and post-operative tendons [23]. Previous studies have documented the reliability of SWE imaging of the patellar tendon [24,25], and have reported how knee position [26], aging [27], and athletic status (i.e., pro vs. amateur) [28] influence SWE-based measures in the patellar tendon. The effects of smoking on ultrasound elastography based measures in the patellar tendon have been evaluated [29,30], as have the effects of patellar tendinopathy [31] and surgical intervention [32]. We are aware of only one study that has used ultrasound elastography to evaluate the patellar tendon after ACL reconstruction [30], however this study used real time elastography instead of shear wave elastography. This previous study reported significant differences between healing and uninjured contralateral patellar tendons, but the study was not designed to investigate if or how specific factors influenced SWE-based outcome measures in the healing patellar tendon.

The primary objective of this study was to use SWE to evaluate the extent to which SWS is associated with time after ACL reconstruction in the healing human patellar tendon. We hypothesized that SWS of the healing patellar tendon would be greater in patients who were further along in recovery, and that SWS of the contralateral patellar tendon would not be associated with time post-surgery. A secondary objective of this study was to evaluate the extent to which SWS was influenced by age, gender, limb dominance, and patellar tendon region.

2. Methods

A prospective cohort study was performed. Following IRB approval and informed consent, SWE images of the patellar tendon were acquired from 60 subjects using a clinical SWE imaging system (Siemens ACUSON S3000, 9L4 probe, Erlangen, Germany). These 60 subjects included 30 asymptomatic control subjects with no history of injury or pain in either knee (age: 22.8 ± 5.4, range: 16–36, 18 males 12 females) and 30 patients who had undergone primary ACL reconstruction with a patellar tendon autograft (PTA, age: 22.5 ± 5.1, range: 16–36, 15 males 15 females). Patients under 16 years old, who had bilateral ACL reconstructions, who underwent revision surgery, who had multiple ligament tears, who smoked, or who were less than 1-month post-surgery were excluded. All PTA patients had their surgery performed by the same surgeon (VM) within the preceding 40 months (mean time from surgery to SWE imaging: 15.5 ± 12.3, range: one to 40 months) using a standard bone-patellar tendon-bone autograft surgical technique as previously described [33] and underwent the same rehabilitation protocol. Following harvest of the bone-patellar tendon-bone graft, the medial and lateral regions of the remaining patellar tendon were sutured together with 0 vicryl, and in a separate layer the paratenon was closed using 2.0 vicryl, to promote healing at the graft site.

SWE images of the patellar tendon were acquired with subjects seated and their knee passively flexed at 20° and at 90°. The SWE imaging probe was manually positioned parallel to the long axis of the patellar tendon and approximately one centimeter

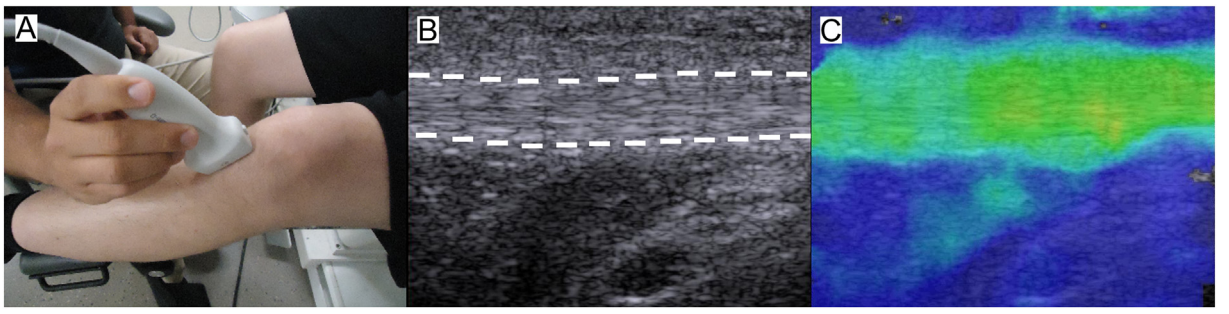

Figure 1. (A) Shear wave elastography images were acquired with the transducer oriented parallel to the long axis of the patellar tendon. For each trial, (B) B-mode and (C) shear wave elastography images were acquired simultaneously. Dashed lines show boundaries of the patellar tendon.

distal to the inferior border of the patella (Figure 1a). SWE images were acquired from lateral, central, and medial regions of the patellar tendon. Probe positioning was facilitated by real-time brightness mode (B-mode) images (Figure 1b). For each subject, five SWE images (e.g. Figure 1c) were acquired for each combination of limb (right, left), knee position (20° flexion, 90° flexion), and patellar tendon region (lateral, central, medial), with a minimum of 15 s between trials.

As previously reported [34], each trial resulted in a brightness mode (B-mode) image and a corresponding SWE image, from which proprietary software calculated SWS at each pixel (resolution: ~0.25 mm per pixel) within a rectangular region of approximately 2.5 × 2.5 cm. To accomplish this, the patellar tendon was first isolated from surrounding soft tissues in the B-mode image using a semi-automated thresholding algorithm. The region corresponding to the patellar tendon was then manually selected as the region of interest (ROI) for each trial, and this ROI was used to select the data from the corresponding SWE image. For each trial, the central 90th percentile of SWS values within the ROI were used for further analysis. The ROI consisted of an average of 1169 ± 298 individual SWS values for the images acquired in 20° flexion and 815 ± 435 individual SWS values for the images acquired in 90° flexion. There was a lower number of SWS values within the tendon in 90° flexion because of the thinning of the tendon related to its stretching. Mean SWS within the ROI was calculated for each trial, and the five trials were averaged for each combination of limb (right, left), knee position (20° flexion, 90° flexion), and patellar tendon region (lateral, central, medial). To assess measurement repeatability, five control subjects were tested by two users (CG, LJ) on the first visit and then again by both users approximately 24 h later. In addition to SWE imaging, knee pain and function were assessed using the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC) score [35], and each subject's physical activity level was assessed using the Habitual Physical Activity (HPA) Index [36].

The intra-class correlation coefficient (ICC) was calculated to assess intra-user, inter-user, and inter-day repeatability. Unpaired t-tests were used to assess: 1) differences in age, activity level (HPA index), and IKDC score between the control and PTA subject groups and 2) the effects of gender on mean SWS in the control and PTA subject groups. Paired t-tests were used to assess: the differences in means SWS between 1) the control subjects' dominant (DOM) and non-dominant (N-DOM) limbs and 2) the PTA patients' involved (INV) and contralateral (CONT) limbs. Linear regression assessed the extent to which age was associated with mean SWS in the PTA and control subject groups. Linear regression also assessed the association between time post-surgery and SWS in the PTA patients. In order to perform a similar analysis in the control subjects, an index time was determined for each control subject by age-matching each control subject with a PTA patient and assigning the PTA patient's time post-surgery to the corresponding control subject. Linear regression then assessed the association between mean SWS and index time in the control subjects. Lastly, a one-way repeated measures ANOVA assessed the effect of tissue region (lateral, central, medial) on mean SWS in both subject populations. A p-value of ≤0.05 was considered significant for all statistical tests.

3. Results

No significant difference was detected between the control subjects and PTA patients in age (control: 22.8 ± 5.4, PTA: 22.6 ± 5.1, n.s.) or activity level (control: 5.6 ± 1.0, PTA: 6.1 ± 1.4, n.s.), but the IKDC score was significantly different between subject groups (control: 98.5 ± 2.9, PTA: 78.8 ± 17.1, $p < 0.001$). Intra-user repeatability of SWE imaging was good to excellent (ICC ranging from 0.83 to 0.96), while inter-user repeatability was moderate to good in 90° flexion (ICC ranging from 0.74 to 0.80) and poor to

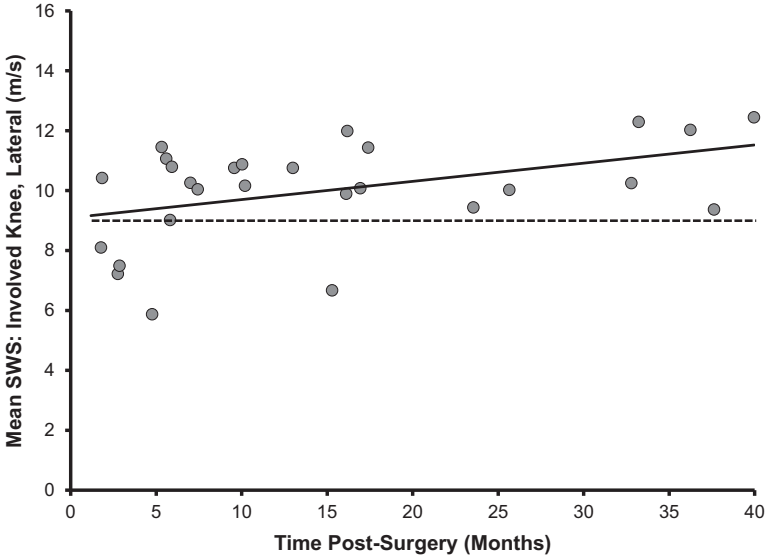

Figure 2. In the patients who had undergone ACL reconstruction, mean shear wave speed of the lateral patellar tendon region of their involved knee in 90° flexion increased significantly with time post-surgery ($p = 0.025$), resulting in a regression value that was approximately 25% greater than controls at 40 months post-surgery.

good in 20° flexion (ICC ranging from 0.40 to 0.84). Finally, inter-day repeatability was moderate to good for 20° and 90° flexion (ICC ranging from 0.52 to 0.81) [37].

Mean SWS in the PTA patients' INV knee increased significantly with time post-surgery, but only in the lateral region in 90° flexion ($p = 0.025$, Figure 2). None of the other combinations of knee position (20° flexion, 90° flexion) and patellar tendon region (lateral, central, medial) showed an association between mean SWS and time post-surgery. The lateral region was similar to control value (~9 m/s) at one month and then surpassed control values, reaching 125% of control value by 40 months. In the patients' CONT knee, mean SWS of the central region decreased significantly with time post-surgery when tested in 90° flexion ($p = 0.022$, Figure 3). The central region was 122% of control value at one month and decreased to control value by ~30 months. By comparison, mean SWS of the control subjects was not significantly associated with index time for any combination of knee position and patellar tendon region.

Few statistically significant differences in mean SWS were detected between DOM and N-DOM limbs of the control subjects (Figure 4a), or between INV and CONT limbs of the PTA patients (Figure 4b). Specifically, in the central region of the PTA patients at 90° flexion, mean SWS of the CONT leg was significantly higher than the INV leg ($p = 0.017$, Table 2). Also, in the lateral region of the control subjects at 20° flexion, mean SWS of the N-DOM leg was significantly higher than the DOM leg ($p = 0.014$, Table 1). No other statistically significant differences in mean SWS between limbs were detected (Tables 1, 2).

The data indicated several statistically significant differences in mean SWS between tissue regions (Tables 1, 2). For the control subjects, no differences in mean SWS were detected between tissue regions when tested in 20° flexion. However, when control subjects were tested in 90° flexion, mean SWS of the medial region was significantly higher than both the central and lateral regions (Table 1). This finding occurred in both DOM ($p < 0.002$) and N-DOM ($p < 0.002$) legs. For the PTA patients, mean SWS of the medial region of the INV knee in 20° flexion was significantly lower than the lateral region ($p = 0.006$). At 90° flexion, the central region mean SWS of the PTA patients' INV knee was significantly lower than the lateral ($p = 0.023$) or medial ($p = 0.018$) regions.

Age and gender had relatively little effect on mean SWS. Age was not found to have a significant effect on mean SWS for any region in CONT subjects ($p > 0.147$) or PTA patients ($p > 0.144$). Gender was found to have a small effect in the medial region of the control subjects' N-DOM leg where males had significantly higher mean SWS than females in 20° flexion ($p = 0.002$, Table 1) and 90° flexion ($p = 0.022$, Table 1). No other statistically significant differences in mean SWS were detected between males and females in the control subjects (Table 1) or PTA patients (Table 2).

4. Discussion

The primary objective of this study was to evaluate the extent to which SWS is associated with time after ACL reconstruction in the healing human patellar tendon. Mean SWS in the lateral portion of the PTA patients' INV knee increased significantly with time post-surgery (Figure 2), while mean SWS in the central portion of the PTA patients' CONT knee decreased significantly with time post-surgery (Figure 3). These findings suggest that there is an association between the mechanical integrity of the patellar tendon and time post-surgery. Our secondary outcomes indicated that mean SWS was not influenced by age, and that gender had only a minor influence on mean SWS. The data also indicated that there were relatively few differences in mean SWS between limbs of the control subjects and PTA patients (Figure 4), but that significant differences in mean SWS occurred between the medial, central, and lateral regions of the patellar tendon.

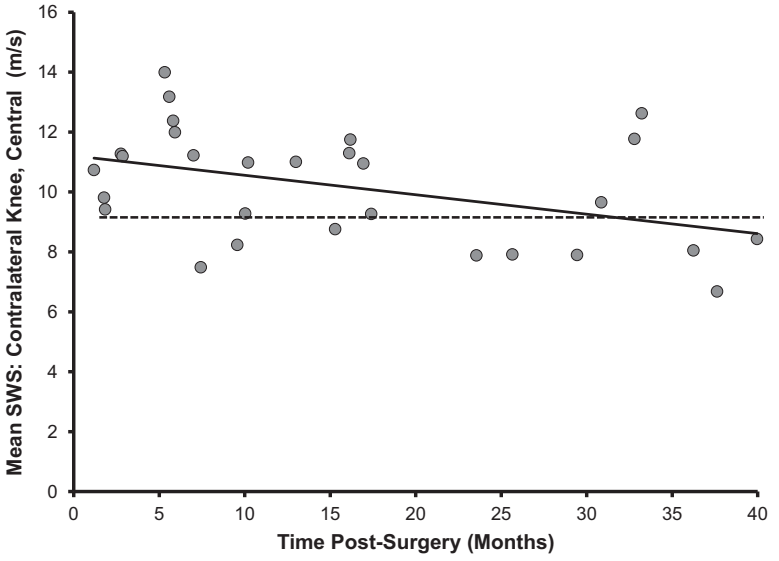

Figure 3. In the patients who had undergone ACL reconstruction, mean shear wave speed of the central patellar tendon region of their contralateral knee in 90° flexion decreased significantly with time post-surgery ($p = 0.022$).

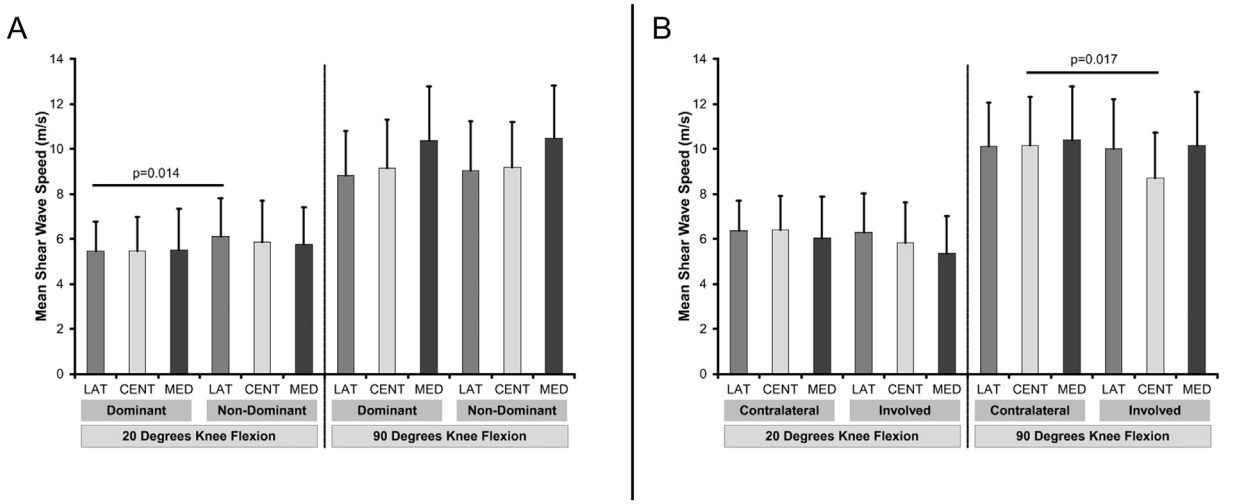

Figure 4. Few statistically significant differences in mean SWS were detected between (A) DOM and N-DOM limbs of the control subjects, or between (B) INV and CONT limbs of the PTA patients.

The data reported here, with measures of mean SWS ranging from approximately 5 to 11 m/s, are in good agreement with previously reported data [27,38]. For example, Coombes and colleagues reported mean SWS values in the patellar tendon ranging from approximately six meters per second to 11 m/s in subjects of similar age (19–24 years) and similar leg position (25–85° flexion). Specifically, Coombes and colleagues reported mean SWS values of approximately six meters per second at 25° flexion and approximately 11 m/s at 85° flexion [38]. The current study compares favorably with these findings, with the data reported here indicating a mean SWS of 5.5 to 6.1 m/s at 20° flexion and 9.0 to 10.5 m/s at 90° flexion.

The control subject data indicated significant differences in mean SWS between DOM and N-DOM limbs in 20° flexion, but not 90° flexion (Table 1). In contrast, the control subject data indicated significant differences between patellar tendon regions in 90° flexion, but not 20° flexion (Table 1). While these findings may seem somewhat contradictory, the differences in 20° flexion (i.e., a position of low tendon strain) suggest that there may be subtle differences in tendon mechanical properties between DOM and N-DOM limbs as a result of asymmetrical loading patterns. Furthermore, the differences in mean SWS between the medial, central, and lateral regions that were detected only in 90° flexion suggest that passive forces associated with knee flexion seem to preferentially load the medial region of the patellar tendon. These findings on regional differences in patellar tendon properties are consistent with the work of Yanke and colleagues, who failed to detect differences between patellar tendon regions during low-load cyclic testing, but reported significant differences between regions when the patellar tendon samples were mechanically tested to failure [39].

For the PTA patients, the central region SWS of the INV knee was significantly lower than the medial and lateral regions when tested in 90° flexion, but in 20° flexion the medial region was significantly lower than the lateral region (Table 2). The differences between 20° flexion and 90° flexion were expected, particularly since previous research has reported that healing tendons are initially characterized by low quality scar tissue which slowly remodels over time with a corresponding increase in strength and stiffness (e.g., [13]). However, it is important to recognize that SWS is influenced by a complex interaction of material properties and tissue tension [40]. Consequently, in

Table 1
Shear wave speed (SWS) of control subjects. All data reported as mean ± standard deviation (range) in units of meters/s.

	20° flexion						90° flexion					
	Dominant (Healthy)			Non-Dominant (Healthy)			Dominant (Healthy)			Non-Dominant (Healthy)		
	lateral	central	medial	lateral	central	medial	lateral	central	medial	lateral	central	medial
All Subjects	5.5 ± 1.3 (2.4 - 8.2)	5.5 ± 1.5 (2.2 - 9.4)	5.5 ± 1.8 (2.0 - 10.2)	6.1 ± 1.7 (3.0 - 11.4)	5.9 ± 1.8 (2.6 - 11.9)	5.8 ± 1.7 (2.4 - 10.1)	8.8 ± 2.0 (3.1 - 12.3)	9.2 ± 2.2 (4.9 - 13.1)	10.4 ± 2.4 (3.3 - 12.9)	9.0 ± 2.2 (2.9 - 12.6)	9.2 ± 2.0 (3.7 - 12.4)	10.5 ± 2.4 (2.7 - 13.6)
Regional Differences	p=0.787			p=0.199			**p<0.001** o p=0.351 o ● **p=0.002** ● ● - - **p<0.001** - - ●			**p<0.001** o p=0.703 o ● **p=0.006** ● ● - - **p=0.002** - - ●		
DOM vs N-DOM	**p=0.014**	p=0.061	p=0.261	--	--	--	p=0.444	p=0.906	p=0.758	--	--	--
Males	5.9 ± 1.0 (4.1 - 8.2)	5.7 ± 1.4 (2.2 - 9.4)	6.0 ± 1.3 (4.0 - 8.6)	6.4 ± 1.6 (4.2 - 11.4)	5.9 ± 1.4 (2.6 - 8.9)	6.4 ± 1.6 (2.9 - 10.1)	9.1 ± 1.3 (6.6 - 12.3)	9.5 ± 2.0 (7.4 - 13.1)	11.1 ± 1.6 (7.0 - 12.9)	9.5 ± 1.6 (7.4 - 12.4)	9.6 ± 1.8 (5.6 - 12.4)	11.4 ± 1.7 (8.5 - 13.6)
Females	4.8 ± 1.5 (2.4 - 8.2)	5.2 ± 1.7 (2.5 - 8.8)	4.8 ± 2.3 (2.0 - 10.2)	5.7 ± 1.8 (3.0 - 9.5)	5.8 ± 2.3 (2.6 - 11.9)	4.7 ± 1.2 (2.4 - 6.6)	8.4 ± 2.7 (3.1 - 11.8)	8.6 ± 2.4 (4.9 - 12.0)	9.4 ± 3.1 (3.3 - 12.6)	8.3 ± 2.8 (2.9 - 12.6)	8.5 ± 2.2 (3.7 - 12.1)	9.2 ± 2.6 (2.7 - 12.1)
Male vs Female	p=0.061	p=0.459	p=0.124	p=0.334	p=0.892	**p=0.002**	p=0.456	p=0.293	p=0.100	p=0.219	p=0.166	**p=0.022**

Table 2
Shear wave speed (SWS) of patellar tendon autograft patients. All data reported as mean ± standard deviation (range) in units of meters/s.

	20° flexion						90° flexion					
	Healthy (CONT)			Involved (INV)			Healthy (CONT)			Involved (INV)		
	lateral	central	medial	lateral	central	medial	lateral	central	medial	lateral	central	medial
All Patients	6.4 ± 2.3 (3.0 - 12.7)	6.4 ± 2.1 (3.6 - 13.7)	6.1 ± 2.1 (2.8 - 10.9)	6.3 ± 2.1 (3.7 - 12.8)	5.8 ± 1.5 (3.4 - 11.0)	5.4 ± 1.7 (2.6 - 12.3)	10.1 ± 2.2 (5.8 - 14.2)	10.2 ± 1.9 (6.7 - 14.0)	10.4 ± 2.3 (6.4 - 14.1)	10.0 ± 1.7 (5.9 - 12.4)	8.7 ± 2.4 (5.2 - 12.6)	10.2 ± 2.3 (4.0 - 13.6)
Regional Differences	p=0.531			**p=0.007** o p=0.098 o o p=0.198 o ● - - **p=0.006** - - ●			p=0.695			**p=0.010** ● **p=0.023** ● ● **p=0.018** ● o - - p=0.813 - - o		
Injured vs Healthy Leg	p=0.817	p=0.179	p=0.188	--	--	--	p=0.849	**p=0.017**	p=0.752	--	--	--
Males	6.2 ± 2.2 (3.0 - 12.7)	6.2 ± 2.4 (3.6 -13.7)	6.1 ± 2.1 (2.8 - 10.8)	6.6 ± 1.4 (5.2 - 10.8)	6.0 ± 1.1 (3.9 - 8.5)	5.4 ± 0.9 (3.6 - 7.0)	10.4 ± 2.3 (6.1 - 14.2)	9.6 ± 1.9 (6.7 - 12.6)	10.9 ± 2.0 (8.3 - 14.1)	10.5 ± 1.3 (7.5 - 12.3)	8.7 ± 2.6 (5.2 - 12.6)	10.8 ± 1.8 (8.0 - 13.6)
Females	6.6 ± 2.5 (3.7 - 12.0)	6.6 ± 1.8 (4.6 - 11.0)	6.0 ± 2.1 (3.1 - 10.9)	6.1 ± 2.6 (3.7 - 12.0)	5.7 ± 1.8 (3.4 - 11.0)	5.3 ± 2.3 (2.6 - 12.3)	9.8 ± 2.1 (5.8 - 14.0)	10.8 ± 1.8 (7.9 - 14.0)	9.9 ± 2.5 (6.4 - 13.2)	9.5 ± 1.9 (5.9 - 12.4)	8.7 ± 2.2 (5.8 - 12.5)	9.4 ± 2.8 (4.0 - 13.5)
Male vs Female	p=0.665	p=0.553	p=0.976	p=0.500	p=0.553	p=0.885	p=0.465	p=0.105	p=0.250	p=0.303	p=0.968	p=0.101

20° flexion (i.e., a position of low tendon strain [41]), the findings seem to suggest there may be only subtle differences in mechanical integrity between the three tendon regions. Although this interpretation is difficult to reconcile with previously reported research on tendon healing, it is also possible that potential differences between the three tendon regions may have been masked by evaluating patients across a wide range of healing from one to 40 months post-surgery. At 90° flexion (i.e., a position of higher patellar tendon strain [41]), the significant differences in mean SWS between the three tendon regions suggest that the passive forces associated with knee flexion are largely being distributed through the healthy tendon tissue in the medial and lateral regions. This finding suggests that changes in patellar tendon load redistribution during post-operative healing may play an important role in restoring function of the patient's INV knee after ACL reconstruction.

The slope of the regression lines for SWS versus time in the PTA patients' INV and CONT knees were in opposite directions, which may suggest changes in loading patterns in response to the ACL injury and/or reconstruction. Specifically, the regression analysis indicated that the lateral region of the INV knee was near control subject levels (approximately nine meters per second) at one month post-surgery and was 25% greater at 40 months post-surgery (Figure 2). In contrast, the regression analysis indicated that the central region of the patients' CONT knee was approximately 22% higher than the corresponding control subject value at one month post-surgery and was near control subject levels at 40 months post-surgery (Figure 3). It is not uncommon for athletes who have undergone ACL reconstruction to return to sport at 8 months post-surgery [42], but these findings suggest that the INV and CONT patellar tendon may continue to adapt out to 40 (or more) months post-surgery. Given that SWS is typically interpreted as an indication of the tissue's shear modulus [19], and that SWS has recently been associated with mechanical integrity, tissue strength, and elasticity [23], these findings suggest that patellar tendon mechanical integrity may not have fully adapted to new load-bearing distributions at typical return to sport timeframe, which may contribute to unacceptably high re-tear and contralateral tear rates [43–49].

Our findings suggest that the lateral region of the INV patellar tendon may primarily compensate for the mechanical structure of the tendon post-surgery, adopting greater mechanical integrity in order to handle the increased stress applied to a tendon with a smaller cross-sectional area. Our findings also suggest the central portion of the CONT tendon may primarily adapt to increased load placed on the knee and tendon immediately after injury, while the CONT leg is bearing more weight. It is plausible that as the INV knee recovers, the patient begins to bear more weight on it, and the central portion of the CONT tendon loses the adaptive force that was driving the observed change. The current study suggests that mean SWS in the PTA patients' CONT knees may not return to control subject levels until approximately 40 months post-surgery, which is consistent with previous research reporting altered gait patterns after ACL injury and reconstruction for up to five years post-surgery [50]. This study was not designed to assess lower extremity kinematics, but changes in gait patterns after ACL injury and reconstruction are a likely explanation for the observed association between patellar tendon mechanical integrity and time post-surgery [3,50].

There were several limitations associated with this study. As a cross-sectional study, it was impossible to know for sure if or how SWS changed over time in any of the patients. A longitudinal study would be necessary to appropriately determine how SWS changes over time, but that study design was not utilized. Although the cross-sectional study design is a limitation, this limitation is somewhat ameliorated by the fact that the subject populations were reasonably homogeneous (i.e., no differences in age, activity level, or IKDC score) and that the same surgeon performed the ACL reconstructions on all of the PTA patients. Additional limitations include the lack of objective data on patellar tendon healing, since no technique currently exists to do so in humans. Lastly, the sample size of 60 subjects (30 PTA patients, 30 control subjects) was largely a convenience sample and limits the power of our findings. However, this sample size is consistent with previous studies that evaluated the patellar tendon using SWE [25,30].

5. Conclusion

The findings suggest that there is an association between the mechanical integrity of the patellar tendon and time post-surgery in both the involved and contralateral limbs after ACL reconstruction. These changes are likely due to maturation of the donor site

tissue in the involved limb and changes in gait/loading patterns following ACL rupture and reconstruction in the contralateral limb. The findings also suggest that it is possible the anterior knee extensor mechanism in both the involved and contralateral knee may not be fully adapted by the time most athletes return to high intensity sports. Furthermore, these findings lend support to the further investigation into the use of SWE as an imaging modality for quantifying patellar tendon healing after ACL reconstruction. Future research efforts should further evaluate SWE for the longitudinal assessment of tendon and ligament properties in response to pathology and clinical intervention.

Author contributions

CG participated in the design of the study, recruited subjects, performed data collection, participated in the analysis and interpretation of data, and participated in drafting of the manuscript. TGB participated in the design of the study, performed the statistical analysis, participated in the analysis and interpretation of data, and participated in drafting of the manuscript. LJ recruited subjects, performed data collection, and participated in drafting of the manuscript. MS performed data collection and participated in drafting of the manuscript. MM participated in the analysis and interpretation of data, and in drafting of the manuscript. AS participated in the analysis and interpretation of data, and in drafting of the manuscript. VM conceived of the study, participated in the analysis and interpretation of data, and participated in drafting of the manuscript. MJB conceived of the study, participated in the design of the study, in the analysis and interpretation of the data, and in drafting of the manuscript. All authors read and approved the final manuscript.

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