

Patellofemoral contact pressures

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A test rig for studying the biomechanical behaviour of post-mortem human knees is built. For loading the quadriceps tendon a special clamping device is constructed, so the forces up to 3000 N could easily be transferred to the tendon. Several post-mortem human knees used in this study are tested to collect data about the general biomechanics of knee joint during squatting. The forces in the quadriceps tendon and in the tibia are measured continuously; the flexion angle is also measured. On this modular test rig, the contact pressures of the patellofemoral joint are measured as well. Therefore a thin pressure film is used. Not only are measured the contact pressures, but the changing contact area is also visualized and measured.

The forces and rotations measured in the joint and in the contact area allowed us to obtain perfectly reproducible values as well as a positive relation between contact area, contact position and working direction of the quadriceps tendon.

Key words: human knees, contact pressure, patellofemoral contact, quadriceps tendon

1. Introduction

A recent review [1] highlighted the lack of understanding of patellofemoral joint biomechanics during gait, with only 6% of papers addressing the subject. This is interesting as two widely used methods of treating this condition, patellar taping and bracing, appear to be efficient in the investigation based on a biomechanical approach. One of the problems the researchers have to face in this field is to define the activities which are functionally relevant to patients and sufficiently stimulating the dynamic stability of the joint. At the same time these activities should not induce any pathological overload and the consequent risk of injury. Gait activities involving level walking are unlikely to present a sufficient challenge to dynamic control of the patella. Researchers are increasingly investigating the variables associated with eccentric control during step descent [2]–[8].

During the controlled lowering phase the knee joint starts from a relatively stable extended position and flexes towards an increasingly unstable position. The increased joint flexion causes a progressive increase in the external flexion moment which is matched by progressively increasing eccentric muscle contraction in order to prevent collapse. In such a case, the internal extensor moment increases during descent as knee flexion occurs. This results from proximal shift of the patella contact zone due to the cam shape of the femoral condyles. This causes the patella tendon lever arm to lengthen and the quadriceps lever to shorten. The effect of the moving contact zone is significant; at the angles of knee flexion less than 60°, the quadriceps lever arm works with a mechanical advantage; however, at the angles of knee flexion greater than 60° the quadriceps works at a mechanical disadvantage [9], [10].

Research on the effects of bracing in the management of patellofemoral problems is limited compared

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to taping, with only 7% of the recent research literature focusing on this modality [1]. The pain-relieving effects of bracing have been attributed to an increased stabilization of the joint which reduces muscle force generation [11]. In particular, patellofemoral braces are designed to “reduce compression of the patella as well as to prevent excessive lateral shifting” [11]. Although the limited results are encouraging, patellofemoral bracing remains controversial.

It is important to note that the majority of previous research on the biomechanics of the patellofemoral joint have either been focused on the sagittal plane or used very simple marker sets [3], [5], [6], [12], [14], [15]. This has led to conflicting results. However, the knee and the patellofemoral joint both have six degrees of freedom of motion. Further, they both have moving centers of joint rotation leading to extremely complex control mechanisms. The importance of this was highlighted by KOWALK et al. [13]. They reported that although the knee abduction–adduction moment is not in the primary plane of motion, it should not be ignored when assessing the stability and function of the knee during stair climbing activities.

Knee pain can be related to early wear of one of the components or to the bad positioning of working angles of the muscles. This means that extra pressure is placed in different positions on the patella during flexion–extension. These pressures are transformed into pain.

This study focuses on the basic understanding of patellofemoral pressures during a normal flexion–extension movement. This occurs in relation to the contact area in the patellofemoral joint during flexion–extension.

2. Materials and methods

For this test a new test rig was developed, based on the Oxford Knee rig [16]. This test rig makes it possible to measure forces (quadriceps and tibia) and rotations (knee flexion, ankle) during flexion and extension. The main overview of the test rig is given in figure 1. This figure shows a complete mechanical setup with post-mortem human knee as mounted during testing. The test rig work is based on pulling the quadriceps muscle by a linear motor. Due to this pulling the forces in the knee joint will increase until the knee starts to extend.

On a table, two sliding bars were vertically mounted (b). These bars make the bridge construction (c) glide smoothly up and down. On this bridge con-

struction the linear motor (a) was placed, with the possibility of moving left and right, but fixed to the construction during testing. The hip joint was simulated by a rotary part (rotation in the sagittal plane, and internal rotation), where also a sensor (d) is placed. The final clamping (f) of the quadriceps tendon is connected to the linear motor via a steel cable (e). This cable is transferred by two separate rollers to guide it smoothly to the motor.

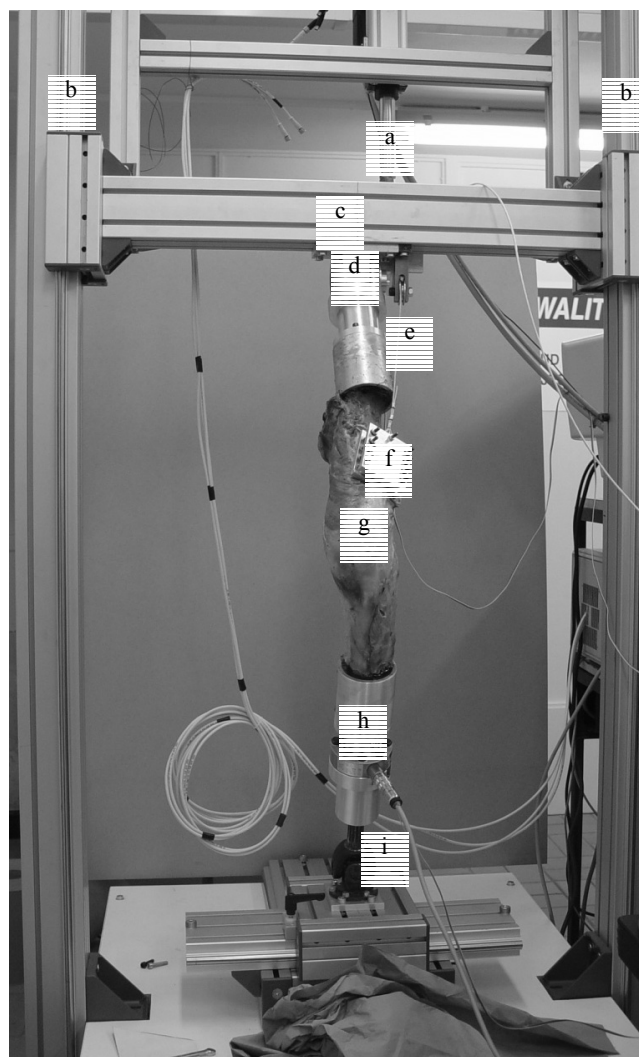


Fig. 1. Test rig with: linear motor (a), linear guiding system (b), bridge construction (body weight) (c), rotative sensor (d), quadriceps muscle simulation (e), clamping (f), cadaveric knee (g), pressure cell lower limb (h), ankle joint (i)

On this “hip” structure it is possible to mount an aluminum cylinder with the post-mortem human knee (g). The same cylindrical structure (h) is used for fixation of the tibia which is connected to Cardan coupling unit, simulating the ankle joint (i). A loadcell was placed between the aluminum cylinder and a rotary sensor to measure to forces in the tibia and the internal rotation.

The ankle joint is fixed to the base table, but its position can be changed by two gliding platforms.

The flexion–extension can be measured by a rotary sensor on the “hip” construction. This registers the change in knee flexion during motion. From the known lengths of the upper and lower limbs the original hip angle can be calculated.

In order to measure the contact area of the patellofemoral joint, a thin film is used. This film (I-scan, Tekscan, Inc.) is a flat and thin (< 1 mm) polymer film with copper lines in it. The sensor is square-shaped and has a total contact area of 1600 mm^2 . Special connection system makes it possible to read out more than 100 signals. Due to the software of the sensor, variations of stresses can be monitored online. A certain contact pressure can be applied to each point (cross-section of two perpendicular lines) and the total contact area is registered (each point is given a constant contact area of 1.6 mm^2).

The sensor was inserted into the knee joints by a lateral incision, and stitching the knee afterwards. After the opening of the knee, the patella was freed so the gluing of the sensor by Dermabond, topical skin adhesive, could be done easily. Due to the thin nature of the sensor, the film could be glued perfectly onto the patella. This allowed the sensor to be kept in position during motion. After that the patella was placed in position again, and the knee was laterally stitched.

A new post-mortem human knee was first treated and cleaned, tibia and femur were prepared for further imbedding, and the quadriceps femoris was released and placed in a newly developed clamping system as can be seen in figure 2. This clamping makes it possible to transfer the forces exceeding 3000 N from the steel cable to the tendon. The clamping system, based on a polymer toothed rack, was designed especially for this purpose. More information can be found in [17].

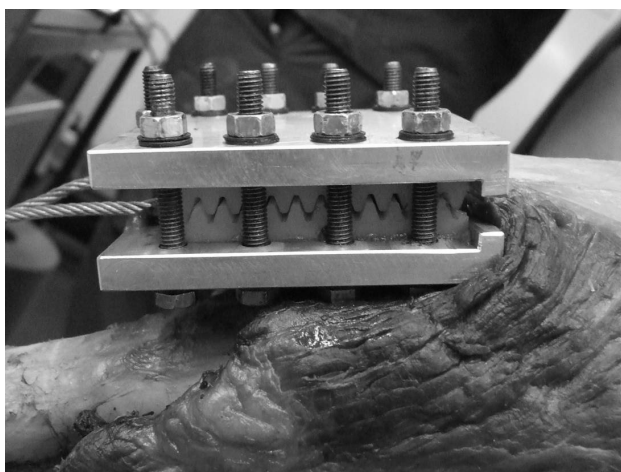


Fig. 2. Clamping of quadriceps tendon

The tibia and femur were then cemented with polyester in two aluminium cylinders. These are constructed to be placed in the test rig, and aluminium is used for later removal of the polyester (heating of the samples). Once placed in the test rig, the motor was correctly positioned. Due to the modular setup the motor can be placed on the right and on the left (see figure 1) of the “hip” construction, so right and left knees can be tested without problems. By pulling on the quadriceps tendon, the knee will extend and flex after extension. Forces and rotations are always measured due to a thin film inserted into the knee joint; also the contact pressures and the contact area can be measured during flexion and extension. The tests were performed at a linear motor speed of 1 or 2 mm/s , resulting in a flexion–extension time from 80 to 100 seconds.

3. Results and discussion

The results of a test without a pressure film are shown in figure 3. In this figure, the duration of extension–flexion was approximately 100 seconds. Line *a* represents the quadriceps force during flexion–extension, line *b* represents the rotation as measured on the hip (0° is fully stretched, positive values mean overstretching).

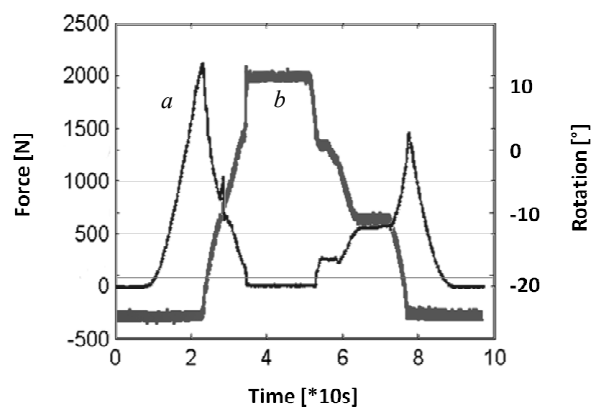


Fig. 3. Overview of test results: quadriceps force during extension–flexion (a), hip rotation during extension–flexion (b)

Starting with a flexed knee (bridge construction is resting on two centerpoints, for safety reasons), a quadriceps force is built up. The time of 0 N force is necessary to bring the steel cable under tension. After that the force in the quadriceps increases up to almost 2200 N , then it suddenly decreases. If compared with the curve *b* this is due to the start of the knee movement. The rotation lowers from 20 to 0 degrees after

± 40 sec. Then suddenly, with a quadriceps force of 0 N, the rotation reaches 10 degrees (+). This was the result of overstretching the knee during extension. After repositioning the knee, the quadriceps force during flexion increases again, and decreases to 0 once the bridge construction, which represents the body weight, rests on two centerpoints on the sliding bars. These points on the test rig keep the maximum flexion angle of the knee within limits (as a result of the Cardan coupling of the ankle joint), and, of course, give a null force if the quadriceps tendon increases in length (by sending out the linear motor), while the whole system is in equilibrium (resting on those two points).

The plateaus in the second part of the graph were due to bringing the enlargement of the quadriceps tendon to a stop during the flexion phase. One can see that this results in a constant force in the quadriceps as well as in a constant knee position (no change in rotation), hence the force required to keep the knee in a certain position remains constant. The strain of the tendon on seconds' scale is small.

The difference between the forces needed for extension and the one available with flexion proved to be slight. A maximum force is reached before extension starts. The maximum in flexion (~ 1500 N) was the result of knee action and did not exceed this value due to the two centerpoints on the sliding bars. The bridge construction rested on these centerpoints to avoid too high flexion and possible damage to the human bone and tissues.

The measurements were repeated several times and each time the same values were reached, although full extension was left behind to avoid overstretching. When using another knee, the results obtained differ, of course, although the general trend remains the same. A higher force at the beginning (before movement) affects an internal knee positioning and the difference in friction (static and dynamic).

After gaining some knowledge about the knee behaviour in the test rig, the tests were performed with pressure films inserted into the knee joint. These films were inserted into the knee via a lateral incision, and fixed to the patella with Dermabond, topical skin adhesive. This type of glue makes it possible to remove the sensor after testing and to reuse it. Such sensors give a calibrated pressure and the total area of contact. They are used for dynamic registration of pressure and contact area. These sensors have the ability to show the contact area during flexion–extension, and if a correct dimension of the sensor was chosen it also showed the maximum force and the force distribution. Figure 4 depicts an overview of the contact area with

time, and figure 5 – the area of contact and pressure distribution on the patella, as measured. The change in contact area follows, to a great extent, the force curve of the quadriceps force. This means that if only the forces in the knee are considered, then greater quadriceps forces result in larger contact areas. An expectation that the contact pressure should remain constant is totally unrealistic. The pressure increases as the force increases and also as the flexion becoming greater.

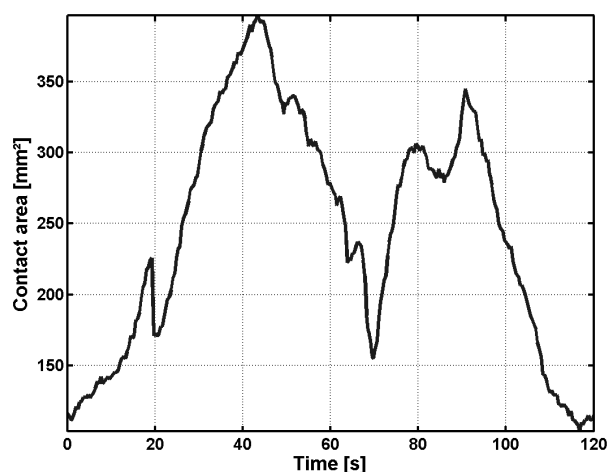


Fig. 4. Contact area in the patellofemoral joint

Figure 4, which shows the contact area during extension–flexion movement, gives what is already known. In full flexion, the contact area ranges from around 350 to 400 mm², while in full extension, the contact area is extremely small. An increase in contact area within 40 s is due to the tension in the quadriceps tendon. At the time 0 the contact area is small, while the knee is in full flexion, but the “body weight” rests on two centerpoints on the gliding bars. Then the steel cable is brought under tension, so the force on the quadriceps increases and the patella is forced against the femur. This results in a very large contact area. Once the movement starts (after 40 s) the contact area decreases, and will increase again if flexion starts over after 70 s. The contact area reaches a maximum within around 90 s and then decreases to its starting value, when the “body weight” rests on its centerpoints again.

The contact area does not decrease to zero; this is due to the non-full stretching of the knee. The patella always is in contact with the femur, and will only lose contact when fully stretched.

The contact area position changes during motion. The medial lower part and the lateral upper part of the patella during extension get more and more stressed. The lateral contact area and the medial lower part in-

crease spectacularly, as shown in figure 6. This contact area lays within the working line of the quadriceps force. This indicates that the change of the working line of the quadriceps can change the contact area and the pressures (BIEDERT et al. [18]).

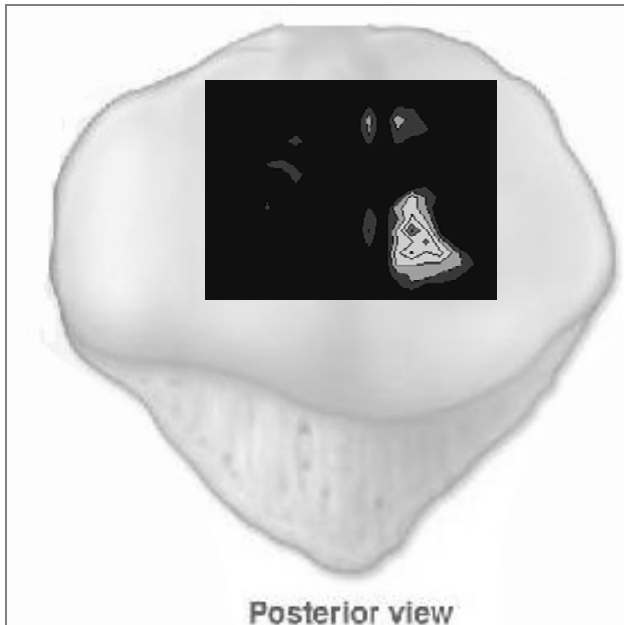


Fig. 5. Patella with indicated contact zone and pressure distribution (after 37 s)

contact area increases with an increase in the force of the quadriceps. The black line in the lateral contact area in figure 6B is due to the missing of one line in the sensor. The sensor, consisting of two films with perpendicular copper lines, sometimes loses contact with one of the lines, which results in a complete 0 line, as shown in the picture.

In figure 6, a posterior view of the patella is given. The zone with “trochlea” is the zone where the patella does not come into contact with the femur and indicates the deepest zone of the trochlea. In this zone, the patella glides within the trochlea; it can be observed that the patella only comes into contact with the sides of the trochlea, and is not in contact with it. The patella is not fully in contact with the femur as a result of the outer form of femur and patella.

The colour scale gives the pressure distribution, from 0 to 3.5 MPa. The fact that the white zone in figure 6B is extremely large means that the local pressure is much higher, but it is restricted due to the use of a sensor with limited capacity (saturation of the sensor). In this zone, an overloading takes place. Better results of pressure distribution will be obtained by using some more appropriate sensor (from around 7 to 7.5 MPa). The pressure distribution and maximum pressure are required for comparing different situations leading to knee pain. This pain is

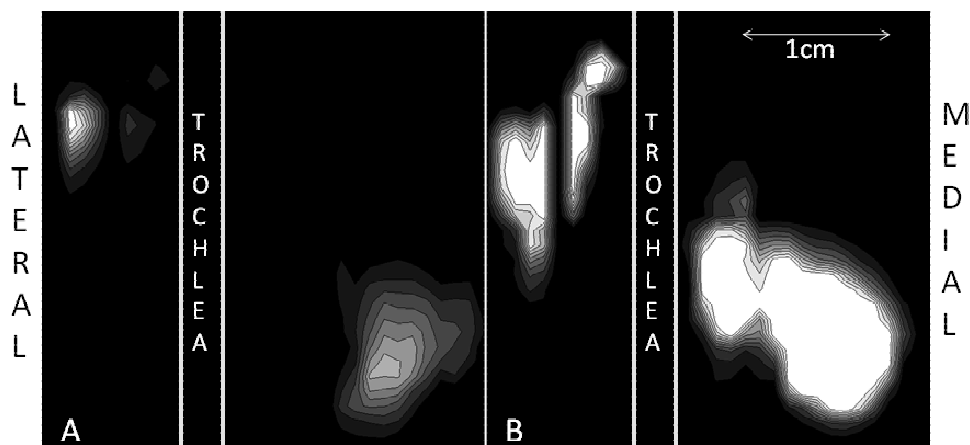


Fig. 6. Pressure films during testing. Left knee, frontal view: (A) Start of the test (knee in full flexion, “body weight” resting on its centerpoints), (B) maximum contact area (just before movement starts)

Figure 6 shows two phases of the pressure distribution during flexion–extension. This figure shows clearly the working line of the quadriceps tendon (A – at the beginning of testing (“body weight” resting on the centerpoints), B – at maximum quadriceps force (just before movement)). Also the change in contact area is clearly shown. This means that the

not only due to wear of the cartilage, but also due to the pressures applied to the joint. Therefore a good understanding of the importance of the contact area as well as the contact pressure, the maximum contact pressure and the contact pressure distribution is required. Therefore more experiments should be carried out.

4. Conclusions

The designed test rig offers great potential for the research of post-mortem human knees. These knees can now be used to gain information about different “special” effects on the knee.

As shown with the contact pressure films, the change in contact area and the contact position of the patella against the femur depends on the force applied to the quadriceps. Changing the parameters, as for instance the Q -angle (by positioning the motor more to the left or right), will provide the information about forces and contact areas if the Q -angle is changed for pain relief.

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