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Modified pre-curved patellar basket plate, reconstruction of the proper length and position of the patellar ligament—A biomechanical analysis

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Abstract

Biomechanical properties of basket plate fixation for fracture dislocation in the distal part of the patella were studied on 22 fresh–frozen lower extremities (human cadaveric knees). The patella and the patellar ligament with the proximal tibia were removed. A comminuted fracture of the distal part of the patella was created with a chisel. The fractured patella, patellar ligament and tibial tuberosity of each specimen were fixed with a basket plate and mounted into the jaws of the testing machine. The measured load to failure was 421.66± 45.90 N, which is approximately 70% higher than the results in other studies. The results of the measurements verified the results of finite element analysis. The modified precurved patellar basket plate developed in this study showed improved performance compared to the pre-existing fixation methods.

Keywords: Fracture of the distal pole of the patella; Modified basket plate; Biomechanical testing; Numerical analysis; Finite element method

1. Introduction

Fractures and fracture dislocations of the distal pole of the patella are relatively rare, representing 0.5–1.5% of all fractures in general [1]. Usually they are a result of direct trauma to the patella, with or without simultaneous quadriceps contraction [2]. Neglected or mistreated fractures often lead to considerable disability in the injured knee, mainly the incapacity for active extension of the knee. The ideal method for proper reconstruction of the patellar extensor mechanism in distal-pole patellar fractures has not yet been identified [1,3–10]. Such a method should enable easy and accurate repositioning of fragments, fixation of the patella in the anatomical position, and early rehabilitation. Descriptions of several surgical techniques are available in the literature concerning different sutures: e.g. sutures

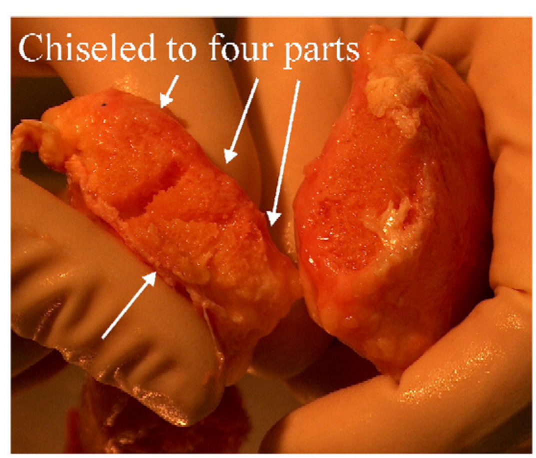

Fig. 1. Dissected and chiselled parts of the patella.

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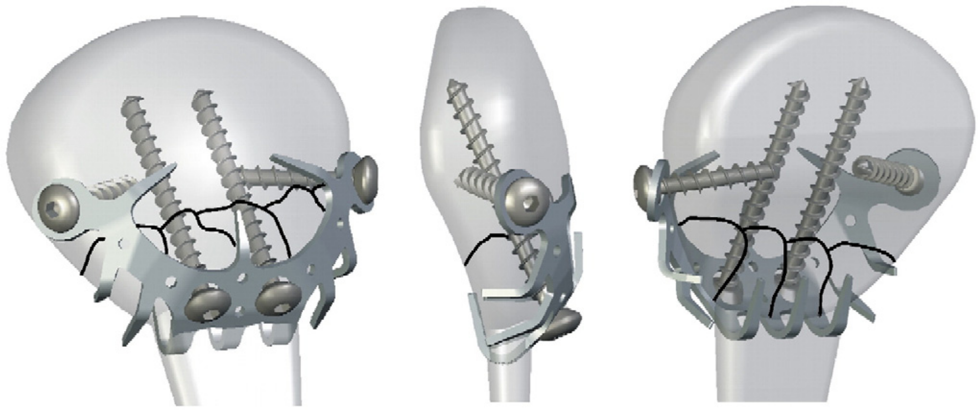

Fig. 2. (Modified) basket plate-fixed fractures.

through the patella, patella extirpation, and augmentation with autografts, allografts, synthetic material [1,5,6,8,11], or wire loop [12], and a patellar basket plate [5,13].

Our surgical experiences have proved that osteosynthesis of the fractured distal pole of the patella with a basket plate is a very successful technique. The basket plate is shaped to fit the geometry of the inferior pole of the patella with several posterior and anterior hooks which embrace the pole fragments. The plate is fixed to the main patellar fragment, with two parallel cancellous screws to provide inter-fragmentary compression, and two cancellous screws which are positioned obliquely to increase stability against tensile loads.

Although the existing pre-curved patellar basket plate developed by Smiljanic [5] offers acceptable fixation of fracture of a distal patellar pole, our experiences have shown some deficiencies, such as problems during implantation; these include difficulties in retaining the position of the basket due to considerable slippage, and shortening of the patellar ligament by about 5 mm on average when longitudinal screws are placed on the apex of the patella. These observations led to a reconsideration of the biomechanical properties of the patellar basket plate and fixation in general. To understand these properties, some experiments and mechanical tests had to be performed.

2. Materials and methods

As a first step in our study, a Smiljanic basket plate was tested on a cadaveric knee.

2.1. Specimens

Specimens for biomechanical analysis were prepared at the Institute of Anatomy, Faculty of Medicine, University of Ljubljana, Slovenia. Two fresh–frozen lower extremities (human cadaveric knees) were dissected, and

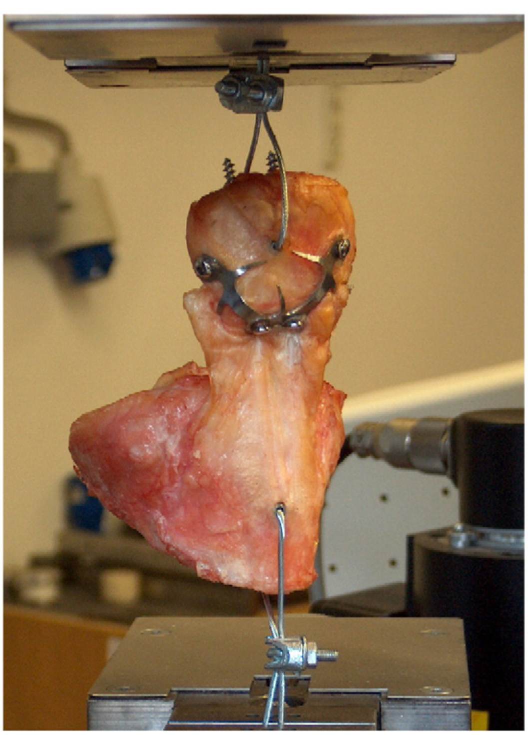

Fig. 3. The specimen mounted into the jaws of the testing machine.

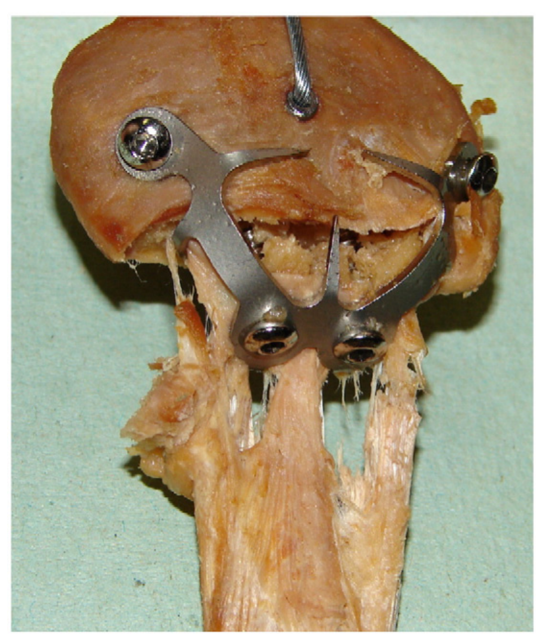

Fig. 4. Disruption of the patellar ligament.

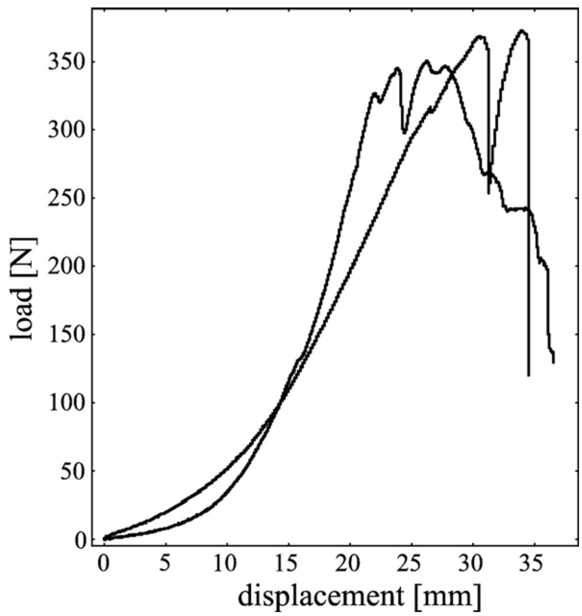

Fig. 5. Load–displacement diagrams for Smiljanic basket plate.

the patella together with the patellar ligament with the proximal tibia were removed. A comminuted fracture of the distal part of the patella was created with a chisel. In an attempt to create comparable fractures, the patellar ligament with a bone insertion was detached from the patella, starting from the articular part of the patella on the transition point between cartilage and bone. Dissected parts of the distal patella were additionally chiselled into four parts (Fig. 1). Fractures were fixed with a Smiljanic patellar basket plate and four fully threaded cancellous screws (Fig. 2). The lengths of the longitudinal and oblique screws were 50 mm and 30 mm, respectively.

2.2. Mechanical testing

The mechanical tests were performed on two specimens where distal fragments of avulsion fractures of the patellar pole were simulated. All tests were performed under the same conditions (temperature 23 °C, humidity 52%, rate of displacement 1 mm/s, etc.) at the Laboratory for Nonlinear Mechanics, Faculty of Mechanical Engineering, University of Ljubljana, Slovenia.

2.3. Testing protocol

The determination of the force–displacement relation and the ultimate force to failure and elongation to break for the disrupted patellar pole was performed by a constant rate of specimen extension (CRE) standard on the universal testing machine type Zwick Z050. The accuracy of the testing machine was 0.5 N for force measurements and 0.04 mm for measurement of displacement. The maximum payload of the machine was 10 kN and the maximum displacement was 0.8 m.

One end of the specimen was held in a virtually stationary clamp, and the other end was gripped in a clamp that was driven at a constant rate. The chosen constant rate of displacement of the moving clamp was 1 mm/s. The specimen was loaded with uniaxial tension and extended until rupture. The (breaking) force and elongation (at the break) were recorded. The test was stopped when the disruption of osteosynthesis or laceration of the patellar ligament occurred.

2.4. Methods of fixation

The fixation of the distal fragments of avulsion fractures of the patellar pole was carried out by a Smiljanic basket plate, as already mentioned, made of a sheet of INOX 316L material 1 mm thick. The fractured patella, patellar ligament and tibial tuberosity of each specimen were fixed with the basket plate and mounted into the jaws of the testing machine (Fig. 3). Before clamping, bone tunnels were made in both ends of each specimen – i.e. patella and tibial tuberosity – and steel tubes were inserted. The lengths of the steel tubes were adapted to the patellar pole and tibial tuberosity diameter for each specimen separately. The patella and tibial tuberosity were then gripped to the moving and stationary clamps, respectively, using steel wire ropes which were inserted through the steel tubes.

2.5. Tests results for Smiljanic basket plate

The results of the experiment using the tensile test machine showed that, when subjected to the ultimate load, fixation with the Smiljanic basket resulted first in a disruption of the central portion of the ligament, followed by a disruption of the lateral part of the osteosynthesis (Figs. 4 and 5). The results of the measurements were 350.68 N and 372.83 N for the ultimate load and 26.29 mm and 34.02 mm for the elongation at the disruption of the composition in the first and second cases, respectively.

Load–displacement diagrams for the Smiljanic plate fixation are presented in Fig. 5.

From these results, some of the main problems of the Smiljanic plate fixation can be identified. A noticeable shortening of the patellar ligament and slippage problems during implantation, rupturing the patellar ligament, can be observed (Fig. 4). A process of laceration of the patellar ligament can also be observed, as the load–displacement curve in Fig. 5 has more than one main peak. This can be explained as follows: the most loaded fibres of the ligament lacerate first (i.e. the first rapid decrease in force), the load is then transmitted to the next fibres which also lacerate (the second rapid decrease in force), and this process continues until the overall failure of the osteosynthesis. It appears that there is a maximum load the patellar ligament can sustain before being shredded by the lower part of the basket, including the basket's teeth; all this is highly dependent on the geometry of the design. Therefore the basket plate should not be conceived to withstand maximum load regardless of the consequences. It should yield before the load in the

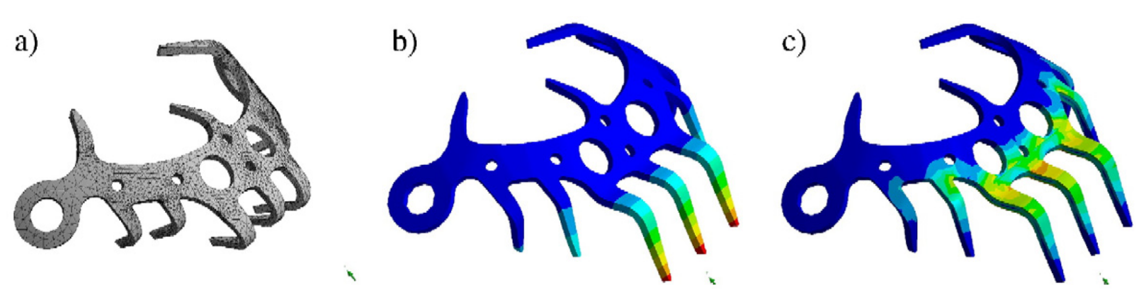

Fig. 6. a) Meshed three-dimensional model of the basket plate; b) Deformation of the basket plate; c) Stresses on the basket plate.

Fig. 7. Modified patellar basket plate before mechanical testing.

ligament exceeds the critical value, i.e., before avulsion of the patellar ligament from the patellar pole. This means that if an osteosynthesis is (accidentally) disrupted, the patellar ligament on the patellar pole should stay intact or sustain minimum damage. Therefore the surgical procedure can be performed with reinsertion of a new basket plate, and no (or minimum) reconstruction of the ligament is necessary.

We believe that this can also happen in vivo as a result of overloading of the patellar ligament, especially in the case of an uncooperative patient.

3. Designing a modified patellar basket plate

The above observations led us to the conclusion that the implant should be improved. The process of designing and fabricating a patellar basket plate has been developed and implemented in collaboration with the team of engineers from the Laboratory for Nonlinear Mechanics, at the Faculty of Mechanical Engineering, University of Ljubljana, Slovenia. As in most applications, the entire design project had to be divided into several sub-problems which were then treated independently, starting with the specification of the problem. The scope was to design a medical implant which would be used operatively to treat patients who have sustained an avulsion fracture of the distal patellar pole. The implant was designed according to the following criteria:

– bending and consequently shortening of the patellar ligament should be reduced to minimum;
– design of the implant should allow easy implantation and later removal;
– ruptures of the patellar ligament (especially in the case of an uncooperative patient) should be reduced to minimum;
– postoperative morbidity should be minimal.

3.1. Numerical analysis

Numerical simulations were performed using ANSYS® software, a general finite element method (FEM) software

Table 1
Results of the measurements

Case	Ultimate force [N]	Elongation [mm]
1	412.62	21.74
2	448.12	28.69
3	411.83	23.93
4	378.44	23.89
5	401.35	22.79
6	388.66	23.22
7	509.71	28.56
8	438.01	28.10
9	392.89	21.64
10	363.12	22.06
11	356.37	31.56
12	418.20	28.03
13	423.31	24.45
14	450.27	25.11
15	428.64	25.42
16	442.61	22.05
17	377.42	21.56
18	380.86	20.91
19	519.14	26.03
20	491.30	26.90

Table 2
Statistics of the measurements (at the break)

No. of specimens	20
Mean load [N]	421.66
Standard deviation [N]	45.90
Maximum load [N]	519.14
Minimum load [N]	356.73
Mean strain [mm]	24.83
Standard deviation [mm]	3.00
Maximum strain [mm]	31.56
Minimum strain [mm]	20.91

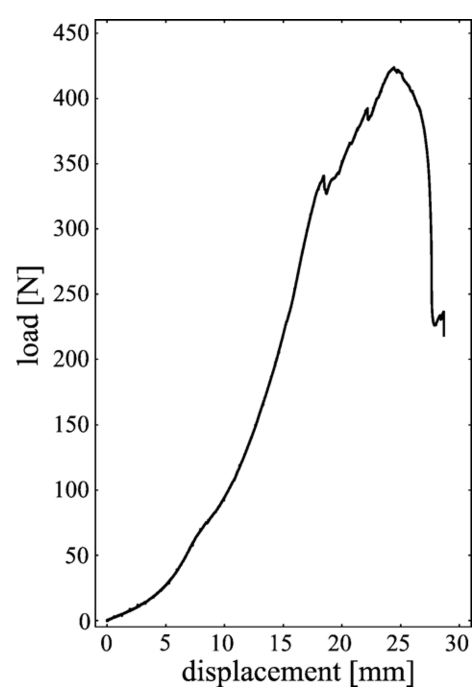

Fig. 8. Load–displacement diagram for modified basket plate, Case 13.

for static, dynamic and multiphysics analysis. In our case a non-linear static analysis of the patellar plate was performed. A three-dimensional model of the plate was imported from SolidWorks® 3D CAD software into the ANSYS® environment and properly meshed (Fig. 6a). Various loads were selected and applied to the model to simulate real biomechanical conditions. Properties of the material from which the basket plate is constructed were obtained from MatWeb database (www.matweb.com) and imported in the analysis to ensure adequate results. The results of the numerical simulation are depicted in Fig. 6b and c.

3.2. Modified pre-curved patellar basket plate

Placing longitudinal screws more dorsally (outside the insertion point of the patellar ligament) prevents shortening of the patellar ligament (patella baja) and its rupture during extreme loading. With a short distance between the teeth on the articular side, the possibility of distal fragment dislocation is diminished. Small holes over the surface of the plate prevent slippage and allow easy reduction and maintenance of the reduction with a two-point reduction clamp or K-wires. Centralization of the medial- and lateral-plate teeth diminishes unwanted contact between the plate or screw heads and the femoral condyles. To reduce the insertion problems even further, the teeth of the plate are placed parallel in anterior–posterior view (Fig. 7).

Ten pairs of specimens were prepared, and mechanical tests were performed under the same conditions as described above. The testing protocol was also the same.

4. Results

The results of measurements for the modified pre-curved patellar basket plate are presented in Table 1. The samples were numbered from 1 to 20 for better identification and classification.

Some statistics of the mechanical testing at the disruption of the osteosynthesis are presented in Table 2.

The load–displacement diagram in Fig. 8 presents case 13, which is closest to the "average" result of the measurement. At the point where the basket plate is bent to the maximum value (at 423.31 N), it yields, and the patellar ligament slips out of the basket and remains undamaged. This phenomenon can also be seen in Fig. 8, as the decreasing part of the curve is smooth, unlike the diagrams in Fig. 5.

It should be noted the patellar basket plate yielded before critical laceration of the patellar ligament in all test cases. In some cases minimal (but not critical) rupture of the ligament occurred. Fig. 9 presents the modified patellar basket plate after mechanical testing. The bent shape of the plate in connection with Fig. 8, together with the accompanying discussion of laceration of the patellar ligament, clearly shows that the ligament has not sustained any serious or critical damage.

From the comparison of Figs. 6b and 9, a good agreement between numerical FEM simulations and mechanical tests can also be found.

Fig. 9. Modified patellar basket plate after the mechanical testing.

5. Discussion

The Smiljanic basket plate is an innovative design [5]. In our opinion it represents a novelty in surgical treatment not only of comminuted fractures in the distal pole of the patella but also of comminuted fractures of the patella itself. However, in articles dealing with the Smiljanic plate, little attention has been paid to functional or biomechanical analyses [5,13]. From our surgical experiences and the literature [10,13] we know that patients with patella baja [14] have substantially more problems than those with a normal position of the patella or even patella alta. Proper restitution of the patellar position is therefore the principal aim of the surgical procedure in question. Placing longitudinal screws through the apex of the patella and through the patellar ligament is sometimes very difficult, because torn ligament is coiled on the drill-bit and even more on the tapping screw. This can also be a reason for dislocation of an already reconstructed distal patellar pole. The solution is to place longitudinal screws outside the patellar ligament insertion. The starting point for insertion of the implant on the patellar ligament is thereby much closer to the apex of the patella, which enables easier and faster insertion and positioning of the modified patellar basket plate. With this manoeuvre, easier screw insertion and preservation of the length of the patellar ligament is achieved, because the need for bending the patellar ligament during the insertion of the basket plate through the patellar ligament is eliminated. Furthermore, it is found that the strength of the implant is also important. In the case of a non-cooperative patient we believe the strength of the implant should not allow rupture of the bone and ligament. The ultimate load to failure in separate vertical wiring [8] was 250.1 ± 109.7 N. In our study the measured load to failure was 421.66 ± 45.90 N. According to the measurements made, it was concluded that the peak force that an implant should sustain would be approximately 400 N, since the implant which is able to bear greater loads causes additional bone fragment avulsion or destruction or patellar ligament destruction. After such an occurrence, re-osteosynthesis of the distal patellar fracture becomes almost impossible. On the other hand, a less rigid construction of the implant allows implant failure before critical damage to the injured area where bone, bony fragments and patellar ligament are all capable of re-osteosynthesis. These findings are essential, especially in cases of overloading of the patellar ligament due to lack of cooperation by the patient. In our opinion, if there is no wound infection, the fracture can easily be addressed in a proper manner.

It should therefore be noted that the patellar pre-curved basket plate designed by the authors of this paper makes possible an easy and accurate fixation of distal-pole patellar fractures, with special emphasis on protection of patellar distal-pole fragments, particularly during unrestrained weight-bearing by an uncooperative patient.

6. Conclusion

The modified pre-curved patellar basket is an implant for the operative treatment of distal patellar fractures. After numerical, biomechanical, in-vitro tests and analysis of the results, some design criteria were determined: e.g. restoration of the anatomical relationships, simple and easy implantation, mechanical properties, etc. The design of the patellar basket plate was in our case an iterative process. Various concepts for a feasible device were studied. The trial designs were analyzed to determine whether they were acceptable, and the design process was terminated once the specified system performance requirements had been satisfied. As presented in our tests, optimization of the basket plate is in finding the right proportion between flexibility of the plate and its strength-bearing properties. An important factor was the size and number of posterior and anterior hooks. It was shown that the correct proportion can lead to less laceration of fibres in the sinew of the patellar pole. At the end of the analysis, good agreement between numerical FEM simulations (Fig. 6b) and mechanical tests (Fig. 9) was achieved.

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