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Original Article

Clinical anatomy and mechanical tensile properties of the rectus femoris tendon

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Abstract: Purpose: We aimed to provide anatomical data and mechanical tensile properties for the rectus femoris tendon to determine if it is a feasible substitute for the anterior cruciate ligament during knee joint reconstruction. Methods: The length and width of the quadriceps femoris tendon were measured from ten adult cadavers (20 knees; age =48±2 years). The anatomic features of the patellar insertion on the quadriceps femoris tendon were also documented. The rectus femoris tendon and anterior cruciate ligament were harvested from an additional five fresh specimens (10 knees; age =41±3 years). To minimize dehydration, each specimen was wrapped in saline-moistened paper towels and stored at -10°C. We imposed tensile stresses on a total of twenty samples in a sample-driven machine at 10 mm/min until the specimens failed. Results: The inserted and discrete widths of the rectus femoris tendon were 3.20±0.33 and 1.28±0.25 cm, respectively. The length of the tendon tissue was 6.96±0.80 cm and the length of mixing zone was 3.81±0.53 cm. The average thickness of the upper pole of the patella was 2.22±0.14 cm. In mechanical tensile properties, the unit modulus and unit maximum load of the rectus femoris tendon were both 63% of the anterior cruciate ligament. Conclusions: Based on its anatomical and mechanical tensile properties, the rectus femoris tendon is a feasible donor site to reconstitute the anterior cruciate ligament.

Keywords: Rectus femoris tendon, anterior cruciate ligament, anatomical, mechanical

Introduction

In most developed and developing countries, outdoor activities have been an entertainment living style. However, some sports such as soccer and basketball often lead to knee injury [1], which has become the most common cause of permanent disability in sport injury, documented in a few epidemiology studies [2, 3]. Particularly, cruciate ligament ruptures, was increased significantly [4]. Currently, the most commonly used method to reconstruct the cruciate ligament is an autologous patellar tendon or hamstring graft. However, this surgery has drawbacks that limit its practical use, i.e., morbidity and muscle weakness in the area where graft was obtained [5].

In recent years, the rectus femoris tendon has been used for anterior cruciate ligament reconstruction with good clinical results [6-8]. However, the clinical applicability of the rectus tendon, i.e., the anatomical and mechanical properties, has not been reported. In this study, we documented the anatomical and biomechanical properties of the rectus tendon, which provided a theoretical basis for the reconstruction of the anterior cruciate ligament using the rectus tendon. Based on our recorded physical properties, the rectus femoris tendon can be used as a substitute for the anterior cruciate ligament in reconstructive surgeries.

Materials and methods

Written informed consents were obtained to take twenty knees from ten adult cadavers (seven males and three females, age =48±2 years). The study protocol was reviewed and approved by the ethics committee of our hospitals. The following data were carefully recorded, including the shape of the quadriceps tendon, location of the lower limb, and relationship between the muscles of the leg. The muscles around the patella were removed to expose the quadriceps tendon where it attaches to the

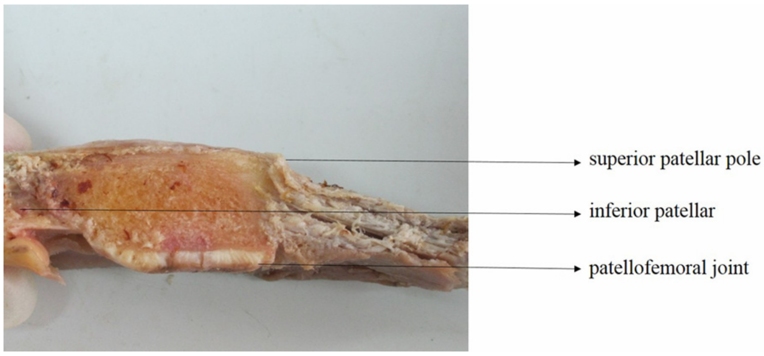

Figure 1. Anatomy of the tendon of the quadriceps femoris and the upper pole of the patella.

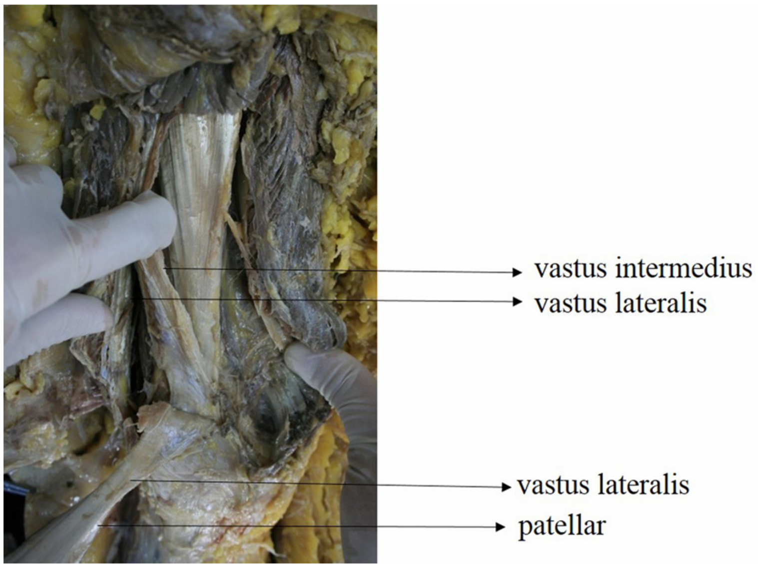

Figure 2. Anatomy of the tendons of the rectus femoris, vastus lateralis, and vastus intermedius.

patella. The length, width, thickness, and mixed length of the tendon, as well as the thickness of the upper pole of the patella were measured by vernier caliper.

We obtained an additional five fresh cadavers, totally ten knees, from three males and two females, with an average age of 41±3 years. Specimens were collected within 9.0-10.0 h after the donors deceased, per requirements for biomechanical experiments. In addition, the vastus lateralis tendon joins the rectus femoris tendon before it connects to the upper pole of the patella. The rectus femoris tendon and anterior cruciate ligament were carefully removed from each knee, wrapped with gauze immersed in physiological salt solution, and stored at -10°C for later use. Before each experiment, the specimens were thawed at room temperature and the rectus femoris tendon and anterior cruciate ligament was cut into 10 samples using a surgical scalpel. The original sample size of the specimens was measured with a vernier caliper.

It is well known that biological materials undergo hysteresis under tensile stress, resulting in a loss of mechanical energy and deformation [9]. Thus, the samples must be pre-conditioned and processed before each experiment. In this study, all samples underwent 10 repeated loading and unloading cycles at the level of 30% in the failure stress test [10]. The test specimens were clamped into an Instron 55-69 material testing machine (Cambridge, Massachusetts, USA) (**Figure 3**), at normal body temperature (36.5±0.5°C). The clamping head is a pressure device, and the tendon was clamped by pressure air to avoid any potential damages to the specimens. A tensile load of 10 mm/min was applied to the samples until they failed, and the computer automatically outputted experimental data. For the rectus femoris tendon and anterior cruciate ligament, maximum load, maximum stress and maximum strain were recorded. Modulus, which is also known as the elastic modulus, is a mechanical property of linear elastic solid materials. It defines the relationship between stress (force per unit area) and strain (proportional deformation) in a material. Load, in mechanics, is the external mechanical resistance against machine. The load can often be expressed as a curve of force versus speed. Stretch in continuum mechanics is the transformation of a body from a reference configuration to a current configuration. A configuration is a set containing the positions of all particles of the body. Stress is a physical quantity that expresses the internal forces that neighboring particles of a continuous material

Figure 3. The Instron 5569 material testing machine used to measure mechanical tensile properties of tissue samples.

exert on each other, while strain is the measure of the deformation of the material.

Statistical analysis

SPSS version 16.0 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. The data were expressed as mean ± standard deviation. A two-tailed value of $P < 0.05$ was considered statistically significant.

Results

Anatomy of the rectus femoris tendon

The quadriceps tendon is attached to the upper three-fourths of the upper pole of the patella; there is no ligament on the patellofemoral articular surface of the upper pole of the patella (**Figure 1**). The proximal four-fifths of the rectus femoris is fully discrete; in contrast the distal one-fifth is fused with the vastus lateralis and vastus intermedius to form the quadriceps femoris tendon, which inserts into the upper three-fourths of the anterior aspect of the upper patellar pole. Dissecting out the tendon of the rectus femoris is challenging (**Figure 2**), because the tendon of the rectus femoris is long, and most of the tendon is mixed with muscle. The region where the rectus femoris mixes with the vastus lateralis is known as the tendon mixed region. The junction of the tendon mixed region with the muscle and tendon of the rectus femoris is known as the starting point, and the upper pole of the patella is known as the ending point.

The width to the ending point of the rectus femoris tendon was 3.20±0.33 cm and the width to the starting point was 1.28±0.25 cm. The length of the tendon mixed region was 3.81±0.53 cm, and the length of the rectus femoris tendon was 6.96±0.80 cm. We observed a distance of greater than 8 cm from the rectus femoris tendon to the superior patellar pole in the 20 specimens. The thickness of the superior patellar pole was 2.22±0.14 cm, and the thickness of the rectus femoris tendon attached to the superior patellar pole was 1.00±0.26 cm.

Biomechanical measurements of the rectus femoris

We measured the length, width, height and volume of the rectus femoris and the anterior cruciate ligament. We also measured the physical parameters including modulus, maximum load, maximum stretch, and maximum stress of the two tendons from 10 subjects. Based on these data listed in **Tables 1** and **2**, we calculated and compared the unit modulus, unit maximum load, stretch and stress between the two groups. There were no any difference in the unit modulus of the rectus femoris and anterior cruciate ligament (0.054±0.038 vs 0.061±0.024, P=0.88) (**Figure 4**). There was also no statistical difference in the maximum load (0.38±0.08 vs 0.22±0.05, P=0.14), the maximum stretch (0.011±0.005 vs 0.0009±0.0003, P=0.09) and the maximum stress (0.017±0.012 vs 0.006±0.002, P=0.43), although the average values of the rectus femoris were smaller. These data together suggest that the rectus femoris tendon is a physical and functional equivalent of the anterior cruciate ligament.

Discussion

Reconstructive surgery of the anterior cruciate ligament is performed frequently, and many

Table 1. Results from the middle third of the rectus femoris tendon

	Number	Minimum	Maximum	Mean	Standard deviation
Unit modulus	10	.012183	.275463	.06144665	.080190036
Unit maximum load	10	.06043	.62310	.2201049	.18074089
Unit maximum stretch	10	.00013	.00260	.0009580	.00105920
Unit maximum stress	10	.00126	.02396	.0066231	.00686781

Table 2. Measurements from the anterior cruciate ligament

	Number	Minimum	Maximum	Mean	Standard deviation
Unit modulus	10	.001918	.417109	.05403902	.127860005
Unit maximum load	10	.06082	.89640	.3841232	.29032002
Unit maximum stretch	10	.00038	.06188	.0113664	.01860083
Unit maximum stress	10	.00093	.13198	.0171797	.04039842

graft choices are currently used [11, 12]. However, there is no ideal graft that prevents postoperative problems, such as complications from the donor site, knee pain, and unsatisfactory clinical results [13]. As the number of cruciate ligament reconstruction surgeries increase dramatically these years, cruciate ligament revision surgery due to failure or other causes must also emerge. In revision surgery, the choice on donors must be considered by clinicians.

In this study, we found that use of the rectus tendon to repair the anterior cruciate ligament is feasible. Anatomical results suggest that the tendon of the rectus femoris muscle is greater than 8.0 cm, and the proximal end is free from surrounding tissue. The thickness of the proximal attachment to the superior patellar pole is approximately 1.00 cm; thus, surgery would not destroy the integrity of the joint capsule and would not increase the difficulty of arthroscopic surgery. The thickness of the superior patellar pole was 2.22 cm, and excising the tendon with a bone block graft would facilitate reconstruction of the anterior cruciate ligament. As for the choice of the substitute, the rectus tendon is safer than the patella-patellar tendon-tibial tuberosity choice, since it does not destroy the vessels or nerves and results in fewer complications. Actually we are not the first to suggest using the rectus femoris tendon to reconstruct the anterior cruciate ligament. Stäubli et al. investigated the biomechanics of the quadriceps tendon and patellar ligament in young patients [14], and Noyes et al. in 1984 compared the biomechanical properties of the rectus femoris tendon, iliotibial band and patellar ligament [15]. Our results suggest that the mechanical tensile properties of the anterior cruciate ligament and rectus femoris tendon provide a theoretical basis for the selection of the appropriate alternative in anterior cruciate ligament reconstruction. The maximum load may be the most important parameter to consider, in that it must be sufficient to withstand the large anticipated in vivo loads that first produced the injury [16]. Compare to result of Noyes, the maximum load withstood by the rectus femoris tendon in our study suggests that it is a feasible alternative for anterior cruciate ligament reconstruction.

Mechanical testing of tendons and ligaments is challenging and prone to error. Two main factors determine the strength of ligaments under load: ligament geometry and load speed. The cross-sectional area of the ligament also affects its tensile strength. An increased number of fibers in the direction of loading, as well as wider and thicker fibers, increase the strength of the ligament. Similar to bone, as the speed of loading increases, ligament strength and stiffness also increase. Indeed, Woo et al. showed that slower loading speeds frequently result in ligament avulsion [17]. Furthermore, Cooper et al. suggested that the distance between grippers in the mechanical tester is not precise enough to calculate the length of stretching because of slipping [18]. For the

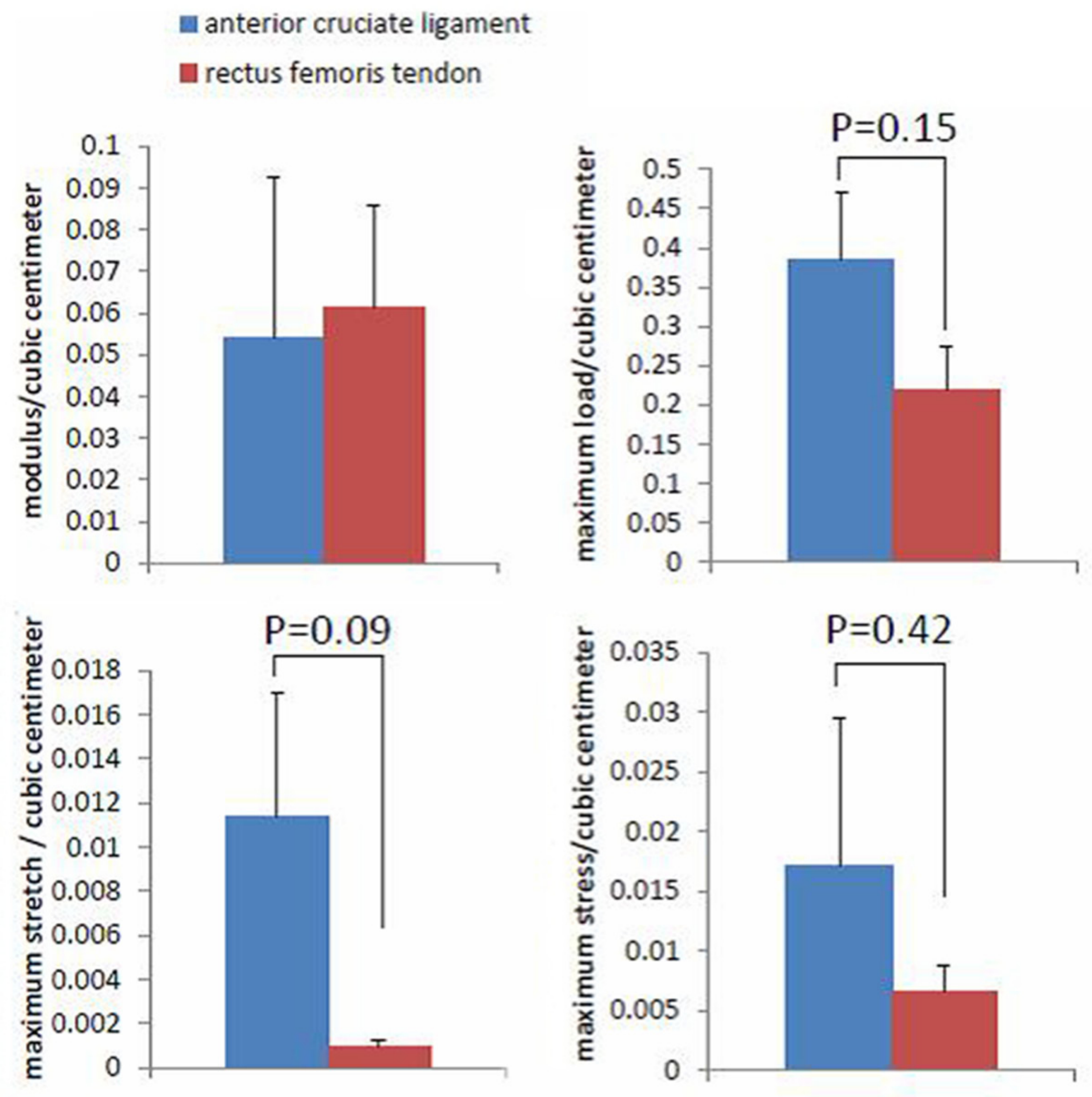

Figure 4. Comparison of the physical parameters between the anterior cruciate Ligament and rectus femoris tendon. N=10.

present study, we used the most advanced mechanical measurement tools available, to reduce the error as much as possible, to measure the tensile properties of tendon and ligament. The grippers of the mechanical tester we used applied the appropriate amount of pressure to avoid destroying tissue samples. This study was performed in vitro, and the in vivo environment is very different owing to issues such as bone tunnel and ligament rotation. Cruciate ligament reconstruction surgery is a very complex task, and many factors affect the clinical efficacy of the surgery, including considerable biomechanical properties, skilled surgical techniques, the correct fixing methods, the appropriate ligament tensioning, and proper postoperative rehabilitation [19, 20]. Thus, the clinical efficacy of using the rectus femoris tendon as a substitute for the anterior cruciate ligament in reconstructive surgery requires practical examination.

In addition, biophysics of tendon probably is varied by subjects, including gender, age, body weight, health condition etc. Here we recorded male versus female, ages and body weight; however, during experiments, we did not measure height and length of legs, which should have provided more information. First, male versus female on tendon's biophysics. In total, the tendons from ten adult cadavers and five fresh specimens were measured. There were seven male cadavers, three female cadavers, two fresh male specimens and three fresh female specimens. We examined whether the tendon parameters measured here is different between male versus female, and the results were not dramatic significant (data not shown). Since there were big variation among subjects, a larger number of subjects should be examined to get a statistical meaningful conclusion. Second, effects of body weight on tendon's biophysics. the body weight of seven male cadavers were respectively range from 60 kg to 63 kg, and the body weight of three female cadavers were 50 kg, 53 kg, and 52 kg. The body weight of two male specimens were 60 kg, 63 kg, and the body weight of three female specimens were 48 kg, 49 kg and 47 kg. Similarly, due to very limited samples, we did not observed significant difference among subjects with different body weights. Lastly, we believe the ages of subjects should affect the biophysical property of the tendons; therefore, we picked the subjects with similar ages, 48±2 years old of cadavers and 41±3 years old of fresh subjects.

Conclusion

In this study, we provided a theoretical basis for the choice of a graft substitute in anterior cruciate ligament reconstruction surgery. Our results demonstrated that rectus femoris tendon can be used as a substitute for the anterior cruciate ligament in the surgery.

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Disclosure of conflict of interest

None.

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