The Knee 21 (2014) 1169–1174

Contents lists available at ScienceDirect

The Knee

MPFL reconstruction using a quadriceps tendon graft
Part 1: Biomechanical properties of quadriceps tendon MPFL reconstruction in comparison to the Intact MPFL. A human cadaveric study

Mirco Herbort [a,*], Christian Hoser [b], Christoph Domnick [a], Michael J. Raschke [a], Simon Lenschow [a], Andre Weimann [a], Clemens Kösters [a], Christian Fink [b]

[a] Department of Trauma-, Hand- and Reconstructive Surgery, Westfaelian–Wilhelms University of Muenster, Muenster, Germany
[b] Sportsclinic Austria, Innsbruck, Austria

ARTICLE INFO

Article history:
Received 9 February 2014
Received in revised form 18 July 2014
Accepted 21 July 2014

Keywords:
Knee
MPFL
Biomechanics
Quadriceps tendon reconstruction
Stiffness

ABSTRACT

Background: The aim of this study was to analyze the structural properties of the original MPFL and to compare it to a MPFL-reconstruction-technique using a strip of quadriceps tendon.
Methods: In 13 human cadaver knees the MPFLs were dissected protecting their insertion at the patellar border. The MPFL was loaded to failure after preconditioning with 10 cycles in a uniaxial testing machine evaluating stiffness, yield load and maximum load to failure. In the second part Quadriceps-MPFL-reconstruction was performed and tested in a uniaxial testing machine. Following preconditioning, the constructs were cyclically loaded 1000 times between 5 and 50 N measuring the maximum elongation. After cyclic testing, the constructs have been loaded to failure measuring stiffness, yield load and maximum load. For statistical analysis a repeated measures (RM) one-way ANOVA for multiple comparisons was used. The significance was set at $P < 0.05$.
Results: During the load to failure tests of the original MPFL the following results were measured: stiffness 29.4 N/mm (+9.8), yield load 167.8 N (+80) and maximum load to failure 190.7 N (+82.8). The results in the QT-technique group were as follows: maximum elongation after 1000 cycles 2.1 mm (+0.8), stiffness 33.6 N/mm (+6.8), yield load 147.1 N (+65.1) and maximum load to failure 205 N (+77.8). There were no significant differences in all tested parameters.
Conclusions: In a human cadaveric model using a strip of quadriceps-tendon 10 mm wide and 3 mm deep, the biomechanical properties match those of the original MPFL when tested as a reconstruction.
Clinical relevance: The tested QT-technique shows sufficient primary stability with comparable biomechanical parameters to the intact MPFL.

1. Introduction

Recurrent dislocation of the patella as a sign of chronic patellar instability is a common diagnosis in young and active patients. Recently reconstruction of the medial patellofemoral ligament (MPFL) (Fig. 1) for the treatment of patellar instability has achieved increased attention [1]. Systematic reviews have concluded that MPFL reconstruction in recurrent patellar dislocation is an adequate procedure with a favorable outcome [2–4]. Several surgical techniques have been described. Most of them use hamstring tendons as the graft of choice [5–16]. Despite good clinical outcomes and small re-dislocation rates, some complications have been noticed [2–4,17–22]. Shah et al. [23] performed a systematic review of complications and failures associated with MPFL reconstruction. The authors found complication rates as high as 26.1%. Typical complications following MPFL reconstruction are implant breakage, patellar fractures through bone tunnels and loss of knee flexion [18, 24–28]. A nonphysiologically tightened MPFL reconstruction can result in loss of knee flexion, increased patellofemoral joint pressure and consequent high risk of chondral damage [25,27]. Besides positioning of the MPFL at the femoral condyle and border of the patella, the structural properties of the MPFL graft can significantly influence the patellofemoral joint pressure.

Currently, there is only very limited information available on the biomechanical properties of the original MPFL [29,30]. A previous biomechanical study investigated the biomechanical properties of various hamstring reconstruction techniques and speculated that the stiffness of these constructs might be much higher than the original MPFL [31].

There are a few reports on MPFL reconstruction using a strip of quadriceps tendon without anchors or bone tunnels in the patella [32–34]. In

* Corresponding author at: Department of Trauma-, Hand- and Reconstructive Surgery, Westfaelian–Wilhelms University of Muenster, Waldeyerstrasse 1, 48149 Muenster, Germany. Tel.: +49 251 8356302; fax: +49 251 8356318.
E-mail address: Mirco.Herbort@gmail.com (M. Herbort).

http://dx.doi.org/10.1016/j.knee.2014.07.026

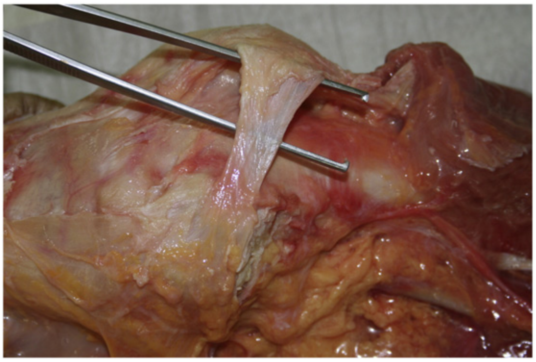

Fig. 1. Dissected the MPFL in a human cadaveric knee.

these procedures a strip of quadriceps tendon is harvested, leaving its attachment to the patella intact. In the technique of Macura and Veselko a 3 mm quadriceps tendon strip is flipped 90° underneath the medial prepatellar tissue in order to allow better fixation and improved healing (Fig. 2) [24]. We have further advanced this technique using a minimally invasive approach and standardized graft harvest instrumentation (Part 2). Regardless of the technical modifications the structural appearance of the quadriceps tendon graft appears to mimic the original MPFL more closely (Fig. 3).

The aim of this study was in the first part to analyze the structural properties of the original MPFL and to compare these results in the second part to a MPFL reconstruction technique using a strip of quadriceps tendon that remained attached to the proximal patellar pole.

We hypothesized that a quadriceps tendon reconstruction technique closely resembles the structural properties of an intact MPFL and shows no significant differences of structural properties in comparison to the intact MPFL.

2. Materials and methods

2.1. Specimens/biomechanical testing

For biomechanical testing 13 fresh frozen human cadaver knees have been used stored at −20 °C before testing. The mean age of the knees was 70.1 (±6.2) years.

Prior to testing the knees were thawed at room temperature for 24 h before use and kept moist with saline irrigation during preparation and mechanical testing to prevent desiccation.

In the tested human cadaver knees the patella and the intact MPFL as well as the whole quadriceps tendon have been dissected leaving the patella–MPFL insertion intact (Fig. 1).

For biomechanical testing the patella was fixed in a custom made device with a Steinman pin and a k-wire. The tested specimen was positioned with proximal and distal pole of the patella in a horizontal line to imitate a worst-case scenario (Fig. 4).

The biomechanical tests are divided in two parts:

Biomechanical testing of the original MPFL:

In the first part the original MPFL was tested.

The MPFL was fixed with the femoral insertion part in a tendon clamp with a remaining free length of the ligament of 60 mm [1, 35]. The tendon clamp was frozen during biomechanical testing to prevent slippage of the tendon. The same freezing clamp was used in previous biomechanical tendon studies [35–37].

The whole specimen was positioned in a uniaxial testing machine (Zwick Roell Z005) (Fig. 4).

In the first part of the study the original MPFL was loaded to failure after preconditioning with 10 cycles between 5 and 20 N. During

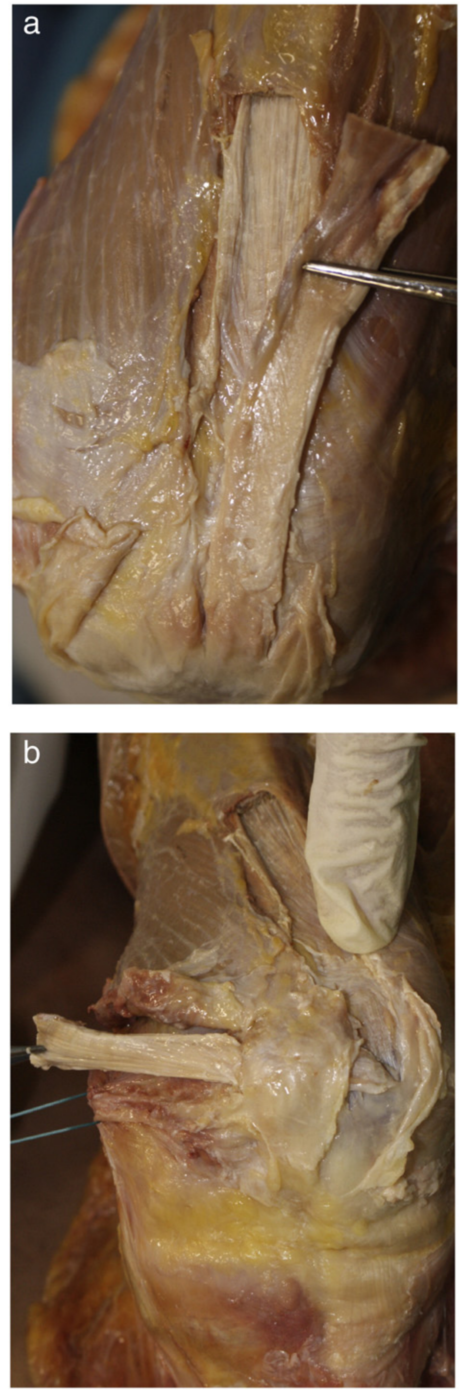

Fig. 2. MPFL reconstruction technique with quadriceps tendon in a human cadaver. a. A tendon flap (width 10 mm, thickness 3 mm) of the middle part of the quadriceps tendon was harvested. b. The tendon strip was lifted off the patella bone for 1.5 cm, diverged 90° and shuttled under the medial part of the quadriceps attachment and the vastus medialis.

the whole biomechanical testing a displacement rate of 200 mm/min was used for testing machine velocity [2–4,37–39].

During load to failure tests the following parameters were assessed: Stiffness, yield load, maximum load and mode of failure. Stiffness was defined as the linear region of the load-elongation curve [36].

The yield load was determined as the point of load elongation curve where the elongation is no longer proportional to the increase in stress.

Biomechanical testing of the quadriceps MPFL reconstruction technique:

Fig. 3. Comparison of the native (marked with sutures) and the reconstructed MPFL with quadriceps tendon.

In the second part of the study MPFL reconstruction with the middle third of the quadriceps tendon was performed within the same specimen. A 10 mm wide, 3 mm thick and 9 cm long strip of quadriceps tendon was prepared. The tendon strip was left attached at the patella and diverged 90° underneath the prepatellar tissue (Fig. 2). At the medial boarder of the patella the tendon strip was fixed with two single No2 non-resorbable sutures to fix the graft with the superficial and profound tissue at the medial patellar boarder. (detailed specification of the operation procedure see in part 2) The free part of the tendon strip was fixed in a tendon clamp with a free length of the graft of 60 mm (similar to the original MPFL) and the patella was positioned in the fixation device identically to the intact MPFL testing in horizontal orientation. Therefore the graft was fixed in a vertical orientation. Afterwards the constructs have been preconditioned with 10 cycles between 5 and 20 N similar to the original MPFL tests. Following preconditioning the constructs were cyclically loaded 1000 times between 5 and 50 N with a displacement rate of 200 mm/min. During cyclic testing the maximum elongation after 1000 cycles has been measured.
Following cyclic testing the constructs have been loaded to failure with a displacement rate of 200 mm/min. The following parameters have been investigated during the load to failure tests: Stiffness, yield load, maximum load and failure mode.

2.2. Statistical analysis

For statistical analysis we used a one-way multivariate analysis of variance with repeated measures (RM-ANOVA) for multiple comparisons to detect any significant difference between testing results. To examine differences between the two testing conditions (intact vs. reconstruction) within each testing method, a post hoc Sidak test was performed. The level of significance was set at $P = 0.05$. Results are presented as mean (standard deviation, SD).

Statistical analysis was performed at the Department of Medical Informatics and Biomathematics of the Westfaelian–Wilhelms University Muenster, Germany using GraphPad Prism (GraphPad Software, version 5.0, San Diego California USA).

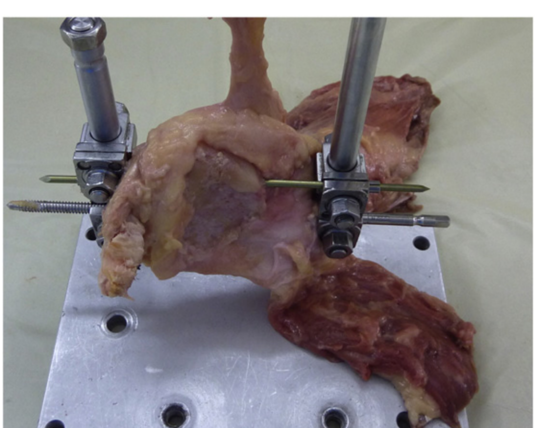

Fig. 4. Human cadaver specimen with dissected MPFL fixed in a horizontal position of the patella with a custom-made fixation device.

3. Results

3.1. Original MPFL

After dissection of the MPFL in the human cadaver knee the original MPFLs were also investigated. The dissected MPFL showed mean length from medial border of the patella to the femoral insertion of 67.5 mm (±3). The tested original MPFLs showed a mean stiffness of 29.4 N/mm (±9.7). The investigated mean yield load was 167.8 N (±80) and maximum load was 190.7 N (±82.8) (Fig. 5a, b, c). For analyzing of the failure mode, the MPFL was divided into three thirds. During load to failure testing two different failure modes were observed: Eight specimens ruptured in the femoral third and five specimens ruptured in the middle part of the ligament.

3.2. Quadriceps-MPFL Reconstruction

In the second part of the study the Quadriceps MPFL reconstructions were cyclically tested. Every specimen of the 13 MPFL reconstructions survived the 1000 cycles

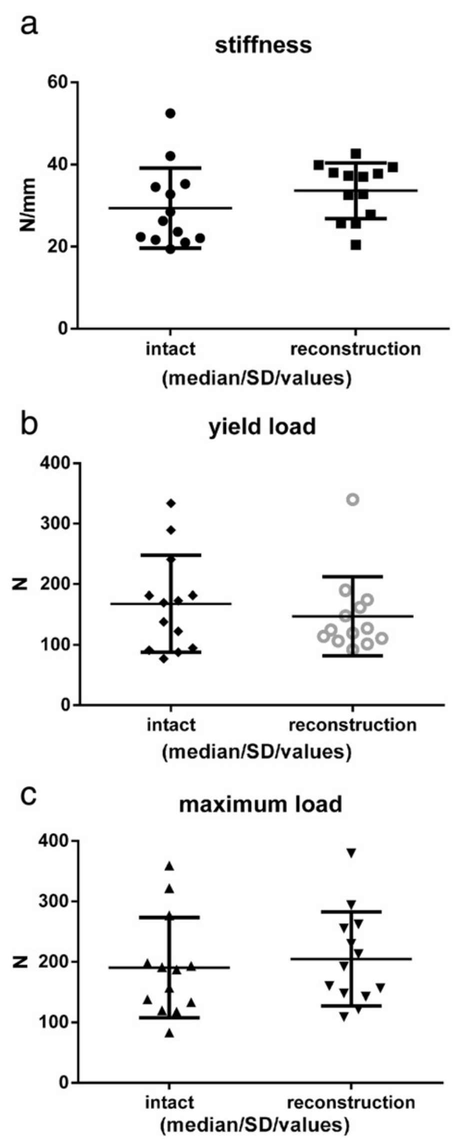

Fig. 5. Graphs of the testing results of load to failure tests: a) stiffness in N/mm; b) yield load in N; c) maximum load in N.

between 5 and 50 N. The mean maximum elongation after 1000 cycles was 2.1 mm (±0.8).

After cyclic testing the constructs were loaded to failure similar to the original MPFL. In the load to failure testing of the quadriceps tendon reconstruction group obtained the following results; Stiffness 33.6 N/mm (±6.8), yield load 147.1 N (±65.1) and maximum load to failure 205 N (±77.8) (Fig. 5a, b, c).

One-way ANOVA showed that dependent variables were significantly affected by the reconstruction method and specimens ($P < 0.05$). After post hoc testing for pairwise comparisons, there were no significant differences in all tested parameters between the intact MPFL and the reconstructed group using quadriceps tendon (stiffness: $P = 0.39$, yield load: $P = 0.88$ and maximum load to failure $P = 0.96$). In the reconstruction group a homogenous failure mode could be identified. Every reconstruction failed by ligament rupture at the patellar attachment.

4. Discussion

The results of the current study support our initial hypothesis that a quadriceps tendon reconstruction technique resembles the structural properties of an intact MPFL and shows no significant differences of structural properties in comparison to the intact MPFL.

Currently in the literature there are few studies about the biomechanical properties of the original MPFL [5–16,40–42]. Mountney et al. [29] investigated the mean strength of the MPFL in 10 fresh cadaver knees and compared these results with two suture techniques and two augmentation techniques in load to failure tests.

They found comparable results of maximum load of the natural MPFL (208 N (±90) as we could investigate in our study (190.66 N (±82.8)). Except the through tunnel tendon reconstruction technique (195 N) the other three techniques showed significantly lower results of primary strength (suture technique: 37 N; suture anchors plus sutures: 142 N; blind-tunnel tendon graft reconstruction: 126 N) [23, 41].

Mountney et al. [29] investigated in their study merely the maximum load but not the yield load and stiffness of the natural MPFL or the reconstruction techniques.

Currently in the literature there is little information about the structural properties of the intact MPFL. Arendt [30] performed a study investigating the stiffness of the MPFL structure in fresh frozen cadavers. They found a mean stiffness of 18.9 N/mm (±1.29) and an ultimate load of 145.6 N (±44) [18,24–28,30]. The investigated stiffness and ultimate load measured in this study are slightly lower than Mountney et al. [29] and our study group could measure in biomechanical studies.

The reason for the difference observed in structural properties could be due to the dissection technique. The MPFL is a very thin structure, which can be easily damaged during dissection. Therefore we have left strong soft tissue structures on the ligament to prevent ligament damage by cutting the thin structure. There are many studies investigating different reconstruction techniques currently in the international literature. Most of these techniques used hamstring grafts (semitendinosus or gracilis tendon) for MPFL reconstruction. Besides the study of Mountney et al. there are two other studies in the current literature investigating biomechanical properties of hamstring MPFL reconstruction techniques [41].

Lenschow et al. investigated the biomechanical properties of five different MPFL reconstruction techniques in a porcine patella model using porcine flexor tendons as graft [31]. During the cyclic and load to failure testing protocol a fixation by 3.5 mm Titanium anchor (group 1), by transosseous 1 mm Ethibond suture (group 2), by interference screw (group 3), by pull through of the tendon under a bone bridge (group 4) and by pull through of the tendon through two bone tunnels (group 5). Except of the bone bridge group all specimens survived the cyclic testing protocol with 1000 cycles with 100 N loadig. The results of elongation after 1000 cycles showed similar amounts between 1.9 mm to 3.7 mm in comparison to 2.09 mm (±0.75) in our study. The results of maximum load in the porcine model of Lenschow et al. were very high (twice the amount of the natural MPFL in our study) [31]. They observed 416 N in group 1, 354.4 N in group 2, 401.5 N in group 3 and 539.5 N in group 5. Merely in the bone bridge group they investigated a maximum load of 146.7 N.

Similar very high results of stiffness could be found in most of the tested hamstring techniques with 97.2 N/mm in group 1, 90.5 N/mm in group 2, 87.4 N/mm in group 3 and 99.6 N/mm in group 5. These results are three times as high as our measurements for the natural MPFL. Solely the docking technique in group 5 showed a comparable stiffness of 30.8 N/mm.

The higher values of stiffness in this porcine study could be caused by the testing material and the porcine patella model. Besides the bone material, the tendon material and tendon structure (hamstring structure) could explain this non-physiologic high stiffness of the hamstring reconstruction.

Hapa et al. performed a biomechanical study in a Sawbone model (polyurethane foam patella models) using bovine extensor tendons for MPFL reconstruction. During their study they compared four different fixation techniques at the medial border of the patella, a tunnel technique, docking technique and two aperture fixation techniques using two interference screws or bone anchors [31,43]. After short cyclic loading with 20 cycles between 2 and 30 N the MPFL reconstructions have been loaded to failure. The authors demonstrate low results for the docking group with 106 N (±41) and 14 N/mm (±2) for ultimate load and stiffness.

The anchor group, tunnel group and interference group showed significantly higher results with 299 N (±116), 304 N (±140) and 241 N (±103) ultimate load and 21 N/mm (±6), 28 N/mm (±3) and 31 N/mm (±6) stiffness. The determined results in this study differ from results by Lenschow et al. [31–34]. This could be caused by the Sawbone model in comparison to the porcine model which has been used in the other study. Especially the patellar bone in young active patients is very hard and most of the bony structure belongs to cortical bone. Therefore the porcine bone model probably mimics the human situation more closely.

Anatomical studies described the MPFL structure heterogeneously as a very thin fascial band with a width from 3 to 10 mm at the femoral attachment to 10–30 mm at the medial border of the patella [44,45]. This structure and shape definitely do not resemble a hamstring graft reconstruction with the typical stiffness of a gracilis tendon (single strand) of 171 N/mm (±11) [46]. Therefore a higher and not physiological stiffness could result of this structural difference matching the results of Lenschow et al. [31]. The quadriceps tendon flap on the other side with a width of 10 mm and a depth of 3 mm seems to imitate the original MPFL structure sufficiently (Fig. 3). In our human biomechanical study we could observe comparable results for strength (yield load and maximum load), as well for stiffness of the original MPFL and the quadriceps reconstruction technique.

The physiological amount of stiffness could be another important factor for patellofemoral joint pressure and resulting osteoarthritis. Many studies investigate an anatomical reconstruction and importance of choosing correct tunnel position for MPFL reconstruction [8,47–49]. The positioning of the femoral tunnel at the medial femoral condyle seems to be an important step for physiological reconstruction and prevention of nonphysiological high patellofemoral joint pressure. Although there are no biomechanical studies regarding this topic, an unnatural high stiffness of a ligamentous construct might also result in increased peak pressure within the joint line.

Another advantage of the quadriceps tendon technique is a remaining attachment of the tendon at the proximal patella pole at anatomical position of the MPFL [50]. Most complications after MPFL reconstruction have been reported as patellar fracture and problems with the patellar fixation [23,24,26]. There is a high risk of morbidity associated with the drilled tunnels or fixation technique to the medial border of the patella. A patellar fracture in active patients within the typical age can result in a not acceptable risk of decreased knee function. Using the quadriceps tendon technique the tendon is still connected with the quadriceps attachment, therefore good biological healing can be expected.

In this biomechanical study we only investigated the initial stability of the construct. The failure mode analysis showed the weak part of this reconstruction technique is at the attachment side of the quadriceps tendon. Especially in the quadriceps tendon technique a quick improvement of the reconstruction strength by direct healing of the tendon fibers at the turning point near to the patellar attachment is to be expected. The presented investigation study has certain limitations: The study is based on a human cadaver in vitro model. Therefore, care should be taken when transferring the results to the in-vivo situation. However, the authors emphasize the comparative character of the current study. The absolute values should not be transferred to the clinical situation. Additionally, several in vivo effects such as healing and remodeling of reconstruction grafts cannot be taken into consideration. The human cadavers used had a mean age of 70 years which is a typical limitation of human cadaveric studies. During the testing not the whole MPFL complex has been tested, we decided to exclude the femoral insertion site and fixed the tendons at femoral side using a freezing clamp. Because of the identical fixation technique of hamstring and quadriceps tendons by using an interference-screw there is no difference expected relating to the femoral fixation.

4.1. Conclusion

In a human cadaveric model using a strip of quadriceps tendon 10 mm wide and 3 mm deep, the biomchanical properties match those of the original medial patellofemoral ligament when tested as a reconstruction.

Conflict of interest declaration

Two of the authors (M.H.) and Prof. Fink (C.F.) are consultant for Kalr Storz. Additionally, one (C.F.) receives product royalties from Karl Storz.

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