Gap formation following primary repair of the anterior cruciate ligament: A biomechanical evaluation

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A B S T R A C T

Background: Historically, inconsistent and unpredictable results of open primary anterior cruciate ligament (ACL) repair were reported. Recently, however, good results of arthroscopic primary ACL repair of proximal tears have been reported. Purpose of this study was to assess the direct postoperative gap formation and maximum failure load following simulated knee motion after primary ACL repair.

Methods: Six matched-paired human cadaveric knees (mean age: 52 years, range: 48 to 56 years) were used. After primary proximal ACL repair with either suture button fixation or suture anchor fixation, knees were cycled five, 50 and 100 times with a simulated active quadriceps force. Gap formation between the femoral wall and ligament was measured using a digital caliper and maximum failure load was tested.

Results: Gap formation after five, 50 and 100 cycles of the knee were 0.30 mm (±0.23), 0.75 mm (±0.55) and 0.97 mm (±0.70), respectively, with no significant differences between both fixation techniques. The overall maximum failure load was 243 N (±143) with no difference between both techniques. Most common failure mode was slipping of suture from the fixation.

Conclusion: Following proximal ACL repair, gap formation of approximately one millimeter was measured after repetitious knee cycling with mean maximum failure load of 243 N. These findings are likely to be sufficient for careful early active range of motion (ROM) when extrapolating from other available studies. Future studies with second-look arthroscopy are necessary to assess the gap formation and healing in patients treated with primary repair.

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1. Introduction

The first treatment of an anterior cruciate ligament (ACL) injury was performed almost 120 years ago by Mayo Robson [1]. He performed open primary repair of a proximal ACL and posterior cruciate ligament (PCL) tear in a 41-year old man and reported a stable knee and resolution of pain symptoms at six-year follow-up [1]. Over the ensuing decades, open primary repair was popularized by Palmer [2] and O’Donoghue [3,4] and the technique was commonly used throughout the second part of the twentieth century. However, inconsistent results were reported [4–8] and it was noted that “although … primary repair of the anterior cruciate may work in some patients, it is an unpredictable operative procedure” [7].

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Years later, Sherman and colleagues showed in a subgroup analysis of their outcomes of open primary ACL repair that patients with proximal ACL tears and excellent tissue quality were associated with better outcomes [9]. Several other studies echoed the findings of better results of ACL repair in patients with proximal tears [10–14]. However, despite these findings and the advantages of ACL preservation including preserved proprioception [15,16], native ACL kinematics [17] and not burning bridges for a possible ACL reconstruction, the technique of open primary ACL repair was abandoned and replaced by ACL reconstruction [50,51].

Modern developments such as magnetic resonance imaging (MRI) can improve patient selection regarding tear type and tissue quality. Furthermore, modern surgical techniques (i.e. arthroscopy) and modern rehabilitation (i.e. accelerated ACL rehabilitation protocols) can minimize the morbidity of surgery, prevent the historically reported stiffness and improve outcomes [6,18]. Not surprisingly, recent studies have reported good to excellent results of patients treated with arthroscopic primary repair of proximal ACL tears [19–21,52–54]. This suggests that arthroscopic primary ACL repair can play a role in treatment of proximal tears while ACL reconstruction remains the gold standard in other tear types.

For optimal treatment and rehabilitation of arthroscopic primary ACL repair, it is important to understand the direct postoperative biomechanical characteristics of primary repair, but these studies are lacking. Therefore, a cadaveric study was performed to assess (1) gap formation and (2) maximum failure load following proximal ACL repair and (3) compare these outcomes between suture anchor fixation and suture button fixation. The hypothesis was that (1) no clinically significant gap would occur following simulated active knee motion, which is important for healing [22–24], (2) the maximum failure load was sufficient for passive range of motion (ROM) exercises in early rehabilitation [25–28] and (3) no difference between both suture fixation techniques existed.

2. Methods

2.1. Cadaveric preparation

Twelve fresh-frozen cadaveric knees (six matched pairs) were used in this biomechanical study (mean age: 52 years; range: 48 to 56 years; 3 males and 3 females). The surrounding skin and musculature were stripped and the patella, patellar ligament, the cruciate ligaments and collateral ligaments were left intact. The quadriceps tendon was dissected five centimeters proximal to the proximal edge of the patella and quadriceps tendon was sutured using one strand of #2 FiberWire and one strand of #2 TigerWire (both Arthrex, Naples, FL, USA). These sutures were directed through a pulley and clamped in a vise, which enabled mechanically activated knee extension. The tibia was dissected approximately 15 cm below the tibial plateau and the knee was allowed to relax at 90° of flexion. A 3.85 kg weight was suspended 15 cm below the tibia plateau in order to simulate the weight of the foot and soft tissues.

2.2. Surgical technique

An arthrotomy was performed to ensure that the ligamentous and capsular restraints were intact and no gross joint degeneration was seen. The ACL was then sharply released from the femoral footprint and the distal ACL stump was prepared with a Bunnel stitch of #2 FiberWire placed into each bundle of the ligament. In the matched-paired specimens one knee was randomly assigned to ACL repair using bone-tunnel suture-button fixation, while the other knee was assigned to repair using knotless suture anchor fixation.

In one knee, two parallel 2.4-mm drill holes were created using a cannulated drill (RetroDrill, Arthrex, Naples, FL, USA) from the femoral footprint towards the lateral femoral cortex. A small incision was made over the lateral femoral cortex to assist the drill out and a nitoil-passing wire was passed through the drill cannulation to shuttle the repair sutures through the lateral femoral condyle. Using a suture-button (RetroButton, Arthrex, Naples, FL, USA), the sutures of the ACL remnant were tensioned and tied at the lateral cortex of the femur, thus fixing the ACL remnant towards the femoral footprint.

In the contralateral knee, two 4.5 × 20 mm holes were drilled into the origin of the anatomic femoral footprint. The suture pairs from each bundle were then passed through a 4.75 mm Vented BioComposite SwiveLock suture anchor (Arthrex, Naples, FL, USA) and each anchor was deployed into the drilled hole in the femoral footprint origin, thus tensioning and fixing the ACL remnant towards the femoral footprint.

2.3. Cadaveric testing

Prepared specimens were mounted onto an Instron 8871 testing machine (Instron Co., Norwood, MA, USA) with a five kilonewton load cell secured to the crosshead (Figure 1). Each specimen was mounted via the sutures through the quadriceps muscle onto the crosshead while the femur was perpendicular to the direction of crosshead motion. The knee was then mechanically cycled from 90° of flexion through full extension with a frequency of 0.1 Hz. After five, 50 and 100 cycles the position of the remnant was recorded using a digital caliper [29,30]. Subsequently, a single maximum pullout force consisting of a load rate of one millimeter per second perpendicular to the femur was performed to determine the maximum failure load of the repair in each specimen. The mode of failure was inspected visually. All data was reported in mean (±SD).

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2.4. Statistical analysis

Statistical analysis was performed using SPSS Version 21 (SPSS Inc., Armonk, NY, USA). Paired t-tests were performed to assess differences in gap displacement and maximum load between the knotless suture anchor technique and the bone-tunnel button-fixation technique. All tests were two sided and differences were considered significant when \( p < 0.05 \).

Table 1
Cyclic displacement after five, 50 and 100 cycles in six matched-paired cadaveric knees.

<table>
<thead>
<tr>
<th>Knee</th>
<th>Age</th>
<th>Sex</th>
<th>Repair</th>
<th>Side</th>
<th>Cyclic displacement (mm)</th>
<th>Repair</th>
<th>Side</th>
<th>Cyclic displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51</td>
<td>F</td>
<td>Button</td>
<td>L</td>
<td>0.49</td>
<td>2.13</td>
<td>2.13</td>
<td>Suture anchor</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>M</td>
<td>Button</td>
<td>L</td>
<td>0.17</td>
<td>0.78</td>
<td>0.78</td>
<td>Suture anchor</td>
</tr>
<tr>
<td>3</td>
<td>56</td>
<td>M</td>
<td>Button</td>
<td>L</td>
<td>0.03</td>
<td>0.49</td>
<td>0.55</td>
<td>Suture anchor</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>F</td>
<td>Button</td>
<td>R</td>
<td>0.02</td>
<td>0.26</td>
<td>0.34</td>
<td>Suture anchor</td>
</tr>
<tr>
<td>5</td>
<td>53</td>
<td>M</td>
<td>Button</td>
<td>R</td>
<td>0.05</td>
<td>0.17</td>
<td>0.17</td>
<td>Suture anchor</td>
</tr>
<tr>
<td>6</td>
<td>56</td>
<td>F</td>
<td>Button</td>
<td>R</td>
<td>0.42</td>
<td>1.01</td>
<td>1.01</td>
<td>Suture anchor</td>
</tr>
<tr>
<td>Total</td>
<td>52.3</td>
<td></td>
<td></td>
<td></td>
<td>0.20 (± 0.21)</td>
<td>0.81 (± 0.72)</td>
<td>0.83 (± 0.70)</td>
<td>0.40 (± 0.22)</td>
</tr>
</tbody>
</table>

M indicates males; F, female; L, left; R, right.
No significant differences were seen between both repair techniques at five, 50 and 100 cycles.

Figure 1. A cadaveric ACL was mounted to the Instron machine in order to determine the maximum failure load.

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3. Results

Overall gap formation between the ACL remnant and the femoral wall was after five cycles 0.30 mm (±0.23), after 50 cycles 0.75 mm (±0.55) and after 100 cycles 0.97 mm (±0.70). No differences were found in gap formation between both fixation techniques (Table 1, Figure 2).

One matched-paired cadaver could not be used to assess maximum failure load because it was damaged during testing. In the other five matched-paired cadavers, overall maximum failure load was 243 N (±143) without significant difference between mean maximum failure load in the button fixation (310 N (±151)) and mean maximum failure load in the suture anchor fixation (176 N (±109); p = 0.144). The lowest and highest maximum failure loads in the button fixation were 260 N and 496 N, respectively, while the lowest and highest failure loads in the suture anchor fixation were 65 N and 299 N, respectively (Table 2).

Most common failure mode observed in the button fixation was slipping of the suture at the femoral tunnel (four knees) while in one specimen the suture broke. Additionally, in two knees a small tear was detected in the ACL and in one knee a complete tear was noted. The most common failure mode in the suture anchor fixation was slipping of the suture at the femoral tunnel (five knees). In addition, in one knee the ligament had a complete tear and in one knee the ligament had a small tear (Table 2).

4. Discussion

Our cadaveric study demonstrated that in knees undergoing primary proximal ACL tear repair, a gap of approximately one millimeter was formed following simulated active knee cycling. Furthermore, it was found that the overall mean maximum failure load was 243 N. No significant differences were found in either outcome between button fixation and suture anchor fixation.

The overall gap formation in this study after 100 cycles was approximately one millimeter without significant differences between both fixation techniques. To our knowledge, no other studies have assessed the gap formation directly after primary ACL repair. Therefore only indirect comparison with other studies is possible. Cabaud et al. performed primary ACL repair of proximal tears with augmentation in 12 dogs [31]. They found intact, healthy-appearing ACL after two weeks, five weeks and four months after primary repair. Other studies have shown that proximal tears can even heal without fixation. Several case reports [32–35] and case series [36–38] reported spontaneous healing of proximal tears. Similarly, three studies reported good results of treating proximal tears by inducing bleeding and approximating the ACL remnant to the femoral footprint without

Figure 2. A right knee is shown following ACL repair with suture anchor fixation. In the left top picture (A) the ACL is shown after tensioning and fixation. After five cycles a gap of 0.32 mm is measured (right top picture, B), after 50 cycles a gap of 0.49 mm is measured (left down picture, C) and after 100 cycles a gap of 0.83 mm was measured (right down picture, D) using the digital caliper. The ruler is displayed to show the proportion between the gap and the distances measured.

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fixation [22–24]. Patients were then treated with a brace locked in full extension for six weeks in order to stabilize the ligament end and the induced marrow clot. These studies show that proximal ACL tears have healing potential and even though most of these studies did not use fixation, healing was ultimately seen. Given the lack of fixation, it could be expected that some gap formation occurred in these non-fixed cases, similar or more to our reported one millimeter. We think our finding of one millimeter gap formation after 100 cycles of the knee indicates that some ROM is possible in early rehabilitation, which could prevent knee stiffness [6,18]. However, we feel that future research on gap formation could have additional value on the exact mechanism of proximal ACL healing, for instance by second-look arthroscopy a few weeks after ACL repair in clinical patients [39].

The maximum load to failure in this study was 243 N without any difference between both fixation techniques. The goal of primary ACL repair is to achieve a fixation strong enough to sustain early ROM, whereas the goal is not to sustain early daily activities or sporting activities. With regard to early rehabilitation, Seitz et al. advocated that a load carrying capacity of the repaired ACL of 60 N is necessary to protect the ACL during the first few weeks [27], a finding based on other studies [25,26,28]. In our study the maximum failure load was higher than 60 N in all cadavers, which would indicate that early cautious ROM is possible. Two studies used an early passive ROM program following primary ACL repair and found no stiffness at follow-up [19,40]. DiFelice et al. initiated ROM exercises in the first days following arthroscopic primary proximal ACL repair in a controlled fashion [19]. During the rest of the day a brace locked in extension was used until voluntary quadriceps muscle control returned. Similarly, Gobbi et al. reported primary ACL repair of 26 partial proximal tears and initiated a continuous passive motion (CPM) machine the day after surgery [40]. Full ROM was allowed around six weeks, running activities after three months and high-contact sports after four to five months. Although an exact protocol for rehabilitation following primary ACL repair does not exist, the findings of this study, taken in combination with the rehabilitation programs of these studies, suggest that early ROM is likely to be possible in these patients without endangering the repaired ACL. Enabling early ROM will likely prevent stiffness, which was reported to be a problem in historical ACL repair [6,18]. More studies are, however, necessary to determine optimal early rehabilitation following arthroscopic primary ACL repair of proximal tears.

With regard to later rehabilitation, several studies have shown that ACL tensile strength following repair increases in the first weeks [31,41]. The aforementioned study by Cabaud et al. showed that the maximum failure load increased significantly from two weeks postoperatively to four months postoperatively [31]. Moreover, Seitz et al. performed proximal ACL repair in 40 sheep and tested ACL tensile strength at two, six, 16 and 52 weeks after cutting of the sutures [41]. They found that the ACL tensile strength between two weeks and six weeks increased 100% and between two and 16 weeks increased 550%, without any further increase after 16 weeks. These studies showed that one could expect tensile strength and maximum failure load to increase during the first few weeks following ACL repair. For later rehabilitation, Seitz et al. stated that a minimum load carrying capacity of 285 N is necessary for outdoor recovery [27,42] while other studies showed that the ACL peak force during walking on flat surface is approximately 150 N to 200 N and during jogging is approximately 450 N to 600 N [42–47]. With the findings of this study and the expected tensile strength increase as found by Seitz et al., one may expect that walking is possible after only a few weeks. This could explain the fast recovery that is reported in recent studies performing ACL repair [19,40].

Failure modes in this study were slipping of sutures in nine cases and suture breakage in one case, which could indicate that further improvement of the fixation technique could increase the maximum failure load. In one knee with button fixation and one knee with suture anchor fixation, a complete ACL tear was noted. The maximum failure load in these knees with complete tears was significantly higher than the average failure load in these fixation techniques (Table 2), which also indicates that fixation technique can improve the maximum failure load. However, small ACL tears were seen in three cadavers of which two occurred at fairly high loads (288 N and 496 N), but in one cadaver this occurred at low load of 65 N. A specific technical explanation for this low value could not be identified.

For many years, a general consensus existed for inconsistent and unpredictable results of open primary ACL repair. The findings of the study of Sherman et al. with their extensive subgroup analysis showed, however, that primary ACL repair might be a good treatment option in patients with proximal tears and excellent tissue quality [9]. This was also noted by multiple other authors [10,12–14,48]. One of the limitations of the historical studies performing open primary ACL repair was that the postoperative regimen immobilized patients with a cast for six weeks resulting in significant stiffness and patellofemoral symptoms [18]. Genelin et al. was one of the few studies that only performed primary ACL repair in proximal tears and reported

### Table 2

<table>
<thead>
<tr>
<th>Knee</th>
<th>Age</th>
<th>Sex</th>
<th>Repair</th>
<th>Side</th>
<th>Ultimate load (N)</th>
<th>Failure mode</th>
<th>Repair</th>
<th>Side</th>
<th>Ultimate load (N)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51</td>
<td>F</td>
<td>Button</td>
<td>L</td>
<td>260</td>
<td>Slipped at tunnel</td>
<td>Suture anchor</td>
<td>R</td>
<td>163</td>
<td>Slipped at tunnel</td>
</tr>
<tr>
<td>2</td>
<td>48</td>
<td>M</td>
<td>Button</td>
<td>L</td>
<td>406</td>
<td>Slipped at tunnel</td>
<td>Complete tear</td>
<td>R</td>
<td>299</td>
<td>Slipped at tunnel</td>
</tr>
<tr>
<td>3</td>
<td>48</td>
<td>M</td>
<td>Button</td>
<td>R</td>
<td>500</td>
<td>Suture broke</td>
<td>Small tear</td>
<td>R</td>
<td>65</td>
<td>Slipped at tunnel</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>F</td>
<td>Button</td>
<td>R</td>
<td>496</td>
<td>Slipped at tunnel</td>
<td>Small tear</td>
<td>L</td>
<td>75</td>
<td>Slipped at tunnel</td>
</tr>
<tr>
<td>5</td>
<td>53</td>
<td>M</td>
<td>Button</td>
<td>R</td>
<td>288</td>
<td>Slipped at tunnel</td>
<td>Small tear</td>
<td>L</td>
<td>276</td>
<td>Slipped at tunnel</td>
</tr>
<tr>
<td>6</td>
<td>56</td>
<td>F</td>
<td>Button</td>
<td>R</td>
<td>260</td>
<td>Slipped at tunnel</td>
<td>Suture anchor</td>
<td>L</td>
<td>176</td>
<td>Slipped at tunnel</td>
</tr>
<tr>
<td>Total</td>
<td>51.6</td>
<td></td>
<td></td>
<td></td>
<td>310 (± 151)</td>
<td></td>
<td></td>
<td></td>
<td>176 (± 109)</td>
<td></td>
</tr>
</tbody>
</table>

ACL indicates anterior cruciate ligament; M, male; F, female; L, left; R, right; N, Newton.

No significant difference in ultimate load was seen between both repair techniques ($p = 0.144$).
excellent outcomes at mid-term follow-up [10]. They noted in their discussion “we believe that, even with the same operational technique, the results can be improved still further by early postoperative treatment with a CPM machine, combined with a brace providing limited knee joint motion”. It is not surprising that in modern studies performing arthroscopic minimally invasive primary ACL repair, motion was encouraged in the early postoperative period and that both studies reported good outcomes of these procedures with fast recovery [19,40]. This biomechanical study is, to our knowledge, the first study that assessed gap formation and maximum failure load following ACL repair of specific proximal tears. Future studies are clearly needed to assess the clinical role of gap formation following ACL repair, for example by second look arthroscopy following arthroscopic primary ACL repair.

When reviewing the literature for biomechanical studies on primary ACL repair in human cadavers, only one study could be identified. Kohl et al. dissected the ACL in human cadavers, repaired the ligament while adding a dynamic intraligamentary stabilization device and assessed the anteroposterior stability [49]. They noted that following primary repair the anteroposterior laxity significantly increased following cycling the knee and suggested to add the DIS device to the ACL repair. Although anteroposterior stability was not assessed in this current biomechanical study, DiFelice et al. [19] and Achtnerich et al. [21] found excellent anteroposterior stability with the Lachman and pivot shift test two years after primary ACL repair. Future studies are therefore necessary to further explore this discrepancy.

Several limitations are present in this study. Firstly, gap formation was measured using a digital caliper and small variations in measurements could be present. However, this measurement method is commonly used in orthopedic studies [29,30] and is the most precise measurement available in our opinion. Secondly, only 100 cycles were performed while some other biomechanical studies performed more than 100 cycles. However, the goal of rehabilitation in the first few weeks is giving the ligament the opportunity to heal, achieving full ROM and preventing stiffness. The goal is not to fully walk or run unprotected in the first few weeks [19,40]. Thirdly, the exact meaning of a one millimeter gap formation is not known. It can only be extrapolated from studies that showed spontaneous proximal ACL healing [32–38] and healing by healing response [22–24] that this gap will be sufficiently stable for subsequent healing. Future studies are necessary to assess the exact role of this gap in early rehabilitation.

5. Conclusion

This cadaveric study found gap formation of approximately one millimeter following primary ACL repair and subsequent cycling of the knee joint with mean maximum failure load of 243 N. When extrapolating other studies available in the literature, these findings are likely to be sufficient for ACL healing and early ROM exercises following ACL repair. Future studies, such as early second-look arthroscopy, are necessary to provide additional information on the role of gap formation and healing in primary repair of proximal ACL tears.

Conflict of interest

Author GSD declares to be a paid consultant for Arthrex. Author JPL declares that he has no competing interests.

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