THE MECHANICAL PROPERTIES OF HUMAN ANTERIOR CRUCIATE LIGAMENT ARE DEPENDENT ON SEX

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INTRODUCTION

Females participating in athletic events injure their ACL more frequently than males (Arendt and Dick., 1995). Various anatomical, neuromuscular, and hormonal factors have been investigated as the cause for the significantly higher rates of the ACL failure incidents in female athletes as compared to their male counterparts. However, after immense amounts of research and athletic training, the root cause of the existing disparity still remains unknown and the sex-based disparity in the ACL injury rates has not diminished (Agel et al., 2005). The disparity is believed to be due to multitude of reasons including lower mechanical quality (defined as a measure of goodness of properties) in females. To date, the possibility that the female ACL is mechanically weaker than the male ACL has not been directly investigated. Although it has been established in the literature that the female ACL is smaller in size (Chandrashekar et al., 2005) the differences in the structural and mechanical properties of the ACL between sexes have not been studied. Any sex differences in the mechanical properties of the ACL might reflect a difference in the internal structure of the ACL. Therefore it is important to investigate how the tensile properties of ACL vary by sex. We hypothesize that male ACL has better structural and mechanical1 properties than female ACL even after considering the donor and ACL anthropometric variables as a covariates.

METHODS

Twenty healthy unpaired knees (10 male and 10 female) were harvested from donors within 12 hours after their death and were frozen at -20^{0}C till the day of the experiment. The average age of donors were 38 years and the range was 17-50 years. The male donors were taller and heavier than the female donors. On the day of the experiment, the knees were thawed and dissected. The average length of the ACL was measured using a vernier caliper and the minimum cross-sectional area and volume of the ACL were measured using a 3D Scanner (Hashemi et al., 2005). The femur and tibia were mounted on a custom made jig and the ACL was tested in tension at 100%/s along the ligamental axis using a tensile testing apparatus. The structural and mechanical properties were calculated with failure being assumed to have occurred at maximum load. . To investigate if sex-based differences in structural properties exist, a multivariate regression analysis was performed for structural properties (elongation at failure, ultimate load, stiffness and energy absorbed) with only age and sex as covariates. To test for sex-based differences in the mechanical properties, age, sex, donor anthropometric variables and ACL size were added as covariates to structural properties and also mechanical properties. The multivariate regression was performed to test if sex is a significant factor determining the tensile properties of the ACL.

RESULTS AND DISCUSSION

Of the twenty ACLs, three (two male and one female) failed by avulsion and hence were excluded from statistical analysis. The male ACLs were significantly longer, had significantly larger cross-sectional area and volume. The measured structural and mechanical properties in both sexes are given in Tables1,2.

Table 1. Structural properties of the ACL stratified by sex

Sex	Elongationt at failure (mm)	Load at Failure (N)	Stiffness (N/mm)	Energy absorbed at Failure (N-mm)
Male (n=8)	8.95 ± 2.12	1818 ± 699	308 ± 89	7280 ± 3624
Female (n=9)	7.48 ± 2.56	1266 ± 527	199 ± 88	4691 ± 3623

When only age and sex were considered as covariates, the multivariate regression model showed sex to be a significant factor in determining the elongation ($p=0.03$), ultimate load ($p=0.01$), stiffness ($p=0.05$) and energy absorbed ($p=0.03$). This showed a sex based differences in the structural properties of the ACL. In order to test if sex based differences in the mechanical properties of the ACL exists; the donor anthropometry and ACL size were added as covariates. The P-value for sex in such model was statistically significant ($p<0.05$) for all the response variables. Though the response variables were structural properties, in this case, since ACL geometric parameters are added as covariates, this is indicative of differences in the mechanical properties of the ACL. However, to verify this, a similar multivariate regression analysis was performed based on the traditional definitions of mechanical properties (Table 2). The results were similar to the earlier model with p-value for sex being less than 0.05 in all cases. This study shows a sex based difference in the mechanical properties of the ACL and can be one intrinsic factor contributing to sex-based differences in ACL injury rate. It is evident that the female ACLs have different tensile properties not only because they are smaller but due to inherent differences in their makeup.

Table 2. Mechanical properties of the ACL stratified by sex

Sex	Strain at Failure	Stress at Failure (MPa)	Modulus of Elasticity (MPa)	Toughness (MPa)
Male (n=8)	0.3 ± 0.06	26.35 ± 10.08	128 ± 35	3.5 ± 1.69
Female (n=9)	0.27 ± 0.08	22.58 ± 8.92	99 ± 50	3.17 ± 2.62

One important limitation of this study is that the activity level of the donors was unknown. Since activity level can potentially affect the tensile properties and generally speaking the mechanical and ultrastructural quality of the ACL, it can influence the outcome. Thus our results should only cautiously be applied to the observed ACL failure rate differences in the athletic population.

CONCLUSION

This study shows that female ACLs are considerably weaker, and have lower mechanical quality. This might play a major role in the higher incidence of ACL injury in female athletes. In addition, sex should be considered as a variable in the analysis of tensile properties. More research regarding the histological and biochemical differences on ACL between sexes with a larger sample size is needed to explore further sex-based differences in the ACL.

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