ELSEVIER

Journal of Biomechanics 35 (2002) 53–60

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Contact area and pressure distribution in the feline patellofemoral joint under physiologically meaningful loading conditions

A.L. Clark, W. Herzog*, T.R. Leonard

The University of Calgary, Faculty of Kinesiology, Human Performance Laboratory, 2500, University Drive NW, Calgary, AB, Canada T2N 1N4

Accepted 1 August 2001

Abstract

The purpose of this study was to determine contact area and mean and peak pressures in the healthy feline patellofemoral joint over the complete range of possible applied force. Furthermore, we wanted to improve upon the repeatability of previous measurements while maximizing the physiological relevance of the results obtained. The patellae and femora were secured in a loading frame approximating an in situ loading configuration. Low- and medium-grade Fuji film was used to assess patellofemoral contact area and pressure distribution, respectively. Constant force was applied to the patellofemoral joints for 2 s (short duration trials) or 5 min (long duration trials). For the short duration trials, contact area was shown to increase logarithmically with the force applied. In contrast, mean and peak pressures increased linearly with force. Furthermore, the rate of increase of peak pressure with force was approximately three times greater than that of mean pressure. For the long duration trials, contact area increased up to 33% compared to the short duration trials. This effect could no longer be detected with our approach after an unloading period of 5–10 s. Increasing contact area is one mechanism that the feline patellofemoral joint may use to regulate the pressures experienced by the cartilage as the force applied to the joint increases. The attenuation of external forces inside a joint is achieved by the specific geometry of the articulating surfaces and the viscoelastic properties of the articular cartilage. It likely represents a natural protection of joints to high external load magnitudes. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Contact area; Pressure distribution; Patellofemoral joint; Feline

1. Introduction

The excellent friction, lubrication and wear characteristics of articular cartilage enable it to fulfill its essentially biomechanical function over the lifetime of a joint under normal physiological conditions. Loading conditions outside the physical norm however, can alter the composition, structure and material properties of articular cartilage. Cartilage degeneration has been initiated experimentally in animals by excessive loading (Moskowitz, 1984), joint immobilization (Jurvelin et al., 1986) and joint disruption by anterior cruciate ligament transection (Herzog et al., 1993). Thus, the mechanical environment of articular cartilage is an important factor affecting its health, and consequently, the function of the joint and the progression of joint degeneration.

The importance of joint loading to the health of articular cartilage has led to investigations into contact area and stress distribution within various joints. The contact area within the tibiofemoral joint was initially investigated using roentgenographic methods (Kettelkamp and Jacobs, 1972) and casting techniques (Walker and Hajek, 1972). These studies helped identify the meniscii as load distributing structures of the knee. Fukubayashi and Kurosawa (1980) combined the casting method with Fuji pressure sensitive film to measure both contact area and pressure distribution in the tibiofemoral joints of degenerated and healthy knees with and without meniscii. Degenerated knees were found to have a larger contact area when compared to healthy joints, and the pressures experienced by the cartilage increased significantly when the meniscii were removed. Ahmed and Burke (1983) and Ahmed et al. (1983) measured static pressure distribution in the tibio- and patello-femoral joints using a micro-indentation transducer. The stress distribution within the patellofe-

*Corresponding author. Tel.: +1-403-220-3438; fax: +1-403-284-3553.
E-mail address: walter@kin.ucalgary.ca (W. Herzog).

0021-9290/02/$ - see front matter
PII: S0021-9290(01)00165-8

moral joint was found to be dependent upon the degree of action of the various components of the quadriceps muscle group.

When using any technique to measure contact area and pressure distribution in an articulating joint, its disruption of the natural contact mechanics of the surfaces must be considered. Instrumented pipes inserted part-way into the articular cartilage from the underlying subchondral bone were used by Inaba and Arai (1989) to evaluate instantaneous contact pressures in the tibio-femoral joint. The severe disruption of the joint and cartilage by this method limits its application to in vivo work. Inserting pressure sensitive film or a transducer between two articulating surfaces will alter the congruency and compliance of the joint and may result in unrealistic stress values. A single packet of Fuji pressensor film, for example, can change the maximum true contact pressures by 10–20% (Wu et al., 1998).

Contact area and pressure distribution have been measured in the cat patellofemoral joint in vivo (Ronsky et al., 1995, Herzog et al., 1998). In these studies, Fuji film was inserted through bilateral rectinacular incisions directly between the articulating surfaces of the joint by retracting the patella. Knee extensor forces were produced by stimulation of the femoral nerve while the tibia was held in position by a restraining bar. The resulting patellofemoral joint contact pattern was recorded directly onto the Fuji film. This technique has enabled comparison of anterior cruciate ligament intact and transected joints as well as early stage osteoarthritic and contralateral joints. Changes in the patellofemoral contact profile shape and location relative to the retropatellar surface resulting from anterior cruciate ligament transection were observed. Peak pressures decreased and contact area increased significantly in the osteoarthritic compared to the contralateral joints.

Despite the increased relevance given by these in vivo measurements, the methods were limited in two ways. Firstly, as pressure sensitive film records all pressures applied during measurement, relative patella sliding during isometric contraction may have resulted in an overestimation of the contact areas and pressures corresponding to the final contraction position. Secondly, because the film was introduced into the patellofemoral joint in a medio-lateral direction, it was constrained to negotiate both of the curvatures found in the 'saddle' of the femoral groove leading to multiple pressure artifacts on the film.

The purpose of this study, therefore, was to determine contact area and mean and peak pressures in the healthy feline patellofemoral joint over the complete range of possible applied force. It was hypothesized that as the force applied to the joint increased, contact area would increase proportionally resulting in constant mean and peak pressures. Furthermore, we wanted to improve upon the repeatability of previous measurements while maximizing the physiological relevance of the results obtained.

2. Methods

2.1. Specimens and preparation

Five fresh frozen feline hindlimbs with all muscles, skin and soft tissues fully intact were used for this study. The limbs were defrosted slowly at room temperature in an extended position and then flexed to a knee angle of 100° against the tension of rigor that was present in the muscles. This knee angle corresponds to the midstance angle at which peak patellofemoral contact forces occur (Hasler and Herzog, 1998). The force through the patellar tendon aided in orientating the patella in a physiologically meaningful way within the femoral groove The patella and femur were then secured in a specifically designed loading frame (Fig. 1) in such a way as to approximate an in situ loading configuration. Two to three small screws were attached though the skin and tendon to the retropatellar surface care being taken not to penetrate the cartilage. Four additional screws were then used to secure the guide part of the loading frame to the distal end of the femur so that the patellar screws could be viewed through the hollow cylinder of the guide. The knee joint and the attached guide were then turned upside-down and freshly mixed dental cement was poured into the top of the patellar cylinder. The cylinder was locked rotationally in place after being pushed up through the guide until the patellar screws were covered by the cement. Once the dental cement had

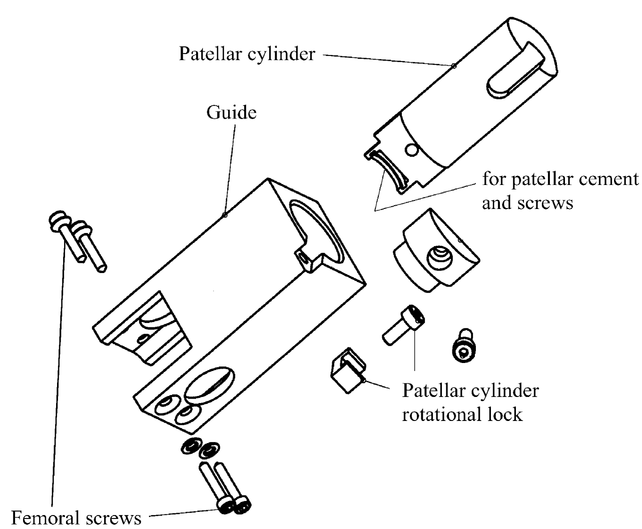

Fig. 1. The patellofemoral loading frame. Accuracy of positioning patella relative to femur; $\pm 40\,\mu m$, $\pm 0.5°$. The direction of force application along the cylinder being approximately perpendicular to the patellofemoral contact area.

hardened, the knee joint was dissected leaving just the femur bone and cartilage with the guide attached to it, and the patella bone and cartilage with the cylinder attached to it. The proximal end of the femur was then potted in a 6-degree-of-freedom loading jig and positioned under an Instron (1122) materials testing machine so that the load was applied centrally to the top of the cylinder.

2.2. Fuji film

Low- and medium-grade pressure sensitive film (Fuji) was used to assess patellofemoral contact area and pressure distribution, respectively. The low- and medium-grade films were prepared separately and not as a multiple film packet due to the increased thickness, stiffness and crinkling potential associated with these packets (Atkinson et al., 1998). The microcapsule and color developing layers of the film were sandwiched between thin polyethylene adhesive layers to seal them (Liggins, 1997). Strips of sealed film were prepared $1 \times 10\,cm^2$ to allow multiple measurements per strip. The strips were inserted into the patellofemoral joint in an anterior/posterior direction, so that the film had to negotiate only one curvature and crinkle artifacts could be avoided.

2.3. Loading protocol

A constant force was applied to the patellofemoral joint and held for 2 s (short duration trials) or 5 min (long duration trials). Short duration trials were performed at twelve force values and long duration trials were carried out at four values. Additionally, pre- and post-load short duration tests were carried out 5–10 s before and after the long duration trials respectively. The loading conditions covered the entire range of possible contact forces (50–500 N) and contained two average values observed in walking and running cats (Hasler and Herzog, 1998). Time was allowed between loads for the cartilage to relax back to a steady state. Each test was repeated with low- and medium-grade Fuji film and nine trials were duplicated to assess repeatability. Following experimentation, the Fuji film strips were subjected to a series of known pressures at the same speed for calibration. A 4 mm diameter cylindrical indentor attached to the Instron machine was used for this.

2.4. Fuji film analysis

Fuji pressure sensitive film has an estimated accuracy of $\pm 10\%$ (Singerman et al., 1987), and introducing the film into the patellofemoral joint causes errors in the actual joint contact mechanics of approximately $\pm 10\%$ (Wu et al., 1998). Furthermore, contact measurements are difficult because of sensitivity at the boundaries. With these limitations in mind, we decided to quantify mean and peak pressures and contact area.

Table 1
Pressure ranges and stain intensity thresholds for the medium-grade Fuji film

Pressure range (MPa)	Stain intensity thresholds (0 = white, 1 = black)
<3.5	0–0.2413
3.5–5.5	0.2413–0.3125
5.5–8	0.3125–0.4054
8–10	0.4054–0.4885
10–12	0.4885–0.5683
12–15	0.5683–0.6505
15–20	0.6505–0.6795
>20	0.6795–1

Digital images were obtained at a resolution of 600 pixels/inch from each Fuji film stain using a digital scanner. MATLAB image processing software was then used to modify the digital images to account for the granular nature of the Fuji film (Liggins et al., 1995). Specifically, the image was divided into sample areas 4×4 pixels large. The intensity of the pixels in these samples was averaged and this average applied across the entire 4×4 pixel sample area. This modification was made to maximize pressure resolution while maintaining satisfactory spatial resolution of the images. Once modified, the mean $\pm$SD intensity of each medium-grade calibration stain was obtained and used to establish meaningful ranges of pressure and their respective stain intensity thresholds (Table 1) (Liggins et al., 1995). The overall range of measurable pressures obtained in this way was noticeably less than 10–50 MPa; the range calculated from the Fuji prescale instruction manual (1991). This discrepancy could be accounted for by the different experimental conditions (temperature, load speed, humidity, etc.) and/or the age of the film.

The medium-grade patellofemoral digital images were adjusted for the granular nature of the film (using the method outlined above) before the pressure ranges were applied to them to produce pressure distribution maps (Fig. 2). From these maps, mean and peak pressure values were obtained. Peak pressure being defined as the largest contact pressure measured in the film over an area of at least $1\,mm^2$. The low-grade patellofemoral images were used to obtain contact area measurements. An intensity threshold was set by visual inspection for each series of stains to define the edges of contact.

3. Results

The Fuji film stains achieved using our modified technique contained no crinkling or folding artifacts

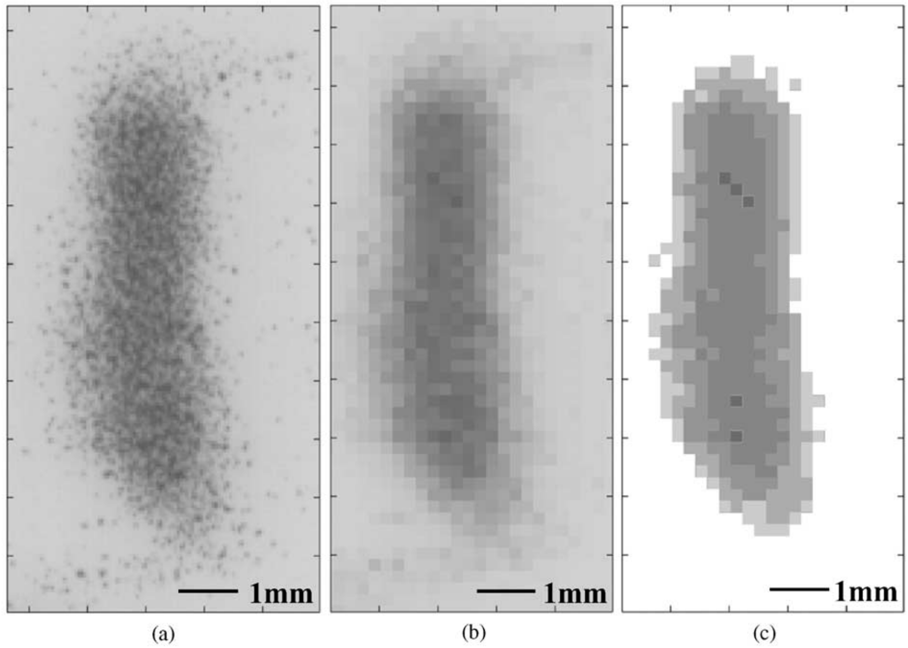

Fig. 2. Analysis of the medium-grade patellofemoral stain for Cat 5 at 200 N. Digital images of (a) the raw stain scanned at 600 pixels/inch, (b) the adjusted stain with averaged intensities calculated over sample areas 4×4 pixels large to account for the granular nature of the Fuji film and (c) the pressure distribution map obtained by applying the stain intensity thresholds. Increasing pressures are associated with increasing stain darkness.

(Fig. 3). There was a large variability in stain shape between animals, though within the stains for each animal, the shapes were consistent. The stains from the low-grade film reached saturation at low loads enabling the edges of the contact areas to be clearly defined (Fig. 3a). The medium-grade film stains enabled the pressure distribution patterns to be observed and the mean and peak pressures to be calculated.

3.1. Short duration trials

Contact area in the patellofemoral joint was shown to increase logarithmically with the force applied (Fig. 4). Increasing the applied force from 50 to 100 N, for example, gave an average increase of 10 mm^2 in contact area, though increasing force from 400 to 450 N, only produced a 3 mm^2 increase in area. The variability in contact area between animals increased noticeably around 200 N of applied force (Fig. 4). This is close to the value of peak patellofemoral contact force that has been observed experimentally in walking cats (Hasler and Herzog, 1998). The repeatability of the contact area stains and their measurements was demonstrated by the five repeated trials (Fig. 5) with all measurements falling within the 95% confidence interval about the predicted regression line $y = x$. Furthermore, the intra-class correlation coefficient of these values is 99.1%. The maximum variability was 4 mm^2 which occurred with Cat 1 at 200 N of applied force (Fig. 5).

In contrast to contact area, mean and peak pressures increased linearly with force (Figs. 6 and 7). Furthermore, the rate of increase of peak pressure with force was approximately three times greater than that of mean pressure. As the applied force increased by a factor of five, mean pressure increased by a factor of two and peak pressure by a factor of three. Four trials were duplicated in order to assess the repeatability of the mean and peak pressure measurements (Table 2). On all repeated trials, both the mean and peak pressures remained the same. This would suggest that the resolution of these measurements was primarily limited by the accuracy of the Fuji film that was defined by the pressure ranges that were established to interpret the stains. There was greater variability in peak pressure than in mean pressure between animals (Figs. 6 and 7). This is likely, again, a factor of the pressure ranges; their magnitude increasing as the pressure increases (Table 1).

Comparison of the contact area (Fig. 4) and pressure graphs (Figs. 6 and 7) reveals that cats with greater contact areas (Cats 1 and 4) had smaller pressures than cats with smaller contact areas (Cats 5 and 2) for a given applied force, as would be expected. There does not appear to be any relationship, however, between the shape of the Fuji stains (Fig. 3) and those animals with greater/smaller contact areas and/or pressures.

Applied force was back calculated by multiplying the average pressure by the contact area obtained from the

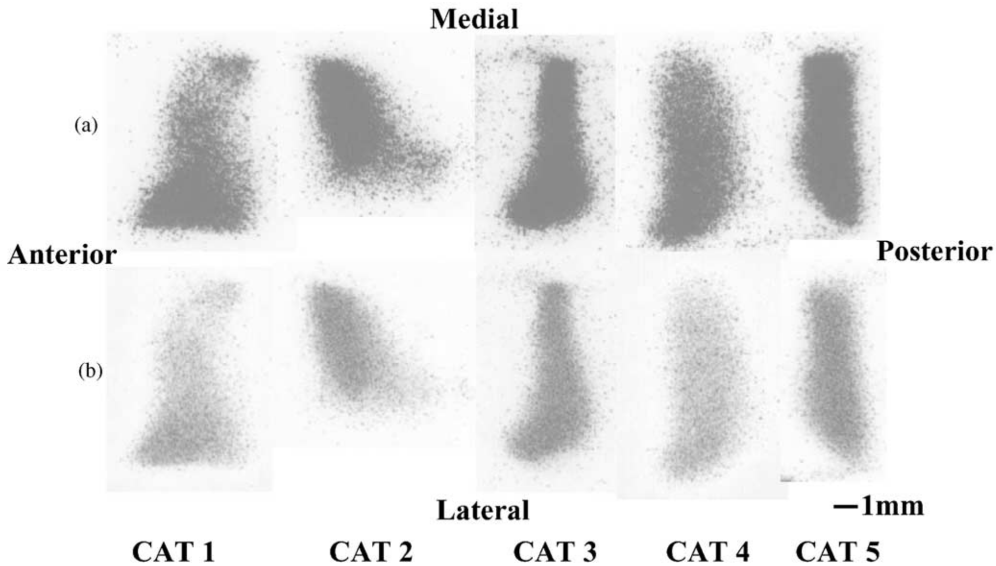

Fig. 3. Patellofemoral Fuji stains for all five cats at 300 N of applied force on (a) low- and (b) medium-grade film. Increasing pressures are associated with increasing stain darkness.

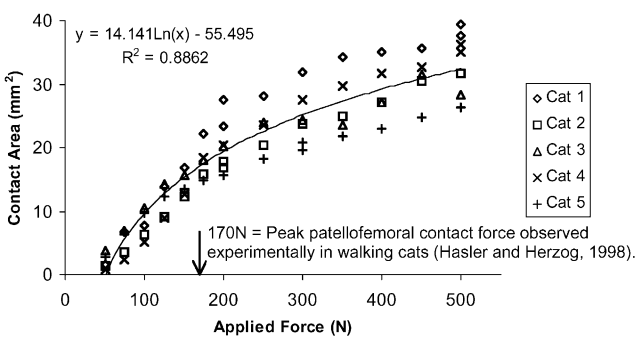

Fig. 4. Contact area as a function of applied force for five subjects under short duration load. Values calculated from low-grade film.

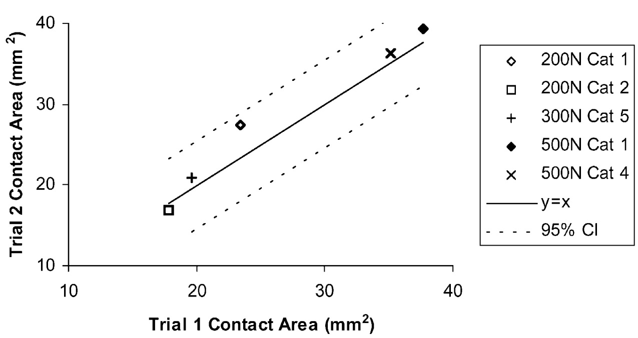

Fig. 5. Trial 1 contact area as a function of trial 2 contact area for the five repeated short duration tests. The 95% confidence interval of the residuals about the regression line $y = x$ is also indicated.

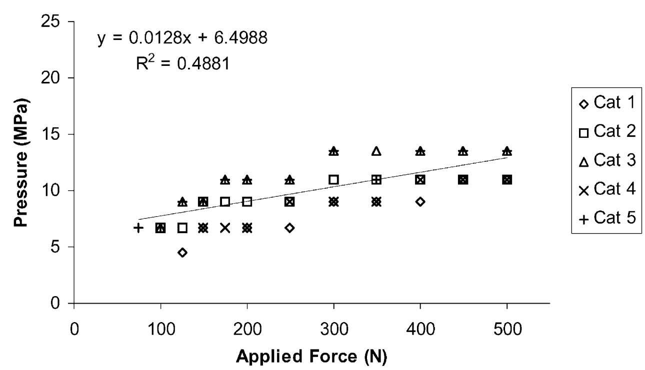

Fig. 6. Mean pressure as a function of applied force for five subjects under short duration load. Values calculated from medium-grade film and plotted as the median value of the pressure range that included the mean pressure (Table 1).

short duration trials to enable a comparison of the calculated force and the applied force (Fig 8). This comparison demonstrates that the calculated force consistently underestimates the applied force by approximately 20%. This discrepancy can be accounted for by considering the sensitivity of the Fuji films at the boundaries of contact. On the one hand, the edges of the contact area where the pressures are below the low film threshold are not observed on the stains, therefore contact area is underestimated. On the other hand, the average pressures from the medium film are overestimation of the actual pressures, and so should offset, at least in part, the underestimation of the contact force associated with the contact area. Our results would suggest that the underestimation of contact area due to these boundary effects has a more significant effect on our back calculation of applied force than the overestimation of average pressure. It also suggests, that had we only used one of the films (either the medium or low sensitivity films), contact force would have been

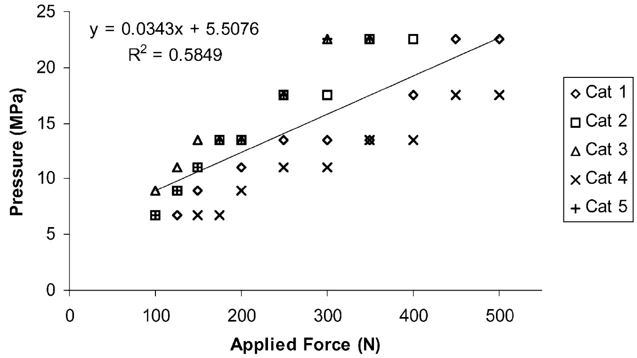

Fig. 7. Peak pressure as a function of applied force for five subjects under short duration load. Values calculated from medium-grade film and plotted as the median value of the pressure range that included the peak pressure (Table 1). Values of peak pressure associated with saturation of the Fuji film (22.5 MPa) are only shown at the two smallest values of applied force at which they occurred for each animal.

Table 2
Repeated short duration trials for the medium-grade Fuji film and the corresponding average and peak pressure values obtained

Cat number	Force (N)	Average pressure (MPa)		Peak pressure (MPa)	
		Trial 1	Trial 2	Trial 1	Trial 2
1	300	9	9	13.5	13.5
4	300	9	9	11	11
5	300	13.5	13.5	22.5	22.5
3	500	13.5	13.5	22.5	22.5

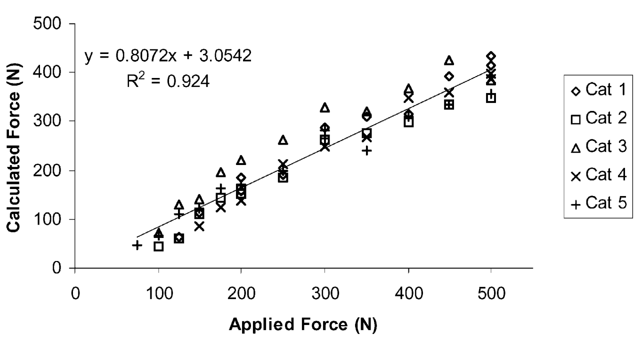

Fig. 8. Calculated force as a function of applied force for five subjects under short duration load. Calculated force was determined from multiplication of the average pressure obtained from the medium-grade Fuji film by the contact area obtained from the low-grade Fuji film for each subject and for each trial.

underestimated to a greater extent than here, probably by about 30–35%.

3.2. Long duration trials

For the long duration experiments, contact area increased up to 33% as the force applied to the joint

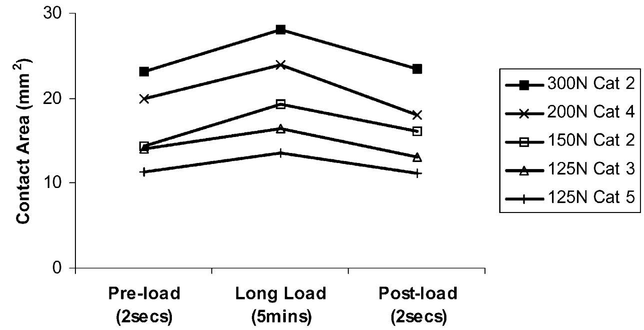

Fig. 9. Contact area for the long duration tests carried out at four values of applied force. Pre- and post-load short duration measurements were taken 5–10 s before and after the long duration loading, respectively.

was held constant for 5 min (Fig. 9). This effect was seen across animals and for a variety of force values, though it was no longer present after an unloading period of 5–10 s. The contact area values from the pre- and post-load short duration tests compare well with one another and also with the values from the other short duration trials (Fig. 4).

4. Discussion

Increasing contact area is one possible mechanism which the feline patellofemoral joint may use to regulate the pressures experienced by the cartilage as the force applied to the joint increases. In our in situ loading configuration, this mechanism appears to be more effective at influencing mean pressure as opposed to peak pressure; mean pressure increasing by a factor of two and peak pressure by a factor of three as the applied force increases by a factor of five. As the change in external in situ loading conditions is mirrored to a certain extent by the change in peak pressure, it is perceivable that large external loading may lead to localized damage of the cartilage tissue in the areas of the joint where peak pressures occur. Mean pressures, on the other hand, may provide a consistent ‘background’ pressure to the articular cartilage. It is pressures of this nature that are more likely to be responsible for maintaining the general health of the tissue by providing the appropriate mechanical stimuli for tissue adaptation and enabling fluid flow to flush out waste products and be replaced by nutrients that are essential for the maintenance and regeneration of articular cartilage. The results of this study, together with earlier findings that demonstrate larger patellofemoral contact areas at joint angles of increased muscle force potential (Ahmed et al., 1983), suggest that one of the design criteria for articular surface shapes and articular cartilage properties may be the maintenance of relatively similar joint contact pressures for a large range of loading conditions and joint configurations.

The logarithmic nature of the relationship between applied force and contact area suggests that this mechanism could be particularly effective at regulating pressures when the forces applied to the patellofemoral joint are equal to or lower than the peak forces experienced during normal walking in the cat. If this result is also apparent in vivo, it is during activities such as running and jumping, where the forces are larger (Walmsley et al., 1978) and therefore the pressures are regulated to a lesser extent by increased contact area, that damage to the articular cartilage is more likely to occur. Furthermore, the increased variability in contact area between animals for a given applied force at these larger forces suggests that it is during these higher impact activities that individual differences in the response of the articular cartilage to load are more likely to be observed.

The results from the long duration loads demonstrate that both load duration and magnitude are factors affecting the possible use of contact area to regulate pressures in the feline patellofemoral joint. The increase of contact area with time for a constant external load reflects the effect of fluid flow and the consequent transfer of load from the fluid phase to the matrix phase and cells of the articular cartilage. Similarly, the recovery of contact area demonstrates the influx of fluid back into the tissue after a short period of unloading.

The viscous behavior of loaded articular cartilage is a phenomenon that will require continuous recording of precise contact area and pressure distribution patterns within a joint for more detailed understanding. Such measurement is beyond the abilities of the present methodology—Fuji film only records the total contact area and the maximal pressures that have occurred throughout a given loading period. Ideally, the measurements should be made in a continuous manner and with a sensor of minimal thickness and stiffness in order to preserve the natural contact mechanics (Wu et al., 1998).

Despite the limitations of current methodologies, the use of the specifically designed loading frame has enabled the clarity and repeatability of the Fuji film stains to be greatly enhanced; eradicating complications due to patella sliding and folding/crinkling artifacts. The absolute values obtained in this study also compare well with in vivo values reported earlier (Ronsky et al., 1995), and unpublished measurements made during a separate experiment carried out in our laboratory.

The relationship between external loads applied to the feline patellofemoral joint and the resulting mechanical environment of the articular cartilage is complex. Understanding this relationship is an important step towards understanding the properties of articular cartilage and the possible mechanisms that can cause the initiation and progression of joint degeneration. Knowledge in this area would benefit greatly from studies tackling the viscous behavior of articular cartilage under load and also the changes in articular cartilage behavior under load resulting from endstage Osteoarthritis disease. Furthermore, combining the techniques reported in this study with those of biologically fixing and/or marking the articular cartilage will enable the effects of external load at a microstructural level to be investigated.

Summarizing, the results of this study suggest that changes in external forces are attenuated to a certain extent inside a joint, specifically on and within the articular cartilage. This attenuation is achieved by the specific geometry of the articulating surfaces and the viscoelastic properties of the articular cartilage. It likely represents a natural protection of joints to high external load magnitudes. Although tested in a specific joint in situ, it is likely that a similar behavior would also be observed in vivo and in other synovial joints of the human and animal musculoskeletal systems.

Acknowledgements

The Arthritis Society and the Canadian Institutes of Health Research.

References

Ahmed, A.M., Burke, D.L., 1983. In-vitro measurement of static pressure distribution in synovial joints—Part I: tibial surface of the knee. Journal of Biomechanical Engineering 105, 216–225.

Ahmed, A.M., Burke, D.L., Yu, A., 1983. In-vitro measurement of static pressure distribution in synovial joints—Part II: retropatellar surface. Journal of Biomechanical Engineering 105, 226–236.

Atkinson, P.J., Newberry, W.N., Atkinson, T.S., Haut, R.C., 1998. A method to increase the sensitive range of pressure sensitive film. Journal of Biomechanics 31, 855–859.

Fukubayashi, T., Kurosawa, H., 1980. The contact area and pressure distribution pattern of the knee. Acta Orthopaedica Scandinavica 51, 871–879.

Hasler, E.M., Herzog, W., 1998. Quantification of in vivo patellofemoral contact forces before and after ACL transection. Journal of Biomechanics 31, 37–44.

Herzog, W., Adams, M.E., Matyas, J.R., Brooks, J.G., 1993. Hindlimb loading, morphology and biochemistry of articular cartilage in the ACL-deficient cat knee. Osteoarthritis and Cartilage 1, 243–251.

Herzog, W., Diet, S., Suter, E., Mayzus, P., Leonard, T.R., Muller, C., Wu, J.Z., Epstein, M., 1998. Material and functional properties of articular cartilage and patellofemoral contact mechanics in an experimental model of osteoarthritis. Journal of Biomechanics 31, 1137–1145.

Inaba, H., Arai, M., 1989. A method for measuring contact pressures instantaneously in articular joints. Journal of Biomechanics 22, 1293–1296.

Jurvelin, J., Kiviranta, I., Tammi, M., Helminen, J.H., 1986. Softening of canine articular cartilage after immobilization of the knee joint. Clinical Orthopaedics 207, 246–252.

Kettelkamp, D.B., Jacobs, A.W., 1972. Tibiofemoral contact area—determination and implications. Journal of Bone and Joint Surgery 54-A, 349–356.

Liggins, A.B., 1997. The practical application of Fuji prescale pressure-sensitive film. In: Orr, J.F., Shelton, J.C. (Eds.), Optical Measurement Methods in Biomechanics. Chapman & Hall, London, pp. 173–189.

Liggins, A.B., Hardie, W.R., Finlay, J.B., 1995. The spatial and pressure resolution of Fuji pressure-sensitive film. Experimental Mechanics 35, 166–173.

Moskowitz, R.W., 1984. Experimental models of osteoarthritis. In: Moskowitz, R.W., Howell, D.S., Goldberg, V.M., Mankin, H.J. (Eds.), Osteoarthritis: Diagnosis and Management. W.B. Saunders, Philadelphia, pp. 109–128.

Ronsky, J.L., Herzog, W., Brown, T.D., Pedersen, D.R., Grood, E.S., Butler, D.L., 1995. In vivo quantification of the cat patellofemoral joint contact stresses and areas. Journal of Biomechanics 28, 977–983.

Singerman, R.J., Petersen, D.R., Brown, T.D., 1987. Quantitation of pressure-sensitive film using digital image scanning. Experimental Mechanics 27, 99–105.

Walker, P.S., Hajek, J.V., 1972. The load-bearing area in the knee joint. Journal of Biomechanics 5, 581–589.

Walmsley, B., Hodgson, J.A., Burke, R.E., 1978. Forces produced by medial gastrocnemius and soleus muscles during locomotion in freely moving cats. Journal of Neurophysiology 41, 1203–1216.

Wu, J.Z., Herzog, W., Epstein, M., 1998. Effects of inserting a pressensor film into articular joints on the actual contact mechanics. Journal of Biomechanical Engineering 120, 655–659.