Comparative Study of Anterior Cruciate Ligament Graft Mechanical Properties

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INTRODUCTION: Anterior cruciate ligament (ACL) tears are a common orthopedic injury, typically demonstrating a peak incidence in young athletic populations. Over the past several decades, the number of ACL reconstructions being performed has significantly increased, with over 200,000 ACL reconstructions being performed annually[1,2,3]. Despite being one of the most common orthopedic procedures, ACL reconstruction is still a topic of debate due to a lack of concrete consensus on graft selection. For primary ACL reconstructions, autografts have been established as superior to allografts for younger patients; however, the type of autograft remains controversial [4,5]. Bone-patellar tendon-bone (BPTB) grafts are often considered the gold standard; yet, combined gracilis tendon and semitendinosus (HT) grafts are used more frequently in clinical practice[4,5]. Additionally, the quadriceps tendon (QT) graft, which was initially introduced in 1979, is increasing both in clinical utilization and research focus[4,6]. However, each have drawbacks, meaning much is still to be explored regarding the appropriate graft selection. Specifically, in evaluation of the mechanical properties for each type of graft in attempt to restore the native mechanical properties of the knee. Moreover, the plastic region of these grafts has yet to be evaluated which could be informative of post-operative instability prior to rupture. Therefore, the objective of this study is to evaluate the plasticity and the failure properties of each graft type.

METHODS: Eleven right cadaveric knees (6 male and 5 female) with a mean age of 71 (range 55-81) were dissected, and the following grafts were harvested: BPTB, HT, and QT. All grafts were fixed using serrated jaw clamps fixed at both ends, as previously recommended for tendon autografts. Since HT and QT autografts did not have bone blocks, both ends were wrapped with a one cm wide nylon belt at both ends to ensure fixation. This method was verified in a pilot study to ensure tendon failure occurred within the midsubstance of the tendon and did not come from failure within the clamp. Prior to mechanical testing the grip-to-grip length was recorded using a digital caliper to determine the working length of the specimen to be used determining the mechanical properties. Each graft was preloaded to 10N to remove any slack in the system and cycled 20 times from 50-250 N at a rate of 1mm/s to remove any viscoelastic effects during testing. Lastly, the grafts were loaded at 100 N/s until failure. Force – Displacement curves for each graft was analyzed using a custom-built in-house MATLAB (MathWorks, Natick, MA) to determine the failure force and was then converted to stress-strain curves, where stress was defined as $\sigma = \frac{F}{W*t}$, and the strain was defined as $\varepsilon = \frac{\Delta L}{L}$ for all data points. The stress-strain curves were then input the open-source software, Dots-on-Plots™**,** which has been developed to analyze soft tissue mechanics. Outputs from this included the linear modulus (MPa), yield stress, yield strain, failure stress, and failure strain, where the yield point was determined as 2% stress deviation from a linear region fit. Finally, the plastic strain was calculated as the $\varepsilon_{Failure} - \varepsilon_{Yield}$. Data were analyzed using a one-way repeated measure ANOVA, for all mechanical properties for the three graft types. The Tukey *post-hoc* test followed analysis for multiple comparisons of simple effects between graft options. Two tailed p values <.05 were considered significant.

RESULTS: The native ACL had a significantly lower failure load, young's modulus, yield strain, failure strain and plastic strain compared to all graft options (**Tables 1** and **2**). Compared to the PT and HT grafts, the ACL also had a significantly lower yield and failure stress. When comparing the graft options the QT has the lowest failure load, was the least stiff (lowest young's modulus) and had the lowest failure strain. However, the QT as the most similar properties to the native ACL.

DISCUSSION: Many previous studies have analyzed the mechanical properties of ACL graft options. However, these studies only evaluated the failure properties. Assessing the plastic properties could provide insight when assessing post-operative instability when a tear is not present. While graft option is important to consider when restoring the native biomechanical properties of knee during ACL reconstruction, donor site comorbidities should also be considered. Our study has shown that the plasticity between grafts was not significantly different. However, when assessing patients post-operatively who present knee instability, knowing if they lie in the plastic region, which could be calculated from MRI, could aid clinical decision making for these patients.

SIGNIFICANCE/CLINICAL RELEVANCE: ACL reconstruction is one of the most common orthopedic injuries, typically seen in the younger athletic population. Proper graft selection is important for timely return to sport and restoration of the native biomechanics of the knee joint. Better understanding of how graft options compare to the native ACL can help improve clinical decision making.

Table 2. *Mechanical properties of native ACL and ACL reconstruction graft options*

Mechanical Property	Anterior Cruciate Ligament (ACL)	Quadriceps Tendon (QT)	Patellar Tendon (PT)	Hamstring Tendon (HT)
Failure Load (N)	238.05 ± 84.36	579.32 ± 155.43	593.03 ± 177.41	828.62 ± 257.89
Youngs Modulus (MPa)	21.54 ± 14.95	110.81 ± 25.29	207.13 ± 51.02	142.90 ± 40.25
Yield Stress (MPa)	2.66 ± 1.37	3.54 ± 1.08	6.54 ± 2.93	5.14 ± 1.76
Failure Stress (MPa)	4.61 ± 1.87	7.47 ± 2.27	11.45 ± 3.40	11.77 ± 4.20
Yield Strain (mm/mm)	0.260 ± 0.112	0.116 ± 0.042	0.159 ± 0.059	0.128 ± 0.042
Failure Strain (mm/mm)	0.396 ± 0.121	0.169 ± 0.054	0.205 ± 0.074	0.207 ± 0.041
Plastic Strain (mm/mm)	0.136 ± 0.046	0.053 ± 0.020	0.046 ± .029	0.078 ± 0.032

Table 2*. Statistical significance between mechanical properties and graft options*

Mechanical Property	ACL vs QT	ACL vs PT	ACL vs HT	QT vs PT	QT vs HT	PT vs HT
Failure Load (N)	0.0027	0.0017	<.0001	0.9983	0.0216	0.0325
Youngs Modulus (MPa)	<0.0001	<0.0001	<0.0001	<0 0001	0.2217	0.0020
Yield Stress (MPa)	0.7869	0.0012	0.0578	0.0072	0.2695	0.3814
Failure Stress (MPa)	0.2544	0.0004	0.0002	0.0349	0.0198	0.9956
Yield Strain (mm/mm)	0.0002	0.0122	0.0007	0.4331	0.9726	0.6959
Failure Strain (mm/mm)	<0.0001	<0.0001	<0.0001	0.6811	0.6536	>0 9999
Plastic Strain (mm/mm)	<0.0001	<0.0001	0.0028	0.9597	0.2812	0.1133