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Notchplasty in anterior cruciate ligament reconstruction in the setting of passive anterior tibial subluxation

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ABSTRACT

Purpose: In an effort to minimize graft impingement among various ACL deficient states, we sought to quantitatively determine requirements for bone resection during notchplasty with respect to both volumetric amount and location.

Methods: A validated method was used to evaluate Magnetic Resonance Imaging scans. We measured the ATT of the medial and lateral compartments in the following four states: intact ACL (27 patients), acute ACL disruption; <2 months post-injury (76 patients), chronic ACL disruption; 12 months post-injury (42 patients) and failed ACL reconstruction (75 patients). Subsequently, 11 cadaveric knees underwent Computed Tomography (CT) scanning. Specialized software allowed virtual anterior translation of the tibia according to the average ATT measured on MRI. Impingement volume was analyzed by performing virtual ACLRs onto the various associated CT scans. Location was analyzed by overlaying an on-screen protractor. The center of the notch was defined as 0°.

Results: Average impingement volume changed significantly in the various groups compared to the intact ACL group (acute 577 ± 200 mm^3, chronic 615 ± 199 mm^3, failed ACLR 678 ± 210 mm^3, $p = 0.0001$). The location of the required notchplasty of the distal femoral wall border did not change significantly. The proximal femoral border moved significantly towards the center of the notch (acute 8.6° ± 4.8°, chronic 7.8° ± 4.2° ($p = 0.013$), failed ACLR 5.1° ± 5.9° ($p = 0.002$)).

Conclusion: Our data suggests that attention should be paid peri-operatively to the required volume and location of notchplasty among the various ACL deficient states to minimize graft impingement.

1. Introduction

The Anterior Cruciate Ligament (ACL) is among the most commonly injured ligaments, with an estimated 200,000 ruptures per year and 100,000 primary ACL reconstructions (ACLR) performed per year in the United States [1]. ACL deficiency leads to altered joint kinematics and symptoms of instability due to anterolateral subluxation of the tibia relative to the femur.

Improved surgical techniques have led to restoration of joint kinematics in 80–95% of patients following ACLR [2–4]. However, clinical failure rates between 3.6% and 15% have been reported [5–7]. Various reports show that technical errors, such as incorrect tunnel placement and graft impingement, account for a substantial portion of graft failures [8,9]. Notch roof impingement occurs when there is premature impaction of the ACL graft on the notch during knee extension [10]. This leads to graft attenuation and deterioration as well as the development of cyclops lesions that may impair range of motion. Therefore, the avoidance of graft impingement is an important surgical consideration in reconstructive ACL procedures. Several authors have suggested that posterior tibial tunnel placement and a generous notchplasty are the solutions for graft impingement [10–14].

Recently, Tanaka et al. introduced a new concept of anterior tibial translation (ATT) in the various ACL deficient states of the knee [15]. The authors found that passive anterior tibial translation varies significantly among the various ACL deficient states. They reported that the ATT is greater in failed ACLR patients than in patients who sustained an acute ACL disruption. This is of considerable importance since various reports show that ACLR is not capable to restore ATT following surgery [16–20]. Since the tibiofemoral relation is chronically altered, even after surgery, additional intraoperative techniques should be used to optimize the position of the graft and minimize impingement. Notchplasty is one of the additional techniques which can be used to optimize the position and integrity of the graft. Therefore the purpose of the current study was to quantify the volume and location of the notchplasty

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required in acute ACL deficiency, chronic ACL deficiency and after failed ACLR state. We hypothesized that the volume and location of the performed notchplasty varies significantly among the various ACL deficient states when fixed tunnel positions are used in performing ACLR.

2. Materials and methods

After Institutional Review Board approval was obtained, an electronic database search was performed for patients who sustained a complete ACL disruption between the 1st of July 2007 and 1st of March 2013. Patients with a history of previous knee surgery were excluded. ACL ruptures were confirmed by an experienced musculoskeletal radiologist on magnetic resonance imaging (MRI) and clinically by an orthopedic surgeon with extensive experience in ACLR. The data extraction resulted in 322 eligible subjects. They were divided in three groups; (1) acute ACL disruption (76 patients), (2) chronic ACL disruption (42 patients) and (3) failed ACLR (75 patients). Twenty-seven healthy subjects were included in the control group and formed the baseline to which all measurements in the study groups were compared. They had an intact ACL, without other pathologic MRI findings.

An acute ACL disruption was defined as a complete disruption of all ACL fibers within two months of traumatic injury. A chronic ACL disruption was defined as a complete disruption of all ACL fibers at least 12 months following traumatic injury. A failed ACLR was defined as a complete disruption of all graft fibers following primary ACLR. The three groups were compared to MRIs of healthy individuals with an intact ACL. One hundred and two patients with MR imaging between two and 12 months post ACL injury were excluded. Patients with an associated meniscal tear were not excluded since it has no proven effect on the ATT [17,19].

The study consisted of two phases. First, the MRIs from patients were analyzed for ATT in the various ACL deficient states. Subsequently the volume of graft impingement and its location in the femoral notch were calculated and analyzed on a cadaveric study where tibial position was changed based on the mean values for our MRI measurements.

2.1. MR analysis — radiographic study

A standardized MRI was performed for each patient. The knee was brought into 0° of flexion and extension. To minimize any motion artifact, the lower extremity was fixed with a sponge in a tight fitting extremity coil (8 channel knee, Medrad). A previously validated method described by Iwaki [21] and Tanaka [15] was used to evaluate the amount of ATT. In the medial compartment, ATT was measured on the sagittal MRI slice where the insertion of the medial head of the gastronemius muscle onto the femur was visible. In the lateral compartment, ATT was measured on the sagittal slice where the most medial aspect of the fibula was visible. Once these sagittal MR planes had been identified, a best fit circle was drawn over the subchondral line of the posterior condyle. A perpendicular line to the tibial plateau was drawn over the posterior border of this circle. Subsequently a second line, also perpendicular to the tibial plateau, was drawn at the posterior border of the tibial plateau. The measured difference between the two perpendicular lines represented the position of the tibia with respect to the femur (Fig. 1). All measurements were performed by the same author (***). Previous studies show the measurement to be reliable and reproducible [15].

2.2. Impingement volume analysis — cadaveric study

Eleven cadaveric knees (mean age 52.5 years; range 29–65) underwent computed tomography (CT) scanning. Any cadaver with evidence of bony deformity, osteoarthritis or an existing ACL deficiency was excluded. The knees were then mounted to a 6° of freedom robot (ZX165U; Kawasaki, Tokyo, Japan) which simulated knee flexion based on a least resistance path. Physical digitizations were performed with reference markers fixed to each cadaveric specimen which are tracked during robotic testing. The markers are CT dense, allowing us to link the virtually constructed joint to the physical experiment and thus permit the determination of the 3D virtual flexion path of the knee. Eleven three-dimensional models, one for each individual cadaveric knee, were generated from the CT (Mimics, Materialise Inc. Leuven, Belgium). The centers of the femoral and tibial footprints were then selected by one of the authors experienced in ACLR, mimicking anatomic ACL tunnel positions. Using sagittal slices of the CT scan we were able to define the outline of the native ACL. The tibial footprint was segmented into two halves on the sagittal section. We then identified the medial and lateral tibial spines on the coronal slices and located the halfway point. The point which corresponded to the half way mark on both the sagittal and coronal slices was used as the center of the tibial footprint. Subsequently, the center of the femoral footprint was located by identifying the lateral intercondylar ridge on 3D CT reconstruction. This was segmented into two halves. A perpendicular line from the midpoint of the lateral intercondylar ridge was then dropped towards the posterior articular cartilage. The midpoint of this perpendicular line represented the center of the femoral footprint.

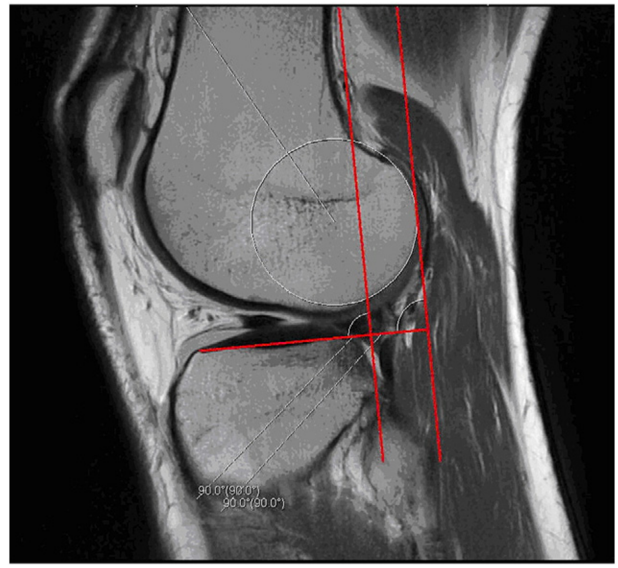

Fig. 1. The figure shows the amount of ATT in the lateral compartment. The distance between the two vertical lines represents the ATT in millimeters.

Impingement volume analysis was performed using 3D modeling software (Geomagic Studio 2013, Geomagic Inc. Rock Hill, United States). A 9 millimeter cylinder was placed between the femoral and tibial tunnel positions, simulating an ACL graft. Impingement was calculated as the amount of volume overlap between the femur and the graft using a Boolean operation. Subsequently the location of femoral notch impingement was analyzed using a protractor overlay (Fig. 2). The center of the protractor was placed in the middle of the femoral condyles. Two lines were then drawn from the center of the protractor to the two outside borders of the area of femoral wall impingement. Border A represents the most proximal (or high) border towards the center of the femoral roof whereas border B is the most distal (or low) located. The locations of the borders were analyzed in amount of degrees that they were located from the center of the femoral roof. For each of our three study groups, using the same 3D modeling software, the medial and lateral parts of the tibia were subluxed anteriorly according to the mean measurements from the MRI ATT analysis (Fig. 3). Impingement volumes and areas were then measured for each state of tibial subluxation (Fig. 4).

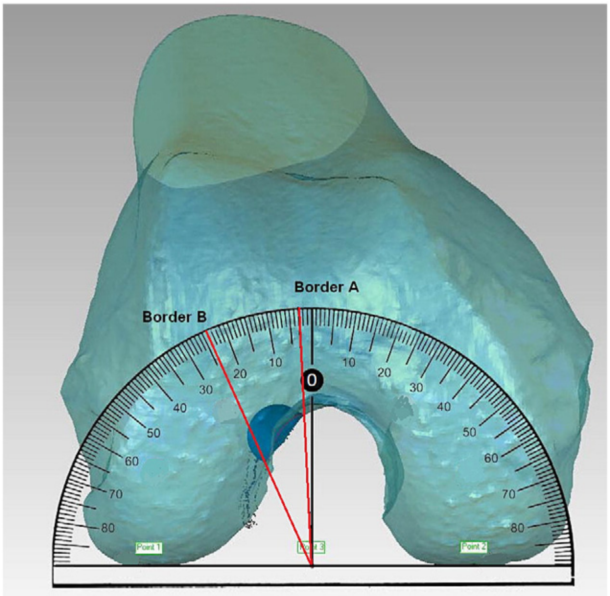

Fig. 2. The virtual protractor which was used for the analysis of the location of the required notchplasty. Border A represents the most anterior (or high) border towards the center of the femoral roof. Border B is the most posterior (or low) located.

2.3. Statistical analysis

Passive ATT was compared between groups using a one-way analysis of variance (ANOVA). Volume of graft impingement in the various states (i.e. acute, chronic and failed ACLR) of passive ATT was analyzed with an unpaired *t*-test. A p-value < 0.05 was considered statistically significant.

3. Results

3.1. MR analysis

Compared to the measurements of the control group, the average ATT in the "acute ACL" group was 1.0 ± 2.51 mm in the medial compartment and 1.56 ± 3.31 mm in the lateral compartment. In the "chronic ACL" group, the average ATT was 1.76 ± 2.38 mm in the medial compartment and 2.75 ± 3.84 mm in the lateral compartment. In the "failed ACLR" group the average ATT was 3.33 ± 2.96 mm in the medial compartment and 3.68 ± 4.19 mm in the lateral compartment. The ATT values in the "chronic ACL" group and "failed ACLR" group were significantly greater than the controls (Fig. 5). Compared to the control, the average ATT of the central tibial socket position was 1.49 mm in the "acute ACL" group, 2.32 mm in the "chronic ACL" group and 3.62 mm in the "failed ACLR" group.

3.2. Impingement volume

Compared to the control group, the volume of graft impingement sequentially increased from the acute group (43 ± 22 mm^3, $p < 0.0001$), to the chronic group (81 ± 21 mm^3, $p < 0.0001$) and was greatest in the failed ACLR group (134 ± 32 mm^3, $p < 0.0001$) (Fig. 6). The increases in graft volume impingement were statistically significant between each tibial subluxation state.

3.3. Notchplasty location analysis

In the acute group, border A was located at $8.6° \pm 4.8°$ from the center of the femoral notch. In the chronic ACL deficient state, border A significantly moved towards the center of the femoral roof, located at an average of $7.8° \pm 4.2°$ ($p = 0.005$). In the failed ACLR group, border A was located at $5.1° \pm 5.9°$ of the femoral notch. This differed significantly from the acute ($p = 0.002$) and chronic ACL deficient states ($p = 0.013$). No significant differences were observed in the location of border B, between the various ACL deficient states (acute $45.9° \pm 6.5°$, chronic $44.9° \pm 6.1°$, and failed ACLR $44.8° \pm 6.8°$).

4. Discussion

To our knowledge this is the first study to report the effect of passive anterior tibial translation in the ACL deficient knee on notch impingement. Our data suggests that ATT differs significantly among the various ACL deficient states, therefore affecting the volume and location of graft impingement onto the femoral notch. Combining these variables we noted that an increase of ATT and graft impingement is observed when the groups were compared with healthy individuals. This is consistent with previous reported findings in literature [22–24]. Although the ATT of only the chronic and failed ACL groups differed significantly, the volume of graft impingement increased in all the three groups compared to the control using a central femoral position and a central tibial socket position. Our data suggests that various ACL deficient states effect the relation of the tibia and femur significantly. Therefore, not only different amounts of bone around the notch should be resected in order to avoid femoral wall impingement of the graft, but also the location of the notchplasty differs significantly. Our data suggests that the notchplasty should be extended towards the center of the femoral roof when the tibia is translated anteriorly (Fig. 7).

Whereas the femoral socket position in ACLR shows to play a dominant role in ACL graft isometry, the placement of the tibial tunnel has proven to be the leading factor of femoral roof impingement [10,11]. Historically it has been suggested that a posterior socket position – if necessary with additional notchplasty – is the solution to minimize graft impingement. However, to our knowledge this study is the first to report the required volume and the location of the notchplasty among the different ACL deficient states. Recent reports, show that anteriorization of the tibial tunnel in ACLR will improve the stability of the knee following ACLR. Bedi et al. [23] demonstrated in a cadaveric study that the anteriorization of the tibial tunnel position will significantly reduce the anterior tibial translation with the Lachman and pivot shift maneuvers of the knee. Similar clinical findings were reported by Inderhaug et al. [25] who studied the stability of knee 12 years following primary ACLR in 83 subjects. They concluded that patients with posterior tibial sockets had a significant higher proportion of rotational instability and additional worse clinical outcome scores. Despite the fact that both studies confirm the positive effect of tibial tunnel anteriorization on the stability of the knee, they identify the associated risk of notch impingement of the graft. Maak et al. [24] reported the influence of the multiple femoral socket positions on the incidence of femoral notch impingement. They concluded that femoral roof impingement was found in all the three femoral socket positions (PL,

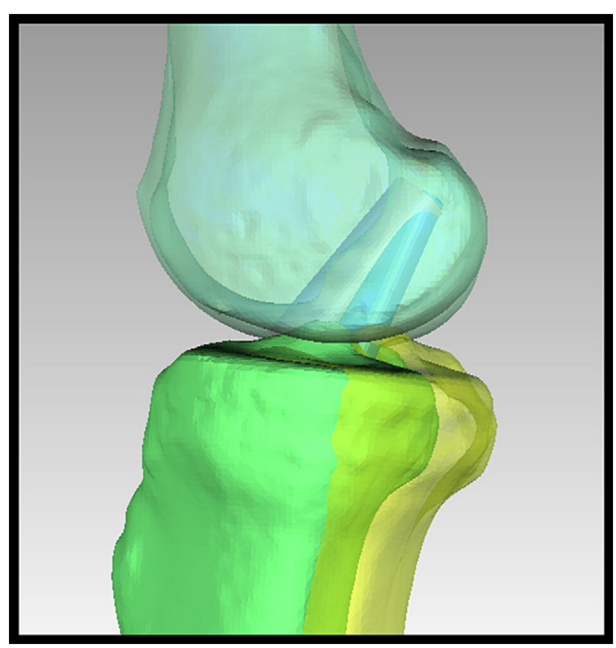

Fig. 3. The yellow femur represents the non-displaced tibia. The green tibia represents the anteriorly translated tibia according to the measured millimeters of ATT obtained from the MRI scans.

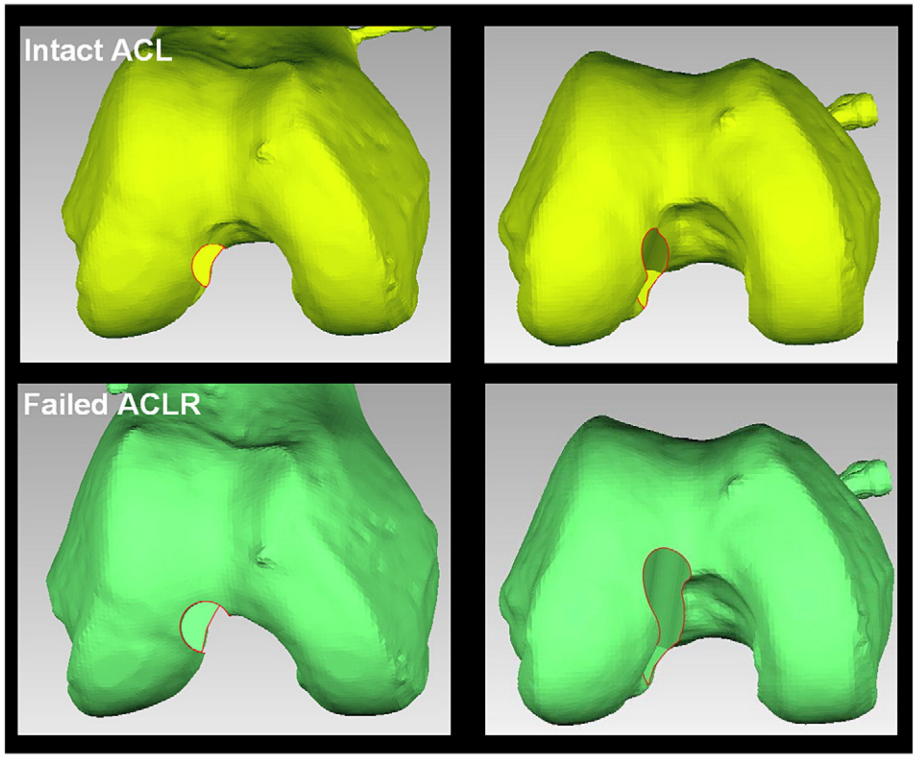

Fig. 4. The different volumes of graft impingement in the healthy control group (yellow) and the failed ACLR group (green).

central femoral and AM). However, significant differences were noted in the knee angle between the femoral AM location and the central femoral and PL femoral socket positions. Therefore the authors concluded that the risk of femoral notch impingement can be minimized by moving the femoral socket from an AM position to a central or PL position, or as they describe; a “down-the-wall” position. However, these positions may be associated with strain on the graft through a range of motion [26]. This finding has been confirmed in an experimental study by Iriuchishima et al. [27], who concluded that the combination of an anteriorized tibial socket position and a highly placed femoral tunnel will induce notch impingement. Van der Bracht et al. [22] performed a risk factor analysis in 20 cadavers to investigate the potential factors which could influence the risk of femoral notch impingement. They concluded that the real risk of notch impingement consists of the diameter of the ACL graft and the drill-guide angle.

Numerous studies have investigated the separate factors (i.e. altered position of the tibia in the ACL deficient knee, impingement and notchplasty) which could potentially influence the condition of the ACL graft and therefore the successful outcome of the ACLR. However, we are not aware of reports which combine these separate factors. In a recent study by Tanaka et al. [15], a comparable technique was used to evaluate the medial and lateral ATT. Groups were subdivided into

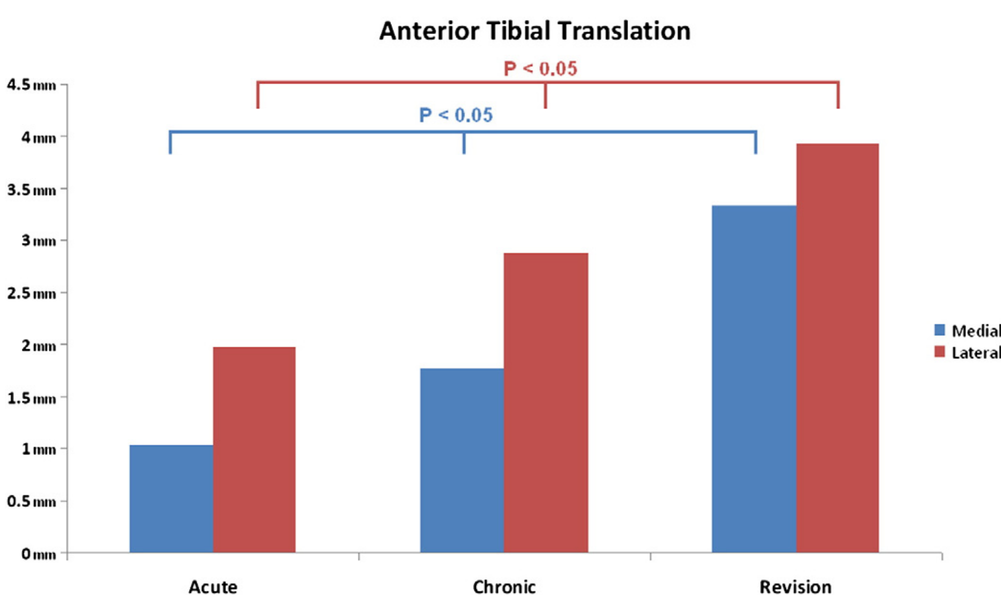

Fig. 5. ATT (relative to the control group) of the medial and lateral compartment in the various ACL deficient states.

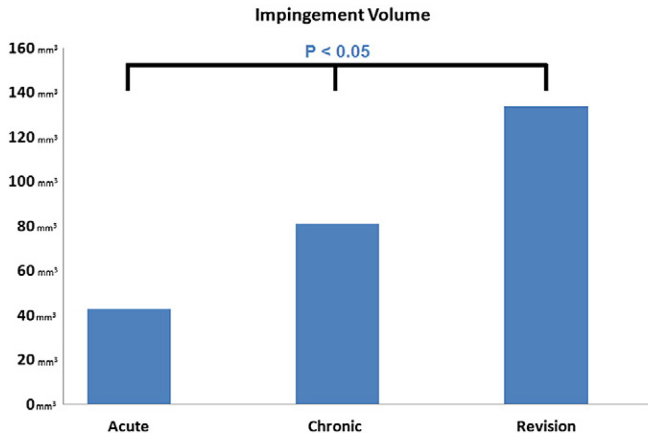

Fig. 6. The volumes of notch impingement among the various ACL deficient states.

acute ACL deficiency and failed ACLRs, and were subsequently compared to a healthy control group. Although the groups were relatively small (27 intact ACL, 62 acute ACL tears and 16 failed ACLRs), the authors found a comparative finding with an average lateral translation in the failed ACLR group of 3.9 mm compared to 0.8 mm in the acute ACL group. 12.5% of the failed ACLRs had an anterior translation greater than 15 mm. The authors suggested that this could be the possible explanation for the suboptimal clinical results following revision of the failed ACLR. Almekinders et al. [28] measured the anterior tibial subluxation in 24 ACL deficient subjects on lateral weight bearing radiographs of the knee. They found that the average position of the posterior margin of the tibial plateau was 0.6 mm anterior to the femoral condyles. This differed significantly from the intact ACL group where the average posterior margin of the tibial plateau was based 3.3 mm posterior to the femoral condyles. However, because measurements were performed on radiographs, the medial and lateral compartments could not be investigated separately.

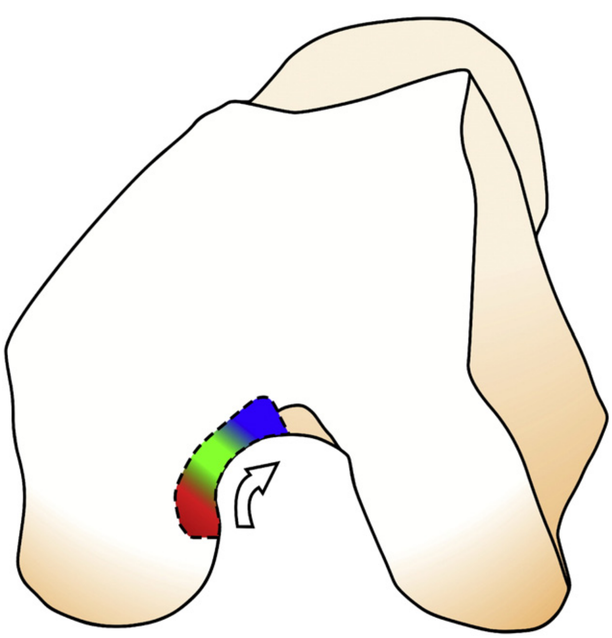

Fig. 7. A schematic overview of the location where the notchplasty needs to be conducted in order to minimize graft impingement. The red area represents the acute ACL deficient state, green the chronic ACL deficient state and blue the state following failed ACLR. The arrow represents the direction in which the notchplasty should be extended if the ATT increases.

Our data demonstrate that chronic ACL deficiency and failed ACL reconstruction is associated with the finding of passive anterior tibial translation [15]. As such, these knees have a different pathoanatomy than patients without this tibial subluxation and may require modifications in surgical technique. We demonstrate that this subluxation is associated with changes in the position of notch impingement and an extended notchplasty may be necessary.

Our work does not assess whether passive tibial subluxation is fixed or reducible with ACL reconstruction. However, previous work [16–20] suggests that this subluxation is not fully correctible. Furthermore, our data likely underestimates the amount of notchplasty required in the chronic and revision setting. Many authors have noted the presence of notch osteophytes in chronic ACL deficiency. Therefore, notchplasty in this setting may require the removal of notch osteophytes in addition to the extended bone resection to accommodate the subluxed tibial position. An additional strategy in this setting can be to move the tibial tunnel further posteriorly to avoid impingement; this strategy however is known to affect control of knee stability [23].

4.1. Limitations

There are several limitations to this present study. The first weakness is the analysis of the ATT. Although all MRI's were obtained following a standardized protocol with fixation of the knee, we can't exclude small rotational artifacts which might influence our measurements. Secondly, variability of the diameter of the femoral condyles may account for minor measurement differences. Thirdly the variance of landmarks which were visible on the MRI examinations could potentially influence the measurements. Additionally, we applied average of tibial subluxation to cadaveric knees. This demonstrates a trend that notchplasty should account for the amount of tibial subluxation but does not provide knee specific recommendations. Individual variations such as the notch width, actual amount of tibial translation, presence of notch osteophytes, size of graft, and tunnel positions should determine the actual location and volume of bony resection necessary for the notchplasty. Lastly, we used fixed tunnel positions. Our future work will be aimed at the variation of tunnel placement in order to minimize femoral notch impingement in addition to obtaining the most stable ACLR.

5. Conclusions

This is the first study that reports the various volumes and directions of the required notchplasty in order to minimize graft impingement among the various ACL deficient states. Based on our study, surgeons should consider an expanded and more anteriorly directed notchplasty in the setting of passive anterior tibial subluxation seen often with chronic ACL deficiency and after failed ACL reconstruction.

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