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FUNCTION OF THE MENISCI IN THE LOAD TRANSFER WITHIN THE KNEE JOINT

FUNKCJA ŁĄKOTEK W PRZENOSZENIU OBCIĄŻEŃ W STAWIE KOLANOWYM

Key words: menisci, fatigue testing, joint deformation, assessment of structures.

Abstract The aim of the study was to conduct strength analysis of a knee joint in order to experimentally determine the destructive fatigue loading under the conditions of cyclic compression. Animal joints were used as the study material. They were periodically subjected to variable axial loading. The degree of joint deformity and damage to articular surfaces and menisci were globally determined after isolation of the joint structures. The application of the variant of axial loading without slip and rolling results in the rupture of the medial meniscus, which is an important biotribological structure. Fatigue testing of the joints allowed for the determination of the parameters of biomechanical extortions, which lead to the loss of normal lubrication conditions and the degradation of the meniscus and cartilage structures on the femoral condyles.

Słowa kluczowe: łąkotki, badania zmęczeniowe, deformacja stawu, ocena struktur.

Streszczenie Celem jest analiza wytrzymałościowa w stawie kolanowym, która pozwala na eksperymentalne wyznaczenie niszczącego obciążenia zmęczeniowego w warunkach cyklicznego ściskania. Materiałem badań były stawy zwierzęce. Poddano je okresowo zmiennym obciążeniom osiowym. Oceniano globalnie stopień deformacji stawu oraz stopień uszkodzeń powierzchni stawowych i łąkotek po separacji struktur stawowych. Wariant obciążeń osiowych bez realizacji poślizgu i przetaczania się prowadzi do pękania łąkotki przyśrodkowej, która stanowi odpowiedzialną strukturę biotribologiczną. Badania zmęczeniowe stawów pozwoliły przybliżyć parametry wymuszeń biomechanicznych, które powodują utratę prawidłowych warunków smarowania i degradację struktur łąkotek oraz chrząstki na kłykciach kości udowej.

INTRODUCTION

The knee is a complex hinge-rotating joint which can be straightened, bent, and turned outside and inside. Rotational movements are possible in the joint thanks to the presence of the menisci, forming a movable acetabulum, which allows for following rotational movements of the tibia. The menisci are built of the fibrous cartilage. The menisci are crescent-shaped, and their cornua, which face each other, are connected by strong ligaments with articular surfaces of both condyles of the tibia. Peripherally, the menisci grow together with the joint capsule. In the cross-section, they have the shape of a wedge whose upper part is directed towards the circumference, and a thin edge faces the joint cavity. With the internal circumference, the menisci adhere to the femoral condyles and receive a significant part of the body weight **[L. 1–5]**. In the knee joint, there is an articulation between the following articular surfaces:

- On the medial condyles, between the femur and tibia;
- On the lateral condyles, between the femur and tibia; and,
- On the kneecap, with the patellar surface of the femur.

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Moreover, the presence of the menisci, which are sliding joint discs, allows for the functioning of the following joints:

- Meniscus-femoral – medial and lateral, and
- Meniscus-tibial – medial and lateral.

Three functional areas can be distinguished in the knee joint: articulatio meniscofemoralis, articulatio meniscotibialis, and articulatio femoropatellaris. When bending, the menisci move backwards, beyond the edge of the tibial condyles (**Fig. 1**). The lateral meniscus can be shifted to a greater extent and exhibits a slight protrusion beyond the edge of the tibial plateau.

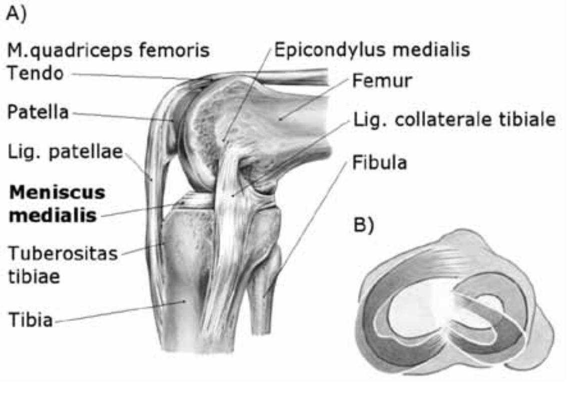

Fig. 1. The menisci of the knee: a) knee in flexion, b) the range of meniscal movements during bending

Rys. 1. Łąkotki stawu kolanowego: a) kolano w zgięciu, b) zakres przesunięć łąkotek podczas zginania

The mobility of the menisci and their presence provide cushioning and the optimal transmission of loads from the femoral to tibial condyles. The results of the research, numerical simulations and analyses of bio-bearings show that, in the biotribological aspect, the loads distributed along the biomechanical axis of the limb without additional articulation movements in the joint are the most unfavourable variant of contact *extortions* **[L. 5–7]**. The aim of the study was to conduct strength analysis of the knee joint in order to experimentally determine the destructive fatigue loading under the conditions of cyclic compression.

MATERIAL AND METHOD

The research was conducted using 7 animal knee joints as a study material. They were collected immediately after slaughter, prepared in such a way as to obtain surfaces of the femur parallel to the tibia. Such preparation of the surfaces allows for the extensory positioning of the examined joints at axial loading. The joints were subjected to periodically alternating axial loads at the frequency $f = 1$ Hz, maintaining the same level of minimum compression force $P_{min} = 500$ N, using different values of maximum compression force P_{max} and various number of cycles N_f; then the degree of the joint wear was assessed. The tested samples together with their load parameters and the number of fatigue cycles are summarized in Table 1. The tests were carried out using a servo-hydraulic fatigue testing machine MTS 810 (**Fig. 2**) steered by a FlexTest SE PLUS controller. The machine with the measurement class of 0.5 allows for conducting static and fatigue tests of any load sequence in the range of ±100 kN. An additional force sensor with a range of ±25 kN (accuracy class 0.5) was used during the tests. Compression was obtained by using handles and applying force to the cut surfaces of the femur and tibia. The position of the actuator was recorded at each peak loading value, thus globally evaluating the degree of deformation, i.e. axial shortening of the tested joint, as a measure of its wear. After generating a predetermined number of fatigue cycles (**Table 1**) or the number of cycles after which the joint was significantly damaged (sample No. 03 – **Table 1**), each joint was isolated and the degree of damage to the articular surfaces and menisci was assessed. The following structures were evaluated:

- The cartilaginous superficial layer in the region of the medial and lateral femoral condyle in the area of direct contact with the tibial plateau and in the contact zone covering the menisci,
- The superficial layer and the state of wear of the medial and lateral menisci coming into contact with the femoral and tibial condyles, and
- The superficial cartilaginous layer in the region of the medial and lateral tibial condyles.

In addition, Sample 07 was subjected to imaging examinations using volumetric tomography (CBCT) immediately before and after the fatigue testing. The 3D reconstruction was used to evaluate destructive changes **[L. 8–11]**.

Fig. 2. A research site used for fatigue testing of the joints

Rys. 2. Stanowisko badawcze wykorzystane w próbach zmęczeniowych stawów

Table 1. The list of load parameters for the examined knee joint samples
Tabela 1. Zestawienie parametrów obciążenia próbek stawów kolanowych poddanych badaniom

No. sample:	Levels of compressive force		Number of load cycles N_f
	P_{min} (N)	P_{max} (N)	
01	500	2000	2 500
02		4000	3 100
03		6000	500
04		3000	5 000
05		3000	10 000
06		3000	15 000
07		3000	15 000

TEST RESULTS

Measurements of joint deformations

The cyclic deformations reported during fatigue tests of the joints in the function of the load were displayed in the form of a hysteresis loop (**Fig. 3**).

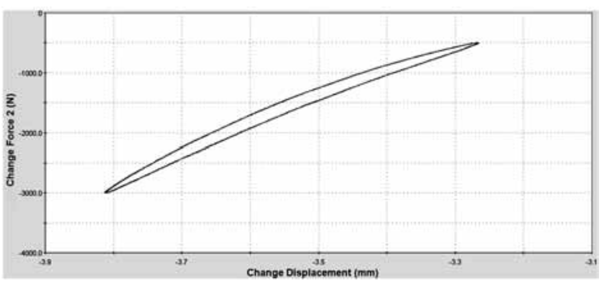

Fig. 3. The example force as a function of joint deformation (sample No. 06, number of cycles N = 2000)
Rys. 3. Przykładowa zależność siły w funkcji odkształcenia badanych stawów (próbka nr 06, liczba cykli N = 2000)

With the increasing number of load cycles, a gradual deformation of the joints was observed. The deformations were continuously monitored by measuring axial shortening and their course, shown as a function of the number of fatigue cycles for individual samples, as presented in **Figs. 4–10** (in the examination of sample No. 01 the registration started after the number of cycles of 1500 N). Deformation of the joint equal to zero each time corresponded to the initial compression, i.e. at the beginning of the test with the force P_{min}=500 N. In most cases, the joint was quickly deformed in the initial phase of loading, after which the rate of deformation decreased until the joint was clearly broken and articular ligaments were ruptured, as in the case of joint No. 03 which was tested at the highest load P_{max}.

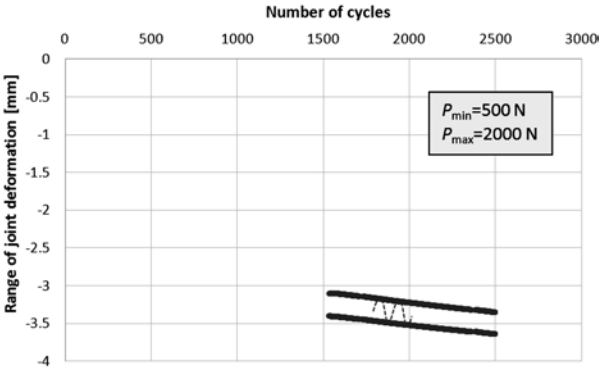

Fig. 4. Change in the range of deformation with the number of cycles in the joint test No. 01
Rys. 4. Zmiana zakresu deformacji wraz z liczbą cykli w badaniu stawu nr 01

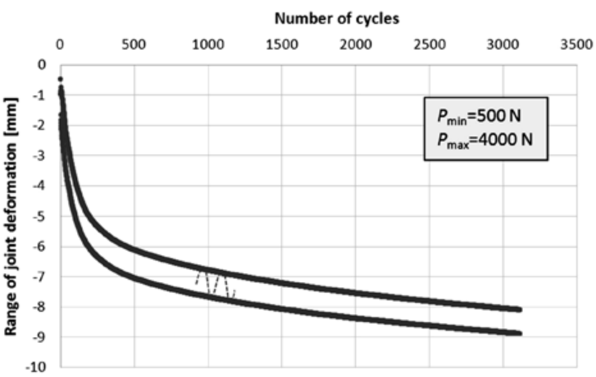

Fig. 5. Change in the range of deformation with the number of cycles in the joint test No. 02
Rys. 5. Zmiana zakresu deformacji wraz z liczbą cykli w badaniu stawu nr 02

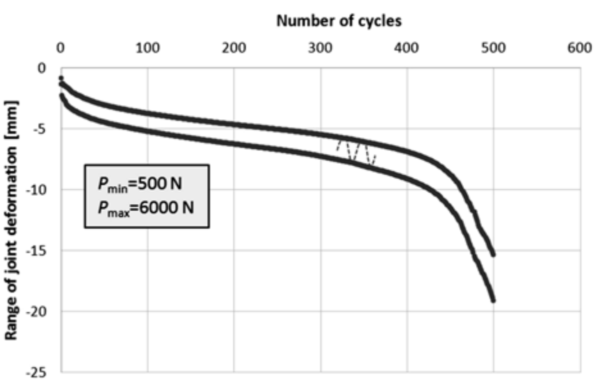

Fig. 6. Change in the range of deformation with the number of cycles in the joint test No. 03
Rys. 6. Zmiana zakresu deformacji wraz z liczbą cykli w badaniu stawu nr 03

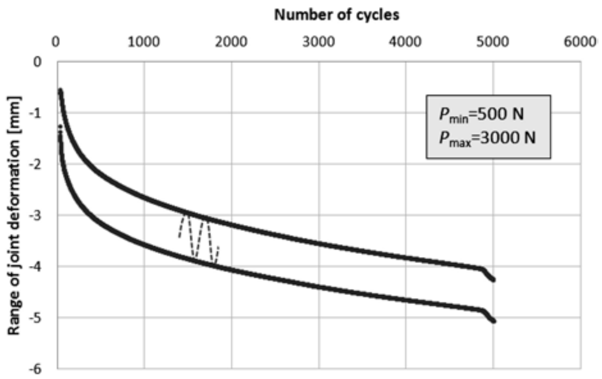

Fig. 7. Change in the range of deformation with the number of cycles in the joint test No. 04

Rys. 7. Zmiana zakresu deformacji wraz z liczbą cykli w badaniu stawu nr 04

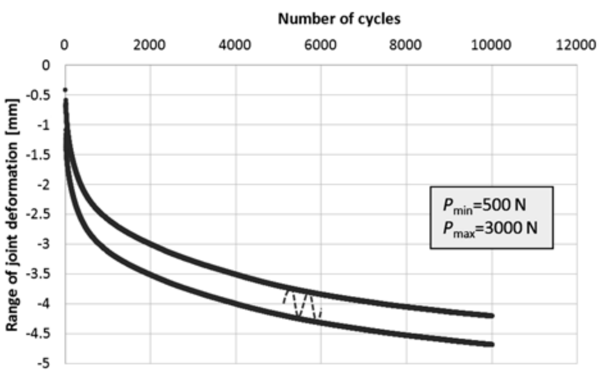

Fig. 8. Change in the range of deformation with the number of cycles in the joint test No. 05

Rys. 8. Zmiana zakresu deformacji wraz z liczbą cykli w badaniu stawu nr 05

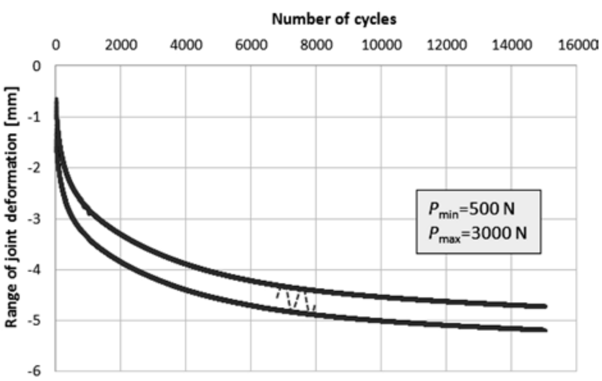

Fig. 9. Change in the range of deformation with the number of cycles in the joint test No. 06

Rys. 9. Zmiana zakresu deformacji wraz z liczbą cykli w badaniu stawu nr 06

Figure 11 presents a comparison of the progress in joint deformation tested at different maximum compression forces. As expected, in terms of quality, there was a clear trend of the increasing rate of joint deformation observed as the level of the load went up. The rate, however, rapidly rose at P_{max} loads above 3000 N. Therefore, further tests were carried out at the same force in order to provide information about the impact of the number of load cycles on the joint wear. A comparison of the graphs presenting the deformation progress in the four joints tested at the load of P_{max} = 3000 N is shown in **Fig. 12**. As observed, only one of these curves, i.e. referring to sample No. 07, clearly stands out from the others (deformation at 15.000 cycles reaches 7 mm).

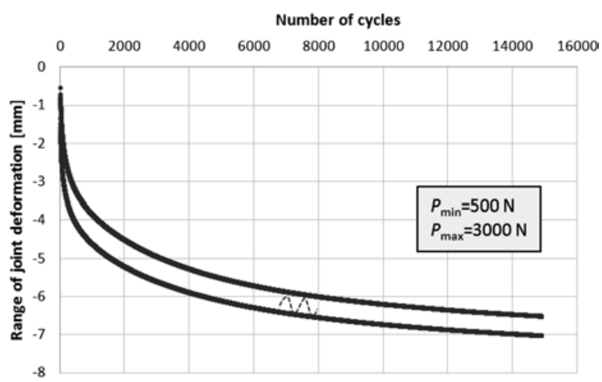

Fig. 10. Change in the range of deformation with the number of cycles in the joint test No. 07

Rys. 10. Zmiana zakresu deformacji wraz z liczbą cykli w badaniu stawu nr 07

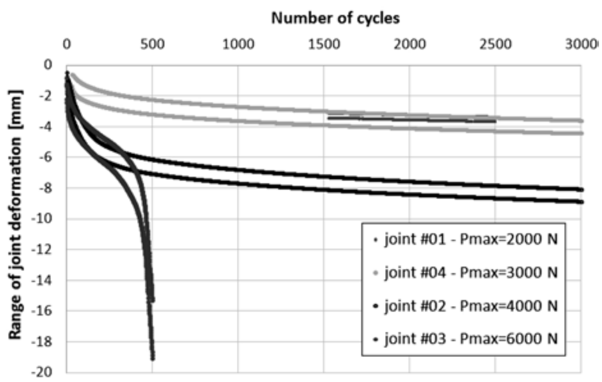

Fig. 11. A comparison of the rate of joint deformation increase at different levels of maximum compression force

Rys. 11. Porównanie tempa narastania deformacji stawów przy obciążeniach o różnych poziomach maksymalnej siły ściskającej

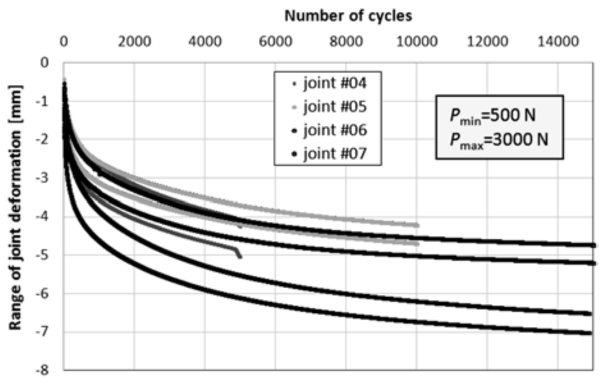

Fig. 12. A comparison of the rate of joint deformation increase in the tests conducted with the same maximum compression force

Rys. 12. Porównanie tempa narastania deformacji stawów w badaniach o takich samych poziomach maksymalnej siły ściskającej

The visual assessment of the degree of joint damage after fatigue testing

The assessment of the degree to damage of the tested samples was conducted by comparing articular structures obtained after fatigue testing (Samples 01-07) with the structures of the joints not subjected to the tests. In the joints not subjected to fatigue tests, the menisci are shiny, covered with a layer of the synovial fluid, with their internal edges showing no signs of fibrous tissue disruption (**Fig. 13**). We should also pay attention to the anatomical plication of the meniscal superficial layer, which forms characteristic lubricating pockets (**Figs. 13c, d**) **[L. 12–13]**. Taking into account the conditions of tribological and physiological cooperation in the knee joint, we can conclude that the variant of axial loading in the range of 500-6000N without slipping and rolling of the working surfaces creates the most unfavourable conditions **[L. 14–21]**. The penetration of the synovial fluid from the inner layer of the articular capsule into the friction area is difficult. This may lead to direct contact of the cartilage structures, the mechanical injury of the menisci, and/or the rupture of the cartilage collagen braid and impaired chondrocyte function **[L. 22]**.

Immediately after fatigue testing, the joint structures were isolated with a scalpel, and photographic documentation was prepared. The superficial layer of the cartilage in the area of the medial condyles of the femur and tibia showed signs of greater overload than the same areas in the lateral condyles. The overloaded areas in the region of the menisci were small compared to the areas of the direct contact between the femoral and tibial condyles. The greatest destruction of the hyaline cartilage was observed on the medial condyle in the area where there was no contact through the medial meniscus. This form of destruction was reported in all examined joints in which the articular surface on the medial condyle of the femur, not protected by the meniscus, is most vulnerable to destruction under axial loading [**L. 5**]. This observation was confirmed by other reports and the outcomes of numerous implantations performed in the medial area of the knee [**L. 23–27**]. After testing, the menisci were clearly dehydrated and compressed. They had cracks or showed thinning on the inner edge, especially in the medial menisci. The example specimen obtained in fatigue testing demonstrated the thinning of the inner edges of the medial meniscus in the area of the anterior and posterior cornu (**Fig. 14**). Fatigue cracks were visible in Samples 03 and 06 on the medial meniscus, within the inner edge, closer to the posterior cornu (**Fig. 15**).

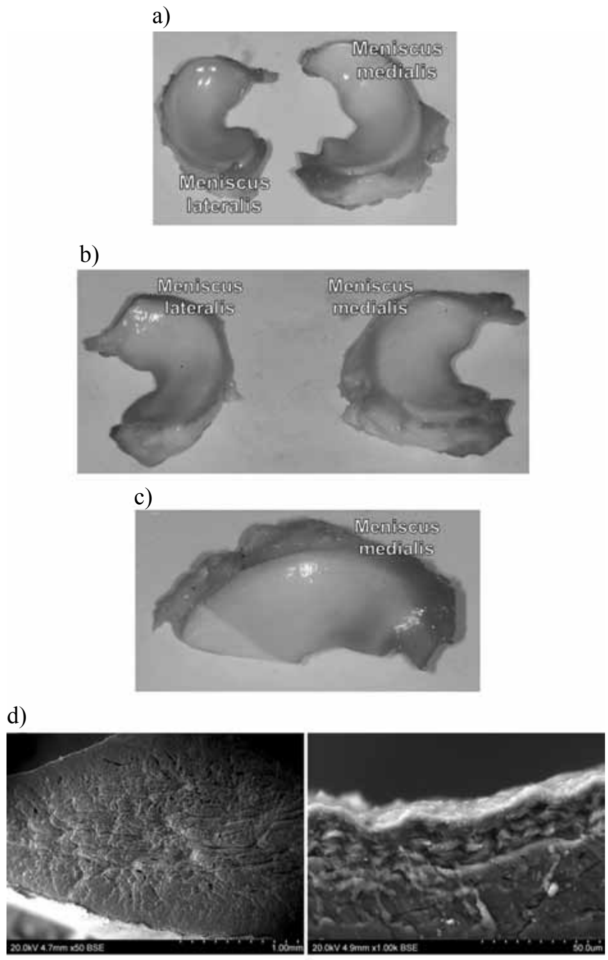

Fig. 13. The menisci isolated from the knee joint not subjected to fatigue testing: a) in the proximal view (contacting the femoral condyles), b) in the distal view (contacting the tibial plateau), c) medial meniscus in the cross-section, d) SEM image of the lateral meniscus cross-section in the close-up of the superficial layer

Rys. 13. Łąkotki wypreparowane ze stawu kolanowego niepoddanego badaniom zmęczeniowym: a) w widoku od strony bliższej (kontaktującej się z kłykciami kości udowej), b) w widoku od strony dalszej (kontaktującej się z plateau piszczeli), c) łąkotka przyśrodkowa w przekroju, d) obraz SEM łąkotki bocznej w przekroju ze zbliżeniem warstwy wierzchniej

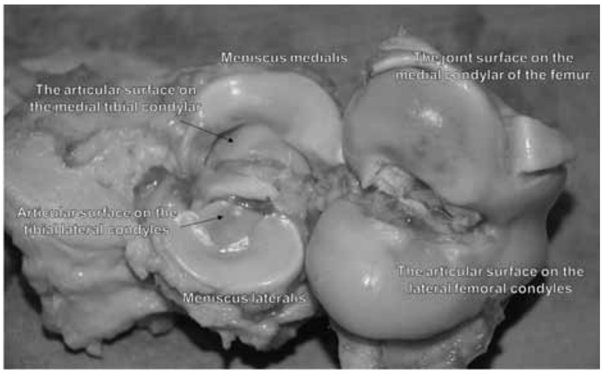

Fig. 14. The left knee joint after fatigue testing (sample No. 07)

Rys. 14. Lewy staw kolanowy po badaniu zmęczeniowym (próbka nr 07)

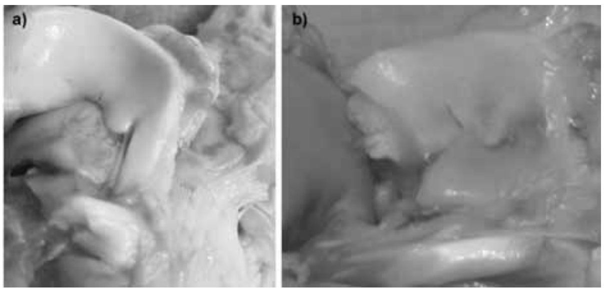

Fig. 15. A fatigue crack of the medial meniscus: a) sample No. 03, b) sample No. 06

Rys. 15. Zmęczeniowe pęknięcia łąkotki przyśrodkowej: a) próbka nr 03, b) próbka nr 06

SUMMARY AND DISCUSSION

The parameters of fatigue testing indicate the extreme conditions that can be observed in the knee joint, e.g., during quasistatic lifting of heavy weights. The range of lifting capacity is individual and varies from person to person. To a large extent, it depends on the efficiency and physical preparation of the group of muscles that coordinates the joint function.

The frequency of 1 Hz was used in the research, since it can reproduce the variability of biomechanical *extortions in real conditions*. The range of values used in compression force examinations was determined based on the course of curves presenting the rate of joint deformation (**Fig. 11**). At a frequency of 1 Hz, an increase of the maximum compression force P_{max} was accompanied by a rise of the value and rate of deformation in the joint. P_{max} of 3000 N should be considered critical to maintain the function of the menisci and hyaline cartilage covering the articular surfaces on the femoral and tibial condyles. At the same time, the deformation rate curves stabilize and are parallel to the abscissae. It should be noted that the rate of joint degradation below 8 mm, in relation to the total thickness of cartilage on the femoral condyle, tibial condyle and the meniscus, is dangerous for these tissues and chondrocytes. Chondrocytes are hyaline cartilage cells that are responsible for the proper functioning of articular surfaces through regeneration and production of the collagen fibre braid. P_{max} of 6000 N caused the rupture of the medial meniscus and the degradation of the joint as a result of deformation already after 500 load cycles (**Figures 11** and **15**). The tests carried out with the same maximum compression force P_{max} of 3000 N indicate that, at 10.000 load cycles, the rate of deformation increase for the cartilage and menisci ranges from 4.2 mm to 6.8 mm, which still preserves the cushioning activity of elastic joint structures. This correlation is shown by the geometric parameters of the menisci and hyaline cartilage in the knee joint. These parameters were determined in the examinations of the normal knee joints (CT, MRI and coordinate measuring) as well as in model and simulation studies **[L. 5, 28–30]**. Simulation numerical tests indicate that, during locomotion, the above structures transfer stresses in the range of 22–24 MPa. Significantly lower values of stresses were reported in the cartilage and subchondral layers of the femur and tibia. The menisci are most vulnerable to exceeding the threshold of physiological tissue capacity. At the same time, they function as cushioning against displacements connected with locomotion and participate in lubrication of the joint. In order to assess the degree of joint structure degradation, sample No. 07 was subjected to CBCT imaging examinations using OP 3D tomography before and after fatigue testing (**Figures 16** and **17**). Bone structures of the femoral and tibial condyles are visible on 3D reconstructions, while the structures of the articular cartilage and hyaline cartilage were not visualized. The examination revealed the space filled with the cartilage layers and located on the medial femoral condyles and lateral tibial condyles as well as the area filled with medial and lateral wedge-shaped meniscus (**Fig. 17a**). After fatigue testing, the

Fig. 16. The joint in the fatigue testing machine holders (sample No. 07): a) before the test, b) after the test

Rys. 16. Staw w uchwytach maszyny zmęczeniowej (próbka nr 07): a) przed badaniem, b) po badaniu

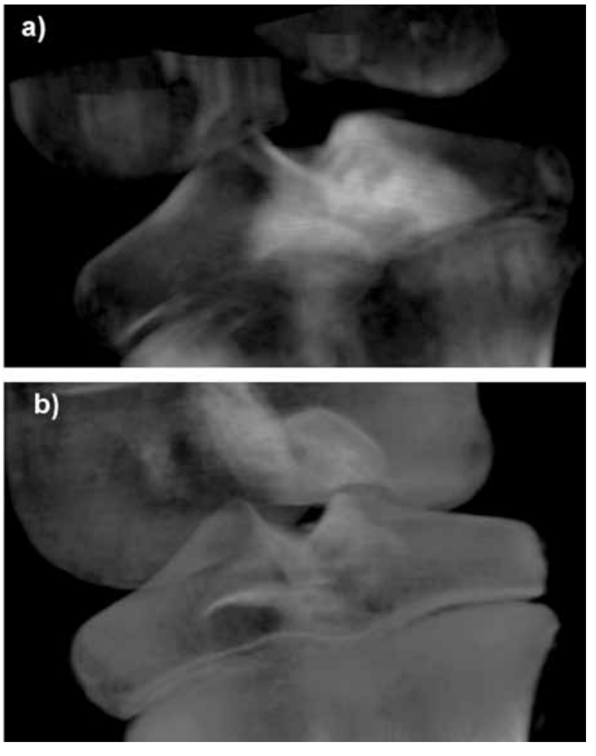

Fig. 17. 3D reconstruction of the knee joint based on CBCT imaging (sample No. 07): a) before fatigue testing, b) after fatigue test

Rys. 17. Rekonstrukcja 3D stawu kolanowego na podstawie obrazowania CBCT (próbka nr 07): a) przed badaniem zmęczeniowym, b) po badaniu zmęczeniowym

joint was degraded (**Fig. 17b**). The femoral condyles moved closer to the tibial plateau and the meniscus space diminished. Moreover, twisting of the joint is apparent, which probably results from degradation of the cruciate and lateral ligaments, and this was probably the cause of the greater deformation of the joint.

CONCLUSIONS

Fatigue testing of the joints revealed the parameters of biomechanical *extortions* that cause the loss of normal lubrication and the degradation of the structures of the menisci and cartilage on the femoral condyles.

The application of the variant of axial loads without slip and rolling leads to the rupture of the medial meniscus, which is an important biotribological structure.

The menisci provide dampening and cushioning against dislocations in the knee joint, and they are responsible for the appropriate distribution of stresses in the layered structure of the bio-bearing. The lack of these structures leads to impaired lubrication and the overload of the hyaline cartilage layers on the femoral and tibial condyles. This results in the cracking of the collagen fibre braid and prevents chondrocytes, which are damaged by compression, from regenerating the fibres. As a consequence, osteoarthritis develops in the joints, which need to be supported by prosthesis.

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