Anatomic anterior cruciate ligament reconstruction: a changing paradigm
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CHAPTER 5

COMPARISON OF THREE-DIMENSIONAL NOTCH VOLUME BETWEEN SUBJECTS WITH AND WITHOUT ANTERIOR CRUCIATE LIGAMENT RUPTURE

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Abstract

Purpose: It has been hypothesized that smaller femoral notch size may lead to greater forces on the anterior cruciate ligament (ACL), increasing the risk of ACL rupture. The aim of this study was to determine if individuals with ACL injuries have smaller notch volumes than uninjured subjects. A secondary aim was to determine the correlation between intra-operative two-dimensional (2D) notch measurements, patient demographic factors and notch volume.

Methods: Manual digital tracings of the femoral intercondylar notch perimeter were performed on axial MRI images to calculate 3D notch volume. Notch volume was compared between 50 patients with ACL injury and 50 patients without ACL injury (controls). From the 50 patients with ACL injury, intra-operative 2D measurements of the notch were taken. These 2D measurement and patient demographic factors were correlated to 3D notch volume, using the Pearson correlation coefficient. In addition, notch size was compared between men and women. All group comparisons were performed using unpaired t-tests.

Results: The notch volume was larger (6.5 ± 1.7 cm³; mean ± standard deviation) for the group with ACL injury compared to controls (5.9 ± 1.4 cm³); this difference approached statistical significance (p = .054). There were no significant correlations between the 2D dimensions and the 3D notch volume. Larger notch volumes were significantly correlated with increased subject height (r = .636, p < .001) and weight (r = .364, p < .001), but not BMI (p = .269). Males had significantly larger notch volumes than females (p < .001).

Conclusions: Contrary to our hypothesis, there was a trend towards larger notch volumes in patients with ACL injury as compared to patients without ACL injury. Intra-operative notch measurements did not correlate with 3D notch volume. Notch volume was related to patient height, weight and gender, but not BMI.

Introduction

Relationships between the anterior cruciate ligament (ACL) and the distal femoral notch have been previously identified. The ACL is tight against the intercondylar shelf in extension, which concentrates forces in the midsection of the ligament. Chondrocytes identified on the ACL surface provide further evidence of notch-ACL contact. From these early studies it was hypothesized that smaller notch size may lead to greater forces on the mid-substance of the ACL, increasing the risk of ACL rupture. Studies evaluating this hypothesis have been inconsistent, with some finding correlations between notch size and ACL rupture whereas others found no such relationships. One of the reasons for this discrepancy might be the simplified two-dimensional (2D) methods employed by these studies, which do not adequately represent the complex three-dimensional (3D) structure of the notch. However, during arthroscopic ACL surgery, 2D measurements as well as
subjective size estimates of the notch entrance influence surgical technique. For example, it is common practice to perform a notchplasty when the notch entrance appears small. However, the 2D dimensions of the notch entrance may not predict the 3D volume of the notch. Since the relationship between the ACL and the notch changes through the range of motion, it is possible that the overall 3D notch volume is more relevant than a single 2D measurement for understanding the effects of notch size on ACL injury and surgery.

Many 2D measurements of the femoral intercondylar notch have been performed, including the intercondylar notch width, notch area, transverse and sagittal notch angle, bicondylar width and the notch width index. These measurements were performed either on plain radiographs, Magnetic Resonance Imaging (MRI), Computed Tomography (CT), or intra-operatively. To our knowledge, only one study has utilized 3D methods for assessing the notch geometry, reporting that men had a larger overall notch volume than women. No previous studies have evaluated the effect of notch size on the incidence of ACL injury.

The primary aim of this study was to compare the 3D notch volume, as measured on MRI, between subjects with and without ACL injuries. A secondary aim was to determine the correlation between intra-operative 2D notch measurements, patient demographic factors and notch volume. Our hypotheses were:

1. Subjects with ACL injury have a smaller notch size than subjects without ACL injuries.
   i. The relationship between notch size and ACL injury differs between men and women.
2. Intraoperative 2D measurements of the notch entrance do not correlate to notch volume.
3. Patient height, weight, BMI and gender are correlated to notch volume.

Materials and Methods

To measure 3D notch volume, a technique similar to that previously described by Charlton et al. was used. Manual digital tracings of the femoral intercondylar notch perimeter were performed on the axial MRI images using Osirix software (Osirix, Geneva, Switzerland). Notch volume was calculated by summing the measured areas of the notch outlines from each slice and multiplying by the slice thickness. The boundaries of the notch were defined based on anatomic landmarks. The most proximal slice was the first image with both femoral condyles visible, as indicated by the articular cartilage. The most distal slice was the last image with continuity between the medial and lateral femoral condyles. The posterior border of the notch was a line drawn between the two points on the inside of the femoral condyles where the cartilage ends (Figure 1 and 2).
Chapter 5: Comparison of 3D notch volume

**Figure 1:** Axial MRI images from a right knee are shown. The borders of the notch are outlined. The box displays the area of this outline. **A.** The first image from proximal to distal is the first slice with both femoral condyles visible. **B.** Image in the middle of the notch. The posterior border of the notch is a line between the two points on the inside of the femoral condyles where the cartilage ends. **C.** The last image is the last slice with continuity between the medial and lateral femoral condyle. The notch volume can be calculated by summating the area of all images within the defined femoral notch and multiplying by the slice thickness.

**Figure 2:** 3D Reconstructed MRI of the knee. One axial MRI slice is shown and the corresponding measured area is outlined in green. The next sequential axial slice locations are indicated in red, with the corresponding measured outlines in green. The notch volume can be calculated by summating the area of all axial slices through the femoral notch and multiplying by the slice thickness.
Routine clinical MRI scans were utilized for this study. To evaluate potential effects of scan quality, a preliminary study was conducted to compare 3D notch measurements using these clinical scans to those obtained using a high-resolution research-grade scan. Five subjects were selected who had undergone a clinical MRI of the knee (1.5 Tesla, T2 TSE sequence with 4 mm slice thickness), as well as a high resolution MRI (3 Tesla, T2 TSE sequence with 1.5 mm slice thickness) for a different research study. The notch volume was calculated from both scans and the results were compared. One observer performed each measurement twice at least one week apart to assess reliability.

Based on the results of this preliminary study, a sample size calculation was performed to identify how many subjects would be needed to identify a difference in notch volume between ACL injured patients and controls. Based on the difference in notch volume found in Charlton’s study (mean group 1: 4.9 cm³, mean of group 2: 5.7 cm³) and the standard deviation from the preliminary study (1.4 cm³), it was determined that 49 subjects in each group would be required to obtain a power of 0.8, with an alpha of 0.95.

To compare notch volume between ACL injured subjects and healthy controls, 50 subjects who underwent ACL reconstruction in a one year span between 10/1/2008 and 10/1/2009 by the senior author were included in this study. The inclusion criteria were skeletally mature subjects with unilateral ACL rupture. Subjects were excluded if they had concomitant injuries to other knee structures, previous injuries or surgeries on the ipsilateral knee, morphologic knee anomalies, open growth plates, or knee arthritis with associated osteophytes seen on plain radiograph, MRI, or arthroscopy.

![Arthroscopic images of the femoral notch of a right knee, anteromedial portal view. The surgical ruler is used to measure the dimensions of the notch entrance. A. The height is measured along the lateral wall of the notch. The width of the notch is measured at the bottom B., middle C. and top D. of the notch.](image.png)
During ACL reconstruction, measurements were taken from the femoral intercondylar notch entrance, under visualization through the anteromedial portal with a 30 degrees arthroscope. The height of the notch entrance, as well as the width of the notch entrance at the bottom, middle (1/3 of the height) and top of the notch (2/3 of the height), were measured with an arthroscopic ruler (Smith and Nephew, Andover, MA) (Figure 3). The subjects’ pre-operative 1.5 T MRI sequence was used to measure the 3D volume of the notch according to the aforementioned method.

The control group consisted of 50 ACL-intact adult subjects who underwent an MRI for isolated meniscus injury. Subjects were excluded if they had concomitant injuries to the knee (other than the meniscus), previous injuries or surgeries on the ipsilateral knee, morphologic knee anomalies, open growth plates, or knee arthritis with associated osteophytes seen on plain radiograph, MRI, or arthroscopy. 3D notch volume was calculated from the 1.5 T clinical MRI.

For all subjects, demographic data (height, weight, gender) were collected from the subjects’ medical chart and BMI was calculated. Two independent observers performed all the MRI measurements of the notch and one observer performed all measurements twice at least one week apart to evaluate measurement reliability. This case-control study was approved by our institutional research board (IRB).

**Statistical methods**

For the 5-subject preliminary study, the intra-class correlation coefficient (ICC) between the notch volume as measured on the 1.5 T MRI and the 3T MRI was calculated. The ICC’s between the first and second measurements for each scan type were also calculated to determine intra-observer reliability.

Reliability of notch volume measurements for the entire study was evaluated by calculating ICC’s for all 100 subjects between measurements obtained from two independent observers (for inter-observer reliability) and between two separate measurements performed by a single observer (for intra-observer reliability). Reliability was further characterized by calculating the 95% confidence interval (95% CI) of notch volume.

For all notch measurements and patient demographic data, the frequency, mean, and standard deviation and standard error of measurement were calculated. Unpaired t-tests were performed to determine differences in notch volume between the ACL-injured and non-ACL-injured (control) subjects, and between male and female subjects. Subgroup analyses (t-tests) were performed after splitting the subjects by gender to evaluate male vs. female differences in the relationship between ACL injury and notch size.

Pearson correlation coefficients were calculated between notch volume and...
notch height, notch width, patient height, weight, and BMI. A stepwise multiple regression analysis was performed using notch height, notch width, patient height, weight, BMI and gender as input variables, to determine which combination best predicted overall notch volume. PASW Statistics (version 17.0, SPSS Inc., Chicago, IL) was used for all statistical analyses. The alpha level for statistical significance was set at p < .05.

Results

The intra-class correlation coefficient from the preliminary study comparing 1.5 T and the 3T notch volume measurements was 0.692. The notch volume (mean ± standard deviation) was 5.66 ± 1.82 cm³ for the 1.5 T measurements and 4.64 ± 1.52 cm³ for the 3 T MRI measurements. The intra-observer reliability was 0.963 using 1.5 T MRI and 0.968 using 3T. Standard error of measurement (SEM) was .352 for 1.5T and .270 for 3T. The good correlation between the 1.5 and 3 T MRI, as well as the similar reliability and SEM between the two scan types, supported use of the 1.5 T MRI sequence for the remainder of the study.

Table 1 displays the demographic data for the ACL-injured and control groups; there were 50 subjects in each group. The subjects in the control group had a higher BMI and were older than those with ACL ruptures (BMI 28 vs. 25, p = .004; age 40 vs. 27 years, p = .001). The notch volume was larger for the group with ACL injury (6.5 ± 1.7 cm³) compared to the control group (5.9 ± 1.4 cm³); this difference approached statistical significance (p = .054).

### Table 1. Demographic data of the included subjects

<table>
<thead>
<tr>
<th></th>
<th>ACL injured Mean (StDev)</th>
<th>Controls Mean (StDev)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient height (cm)</td>
<td>174.8 (11.2)</td>
<td>174.2 (9.4)</td>
<td>.268</td>
</tr>
<tr>
<td>Patient weight (kg)</td>
<td>76.0 (19.8)</td>
<td>87.2 (22.3)</td>
<td>.311</td>
</tr>
<tr>
<td>Patient BMI</td>
<td>24.5 (4.0)</td>
<td>28.4 (5.8)</td>
<td>.004†</td>
</tr>
<tr>
<td>Gender (female: male)</td>
<td>1.38</td>
<td>1.52</td>
<td>.100</td>
</tr>
<tr>
<td>Age (years)</td>
<td>26.6 (10.7)</td>
<td>39.9 (14.5)</td>
<td>.001†</td>
</tr>
</tbody>
</table>

† Statistically significant difference between ACL-injured and control group
StDev = standard deviation. BMI = body mass index.

Subgroup analysis by gender yielded no difference in notch volume between groups for women (5.2 cm³ vs. 5.3 cm³, p = .517), but men with ACL injuries had a larger notch volume than men without ACL injuries (7.4 cm³ vs. 6.5 cm³, p = .032). Correlations between the 2D notch entrance measurements, demographic factors and the 3D notch volume are displayed in Table 2.
Chapter 5: Comparison of 3D notch volume

Table 2. Correlation between notch volume and different 2D measurements and demographic factors

<table>
<thead>
<tr>
<th>Correlation between notch volume and:</th>
<th>Pearson correlation coefficient</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notch height</td>
<td>.071</td>
<td>.774</td>
</tr>
<tr>
<td>Notch width bottom</td>
<td>.164</td>
<td>.254</td>
</tr>
<tr>
<td>Notch width middle</td>
<td>.142</td>
<td>.326</td>
</tr>
<tr>
<td>Notch width top</td>
<td>.124</td>
<td>.390</td>
</tr>
<tr>
<td>Patient height</td>
<td>.636</td>
<td>&lt;.001†</td>
</tr>
<tr>
<td>Patient weight</td>
<td>.364</td>
<td>&lt;.001†</td>
</tr>
<tr>
<td>Patient BMI</td>
<td>.118</td>
<td>.269</td>
</tr>
<tr>
<td>Age</td>
<td>.012</td>
<td>.909</td>
</tr>
</tbody>
</table>

† Statistically significant correlation

There were no significant correlations between any of the 2D notch entrance measurements and the notch volume. Larger notch volumes were significantly correlated with increased subject height and weight, and males had significantly larger notch volumes than females (all p < .001). There were no significant correlations between notch volume and BMI or age. Stepwise multiple regression analysis identified only patient height as a significant predictor of notch volume (R² = 0.418, p = .003).

The intra-observer reliability of the 1.5 T MRI measurements of the 100 included subjects was .960 (95% CI: .941 - .973). The inter-observer reliability of the 1.5 T MRI measurements of the 100 included subjects was .890 (95% CI: .837 - .926).

Discussion

The current study is the first to investigate the relationship between ACL injury and notch size assessed using a 3D volumetric technique. The study focused on notch volume because two-dimensional measurement techniques are inherently less reliable and accurate, partly due to their sensitivity to rotation and angulation. The 3D MRI technique employed for this study was shown to be reliable; with intra- and inter-observer ICC’s all greater than .890. Notch volume magnitude and variability were also similar to previously reported values. No significant correlations were found between intra-operative 2D notch measurements and MRI-based 3D notch volume, suggesting that these measurements assess different aspects of the femoral notch geometry; i.e. notch volume is relatively independent of the size of the notch opening. Though somewhat surprising, this observation highlights the complexity of the notch.
geometry, which may confound attempts to use relatively simple measurements for characterizing notch properties. This finding is in accordance with existing literature\textsuperscript{14}.

Though the volume measurements proved to be reliable, the primary hypothesis of this study, that subjects with ACL injury have a smaller notch volume than subjects without ACL injuries, was not supported by the data. In fact, there was a trend in the opposite direction, towards larger notch volumes in the ACL-injured subjects. The difference was statistically significant only for men, with ACL-injured knees having average notch volumes 0.9 cm\textsuperscript{3} (approximately 13\%) larger than knees of uninjured male subjects. The clinical significance of this difference is unclear, but the direction of the difference raises doubt about the utility of MRI-based notch volume measurements for predicting ACL injury risk.

These findings do not rule out notch size as an influencing factor in ACL rupture risk or as a determining factor in surgical management (i.e. single- or double-bundle reconstruction, need for notchplasty). Rather, the results of this study suggest that certain 2-dimensional measurements of the notch could be better predictors of ACL rupture risk than notch volume. As discussed above, notch volume and notch entrance size are relatively independent. If contact between the ACL and the notch entrance is a source of ACL damage, then the size of the notch entrance may be a more meaningful predictor of ACL injury than the overall notch volume. However, previous studies of notch entrance size and ACL injury risk have produced varying results, perhaps due to variation in measuring technique. Intra-operative evaluation and measurements of the notch entrance may be needed to better identify the specific region(s) of the notch most closely related to the ACL\textsuperscript{15}.

Lastly, we hypothesized that patient demographic factors such as height, weight, BMI and gender are correlated to notch volume. This hypothesis was partially supported, since patient height, weight and gender influenced the notch volume, but BMI did not. Men, taller and heavier subjects had a larger notch volume. This is consistent with existing literature that shows a larger 2D notch size in men compared to women\textsuperscript{10,16-19}. In addition, previous studies also reported positive correlations between patient size and 2D notch size\textsuperscript{10}. However, based on stepwise multiple regression analysis, only patient height was a significant predictor of notch volume, accounting for 42\% of the variability in notch volume; adding any of the other variables did not improve the regression. A possible explanation for this is that the significant demographics factors are interrelated and multi-factorial. The men in our study were on average taller than the women, and the heavier subjects were taller than the lighter subjects. This confounding of gender, height and weight is consistent with existing literature\textsuperscript{10}.

**Limitations**

A limitation to this study was that our control group did not consist of
healthy knees. MRIs of subjects with isolated meniscus injuries were used because they were readily available and therefore cost efficient with no extra time and risks for the patients. However, the subjects were carefully screened and excluded if there was any sign of possible ligamentous injury to the knee or any osteoarthritic changes. Another limitation was that there was a difference between the ACL-injured group and the control group in age and BMI. However, Pearson correlation coefficient in the current study indicated that age and BMI do not influence the notch volume (Table 2). Another possible limitation is the use of clinical-quality 1.5T scans. However, there was a good correlation between the 1.5 T and high-quality (3T) MRI in our preliminary study, and the intra- and inter-observer reliability of the 1.5 T MRI sequence was excellent. Thus, the additional cost and subject inconvenience to obtain additional scans did not appear to be justified, and it is unlikely that higher-quality scans would have significantly altered the findings of the study. MRI for outlining bony structures has a known limitation in distinguishing bone from surrounding tissue. CT scan is more accurate when looking at bone. However, MRI has the benefit of displaying cartilage, which may be used as a landmark in identifying the borders of the notch. In the present study validity of the notch volume measurements on MRI was not tested, since the method we applied has been used in the past and has been validated for calculation of ACL volume.

Conclusion

In conclusion, patients with ACL injury did not have smaller notch volumes than patients without ACL injury. Neither height nor width measurements of the notch entrance were reliable for estimating notch volume. Though MRI measurements of the notch proved to be highly reliable and may provide a better indication of overall notch size, the results of this study raise doubt about the utility of either 2D or 3D measurements of the notch for estimating risk of ACL injury.

References

4. Simon RA, Everhart JS, Nagaraja HN, Chaudhari AM. A case-control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch
