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Original Article

Mechanical testing of patellofemoral instability after induced failure of the patellofemoral ligament reconstruction using four different cadavers grafts

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ABSTRACT

Purpose: To ascertain whether differences exist in joint instability after experimentally induced failure of medial patellofemoral ligament (MPFL) reconstruction in the cadaver knee with the four graft types most widely used for this procedure, and whether any of these grafts are associated with decreased risk in the event of failure.

Methods: Between March 2011 and March 2012, eight cadavers obtained from the local medical examiner's office were randomly allocated into four groups (four knees each). In each group, a different graft technique was used for MPFL reconstruction. The forces required to induce lateral dislocation of the patella before reconstruction and after experimental failure of surgical reconstruction were recorded. The tested graft techniques were then compared to assess which was associated with the least instability after failed reconstruction.

Results: When we compared the groups I (semitendinosus) and II (patellar tendon), the mean differences of the force required to produce a dislocation of the patella before and after the failure were 0.5 N and 12.5 N, respectively ($p = 0.028$). In comparison between groups I and III (medial third of the quadriceps tendon) the mean differences of the force required to produce dislocation before and after the failure caused were 0.5 N and 22 N, respectively ($p < 0.001$). In comparison between groups I and IV (Medial third of the quadriceps tendon) we found the mean differences of the force required to produce dislocation before and after the failure caused were 0.5 N and 5 N, respectively ($p > 0.999$).
Conclusions: There were differences in residual instability after simulated MPFL reconstruction failure depending on graft type. Use of the free semitendinosus graft technique was associated with the least risk of residual instability in case of reconstruction failure.

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1. Introduction

Patellar dislocation is characterized by a breakdown in the stability of the patella between the femoral condyles. Dislocation may be due to torsional strain, when a patient's body rotates while the foot remains planted on the ground; less commonly, direct trauma to the medial aspect of the patella may lateralize it to the point of dislocation. Medial dislocations are rare in patients without a history of lateral retinacular release surgery.¹

The medial patellofemoral ligament (MPFL) is a retinacular band of organized fibrous tissue that connects the medial femoral condyle to the medial border of the patella. This ligament is the main structure responsible for restricting lateralization of the patella,² accounting for 60% of total restraint.³ The integrity of the MPFL is compromised since the very first episode of dislocation. Repair is very poor, and only rarely will the ligament recover full function. MPFL reconstruction is a valuable technique in cases of recurrent dislocation. Since it was first described in 1992,⁴ over 100 techniques for this procedure have been reported in the literature.^{5–8}

The incidence of first-time (primary) patellar dislocation is 5.8 per 100,000, increasing to 29 per 100,000 among children in the 10-to-17-year age group. The recurrence rate ranges from 15% to 44% after non-operative treatment. If the patient has a subsequent patellar dislocation after the primary episode, there is a 50% of recurrence.⁹

The natural history of non-operative treatment of patellar dislocation involves recurrent dislocation in 1 out of 6 cases and residual symptoms in 2 out of 6, with the 3 remaining patients following an asymptomatic course.¹⁰

Treatment of patellar instability is similar to that of acute dislocation, that is, non-operative at first and surgical if this approach fails. The available methods for repair may be classified into proximal realignment, distal realignment, proximal and distal realignment, lateral retinacular release, and medial retinacular imbrication.^{11,12}

The patellar and quadriceps tendons provide a strong posterior force vector during flexion of the knee, thus increasing stability during this motion.² Therefore, surgical procedures that use these structures for MPFL reconstruction¹³ actually carry the risk of aggravating patellar instability in the event of reconstructive failure, leading to a further decline in the patient's condition, whereas techniques employing structures that do not play a primary role in patellofemoral stability⁴ should be comparatively safer. Therefore, this experiment compared preoperative and post-simulated failure patellofemoral instability in cadavers subjected to these procedures.

The purpose of this study was to assess, using a paired experimental design, patellar stability outcomes after simulated failure of medial patellofemoral ligament reconstruction with the four graft techniques most widely used for this procedure. The study hypothesis was that reconstruction techniques which employ structures from the extensor apparatus are associated with poorer stability outcomes in the event of reconstruction failure. This same hypothesis could have been tested with flexor or adductor magnus tendon grafts. However, as irregular size and consistency have been reported with the latter in previous studies, we chose to use semitendinosus grafts alone as the comparator.

2. Methods

Sample size was calculated for a statistical power of 80%, a significance level of 5%, a 100% likelihood of preserved patellar stability after simulated failure of patellar reconstruction with a semitendinosus graft, and a 100% likelihood of decreased patellar stability after simulated failure of patellar reconstruction with a patellar tendon or quadriceps tendon (central or medial third) graft. The minimum sample size was calculated as four specimens (knees) per technique, for a total of eight cadavers.

Our criteria for defining outcomes as successful or unsuccessful were based on comparison between the traction loads used before the surgical procedure (immediately after release of the MPFL) and after simulated failure of the procedure. The outcome was considered unsuccessful when the load measured after simulated repair failure was less than the load measured immediately after MPFL release, and successful when the load measured after simulated failure remained the same as shortly after MPFL release.

Between March 2011 and March 2012, eight male cadavers meeting the following criteria were obtained from the office of the medical examiner:

Inclusion criteria:

- Age 15–50 years at the time of death, no more than 18 elapsed since death (rigor mortis), and intact knees (good flexion, extension, and resistance to maneuvers for assessment of patellar dislocation).

Exclusion criteria:

- Signs suggestive of prior ligament injury, knee surgery, or recurrent patellar dislocation; clinical history of ligamentous laxity.

The next of kin of selected cadavers provided informed consent for their use in the study. Sixteen knees from eight cadavers were selected. These were then randomly allocated (by envelope randomization after a computer-generated drawing) across four groups:

- Group I. Semitendinosus tendon graft technique (n = 4);
- Group II. Patellar ligament graft technique (n = 4);
- Group III. Medial quadriceps tendon graft technique (n = 4);
- Group IV. Central quadriceps tendon graft technique (n = 4).

All knees were inspected (to detect a potential history of knee surgery or knee trauma, including ligament injury) and subjected to joint stability tests, to ensure that the knee joint was free of pathological conditions such as decreased range of motion, patellar laxity (using the glide test and dislocation tests), and osteoarthritis (using the facet tenderness test).

2.1. Operative technique

All surgeries were performed by the same operator. In all knees, a parapatellar arthrotomy was performed, accompanied of macroscopic assessment of the patellofemoral joint,

and the experiment was conducted. The experiment consisted of objective assessment of patellar stability by means of a small double hook attached to the medial border of the patella and to a length of thin steel cable. On the end of this steel wire, a container was hung and then gradually filled with water (Fig. 1). This simple method assessed the ability of the extensor apparatus to withstand lateral traction until lateral dislocation of the patella occurred.

Only one graft technique was used in each knee, which served as its own before-and-after control for the technique employed, providing paired sample data for later analysis.

In group I (semitendinosus), a longitudinal incision (mean length 20 cm) was made on the skin overlying the anterior aspect of the knee and medial parapatellar arthrotomy was performed with concomitant division of the medial patellofemoral ligament (MPFL). To determine the upper limit of the arthrotomy, the overall length of the patella was measured with calipers and a medial paratendinous incision was fashioned from the quadriceps to the boundary of this measurement (Fig. 2A and B). The arthrotomy was then extended from the upper pole of the patella to the attachment of the patellar ligament at the tibial tuberosity. The knee was flexed 30° and the lateral traction system was installed. This system consisted of a metal arm, attached to the dissection table and with a pulley at the free end, and a 5 mm-thick steel cable, which ran through the pulley and had at one end, a double hook attached to the medial border of the patella and at the other, a plain hook from which a 10 L bucket was hung. With the aid of a measuring cup, the bucket was gradually filled with water until dislocation of the patella occurred (Fig. 3). The content of the bucket was immediately weighed on a precision balance and the mean, in grams, between the fluid volume poured from the measuring cup and the mass measured on the balance was calculated to determine the force required to induce lateral patellar dislocation. Data collection was followed by stage two of the experiment, also in group I, in which MPFL reconstruction was performed with a free semitendinosus tendon graft.

The semitendinosus tendon was removed as a free graft with the aid of an extractor. The patella was drilled through its

Fig. 1 – Apparatus used to induce experimental lateral dislocation of the patella. The knee was flexed 30°, a double hook attached to a steel cable was fixed to the medial border of the patella, and a bucket was hung from the free end of the cable and gradually weighted until lateral dislocation occurred.

Fig. 2 – A. Measurement of the length of the patella to determine the upper limit of arthrotomy. B. Use of the patellar length measurement as a landmark for the upper limit of arthrotomy.

medial third with a 2.7-mm bit, medial to lateral, and the first 10 mm of the resulting tunnel at the medial side were widened with a 3.2-mm bur. Sutures were placed onto one of the free ends of the tendon, which was then threaded through the widened portion of the patellar tunnel, medial to lateral, and sutured in place over the lateral retinaculum. The graft was threaded under an osteoperiosteal tunnel fashioned at the femoral attachment of the adductor magnus tendon and sutured onto itself.¹⁴

After reconstruction was completed, the graft was bisected, to simulate failure, and the lateral traction apparatus was used again to measure the force required to induce lateral dislocation of the patella. As before, the volume of fluid in mL was measured with a measuring cup and its mass (in g) on a

Fig. 3 – Experimental dislocation of the patella with the lateral traction apparatus.

precision balance. This procedure provided an exact dimension of the difference in force required to induce dislocation before and after reconstruction.

In group II (patellar ligament), the procedure was the same as in group I through attachment of the lateral traction system, experimental dislocation of the patella, and data collection, including the same sequence of medial structure release. The second stage of the experiment, however, consisted of measurement of the width of the patellar ligament at its exact point of attachment to the lower pole of the patella, with the aid of calipers. This measurement was then divided in three and a longitudinal graft was harvested from the medial third of the tendon (mean length, 11 cm). The graft was released from the tibial tuberosity and part of the patellar periosteum was left on for added length, with the attachment at the upper pole of the patella left intact. The free end of the graft was then attached to the medial epicondyle of the femur to complete MPFL reconstruction.¹² The graft was then immediately bisected at the middle third to simulate reconstruction failure, as in group I. Again, the lateral traction apparatus was used as described above, to provide an exact dimension of the difference in force required to induce dislocation before and after reconstruction (Fig. 4A and B).

In group III (medial quadriceps tendon graft), the procedure was the same as in groups I and II through attachment of the lateral traction system, experimental dislocation of the patella, and data collection, including the same sequence of

medial structure release. The second stage of the experiment, however, consisted of measurement of the width of the quadriceps tendon at its exact point of attachment to the upper pole of the patella, with the aid of calipers. This measurement was divided in three and a longitudinal graft was harvested from the medial third of the tendon (mean length, 13 cm), with the attachment at the upper pole of the patella left intact. The free end of the graft was then attached to the medial epicondyle of the femur to complete MPFL reconstruction.¹³ The graft was then immediately bisected at the middle third to simulate reconstruction failure, as in groups I and II. Again, the lateral traction apparatus was used as described above (Fig. 5A–C), to provide an exact dimension of the difference in force required to induce dislocation before and after reconstruction.

In group IV (central quadriceps tendon graft), procedure was the same as in groups I and II through attachment of the lateral traction system, experimental dislocation of the patella, and data collection, including the same sequence of medial structure release. The second stage of the experiment consisted of measurement of the width of the quadriceps tendon at its exact point of attachment to the upper pole of the patella, with the aid of calipers, as in group III. This measurement was divided in three and a longitudinal graft was harvested from the central third of the tendon (mean length, 14 cm), with the attachment at the upper pole of the patella left intact. The free end of the graft was then attached to the medial epicondyle of the femur to complete MPFL reconstruction.¹³ The graft was then immediately bisected at the middle third to simulate reconstruction failure, as in the other groups. Again, the lateral traction apparatus was used as described above (Fig. 6A–C) to provide an exact dimension of the difference in force required to induce dislocation before and after reconstruction.

Fig. 4 – A. After experimental dislocation, the medial patellofemoral ligament is reconstructed (example image showing a patellar tendon graft). **B.** The patella is tested for instability after simulated failure of medial patellofemoral ligament reconstruction with a patellar tendon graft.

3. Outcome measures

Knees were assessed on the same day, before and after the experiment. The force required to induce lateral patellar dislocation was measured before and after experimental induction of MPFL reconstruction failure in each of the graft technique groups. The mass of water required to induce lateral patellar dislocation was measured using a measuring cup and a precision balance.

4. Statistical analysis

Power analysis was carried out under the assumption that a maximum difference of 10% in force required for dislocation before vs. after reconstruction failure would be clinically significant.

Data were expressed as absolute and relative frequencies for between-group comparison. Analyses were carried out in SPSS 18.0 and the significance level and statistical power were set at 5% and 80% respectively. The Shapiro–Wilk test confirmed that the data were normally distributed, and analysis of variance (ANOVA) was carried out for between-group comparisons.

Fig. 5 – A. Medial patellofemoral ligament reconstruction with a medial quadriceps tendon graft. **B.** Simulated failure of medial patellofemoral ligament reconstruction. **C.** Experimentally induced lateral dislocation of the patella after simulated failure of medial patellofemoral ligament reconstruction (in the example image, reconstruction was performed with a medial quadriceps tendon graft).

5. Results

Eight cadavers were randomly distributed, by computer-based envelope randomization, into four groups of two cadavers each (four knees per group). Group I consisted of knees in

Fig. 6 – A. Reconstruction of the medial patellofemoral ligament with a central quadriceps tendon graft. **B.** Simulated failure of medial patellofemoral ligament reconstruction with a central quadriceps tendon graft. **C.** The patella is tested for instability after simulated failure of medial patellofemoral ligament reconstruction.

which MPFL reconstruction was performed using the free semitendinosus tendon graft technique. Group II consisted of knees in which MPFL reconstruction was performed using the medial patellar tendon graft technique. Group III consisted of knees in which MPFL reconstruction was performed using the medial quadriceps tendon graft technique. Finally, Group IV

consisted of knees in which MPFL reconstruction was performed using the central quadriceps tendon graft technique.

In group I, the mean force required to induce lateral patellar dislocation was 4.541 kgf (45.5 N) in the first stage of the experiment—before MPFL reconstruction—and 4.517 kgf (45.5 N) in the second stage of the experiment, i.e., after reconstruction and section of the ligament. Therefore, in group I, after induced failure of the reconstructed MPFL, the force required to dislocate the patella laterally was equivalent, on average, to 99.45% of the force required to induce dislocation before MPFL reconstruction.

In group II, the mean force required to induce lateral patellar dislocation was 3.768 kgf (37.6 N) in the first stage of the experiment, i.e., before MPFL reconstruction, and 2.506 kgf (25 N) after reconstruction and section of the ligament. Therefore, in group II, after induced failure of the reconstructed MPFL, the force required to dislocate the patella laterally was equivalent, on average, to 66.50% of the force required to induce dislocation before MPFL reconstruction.

In group III, the mean force required to induce lateral patellar dislocation was 4.319 kgf (43 N) in the first stage of the experiment, i.e., before MPFL reconstruction, and 1.216 kgf (12 N) after reconstruction and section of the ligament. Therefore, in group III, after induced failure of the reconstructed MPFL, the force required to dislocate the patella laterally was equivalent, on average, to 28.15% of the force required to induce dislocation before MPFL reconstruction.

In group IV, the mean force required to induce lateral patellar dislocation was 3.888 kgf (38 N) in the first stage of the experiment, i.e., before MPFL reconstruction, and 3.307 kgf (33 N) after reconstruction and section of the ligament. Therefore, in group II, after induced failure of the reconstructed MPFL, the force required to dislocate the patella laterally was equivalent, on average, to 85.05% of the force required to induce dislocation before MPFL reconstruction.

In this paired experimental study, we found that differences exist between the various grafts used for MPFL reconstruction with respect to patellar stability in case of reconstructive failure. Comparison between groups I (semitendinosus graft) and II (patellar tendon graft) showed a substantial difference between the two techniques: the force required to induce dislocation after experimentally simulated reconstruction failure was 99.45% of the pre-failure force in group I and 66.5% of the pre-failure force in group II, that is, the force required for dislocation was 35% less in group II. On post-hoc analysis, this difference between groups I (semitendinosus) and II (patellar tendon) was significant ($p = 0.028$).

Comparison between groups I (semitendinosus) and III (medial quadriceps tendon graft) also showed a difference between these two techniques: the force required to induce dislocation after experimentally simulated reconstruction failure was 99.45% of the pre-failure force in group I, as mentioned above, and 28.16% of the pre-failure force in group III, that is, the force required to induce dislocation was 72% less in group III. On post-hoc analysis, this difference between groups I (semitendinosus) and III (medial quadriceps tendon) was significant ($p < 0.001$).

Comparison between groups I (semitendinosus graft) and IV (central quadriceps tendon graft) again showed a difference between these two techniques: the force required to induce dislocation after experimentally simulated reconstruction

failure was 99.45% of the pre-failure force in group I, as mentioned above, and 85.05% of the pre-failure force in group IV, that is, the force required to induce dislocation was 15% less in group III. On post-hoc analysis, this difference between groups I (semitendinosus) and IV (central quadriceps tendon) was not significant ($p > 0.999$).

In short, statistical analysis showed significant differences between groups I and II and between groups I and III ($p < 0.05$). Although there was a difference between groups I and IV, it did not reach statistical significance (Fig. 7).

6. Discussion

Patellar dislocation is characterized by a breakdown in the stability of the patella between the femoral condyles. The medial patellofemoral ligament (MPFL) connects the medial femoral condyle and the medial border of the patella. This ligament is the main structure responsible for restricting lateralization of the patella.² Its integrity is compromised from the very first episode of dislocation, and only rarely can it be restored to full function. MPFL reconstruction is invaluable in cases of recurrent dislocation, but some of the techniques used for reconstruction may affect stabilizing factors, and there have been few reports of complications in the event of failed reconstruction, even though a multitude of studies have been published on MPFL reconstruction techniques and their outcomes.^{3,4,12,13} Other authors have reported potential causes of treatment failure.^{14,15} However, there have been no studies of the outcomes of different reconstruction techniques in case of failure. The patellar and quadriceps tendons provide a strong posterior force vector during flexion of the knee, thus increasing stability during this motion.² Therefore, surgical procedures that use these structures for MPFL reconstruction¹⁴ actually carry the risk of aggravating patellar

Fig. 7 – Mean differences and standard deviations between the force required to induce lateral dislocation of the patella before and after simulated failure medial patellofemoral ligament reconstruction in the four study groups. Group 1 = Semitendinosus; Group 2 = Patellar Tendon; Group 3 = Medial 1/3 of Quadriceps Tendon; Group 4 = Central 1/3 of Quadriceps Tendon.

instability in the event of reconstructive failure, leading to a further decline in the patient's condition. Conversely, graft techniques that use structures not primarily associated with patellofemoral stability^{5–15} should be safer.

In this study, there were differences in post-reconstruction failure patellar instability between the group in which reconstruction was performed with the semitendinosus tendon graft and groups in which reconstruction was performed with the patellar or quadriceps tendon. This difference was significant ($p < 0.05$) between the semitendinosus group and the patellar tendon group and between the semitendinosus group and the medial quadriceps tendon group.

Some authors¹⁴ have only reported complications associated with surgical technique, such as avulsion of the quadriceps tendon insertion at the upper pole of the patella. Noyes and Albright¹⁵ note rotational disturbances as potential sources of failure after MPFL reconstruction and distal realignment. Our review of the literature failed to find any previous studies assessing the force required to induce patellar dislocation after failure of reconstruction.

How critical to our study, we can mention the fact of we did not close of the donor site after reconstruction and induced failure of the reconstructed MPFL. We know the importance of the medial structures, muscles and other soft tissues to restriction of the patella dislocation, but the closure of the donor site would become a confounding bias in this study. We draw on the literature to support this approach. Besides that, since we are studying the failure of different types of autologous graft, the interference of the graft donor site in the extensor mechanism should also being taken into account.

7. Conclusion

We conclude that, in the cadaver knee, the four different graft techniques most often used for medial patellofemoral ligament (MPFL) reconstruction result in different degrees of residual instability in case of reconstruction failure. Furthermore, we conclude that the free semitendinosus graft technique poses the lowest risk in case of reconstruction failure, as it was not associated with any difference in the force required to induce lateral patellar dislocation before and after simulated reconstruction failure.

Conflicts of interest

All authors have none to declare.

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