Introduction: The relative risk of a non-contact anterior cruciate ligament (ACL) injury has been shown to be two to eight times higher in female intercollegiate athletes than their male counterparts [2]. Hormonal [6,8,10], intrinsic anatomical [1,4,5], and biomechanical [1,6,7] factors have all been investigated as causes for this disparity. Identifying structural and material properties of the ACL has been an intense area of research, and studies have determined that ACL volume and cross-sectional area are correlated to gender, height, age, and weight [1,4]. Another cadaver study has also observed that female ACLs have lower material properties than male ACLs, independent of height [5]. However, no direct link between ACL size and injury has been investigated, as previous comparative studies on ACL morphology have all focused on gender comparisons. A narrower ACL in vivo could identify a predisposition for non-contact ACL injury for males as well as females. Given previous data that the material properties of individual fascicles of ACL are similar to other ligaments within an individual [3], a narrower ACL may just contain fewer fascicles, leading to inferior strength. Cross-sectional area and volume are both appropriate measures of a narrow ACL, but volume may potentially be a more robust measurement in vivo than a single point measurement of cross-sectional area [1].

The purpose of this study was to test the hypothesis that a smaller ACL leads to ACL injury, controlling for gender, height, age, and weight, by comparing the ACL volumes of the contralateral knees of individuals who previously experienced a non-contact ACL injury to control subjects matched for gender, height, age, and weight.

Materials and Methods: 54 subjects (34 male) participated in this study after providing IRB-approved informed consent. They were divided equally into 2 groups. The injured group consisted of the healthy, contralateral knees of individuals who had experienced a non-contact ACL injury. The control group consisted of knees of uninjured subjects matched for gender, height, age, and weight to the injured group. Height differences were not to exceed 2 inches in any matched pair, and the average heights for the control and injured subjects were within 0.30 inches (68.90 in vs. 68.61 in).

MR images (1.5T, sagittal 3D-SPGR, voxel size 0.55mm x 0.55mm x 1.5mm) were taken of a single knee for the control subjects and of the healthy knee of the injured group. Under the guidance of an experienced orthopedic surgeon, the ACL of each subject was segmented from the MR images using standard software (Medical Image Processing, Analysis, and Visualization, v2.7.45) [9]. The volume of each ACL was calculated by MIPAV from the manually drawn contours. The volumes were compared between groups using a paired one-tailed Student t-test ($\alpha = 0.05$). For comparison to previous studies, the correlation of ACL volume to height was also calculated.

Results: The average ACL volume for the injured group was 1955 mm$^3$, significantly smaller than the average volume for the control group (2117 mm$^3$)(p=0.037), with 16 of the 27 injured subjects having smaller ACLs than their matched control (Fig. 1). The correlation of volume to height across all subjects was 0.57.

Discussion: The results of this study show that patients who have suffered a non-contact ACL injury have a significantly smaller ACL volume in their contralateral knee than matched controls. This result is consistent with a smaller ACL being weaker, and therefore at greater risk of injury.

Similar results have been found when comparing male vs. female ACL volume [4], with a larger difference due to gender than what we have observed between injured and control subjects. However, the previously observed difference in ACL volume between males and females may have been largely due to stature, as males and females were of significantly different heights. Our observed correlation between body height and ACL volume was also consistent with the previously published value of 0.58 [4].

One major limitation of this technique was the use of manual segmentation of the ACL from MRI. The ACL can often be difficult to distinguish from surrounding tissue, possibly leading to errors in the subsequently calculated volume. Another limitation is the use of the contralateral ACL to represent the volume of the ruptured ACL, since the side-to-side variability in ACL volume in healthy subjects remains unknown.

ACL volume may be a risk factor for non-contact ACL rupture, in conjunction with the many other potential risk factors that have previously been identified. A future comprehensive study that attempts to create screening metrics based on as many of these factors as possible, including ACL volume, may prove to be the most effective in identifying at-risk individuals.

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