PATELLOFEMORAL CONTACT DURING SQUAT SIMULATION ON CADAVERIC KNEES

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Abstract The Ghent Knee Rig was built in 2006 for studying the biomechanical behavior of post-mortem human knees. To validate this test rig the patellofemoral contact pressures and areas were investigated in 3 post-mortem knees tested under the same circumstances and compared to results in literature. To load the quadriceps, the vastus intermedius and rectus femoris were separated and clamped together. The pulling cable was aligned according to the shaft of the femur to keep the Q-angle at physiological values. A pressure film was inserted in the patellofemoral joint to measure the patellofemoral contact area and pressure. The results follow the general accepted trends of patellofemoral contact during knee flexion and extension; when the patella enters the trochlear groove at approximately 20 degrees of knee flexion, the intra articular contact pressure and area start to build up and the contact area on the patella shifts from distal to proximal. Though working with cadaveric specimens remains a simulation of in vivo situations with well known limitations, the test rig shows a good repeatability and reliability. The next stage of this research project is a comparison of normal with pathological knees.

Keywords knee biomechanics, experimental, patellofemoral joint

1 INTRODUCTION

The purpose of this study is to validate the Ghent Knee Rig, developed in 2006 by the department of mechanical construction and production at Ghent University [1]. Our main interest is the patellofemoral contact area and pressure since increased patellofemoral pressures are often associated with anterior knee pain.

The patella plays an essential role in increasing the mechanical advantage of the quadriceps mechanism. The main biomechanical function of the patella consists of increasing the moment arm of the quadriceps by shifting the quadriceps tendon anteriorly [1] [3]. As a result the knee extension torque expands during extension. Due to the insertion of the patellar tendon on the tibial tuberosity, a great amount of force is necessary to displace the rather small weight of the foot, leading to high compressive forces in the patellofemoral joint. In closed kinetic chain movements, like squatting, the force of the quadriceps rises radically towards 90°, the contact area also increases but not in proportion, so the contact stress in the patellofemoral joint rises with deeper knee flexion. Research on patellofemoral biomechanics often focuses on patellar kinematics, extensor forces, and patellofemoral contact pressure and contact area.

In this study cadaveric knees were mounted in the Ghent Knee Rig to simulate a weight bearing squat. During this dynamic flexion-extension movement, the patellofemoral contact areas and pressures are continuously monitored.

2 MATERIALS AND METHOD

2.1 Specimens and specimen preparation

Since 2006, eighteen human post mortem knees were obtained from the anatomy lab of Ghent University and were tested in the Ghent Knee Rig. Three unpaired knees were selected for statistical analysis reported in this paper. The other knees showed variability in test conditions (e.g. movement speed, Q-angle, preparation method of the knees, flexion range), early failure of the specimen caused by low quality of the knee specimen, and dysfunction of the pressure-sensitive sensor. The three selected knees had a mean age of 90 years (± 7.4).

All knees were embalmed with a mixture of formol, phenol and thymol and were considered to be macroscopically intact, radiographic images didn't reveal any bony abnormalities. Each knee was amputated through the tibia and femur at approximately 20 cm from the apex of the patella. For mounting purposes, a complete dissection of all structures surrounding the bones was done at approximately 8 cm at the free end of the tibia, fibula and femur. The bones were placed in an aluminium cylinder and fixed with a polyester resin. At the knee joint care was taken to protect the retinacula, the medial and lateral collateral ligament and the tendon of quadriceps and patella from damage. The quadriceps were then further dissected into its 4 parts. The VI and RF were separated from the femur and their tendons were clamped together at approximately 5cm from the proximal pole of the patella. The clamping system, based on a polymer toothed rack, was designed especially for this purpose. (Figure 1)

Figure 1. The clamping system for the rectus femoris and vastus intermedius

By applying the definition given by Insall et al. [5] and Minkowitz et al. [5], the pulling cable was aligned according to the shaft of the femur. Doing so, the Q angle was kept at physiological values.

2.2 Test set-up

For the kinematic tests the department of mechanical construction and production developed a test rig, based on the Oxford Knee rig [6]. The set-up of the Ghent Knee Rig is shown in Figure 2.

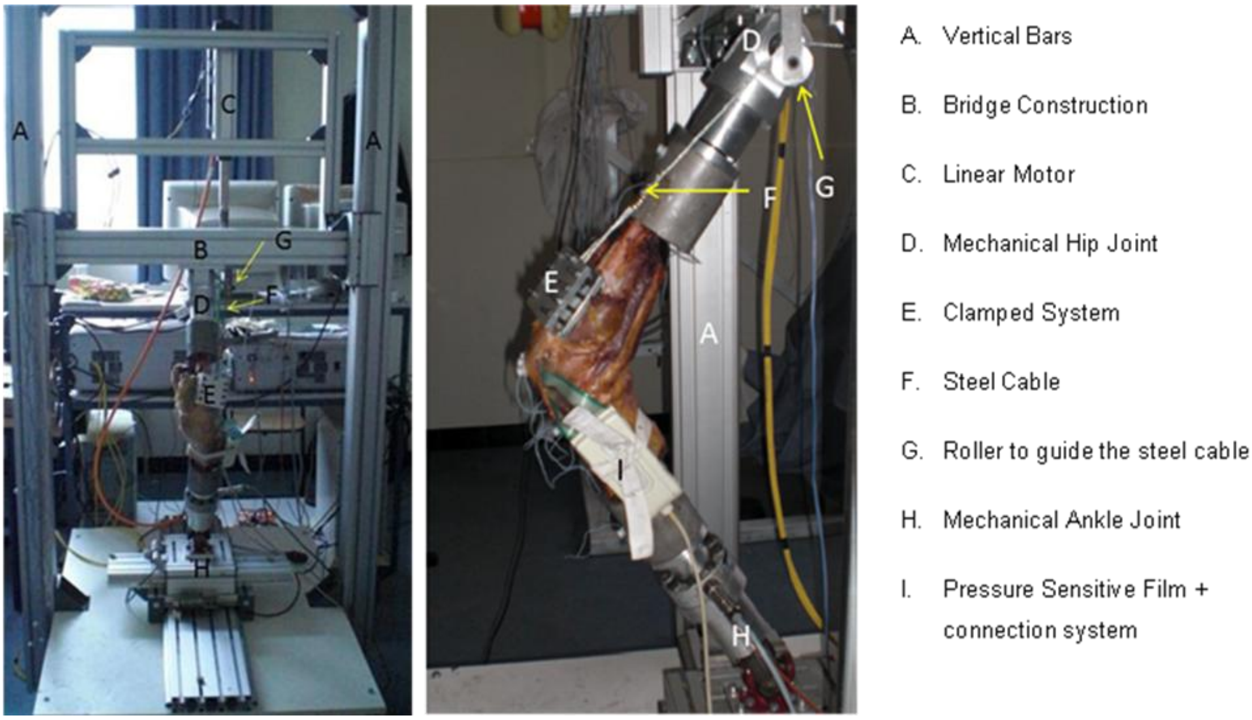

Figure 2. Experimental set up of the Ghent Knee Rig

Starting form a solid table, two vertical bars are responsible for the smooth gliding of a bridge construction, allowing the knee to flex and extend smoothly. The bridge construction rests on two mobile center points on the vertical sliding bars, which keep the knee flexion within its safety limits, taking the quality of the knee specimens into account. The total weight of the moveable part of the

construction is approximately 30 kg. This serves as a simulation of the body weight of a person during a squat movement.
The linear electrical motor unit is secured on the bridge construction and produces a maximum constant force of 1358 N and a maximal peak force of 3000 N. This force is transmitted to the quadriceps tendon through a steel cable and two pulleys. As a result the tension in the quadriceps tendon is being build up until the knee starts to extend.
The mechanical hip joint is also secured on the bridge construction and consists of an aluminum cylinder with two rotation axes which allow flexion-extension and internal-external rotation.
The mechanical ankle joint is fixed on two gliding platforms on the supporting table. These platforms allow simulating different positions of the ankle joint and consequently different positions of the knee. The aluminum cylinder is fixed with three screws on a cardan coupling unit, simulating the ankle joint. The unit has three rotational axes; flexion-extension, abduction-adduction and external-internal rotation of the tibia.
The knee flexion angle, the forces applied on the quadriceps tendon and the axial forces on the tibia are continuously measured together with the rotations of the tibia during flexion and extension. This test rig is built in such a way that it allows the six degrees of freedom of the knee joint.
In order to measure the contact area of the patellofemoral joint a 5051 I-scan pressure film (Tekscan Inc., South Boston, MA, USA), especially designed for intra articular measurements, is used with a pressure range of 8273 kPa (1200 model). The sensor is 0.1 mm thick and it has a 56 mm * 56 mm matrix consisting of 1936 sensing elements with a total contact area of 1600 mm^2. Sensors were calibrated before use in accordance with the manufacturers' guidelines. The pressure film was inserted in the patellofemoral joint through a lateral incision as described by Ostermeier et al. [7]. (Figure 3)

Figure 3. Positioning of the pressure film sensor.

The joint was opened with a lateral parapatellar incision. The pressure film was attached on the patella using a topical 2-octylcyanoacrylate tissue adhesive, Dermabond® (Ethicon NV, Johnson & Johnson, Somerville, New Jersey, USA). Prior to closing the incision with single stitches to restore physiological conditions, the margins of the retro-patellar facets were digitized by probing the I-scan sensor. The I-scan software was used to collect the contact area and pressure during testing.

3 RESULTS

For the three selected knees, all together 8 successful tests, each consisting out of 5 flexion – extension cycles were obtained.
In each test, the knees expressed a similar pattern of contact pressure distribution during the flexion and extension cycles. Pressure increased as the knee flexed and decreased as the knee extended.
The mean patellofemoral contact area measured in this study ranged from 68.8 (± 8) mm^2 at 20° to 336.5 (± 64.7) mm^2 at 60° knee flexion. The mean contact pressure ranged from 0.7 (±0.15) MPa at 20° flexion to 5.5 (± 1) MPa at 60°.
The contact areas on the patellar facets shifted from distal to proximal during knee flexion and from proximal to distal during extension, which is visualized in figure 4. Another remarkable observation is the difference between the flexion and extension phase (see figure 4).

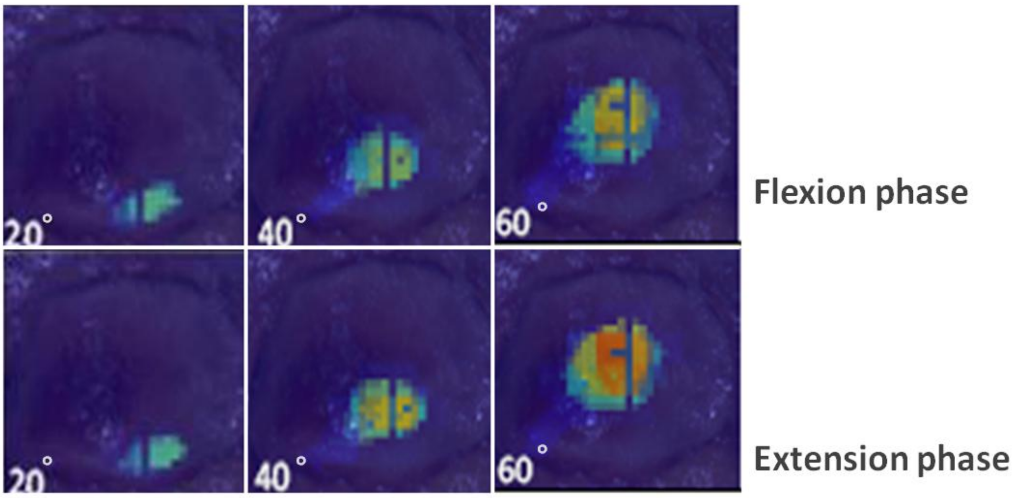

Figure 4. Patellofemoral contact area for 3 different knee angles (20°, 40°, 60°) during the flexion and extension phase

Statistical analysis of the contact area and pressure was done for knee flexion angles of 20°, 30°, 40°, 50° and 60° and for the flexion and extension phase separately. Out of the 5 x 2 conditions, 3 conditions did not have a normal distribution, so a Wilcoxon Signed Ranks Test was performed; a significant difference between the 2 movement phases for the contact area ($p < 0.001$, $z = -4.341$) as well as for the contact pressure ($p < 0.001$, $z = -4.627$) was found, with higher values for the extension phase compared to the flexion phase. This difference can be observed on figure 5.

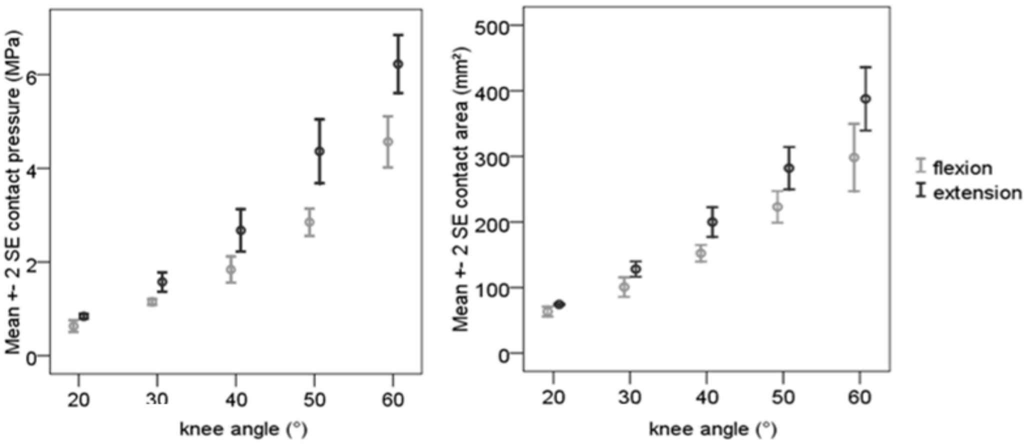

Figure 5. Mean patellofemoral contact area and contact pressure ± 2SE for 5 different knee angles

To reveal the predicting variables of the contact area and pressure, a linear regression was performed with the knee angle, flexion-extension phase and quadriceps force as independent variables. For the contact area as well as the contact pressure, the multiple regression models with these 3 independent variables show a very good correlation with the data, with respectively $R^2 = 0.88$ and $R^2 = 0.85$. However, care should be taken in the interpretation of these results since the quadriceps force is highly correlating with the knee angle ($p < 0.001$) as well as the movement phase (flexion - extension) ($p < 0.001$). Mean values for the applied quadriceps force are reported in table 1.

Knee angle (°)	Mean quadriceps force ± SD (N)		
	Flexion phase	Extension phase	Total
20	281 ± 18	530 ± 51	419 ± 136
30	427 ± 40	800 ± 134	614 ± 215
40	589 ± 60	1091 ± 148	840 ± 281
50	851 ± 62	1438 ± 171	1145 ± 328
60	1093 ± 51	1714 ± 232	1404 ± 367
Total	639 ± 263	1095 ± 412	870 ± 414

Table 1. Mean quadriceps force for different knee angles and for the flexion – extension phase separately

This collinearity does not reduce the predictive power or reliability of the model as a whole; it only affects the reliability of the individual predictors. The model cannot provide valid results about any individual predictor, or about which predictors are redundant with others.

4 DISCUSSION

The experiments with the Ghent Knee Rig differ from previous experiments because the current knee rig simulates a dynamic weight bearing squat, which represents a high demanding exercise for the knee joint. Previous work on cadaver specimens either focused on dynamic measurements without simulation of a body weight or on static measurements with a certain load. In some studies, the sequences of static measurements are used as basic principle to represent kinematic data [8]. Reports have been published stating that the joint force in the patellofemoral joint during squatting can rise up to 7 times the body weight [12]. Due to its capabilities, the Ghent Knee Rig makes it possible to investigate the behavior of biomechanical characteristics during a simulation of such exercise. The assumption was made that a more complete image of pressure alterations could be obtained. Technical limitations however have lead to some restrictions. The RF and VI are the only two vasti loaded, this choice was based on a study performed by Elias et al. who performed EMG research on the quadriceps muscle and revealed that the forces necessary for knee extension are for 70% generated by the RF and the VI [13]. Nevertheless, this approach remains a simplified representation of the complex activity pattern of the quadriceps muscle. More and more authors tend to shift towards loading all four or even six parts of the quadriceps in order to obtain a more realistic representation of the quadriceps force. Besides the challenge of implementing very heavy extra linear motors on the bridge construction, it is not feasible to realistically simulate the physiological interactions between different muscles such as co-contraction, muscle activation sequence and the interaction between anta- and agonists in cadaver studies.

In order to measure the intra articular contact pressures and contact areas, an I-scan pressure sensitive film was inserted in the patellofemoral joint. This sensor is especially designed to determine pressure distribution in joints. Wilson and coworkers investigated the accuracy and repeatability of the I-scan pressure measuring system and the effect of cementing the sensors onto the retro patellar surface [14]. They conclude that the I-scan system is a valuable tool for assessing pressure and pressure distribution in the patellofemoral joint but that cementing reduces the sensors accuracy. As an alternative some authors have suggested to fixate the sensor by surrounding sutures [15]. In this study, the pressure film was fixated with a topical 2-octylcyanoacrylate tissue adhesive so that a complete inversion of the patella could be avoided.

Although the applicability of the I-scan system in the patellofemoral joint has been proven, careful interpretation is warranted. To insert the sensor, the knee joint was opened through a lateral incision, which might have an effect on the pressure distribution. Ostermeier and colleagues studied the effect of a lateral release on eight cadaver knees and no medialisation of the patella due to a lateral release was found and they observed no reduction of lateral instability of the patella, especially in extension. However, they state that there might be a relieving effect on the lateral patellar facet in knee flexion [15]. Therefore the influence of the sensor placement through lateral release on the measurements remains uncertain. Despite this potential influence on the knee joint, the results seem to follow the general accepted pattern of pressure distribution during knee flexion and extension.

When the patella engages in the femoral trochlear groove at approximately 20 degrees of knee flexion, the intra articular pressure and contact area start to build up, and increase further with deeper knee bending. Early in-vitro studies by Hehne, Huberti et al. and Goodfellow et al. have reported on this phenomenon [9] [16] [17]. More recently, Luyckx et al. found that a maximum contact area is obtained at ninety degrees of knee flexion [18]. Besides the increase in contact area, a shift in contact area from distal to proximal on the patella was also observed during knee flexion. The results presented here show a similar pattern. As shown in figure 5, the contact area increases with the flexion angle. Furthermore, figure 4 nicely demonstrates that the contact area moves from distal to proximal during knee flexion.

Besides these well described patterns in literature, the present results also revealed a difference in contact area and intra articular pressure between the upward and downward squatting phase: lower contact pressures and smaller contact areas were observed during the downward phase. This difference needs to be further investigated; in the upward phase the linear motor systematically produces a greater force than in the downward phase, this difference in quadriceps force is correlated with the knee flexion angle, which makes it impossible to determine in which amount the difference in contact area and pressure between extension and flexion phase can be attributed to the knee angle, the quadriceps force and the direction of movement.

Some investigators have pointed out that the contact areas in the patellofemoral joint alter when the quadriceps tendon is loaded with different amount of forces [16] [19]. Most likely, these changes can be attributed to the greater amount of cartilage that comes in contact if the loads on the patellofemoral joint are augmented. Therefore the load on the quadriceps tendon should always be taken in mind when investigating the contact areas and pressures.

Comparing the results of contact pressures and areas of the present study with those found in literature, some similarities and some differences can be noticed. One possible explanation for the wide variation between all results is the difference in methods used to investigate the knee joint. These differences are demonstrated in table 2.

	Study conditions	Contact Area (mm²)			Contact Pressure (Mpa)
		30°	60°	90°	
Matthews et al. [19]	Experimental in-vitro Static	230	380	-	-
Huberti et al. [17]	Experimental in-vitro Static F_q: 125N tot 340N	260 (20°)	-	410	-
Csintalan et al. [20]	Experimental in-vitro	224	285	-	0,7 (60°)
Bohnsack et al. [21]	Experimental in-vitro Dynamic	75 (25°)	200	-	2 (60°)
Melegari et al. [22]	Experimental in-vitro Static F_q: 230N – 300N	272	-	479	1,2 (90°)
Ghent Knee Rig	Experimental in-vitro Dynamic F_q: up to 2000N	114	337	-	5,5 (60°)

Table 2. Overview of cadaver experiments

First of all, none of the other studies performed measurements in a weight bearing situation, and only in the study by Bohnsack et al. measurements were performed under dynamic conditions. Compatring the contact areas, it can be observed that the contact areas at 30° knee flexion in both our and Bohnsack's study are smaller. Maybe this can be explained by the test circumstances, a dynamic versus a static test setup. A wider variation can be seen in the intra articular patellofemoral pressure. The intra articular pressures found in current work seem to be greater than those found by other investigators. A possible explanation for this phenomenon are the substantially greater forces applied on the quadriceps tendon in the current study, which might result in larger intra articular pressures.

Due to different test setups, it remains difficult to compare different studies with each other. In addition, a limited number of knees are presented in this study and further work is necessary, however, the general trends that are found in biomechanical research of the patellofemoral joint by previous work, can be seen in the results of current work as well.

5 CONCLUSIONS

Analysis of these data shows that there is consistency of previous findings reported in the literature and our findings. It has also been proven that good quality cadaveric knees tested in the Ghent Knee Rig can provide us with reproducible results. It must be noted, however, that in the in-vivo patellofemoral joint, the investigated variables can't be considered as independent but should be seen as a complex related unit that interacts in a way that is still not fully understood.

Thanks to the repeatability and reliability of the designed test rig, it offers great potential for the research on pathological knees. Post-mortem knees can now be used on the Ghent Knee Rig to gain information about different kinds of morphological abnormalities of the knee and subsequently different kinds of treatments already used in surgery, but not yet fully understood. Final goal of this project is to better understand the biomechanical influence of knee abnormalities and their treatments, in order to provide an optimal and more objective approach in orthopedics.

6 REFERENCES

[1] J. Quintelier, F. Lobbestael, P. Verdonk, P. De Baets, F. Almqvist, *Patellofemoral contact pressures*, Acta of Bioengineering and Biomechanics, 10(2):23-28, 2008

[2] J. Bellemans, *Biomechanics of anterior knee pain*, Knee 10(2):123-126, 2003

[3] J.J. Mason, F. Leszko, T. Johnson, R.D. Komistek, *Patellofemoral joint forces*, Journal of Biomechanics, 41(11):2337-2348, 2008

[4] J. Insall, K.A. Falvo, D.W. Wise, *Chondromalacia Patellae. A prospective study*, Journal of Bone and Joint Surgery Am., 58(1):1-8, 1976

[5] R. Minkowitz, C. Inzerillo, O.H. Sherman, *Patella instability*, Bull NYU Hosp Jt Dis., 65(4):280-293, 2007

[6] A.B. Zavatsky, *A kinematic-freedom analysis of a flexed-knee-stance testing rig*, Journal of Biomechanics, 30(3):277-280, 1997

[7] S. Ostermeier, M. Holst, C. Hurschler, H. Windhagen, C. Stukenborg-Colsman, *Dynamic measurement of patellofemoral kinematics and contact pressure after lateral retinacular release: an in vitro study*, Knee Surgery, Sports Traumatology, Arthroscopy,15(5):547-554, 2007

[8] A.A. Amis, W. Senavongse, A.M. Bull, *Patellofemoral kinematics during knee flexion-extension: an in vitro study*, Journal of Orthopaedic Research, 24(12):2201-2211, 2006

[9] H.H. Huberti, W.C. Hayes, *Patellofemoral contact pressures. The influence of q-angle and tendofemoral contact*, Journal of Bone and Joint Surgery Am., 66(5):715-724, 1984

[10] D.S. Hungerford, M. Barry, *Biomechanics of the patellofemoral joint*, Clinical Orthopaedic and Related Research, (144):9-15, 1979

[11] A.B. Zavatsky, A *kinematic-freedom analysis of a flexed-knee-stance testing rig*, Journal of Biomechanics, 30(3):277-280, 1997

[12] N.J. Dahlkvist, P. Mayo, B.B. Seedhom, *Forces during squatting and rising from a deep squat*, Eng Med. 1982;11(2):69-76.

[13] J.J. Elias, D.R. Bratton, D.M. Weinstein, A.J. Cosgarea, *Comparing two estimations of the quadriceps force distribution for use during patellofemoral simulation*, Journal of Biomechanics, 39(5):865-872, 2006

[14] D.R. Wilson, M.V. Apreleva, M.J. Eichler, F.R. Harrold, *Accuracy and repeatability of a pressure measurement system in the patellofemoral joint,* J Biomechanics, 36(12):1909-1915, 2003

[15] S. Ostermeier, M. Holst, C. Hurschler, H. Windhagen, C. Stukenborg-Colsman, *Dynamic measurement of patellofemoral kinematics and contact pressure after lateral retinacular release: an in vitro study,* Knee Surgery, Sports Traumatology, Arthroscopy 15(5):547-554, 2007

[16] H.J. Hehne, *Biomechanics of the patellofemoral joint and its clinical relevance,* Clinical Orthopaedics and Related Research, (258):73-85, 1990

[17] Goodfellow J, Hungerford DS, Zindel M., *Patello-femoral joint mechanics and pathology. 1. Functional anatomy of the patello-femoral joint*, Journal of Bone and Joint Surgery Br., 58(3):287-290, 1976

[18] T. Luyckx, K. Didden, H. Vandenneucker, L. Labey, B. Innocenti, J. Bellemans, *Is there a biomechanical explanation for anterior knee pain in patients with patella alta?: influence of patellar height on patellofemoral contact force, contact area and contact pressure*, Journal of Bone and Joint Surgery Br., 91(3):344-350, 2009

[19] L.S. Matthews, D.A. Sonstegard, J.A. Henke, *Load bearing characteristics of the patello-femoral joint,* Acta Orthopaedica Scandinavica, 48(5):511-516, 1977

[20] R.P. Csintalan, M.M. Schulz, J. Woo, P.J. McMahon, T.Q. Lee, *Gender differences in patellofemoral joint biomechanics*. Clinical Orthopaedics and Related Research, (402):260-269, 2002

[21] M. Bohnsack, P. Klages, C. Hurschler, A. Halcour , A. Wilharm, S. Ostermeier, O. Ruhmann, C.J. Wirth, *Influence of an infrapatellar fat pad edema on patellofemoral biomechanics and knee kinematics: a possible relation to the anterior knee pain syndrome*. Archives of Orthopaedic and Trauma Surgery, 129(8):1025-30, 2009.

[22] T.M. Melegari, B.G. Parks, L.S. Matthews, *Patellofemoral contact area and pressure after medial patellofemoral ligament reconstruction*. Am. Journal of Sports Medecine, 36(4):747-752, 2008