ANALYZING THE UTILITY OF TENDON MECHANICAL PROPERTIES AND THEIR RELATIONSHIP WITH CLINICAL OUTCOME MEASURES FOR PATELLAR TENDINOPATHY

by

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ABSTRACT

Patellar tendinopathy is a chronic overuse injury of the patellar tendon, which connects the kneecap to the lower leg. This injury most commonly presents in athletes who undergo repetitive jumping motions, especially elite volleyball and basketball players. Patellar tendinopathy presents in 44% and 32% of these cases, respectively, and it is estimated that 50% of affected individuals may be forced to retire from sport prematurely.

Patellar tendinopathy is characterized by an overall decrease in patellar tendon health. Patellar tendon health encompasses tendon structure, assessed via ultrasound imaging, symptom severity and duration, assessed by patient-reported outcome measures, and lower extremity function, assessed through squatting and jumping tests. Moreover, decreased patellar tenon health is associated with impairments in patellar tendon mechanical properties, such as shear modulus or viscosity. These mechanical properties are relatively new measures of tendon health, and it is not yet known how they might fit into the management of tendinopathies. Before making clinical applications, it may be of interest to determine if relationships exist between mechanical properties and other clinical outcome measures for patellar tendinopathy. Furthermore, mechanical properties should be considered in individuals with and without patellar tendinopathy, for the purpose of identifying changes with respect to injury.

Seventeen injured and thirteen uninjured participants completed the study. No statistically significant differences between shear modulus or viscosity were detected across cohorts; however, this study found significant differences in symptom severity, knee-related quality of life, kinesiophobia, and pain catastrophizing tendencies.

Moderate positive relationships were found in the uninjured cohort between shear modulus and functional performance via the single-leg countermovement jump (CMJ) and drop countermovement jump (Drop CMJ) tests. Moreover, moderate to strong positive relationships existed in the uninjured cohort between viscosity and CMJ and Drop CMJ heights. In the injured cohort, only a moderate positive relationship was detected between viscosity and CMJ height.

Based on the results of this study, it appears that the difference in relationships between injured and uninjured is due to confounds associated with injury. These may include pain, kinesiophobia, or muscle weakness or inhibition. Any one of these injurious impairments may be accounting for the changes in patellar tendon mechanical properties, so it is imperative that clinicians utilize a variety of clinical outcome measures on an individualized basis. This holistic approach may result in better outcomes for patients with patellar tendinopathy.

Chapter 1

INTRODUCTION

The patellar tendon is an extension of the quadriceps tendon and the quadriceps muscle group. The patellar tendon attaches proximally at the inferior pole of the patella and inserts distally at the tibial tuberosity of the tibia. In gait and sport, the patellar tendon plays an important role in transmitting forces from the quadriceps muscles to the lower leg.[1] Patellar tendinopathy is a painful overuse injury of the patellar tendon, most commonly seen in individuals who undergo repetitive jumping movements. It is estimated that 32-44% of elite volleyball and basketball athletes present with patellar tendinopathy.[2] These individuals experience altered lower extremity function, decreased athletic performance, and greater losses in playing time, amongst other problems.[3] Furthermore, up to 50% of athletes with patellar tendinopathy will prematurely retire from sport due to recurrent symptoms.[4]

Patellar tendinopathy, often referred to as “jumper’s knee”, primarily presents with pain at the inferior pole of the patella or the proximal patellar tendon. Patellar tendinopathy is hallmarked by load-dependent symptoms, with increased loads resulting in increased symptom severity.[5] Certain intrinsic and extrinsic risk factors may exist for patellar tendinopathy, including body mass index (BMI), quadriceps flexibility, or vertical jump performance; however, there is a lack of evidence supporting the significance that these factors might have in predicting patellar tendinopathy.[6] Moreover, limited knowledge exists regarding modifiable risk factors, making it difficult to identify predispositions for patellar tendinopathy in athletics or in the general population.[7]

Patellar tendinopathy is associated with an overall decrease in patellar tendon health. Patellar tendon health is an inclusive term, encompassing symptom severity and duration, tendon structure and morphology, tendon mechanical properties, and lower extremity function. At the tissue level, patellar tendinopathy is characterized by collagen fiber disorganization and degradation, increased ground substance, neovascularization, and localized swelling.[8] These changes result in altered mechanical properties, such as stiffness or Young's modulus,[8] and changes in tendon morphology, including increased thickness and cross-sectional area (CSA).[9] Clinically, patellar tendinopathy often presents with specific symptoms, such as pain or crepitus, as well as variations in lower extremity functional performance.[5]

To best assess and treat patellar tendinopathy, clinicians must focus on restoring all components of tendon health. Typically, symptom severity has been assessed through patient-reported outcome measures, while lower extremity functional performance has been assessed using a variety of squatting and jumping tests. Impairments in tendon structure, seen as hypoechoic regions, disorganized fiber alignment, and increased thickness and CSA, have been measured through diagnostic ultrasound imaging.[10] While these structural changes are useful in measuring long-term tendon health, they occur slowly and may not be the most useful assessment of acute alterations in patellar tendon homeostasis.[11] Instead, tracking changes in tendon mechanical properties may be a more responsive measure.[12]

Patellar tendon mechanical properties, including shear modulus and viscosity, can be quantified by continuous shear wave elastography (cSWE), a form of real-time ultrasound imaging. In short, shear modulus refers to a tendon's resistance to a shearing force, while viscosity refers to a tendon's response to a rate-dependent load. These mechanical properties have been identified as a relatively new measure of tendon health, and it is not yet known how these properties might fit into the assessment of tendinopathies.[13] Before making clinical applications, it may be of interest to first investigate relationships between tendon mechanical properties and other outcome measures for patellar tendinopathy. Moreover, these relationships should be considered in both injured and uninjured individuals, for the purpose of identifying changes with respect to injury. This may allow for a better understanding as to what role mechanical properties play in the context of patellar tendon health. Therefore, the purpose of this thesis is to analyze relationships between tendon mechanical properties and injury characteristics, patient-reported outcome measures, tendon structure, and lower extremity function in individuals with and without patellar tendinopathy.

Chapter 2

METHODOLOGY

This cross-sectional study was conducted at the University of Delaware's Tendon Research Laboratory under Institutional Review Board (IRB) approval. An informed consent process took place prior to each data collection. All participants had height and weight recorded and were then asked to complete a series of questionnaires, including past and present history of injury, injury characteristics, subject demographics, and patient-reported outcome measures. Tendon structure and tendon mechanical properties were then measured using B-mode ultrasound imaging and continuous shear wave elastography (cSWE), respectively. Finally, lower extremity functional performance was assessed through the single-leg countermovement jump (CMJ) and drop countermovement jump (Drop CMJ) tests.

2.1 Subject Recruitment

This study consisted of injured and uninjured cohorts. Inclusion criteria for the injured cohort consisted of a clinical diagnosis of unilateral or bilateral patellar tendinopathy. This clinical diagnosis was defined by pain in the proximal patellar tendon with load-dependent symptoms.[5] Inclusion criteria for the uninjured cohort consisted of uninjured patellar tendons bilaterally, confirmed by a clinical examination. Exclusion criteria for all participants consisted of present or past history of patellar tendon injection, patellar tendon autograft, patellar tendon rupture, or any other lower extremity injury deemed to affect loading at the patellar tendon.

2.2 Injury Characteristics

For injured participants with bilateral patellar tendinopathy, the more symptomatic limb was considered the injured limb. This distinction was made based on scores from the Victorian Institute of Sport Assessment – Patella (VISA-P),[14] as well as a clinical examination. Both uninjured and injured participants also self-reported past and present history of injury and symptom severity and duration.

2.3 Patient-Reported Outcome Measures

Patient-reported outcome measures included the Victorian Institute of Sport Assessment – Patella (VISA-P), the Knee Injury and Osteoarthritis Outcome Score – Quality of Life Subscale (KOOS-QOL),[15] the Pain Catastrophizing Scale (PCS), [16] the Tampa Scale for Kinesiophobia (TSK),[17] and the Physical Activity Scale (PAS).[18]

Symptom severity was assessed using the VISA-P questionnaire. The VISA-P is a patellar tendinopathy-specific measure of symptom severity and has established reliability and validity at the patellar tendon.[14] Scores range from 0-100, with lower scores indicative of greater symptoms severity.

Knee-related quality of life was assessed using the KOOS-QOL questionnaire. The KOOS-QOL is a measure of injured participants' mental and social aspects associated with knee injury. It has demonstrated reliability and validity for knee-related injuries.[15] The KOOS-QOL is scored from 0-100%, with lower scores indicating more extreme problems associated with knee injury and the impact on overall quality of life.

Participants' perception of pain was assessed using the PCS. The PCS asks a series of questions regarding pain due to knee injury, and it is valid for the general population.[16] Scores range from 0-52, with scores above 30 indicative of a higher pain catastrophizing tendency.

Participants' fear of movement was assessed through the TSK. The TSK gauges participants' beliefs about moving with pain and risk of reinjury, and it has been proven reliable and valid for individuals with chronic pain.[17] The TSK is scored from 17-68, and scores above 37 are indicative of a high degree of kinesiophobia.[19]

Physical activity level was assessed through the PAS. The PAS is a measure of weekly physical fitness and is scored on a scale from 1-6. A score of 1 equates to "hardly any physical activity", a score of 2 equates to "mostly sitting, sometimes a walk, easy gardening or similar tasks", a score of 3 equates to "light physical exercise around 2-4 hours a week, e.g. walks, fishing, dancing, ordinary gardening, including walks to and from shops, a score of 4 equates to "moderate exercise 1-2 hours a week, e.g. jogging, swimming, gymnastics, heavier gardening, home-repairing or easier physical activities more than 4 hours a week, a score of 5 equates to "moderate exercise at least 3 hours a week, e.g. tennis, swimming, jogging, etc, and a score of 6 equates to “hard or very hard regularly and several times a week, where the physical exertion is great, e.g. jogging, skiing.”

2.4 Tendon Morphology

Patellar tendon structural properties of thickness (cm) and CSA (cm^2) were obtained using B-mode ultrasound imaging (GE LOGIQ e, GE Healthcare, Chicago, IL) with extended field of view settings.[20] Participants were seated in ninety degrees of hip flexion and thirty degrees of knee flexion. Thickness measures were recorded in long-axis view, while CSA measures were recorded in transverse view (Figure 1). For all images, the ultrasound probe was centered at the proximal patellar tendon, one centimeter distal to the inferior pole of the patella. Averages for both thickness and CSA were calculated from three trials for each measurement.

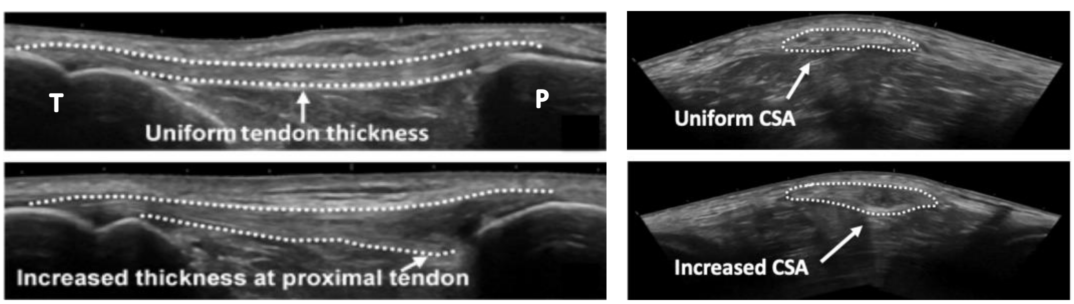


Figure 1 – Ultrasound imaging for uninjured (top) and injured (bottom) patellar tendons. Long-axis images are displayed on the left, and short-axis images are displayed on the right. The inferior pole of the patella (P) and tibial tuberosity of the tibia (T) are shown in long-axis view for the uninjured tendon.

2.5 Tendon Mechanical Properties

Patellar tendon mechanical properties were measured using continuous shear wave elastography (cSWE) (MDP, Ultrasonix, Vancouver, Canada).[12] cSWE has demonstrated reliability and validity at the Achilles tendon, and the method to establish its reliability at the patellar tendon is still being developed.[21] Participants were seated in ninety degrees of hip and knee flexion, with the legs stabilized to limit muscular contraction (Figure 2) The superior border and inferior pole of the patella and the tibial tuberosity were identified on ultrasound imaging and marked (Figure 1). A mechanical actuator was placed on the quadriceps tendon, one centimeter proximal to the superior border of the patella. The mechanical actuator generated shear waves at eleven different frequencies, ranging from 322-643 Hz. An ultrasound probe was held by a ring stand clamp and centered over the patellar tendon, one centimeter distal to the inferior pole of the patella. The mechanical actuator then transmitted a vibration of shear waves through the quadriceps tendon, across the patella, and into the patellar tendon, where the resultant tissue displacement was then recorded by the ultrasound probe.

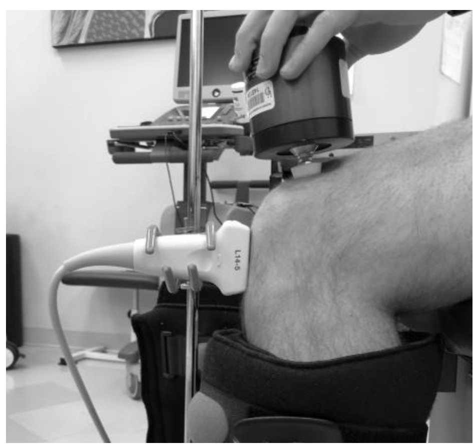


Figure 2 – Set-up of cSWE at the patellar tendon.

Three trials were performed per limb. Data was post-processed using a custom code (MatLab, Mathworks, Natick, Massachusetts) and yielded averages in shear modulus (kPa) and viscosity (Pa*s), as shown in Figure 3.

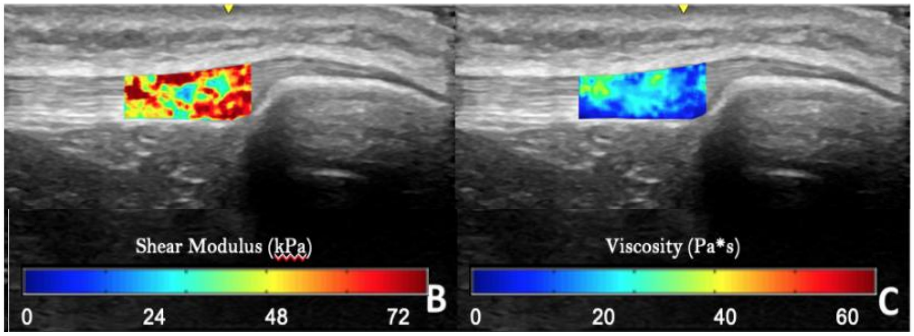


Figure 3 – Wave maps for shear modulus (left) and viscosity (right) of uninjured patellar tendons.

2.6 Lower Extremity Functional Performance

Lower extremity function was assessed through the single-leg countermovement jump (CMJ) test[22] and the single-leg drop countermovement jump (Drop CMJ) test.[23] For both tests, participants completed three alternating trials per limb, beginning with the right limb each time. The average jump height (cm) was recorded and used for statistical analyses. Jump height was determined from flight time using an infrared optical contact grid (MuscleLab, Ergotest Technology, Porsgrunn, Norway), and self-reported pain (0-10) measures were recorded after every jump trial.[24]

For the single-leg CMJ test, participants were asked to stand on one limb on the contact grid. Each participant was asked to perform a maximal vertical jump, with the hands behind the back (Figure 4).

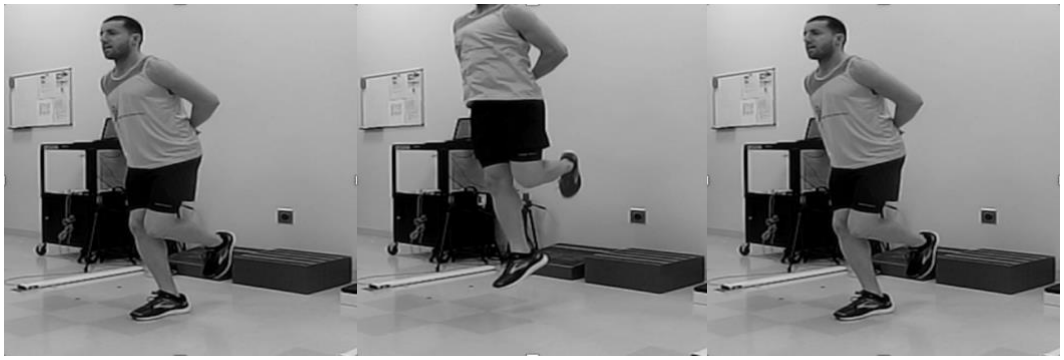


Figure 4 – Demonstration of the single-leg CMJ test, using MuscleLab technology.

For the single-leg Drop CMJ test, participants first began on a twenty-centimeter box. Each participant was asked to drop off of the box, before immediately performing a maximal vertical jump when contacting the ground (Figure 5).

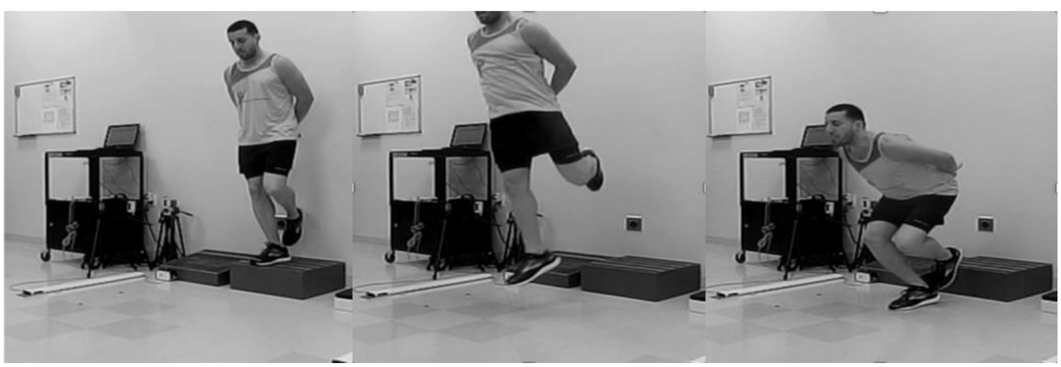


Figure 5 – Demonstration of the single-leg Drop CMJ test, using MuscleLab technology.

Chapter 3

STATISTICAL ANALYSIS

Main outcome measures included symptom duration for injured participants, all patient-reported outcome measures, average tendon thickness and CSA, average shear modulus and viscosity, and average height displacement on the single-leg CMJ and Drop CMJ tests. For statistical analyses, nonparametric assumptions were made based on non-normal distributions and small sample sizes. Mann-Whitney u-tests were used to analyze differences between cohorts for all applicable main outcome measures. Differences were considered statistically significant if $p < 0.05$. Cohen's d was also used to analyze effect sizes between cohorts for all u-tests. Effect sizes were considered large if $d = 0.80$, medium if $d = 0.5$, and small if $d = 0.2$.[25] Relationships between all main outcome measures were analyzed using Spearman's correlations ($\alpha = 0.05$). Relationships were considered strong if $0.68 \leq |\rho| \leq 1.0$, moderate if $0.36 \leq |\rho| < 0.68$, and weak if $0.0 \leq |\rho| < 0.36$.[25] Throughout the study, the right limb was used as the control limb in the uninjured cohort. For the injured cohort, the most symptomatic limb was taken as the intervention limb. All data was compiled using RedCap software and analyzed using IBM SPSS and G*Power. Of the thirteen uninjured participants, values for shear modulus and viscosity were excluded for one individual due to cSWE equipment failure.

Chapter 4

RESULTS

4.1 Subject Demographics

Subject demographics for each cohort can be seen in Table 1. All applicable quantitative values are displayed in terms of mean ± standard deviation (SD). There were no significant differences in age, height, or weight between injured and uninjured cohorts ($p > 0.05$).

Table 1 – Subject demographics. Applicable quantitative values reported in terms of mean ± SD.

Cohort	**All**	**Uninjured**	**Injured**
n	30	13	17
Age (years)	26.0 ± 11.1	22.1 ± 4.2	29.0 ± 14.0
Sex	16 male	5 male	11 male
Height (cm)	173.3 ± 10.4	170.0 ± 8.4	176.2 ± 11.0
Weight (kg)	71.7 ± 14.8	68.7 ± 13.7	73.5± 15.6

All applicable quantitative values reported in terms of mean ± SD.

4.2 Symptom Duration and Severity

Of the seventeen participants in the injured cohort, two participants had right unilateral patellar tendinopathy, eleven participants had left unilateral patellar tendinopathy, and four participants had bilateral patellar tendinopathy. Of those with bilateral patellar tendinopathy, two participants indicated that the right limb was the more symptomatic limb. VISA-P scores for symptom severity and symptom duration values are shown in Table 2.

Table 2 – Injured cohort injury characteristics.

n = 17	Mean ± SD
Symptom Duration (months)	20.3 ± 24.9
VISA-P (points)	55.8± 16.9

4.3 Differences Between Uninjured and Injured Cohorts

Mean ± SD values for, and significant differences between, applicable main outcome measures are displayed in Table 3. Median ± interquartile range (IQR) values were reported for PAS scores. While there were significant differences for tendon thickness and scores on the VISA-P, the KOOS-QOL, the PCS, and the TSK, no significant differences between cohorts for PAS scores, shear modulus, viscosity, or CMJ and Drop CMJ heights could be identified ($p > 0.05$).

Table 3 – Mean ± SD values for all outcome measures.

Outcome Measure	Uninjured Cohort (n=13)	Injured Cohort (n=17)	p-value	Cohen's d
VISA-P (points)	96.0 ± 4.73	55.8 ± 16.9	$< 0.001^{\Pi}$	3.24
KOOS-QOL (points)	100 (n=12)	54.8 ± 16.5	$< 0.001^{\Pi}$	3.87
PCS (points)	1.54 ± 3.31	5.53 ± 5.58	$< 0.001^{\Pi}$	0.87
TSK (points)	25.6 ± 5.03 (n=12)	34.7 ± 5.55	$0.020^{\#}$	1.72
PAS score	5.0	5.0 ± 2.0	0.742	0.24

Tendon Thickness (cm)	0.342 ± 0.076	0.492 ± 0.195	0.043#	1.01
Tendon CSA (cm^2)	0.768 ± 0.116	1.06 ± 0.431	0.059	0.93
Shear Modulus (kPa)	55.51 ± 13.09 (n=12)	64.8 ± 14.0	0.097	0.69
Viscosity (Pa*s)	21.47 ± 10.30 (n=12)	26.8 ± 9.52	0.152	0.18
CMJ Height (cm)	11.5 ± 3.72	11.3 ± 5.03	1.00	0.05
Drop CMJ Height (cm)	12.0 ± 4.40	12.6 ± 4.43 (n=13)	0.479	0.14

PAS scores displayed in terms of median ± IQR. Significant differences between all main outcome measures across cohorts are indicated by # if p <0.05 or Π if p < 0.001. Cohen's d values indicated large effect sizes if d = 0.8, medium effect sizes if d = 0.5, and small effect sizes if d = 0.2.

4.4 Relationships Between Main Outcome Measures

4.4.1 Uninjured Cohort Relationships

Significant relationships between tendon mechanical properties and all other main outcomes within the uninjured cohort can be seen in Table 4. Moderate positive relationships between CMJ (Figure 6) and Drop CMJ (Figure 7) heights and shear modulus were present. Additionally, relationships between CMJ (Figure 8) and Drop CMJ (Figure 9) heights and viscosity were moderately to strongly positive. No other statistically significant relationships for any of the main outcome measures were found within the uninjured cohort ($p > 0.05$).

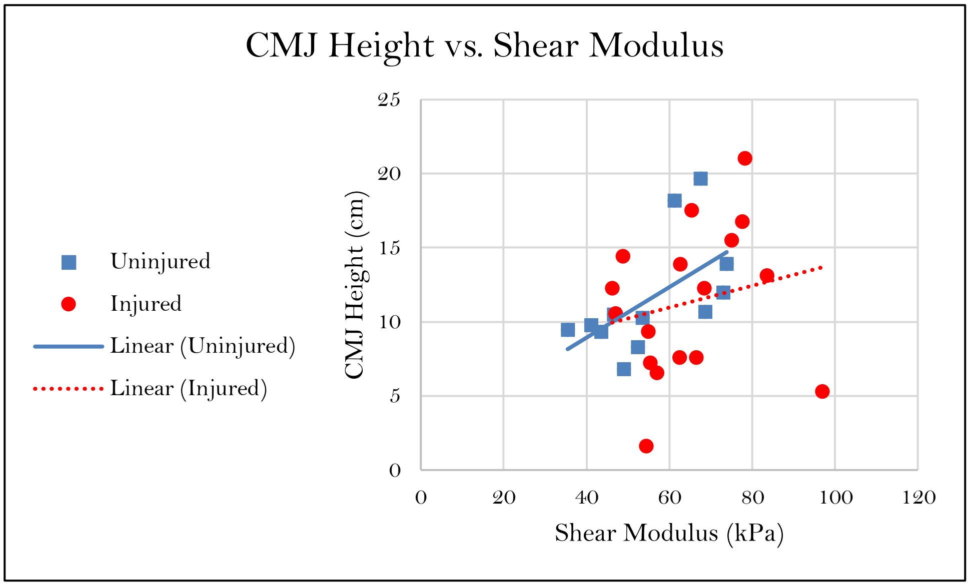
Table 4 – Significant relationships between tendon mechanical properties and all other main outcome measures within the uninjured cohort.

		CMJ Height	**Drop CMJ Height**
Shear Modulus	**rho(ρ)**	0.650	0.629
	p-value	$0.022^{\#}$	$0.028^{\#}$
	n	12	12
Viscosity	**rho(ρ)**	0.650	0.713
	p-value	$0.022^{\#}$	$0.009^{\#}$
	n	12	12

Relationships were considered strong if $\rho > 0.68$, moderate if $0.36 \leq \rho < 0.68$, and weak if $\rho < 0.36$.
$^{\#}p < 0.05$

4.4.2 Injured Cohort Relationships

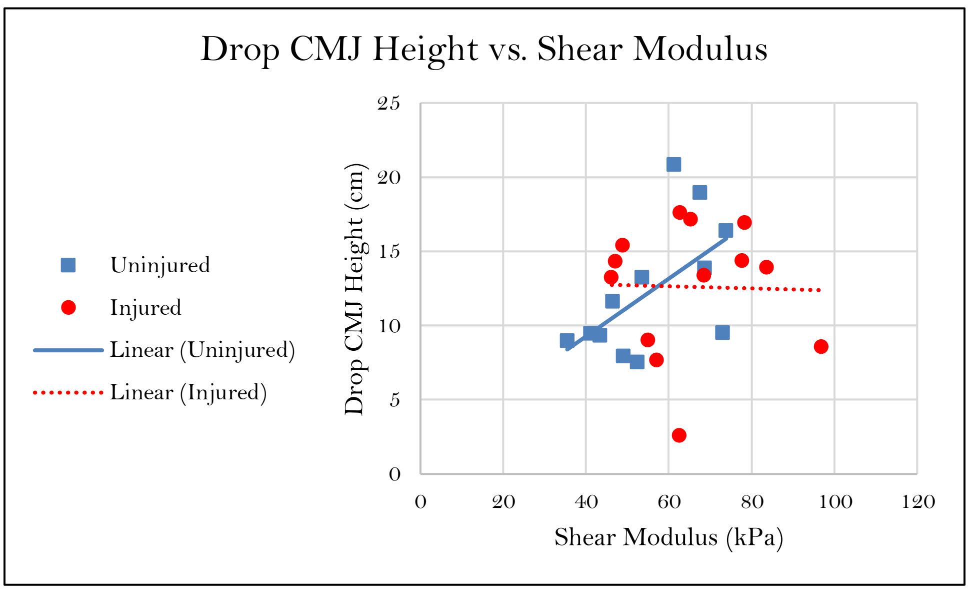
In the injured cohort, a moderate positive relationship between CMJ height and viscosity [n = 17, rho(ρ) = 0.500, p = $0.048^{\#}$] was observed, as seen in Figure 8; however, no relationship between Drop CMJ height and viscosity (Figure 9) could be established, nor were there any significant relationships between CMJ (Figure 6) and Drop CMJ (Figure 7) heights and shear modulus. Significance is for all figured is denoted by $^{\#}p < 0.05$.



Uninjured	
rho (ρ)	0.650
p-value	0.022#
n	12

Injured	
rho (ρ)	0.274
p-value	0.305
n	17

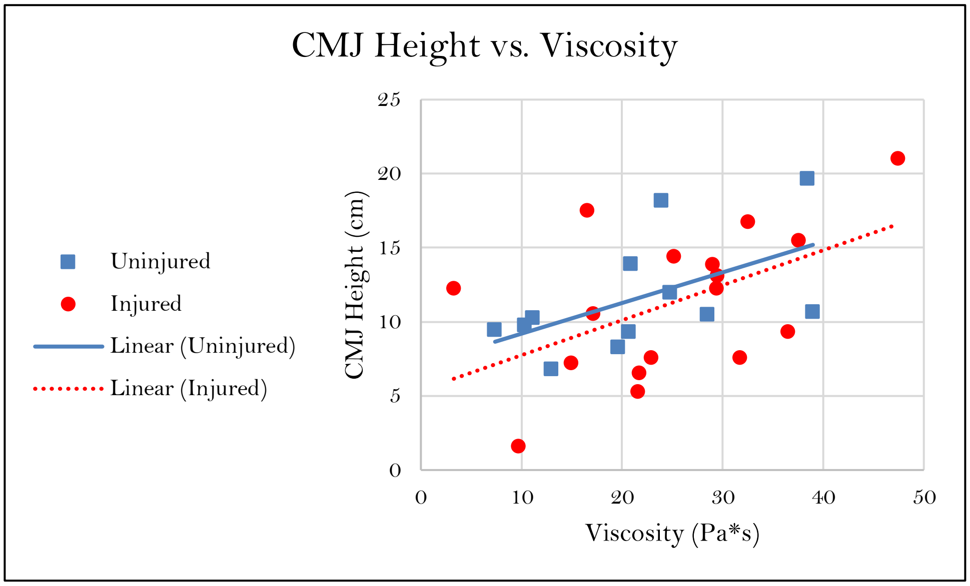
Figure 6 – Relationships between functional performance on the single-leg CMJ test with shear modulus in both cohorts. There was a moderate positive relationship in the uninjured cohort, but there was no significant relationship in the injured cohort.



Uninjured	
rho (ρ)	0.629
p-value	0.028#
n	12

Injured	
rho (ρ)	0.042
p-value	0.897
n	13

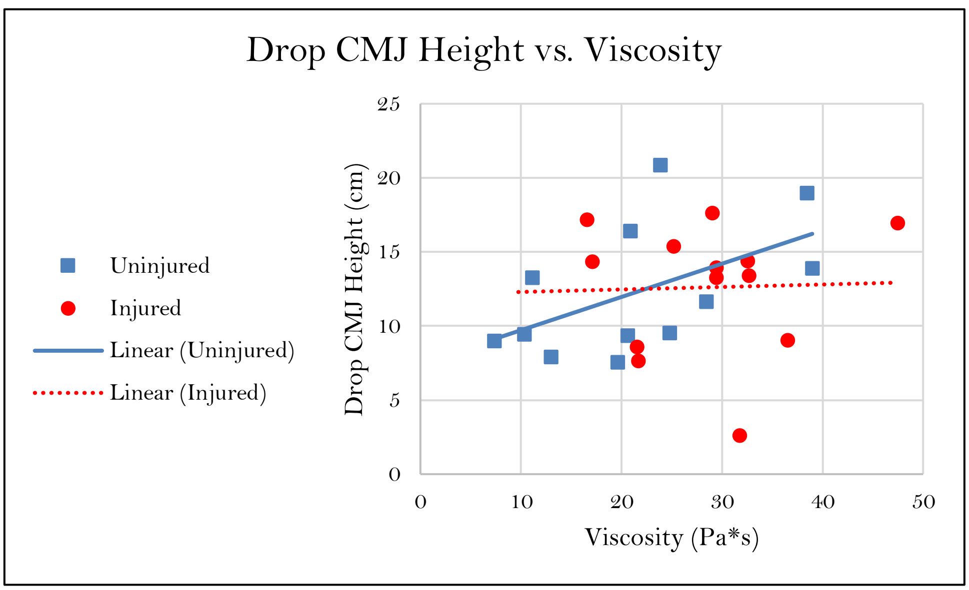
Figure 7 – Relationships between functional performance on the single-leg Drop CMJ test with shear modulus in both cohorts. There was a moderate positive relationship in the uninjured cohort, but there was no relationship in the injured cohort.



Uninjured	
rho (ρ)	0.650
p-value	0.022#
n	12

Injured	
rho (ρ)	0.500
p-value	0.048#
n	17

Figure 8 – Relationships between functional performance on the single-leg Drop CMJ test with viscosity in both cohorts. There was a moderate positive relationship in the uninjured cohort, but there was no relationship in the injured cohort.



Uninjured	
rho (ρ)	0.713
p-value	0.009#
n	12

Injured	
rho (ρ)	0.217
p-value	0.499
n	13

Figure 9 – Relationships between functional performance on the single-leg Drop CMJ test with viscosity in both cohorts. There were moderate positive relationships in both the uninjured and injured cohorts.

Chapter 5

DISCUSSION & CLINICAL RELEVANCE

This study found no significant differences in subject demographics, including age, height, or weight. Significant differences in all patient-reported outcome measures, except for PAS scores, existed between injured and uninjured individuals. Although there was a significant difference in tendon thickness across cohorts, there was no evidence to suggest a significant difference in tendon CSA. Moreover, there were no significant differences in tendon mechanical properties, nor were there significant differences in lower extremity functional performance. For relationships between cohorts, significant relationships between tendon mechanical properties and lower extremity functional performance were identified in uninjured individuals; however, these relationships were limited in individuals with patellar tendinopathy.

It is worth noting that the majority (~65%) of injured participants were male, which holds true with the understood epidemiology of patellar tendinopathy.[2] We noted that, while there were only five males (~38%) in the uninjured cohort, more research can be conducted to further understand how patellar tendinopathy is affected by sex. In an ideal study, an even distribution of males and females would have been controlled for; however, demographics were still statistically significant for this convenience sample.

Looking at the results of the Mann-Whintey u-tests, both statistically significant and insignificant differences were found. Symptom severity (VISA-P) was significantly different between cohorts, as was knee-related quality of life (KOOS-QOL). Both of these patient-reported outcome measures have been proven as valid and reliable tools to evaluate the effect of injury, so the significant differences between injured and uninjured cohorts are expected.[14,15] Injured participants scored an average VISA-P score of 55.8/100, indicating that they were dealing with symptoms during collection. Moreover, all thirteen uninjured participants scored a perfecto 100/100 on the KOOS-QOL, indicating no limitations in activities of daily living due to knee injury.

Significant differences also existed in kinesiophobia and pain catastrophizing tendencies across cohorts. Past research has shown that individuals with patellar tendinopathy are more likely to exhibit pain-avoidance behaviors, and that these behaviors may come to affect other outcomes, such as lower extremity function.[26] Seeing these differences, this study also tested for relationships between average TSK and PCS scores and CMJ and Drop CMJ heights. While these relationships proved to be weak and insignificant, kinesiophobia and pain catastrophizing tendencies may still be influencing performance to some degree. For example, it is worth noting that only thirteen out of seventeen uninjured individuals completed the Drop CMJ height, possibly due to kinesiophobia associated with the movement.

Of all the patient-reported outcome measures used in this study, only scores on the PAS did not differ significantly between cohorts. Commonly, individuals with patellar tendinopathy continue athletic competition or physical activity despite symptoms.[5] This, coupled with the lack of baseline data for both cohorts, could help explain the insignificant difference in physical activity levels, since it is not known if the injured cohort had changed their activity levels due to injury.

For the observed differences in tendon structure, this study found a significant difference in patellar tendon thickness between cohorts; however, no significant difference was found in patellar tendon CSA. Previous studies have prospectively tracked long-term changes in patellar tendon morphology in athletes with and without patellar tendinopathy.[3,10] In both instances, the majority of evidence indicates significant differences between uninjured and injured individuals.[3,10,20,27] Furthermore, these findings have also suggested that ultrasonography may possess utility in diagnosing patellar tendinopathy and other musculoskeletal injuries.[5,20,27] Although the observed difference in CSA proved to be non-significant ($p = 0.59$), this is likely due to small sample sizes in each cohort.

For differences in tendon mechanical properties, it is possible that this study may have been underpowered in detecting a difference in shear modulus ($d = 0.69$). A power analysis revealed that the addition of 49 participants in each cohort would likely allow for the detection of a significant difference. Therefore, a larger study is needed to determine the importance of tendon mechanical properties.

It is worth noting that shear modulus had a relatively high variance and a mean difference of approximately 10.0. The minimal detectable change for shear modulus is listed at 6.0 in Achilles tendons, and the method for patellar tendons is ongoing.[21] It may also be possible that shear modulus is a more sensitive measure to detect differences between uninjured and injured patellar tendons. The reliability of the methods used in this study should be evaluated further to determine if the observed difference is actually relevant or simply due to measurement error. It may be expected that shear modulus would change due to patellar tendinopathy, given that its relationships in the uninjured cohort are different from its relationships in the injured cohorts. On the other hand, viscosity demonstrated relationships with functional performance in both cohorts, so it is possible that this measure might not be as influenced by injury.

Past research has shown significant differences in Achilles tendon mechanical properties between injured and uninjured individuals; however, these studies use commercial shear wave elastography units that do not differentiate between shear modulus or viscosity.[28] Moreover, the inclusion criteria in similar studies is also limited to total tendon rupture, rather than tendinopathy. Other research has focused on elastic modulus, another mechanical property not measured through shear wave elastography. Elastic modulus is obtained through muscle contraction and tendon loading, which may be contraindicated in individuals with patellar tendinopathy due to the pain it elicits.[29] Based on the results of this study, it appears that measuring multiple mechanical properties using cSWE, in individuals with and without patellar tendinopathy, may be more clinically-relevant than focusing on a single outcome measure in individuals with and without total tendon rupture.

In addition to tendon mechanical properties, there was no evidence to suggest a significant difference in lower extremity functional performance as assessed by the single-leg CMJ and Drop CMJ tests. It is likely that the lack of baseline data in the injured cohort may explain these insignificant differences. Patellar tendinopathy most commonly effects male athletes in jumping-intensive sports, so it is possible that the injured participants in this study had higher jump heights prior to injury. Moreover, it is possible that these injured athletes are compensating at the hip or ankle to maintain lower extremity function. Other studies have shown similar findings to indicate that functional performance is a measure independent of injury. [3,5,10,30] In fact, some prospective studies have shown that maximum vertical jump heights have increased in athletes with patellar tendinopathy over time.[30]

Looking at the results of the relationships within the uninjured cohort, tendon mechanical properties appear to be associated with lower extremity functional performance in individuals without patellar tendinopathy. For these uninjured individuals, patellar tendon mechanical properties and lower extremity performance would be expected to present without impairments. Moreover, individuals without patellar tendinopathy have better overall patellar tendon health, compared to those with patellar tendinopathy.[8] There is knowledge to suggest that mechanical properties contribute to normal gait and lower extremity function, so the findings within the uninjured cohort would be expected.[12,13,31]

Nonetheless, it may be of interest to utilize the single-leg CMJ and Drop CMJ tests in baseline assessment of uninjured individuals. For example, clinicians could test volleyball or basketball athletes prior to the start of a competitive season. If changes occur in jumping performance during the season, then this might be an indication of changes in patellar tendon health. Therefore, clinicians could address mechanical properties without directly assessing them, which might not be feasible considering the relatively limited availability of shear wave elastography in clinical settings.[12]

As previously discussed, viscosity appears to be a less sensitive value compared to shear modulus. The fact that we found an insignificant difference ($p = 0.152$) with a small effect size ($d = 0.18$) may point to the idea that viscosity is less effected by patellar tendinopathy in comparison to shear modulus ($p = 0.097$, $d = 0.69$). Furthermore, given that no relationships within the injured cohort existed for shear modulus, it might just be that this is a measure more dependent on injury. Regardless of the reason, it is important to note that patellar tendon mechanical properties, shear modulus and viscosity, appear to be measuring separate constructs due to injury.

Again, looking at lower extremity functional performance, it appears that jump height is largely independent of patellar tendinopathy.[3,5,10,30] Even though we do not see a significant relationship between viscosity and Drop CMJ height, it is worth noting that only thirteen out of seventeen participants completed this test. Given that we also see relationships between viscosity and CMJ height in our results, it may be possible that viscosity alone possesses some utility in monitoring changes in function due to patellar tendinopathy.

If this is not the case, then there are likely additional confounding variables at play to account for the differences in relationships across cohorts. In fact, it is possible that factors due to injury, including pain, kinesiophobia, or muscle weakness or inhibition, may be affecting lower extremity function, normal tendon loading, and gait. It is well understood that pain and kinesiophobia play a substantial role in musculoskeletal injuries.[5,8,26] As previously mentioned, this study showed significant differences in pain catastrophizing tendencies and kinesiophobia in individuals with and without patellar tendinopathy. Moreover, injured individuals had increased symptom severity, worsened quality of life, and impairments in tendon structure, furthering the notion that both psychological and physiological confounds may be present.

While a number of specific causes can be hypothesized, these injurious impairments should be addressed on an individual basis. Therefore, it is imperative that clinicians implement a variety of clinical outcome measures in their assessment and management of individuals with patellar tendinopathy. Using a holistic approach to identify specific confounds, clinicians may achieve better outcomes for individuals in this patient population.

Chapter 6

CONCLUSION

It is important to understand that tendon mechanical properties have previously been identified as a relatively novel component of tendon health.[12,13] After testing for relationships between mechanical properties and other outcome measures, we found that these relationships differ in individuals with and without patellar tendinopathy. In healthy individuals, tendon mechanical properties relate to jumping performance, but this relationship was not found in injured individuals. The differences in relationships might be due to confounding variables associated with injury, such as kinesiophobia, pain, or muscle weakness or inhibition affecting jumping performance. Therefore, in order to best evaluate tendon health and rehabilitate patients with patellar tendinopathy, it is recommended that clinicians apply an array of outcome measures, including patient-reported outcome measures, diagnostic ultrasound imaging, cSWE, and functional testing, on an individualized basis.

Chapter 7

LIMITATIONS & FUTURE CONSIDERATIONS

Two major limitations from this study were sample size and subject diversification. The original proposal for this thesis was presented in August 2018, leaving only six months to collect data and prepare a defense. Due to outside academic and clinical obligations and technological malfunctions, a limited number of participants were recruited for the uninjured cohort and included in the results. Moreover, the majority of these participants were student volunteers from a similar population within the University of Delaware. Future studies should have a controlled design and match participants for sex, age, and activity level.

Given that this study was cross-sectional in nature, it lacked pre-injury data for the injured cohort. The use of baseline data could have been important in accounting for possible confounding variables. Additionally, this information may have accounted for or helped explain some of the insignificant differences between injured and uninjured cohorts.

Another limitation was lack of established reliability and validity with regards to performing cSWE at the patellar tendon. As mentioned above, cSWE has been proven valid and reliable at the Achilles tendon, and its reliability is still under investigation at the patellar tendon.

Future studies that are interested in only analyzing an injured or tendinopathic cohort should consider using Limb Symmetry Indexes (LSIs) to establish normative values for all applicable main outcome measures. LSIs are reported as percentages and are calculated by dividing injured values by uninjured values. LSIs were not used for this study, given the inclusion of individuals with bilateral patellar tendinopathy;

however, application of LSIs might have relevance for another study focused solely on individuals with unilateral patellar tendinopathy. Moreover, LSIs may eliminate the need to collect data on uninjured individuals while also controlling for confounds.

Finally, future research should adopt longitudinal or prospective designs to determine if the results of this study hold true over time. Tracking changes in outcome measures, specifically mechanical properties, may provide the most relevant information to clinicians in their assessment and rehabilitation of patellar tendinopathy.

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