Proceedings of the National Science Council, ROC
Part B: Life Sciences
Vol. 21, No. 1, 1997. pp. 20-25

Weight Bearing Influence on Knee Joint Bony Contact Movements: An *In vivo* Video-fluoroscopy Study

CHENG-KUNG CHENG*,+, NAN-KUANG YAO**, AND HWA-CHANG LIU***

**Institute of Biomedical Engineering*
National Yang Ming University
***Department of Electrical Engineering, and*
****Department of Orthopaedic Surgery*
National Taiwan University
Taipei, Taiwan, R.O.C.

(Received September 19, 1996; Accepted November 29, 1996)

ABSTRACT

In order to understand the effects of body weight-bearing on knee joint bony contact movements, a video-fluoroscopic digitizing system with *in vivo* human knee extension-flexion motions of 12 healthy adults under body weight-bearing and non-weight-bearing conditions was studied. These 12 subjects were equally separated into two groups consisting of a body weight-bearing group and a non-weight-bearing group. Video-fluoroscopic images were digitized to get three parameters from the knee joint bony geometry. These three parameters were the radius of rotation, the arc length of rotation, and the contact point of the tibiofemoral joint, and they were used to decide the knee joint bony contact status of the sliding, spinning and rocking motions. The results showed that the knee bony contact movements under body weight-bearing conditions had about 4 times the incidence rate of the sliding motion under non-weight-bearing conditions. The incidence rate of the sliding motion was greatest when the knee flexion was less than 30°. The knee bony contact movements under non-weight-bearing conditions had a larger spinning motion incidence rate and smaller rocking motion incidence rate than they did under weight-bearing conditions. The larger spinning motion incidence rate when the knee joint flexion was greater than 60°. In conclusion, the body weight-bearing factor should be considered in studying knee joint bony contact movements.

Key Words: knee joint; bony contact motion; body weight-bearing; video-fluoroscopy; *in vivo*.

I. Introduction

The knee joint has unique functions in the motion of the human body. It transmits the load caused by body weight and motion. The muscles around the knee act as dynamic stabilizers. The conditions of balance among the muscle forces are different in knee flexion-extension exercises under body weight-bearing and non-weight-bearing conditions because the muscle force distributions are different. Therefore, knee joint bony contact movements under body weight-bearing and without body weight-bearing should be different. However, few studies in the literature have mentioned this issue.

Many studies on knee biomechanics have been cadaveric (Duke *et al.*, 1977; Panjabi, 1979; Soudan *et al.*, 1979; Panjabi *et al.*, 1982; Ahmed *et al.*, 1987; Buff *et al.*, 1988; Star *et al.*, 1996) because it is difficult to measure the forces and knee joint motions that act on the *in vivo* knee joint during knee flexion-extension exercise. The normal balance of the muscle force around the knee joint disappear in cadavers and it is doubtful whether the forces exerted by a testing machine can accurately reflect the true situation of muscle force balance during knee exercise. The factor of body weight-bearing has not been taken into account in cadaver studies because it has been even more difficult to simulate knee exercises under body weight-bearing conditions in *in vitro* prepared cadaver knees. Koh *et al.* (1992) developed a technique

+Correspondence and reprint requests to: Cheng-Kung Cheng, Ph.D., Orthopaedic Biomechanics Laboratory, Institute of Biomedical Engineering, National Yang Ming University, No. 155, Li-Nung St., Shih-Pai, Taipei, Taiwan, R.O.C.

for *in vivo* tracking of the human patella. In their study, intracortical pins were inserted into the patella, femur and tibia. In their method, a skin incision had to be made, and soft tissue damage was inevitable. Furthermore, this method created a certain chance of infection in the study subject. To overcome this problem so as to understand whether body weight bearing really influences knee joint bony contact movements, the video-fluoroscopic digitizing system (Stiehl *et al.*, 1995; Cheng *et al.*, 1995, 1996; Banks and Hodge, 1996) was applied in this study to record and analyze knee joint motions under body weight-bear-ing and non-weight-bearing conditions. The influence of body weight-bearing on knee joint contact movements could then be explored. Therefore, the purpose of this study was to test the hypothesis that body weight-bearing influences knee joint contact movements.

II. Materials and Methods

Twelve healthy adults, nine men and three women, volunteered to take part in this study. Informed consent was obtained from every volunteer after a detailed explanation of the possible radiation hazard had been provided. The subjects were randomized into two groups. Group 1 consisted of three men and three women with mean age of 19.5 years, mean height of 163.5 cm and mean weight of 57.1 kg. Group 2 consisted of six men with mean age of 24.2 years, mean height of 168.8 cm and mean weight of 63.3 kg. Group 1 was asked to perform knee extension exercise under body weight-bearing (Fig. 1). The left foot of the study subject stepped on the ground, and the right lower leg, together with the right foot, was fixed using a self-made fixture. The ankle joint was kept at 90 degrees of dorsiflexion. Then the right leg stepped up to simulate the action of stair ascent. The right knee was then extended from 90 degrees of flexion to full extension. The study subjects were asked to flex their right knees back to 90 degrees of flexion once full extension had been reached. Group 2 was asked to perform knee flexion-extension exercise under non-weight-bearing conditions. They were asked to sit on a chair with the right thigh unsupported and raised parallel to the ground to obtain knee extension. Then, flexion-extension exercise of the right knee was performed. The whole process of knee flexion-extension exercise in every study subject was recorded by the fluoroscope (Toshiba DC-15 KB RTH, 9202-G1, Japan) at an image frequency of 30 frames / second for two seconds. A video tape recorder was connected to the fluoroscope, so all the images obtained from the fluoroscope could be recorded and saved by the tape

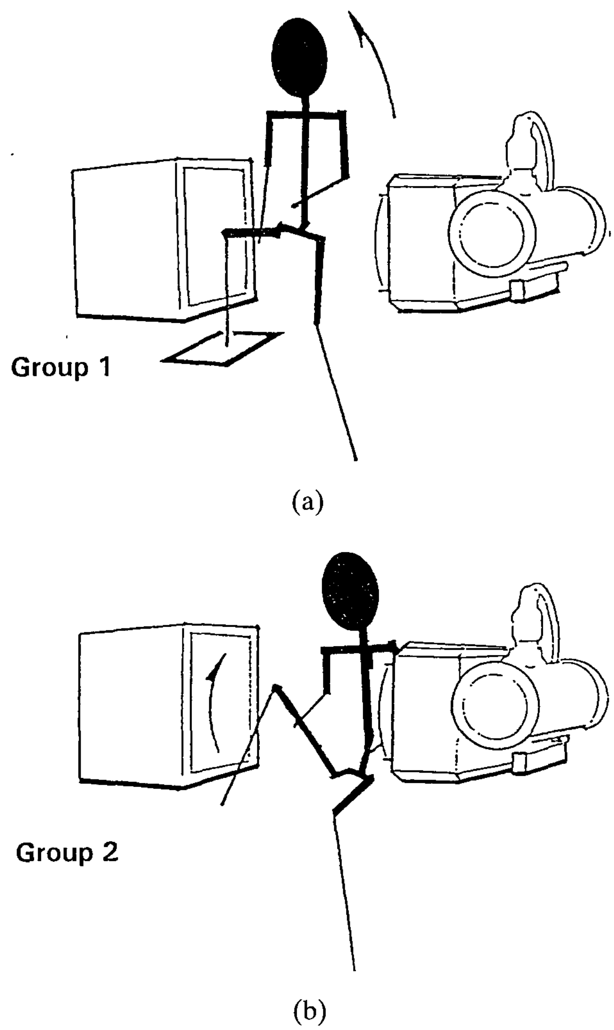


Fig. 1. (a) Group 1 performed knee flexion-extension exercise under body weight-bearing conditions and (b) Group 2 performed knee flexion-extension exercise under non-weight-bearing conditions.

recorder (Fig. 2). The images were then digitized using an image digitizer (NAC, HSV-400, Japan). It has been noted that severe distortion could take place when an image intensifier and the recorder system were used in cooperation with the fluoroscopic system (Wallace and Johnson, 1981). The method used to correct distortion was to place a calibration grid in front of the X-ray tube during measurement (Fig. 3). The grid was composed of a sheet with metal wiring forming 1.5 centimeter squares. Thus, it produced a distorted X-ray image of an array of boxes. The corners of each box were identified using the same processing procedure, and the linear transformation matrices were incorporated into a computer program to correct the image in this study (Yao *et al.*, 1992; Banks and Hodge, 1996). All the cor-

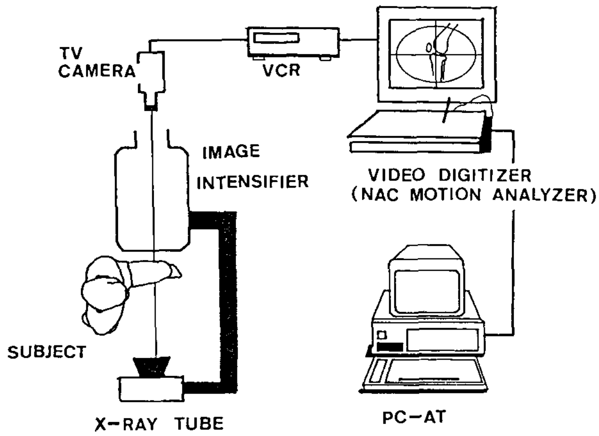


Fig. 2. The images obtained from the fluoroscope were recorded using a TV camera and VCR; all the recorded images were then digitized by a video digitizer and processed on a personal computer.

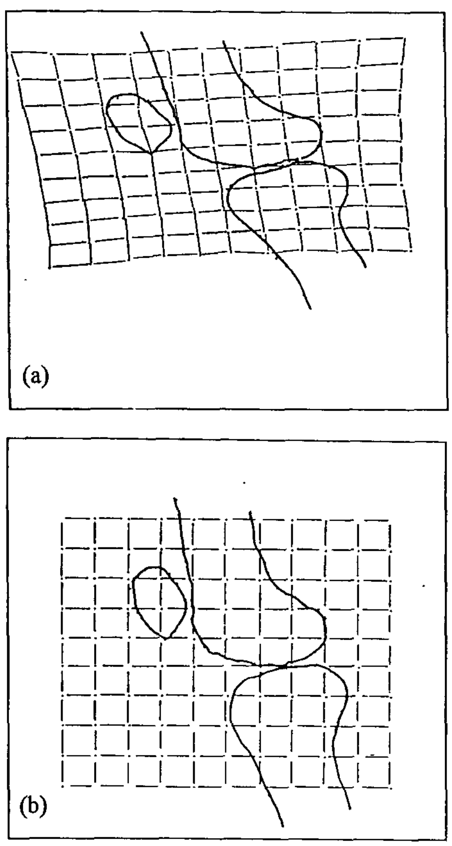


Fig. 3. (a) The pre-correction results of the distorted X-ray images. (b) The corrected results.

rected images were then digitized and analyzed on the IBM compatible personal computer.

The following parameters were measured and calculated in both groups and were compared to explore the effects of body weight-bearing on knee joint bony contact movement. The knee flexion angle was the angle formed by the axis of the femoral shaft and the axis of the tibial shaft; thus, the knee flexion angle in every image could be measured. The instantaneous center of rotation (CR), radius of rotation (Radius) and arc length of rotation (Arc L.) were estimated using the rigid body method (Spiegelman and Woo, 1987). The tibiofemoral contact point(p%) was defined as the point at which the distance between the tibia and the femur in the lateral view was the shortest and was measured from the anterior edge of the tibial plateau (Fig. 4). The total depth of the tibial plateau was normalized as 100%. Three parameters, Radius, Arc L., and p%, were then used to determine the status of the tibiofemoral joint contact movement. When a very large or infinite value of the Radius combined with a zero Arc L. and no change of p% were obtained, the tibiofemoral joint contact status was considered to have no movement. When a very large or infinite value of the Radius and zero Arc L. combined with p% change, the tibiofemoral joint contact status was considered to have sliding motion. If a small Radius and no change of p% combined with a non-zero Arc L. were obtained, the tibiofemoral joint contact status was then considered to have spinning motion. If a small Radius and p% change combined with a non-zero Arc L. were obtained, it was rocking motion. After the tibiofemoral joint contact status was determined frame by frame, we then calculated the incidence rate (in percentage) of the joint motions during different ranges of knee flexion angles. Only the mean value of the data of each group was reported.

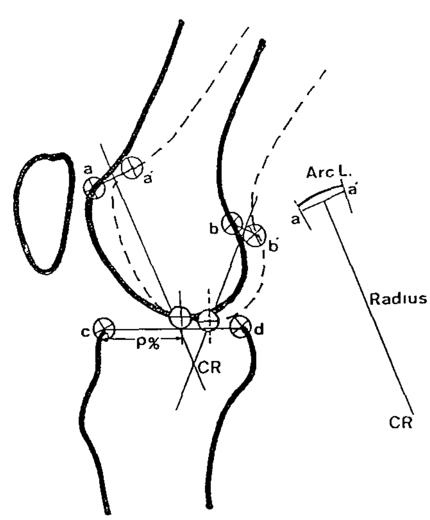


Fig. 4. An illustration of the measured parameters used for estimation of the tibiofemoral joint contact movement.

III. Results

The in vivo measurement of the knee extension-flexion motions was carried out using the video-fluoroscopic digitizing system in this study, which had been demonstrated to be a useful tool for dynamic measurement of the knee joint motions. The influence of knee joint contact movements under body weight-bearing and non-weight-bearing conditions were also explored.

The knee joint movements of the two groups were reported based by the changes of the knee joint flexion angles and the incidence rates of the motions of the tibiofemoral joint. The knee flexion angles during knee flexion-extension exercise under body weight-bearing and non-weight-bearing conditions were quite different as shown in Fig. 5. In Group 1, the knee extended rapidly from 90° flexion then extended slowly at the angles between 10° and 20° and achieved full extension at an even slower speed to maintain stability of the knee. The same situation was noted when the knee flexed from full extension. The knee initially flexed very slowly and suddenly accelerated after 20° flexion. However, in Group 2 the knee extended and flexed at almost constant speed because the flexion-extension angle of the knee under non-weight-bearing conditions was almost linear with constant angular speed.

In the tibiofemoral joint motion analysis, Group 1 showed a greater sliding motion incidence rate than did Group 2 (Fig. 6). In Group 1, the incidence of the sliding motion was about four times that of Group 2. Most of the sliding motion occurred under knee flexion angles of less than 30° in both groups, which showed that the predominant knee joint sliding motion was close to knee extension. Furthermore, the results also showed that the incidence rate of the sliding motion from 0° to 30° flexion was greater then that of the motion from 30° to 0° flexion.

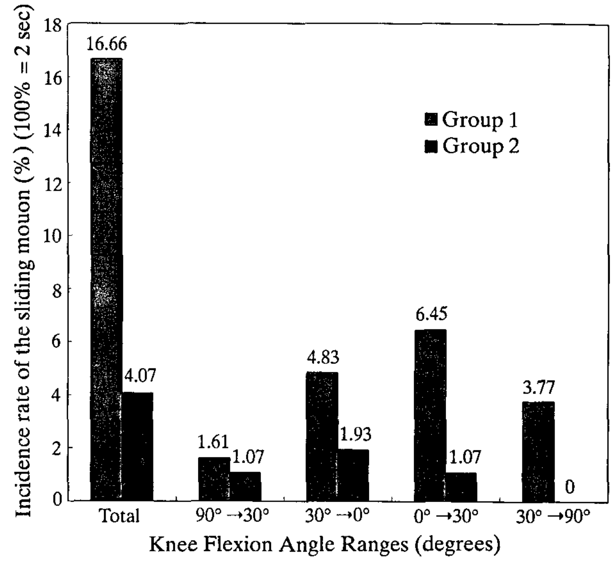


Fig. 6. The incidence rate of the sliding motion for different ranges of the knee flexion angle in both groups.

In the spinning and rocking motion analysis, most of the spinning motions occurred when the angle ranged from 30° to 90° flexion, and rocking motion occurred mostly when the angle ranged from 0° to 30° flexion (Fig. 7). In general, Group 2 had a larger incidence rate of spinning motion than did Group 1. Both groups had similar incidence rates of rocking motion.

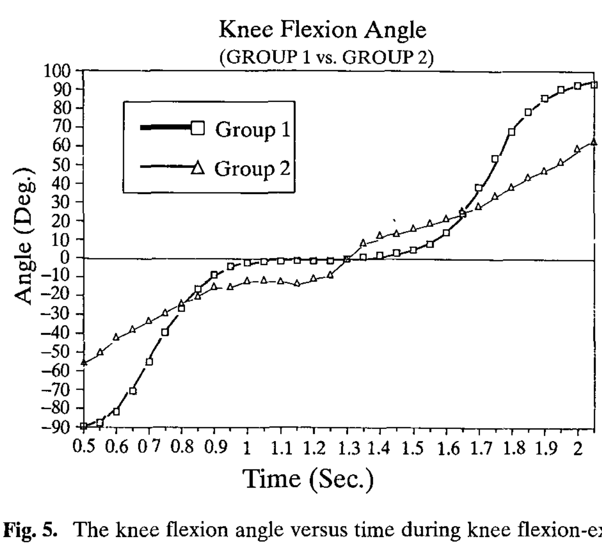
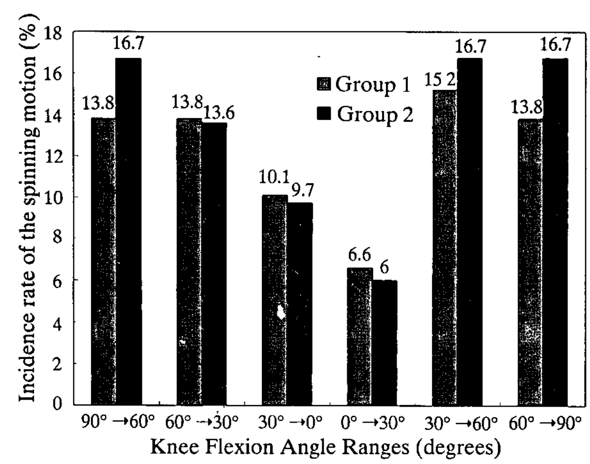


Fig. 5. The knee flexion angle versus time during knee flexion-extension exercise under body weight-bearing and non-weight-bearing conditions.

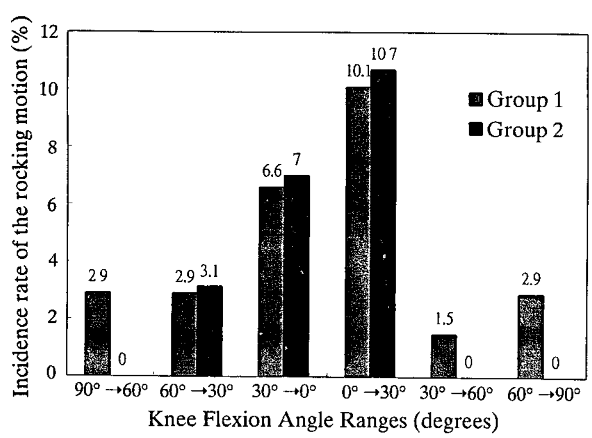
IV. Discussion

Many studies on knee joint biomechanics have been cadaveric. It has been difficult to include real conditions of body weight-bearing of the knee joint with active muscle involvement. Whether externally applied loads from testing machines can reflect *in vivo* muscle forces is also questionable. Also, the question of whether the body weight-bearing influences knee joint contact movement has not been explored. In order to observe the *in vivo* functions of knee extension-flexion, this *in vivo* study was carried out, and a video-fluoroscopic digitizing system was used. The influence of weight-bearing on knee joint contact movement was studied.

An important aspect of this study was use of a fluoroscope and image correction. Fluoroscopes using image intensifierd have become increasing popular and has superseded cine-radiography because they



(a)



(b)

Fig. 7. The incidence rate of the (a) spinning and (b) rocking motions for different ranges of the knee flexion angle in both groups.

are both easier to operate and involve the use much smaller doses of radiation (Breen *et al.*, 1989; Cox *et al.*, 1990; Cholewicki *et al.*, 1991; Cheng *et al.*, 1995; Stiehl *et al.*, 1995; Cheng *et al.*, 1996; Banks and Hodge, 1996). In our study, every subjects were exposed to radiation for only 2 seconds. Two groups were used in the experiment to avoid the possibility of high radiation exposure during short time periods. The anthropometric data of the two groups were assumed to not be significantly different. The method used to correct image distortion was to place a calibration grid with a linear transformation matrix on each grid (Yao *et al.*, 1992; Banks and Hodge, 1996).

The results showed that Group 1 had a higher incidence rate of sliding motion and a lower incidence rate of spinning motion than did Group 2. It was demonstrated that, in Group 1, the subjects needed to maintain joint stability during trunk weight shifting so as to induce more sliding and less spinning in the tibiofemoral joint. However, in Group 2, it was not necessary to take into account body weight shifting to get a larger incidence rate of spinning motion. This phenomenon was also demonstrated for the knee joint angular speed, which had almost constant angular motion in Group 2 (Fig. 5).

In conclusion, by means of a digitized videofluoroscopic system this study has demonstrated that body weight-bearing influences knee joint contact movement. Therefore, we suggest that knee joint biomechanical studies should take the body weight-bearing factor into consideration.

Acknowledgment

The authors gratefully acknowledge financial support provided by the National Science Council of the R.O.C. (Grant NSC 80-0412-B-002-215).

References

Ahmed, A.M., Burke, D.L. and Hyder, A. (1987) Force analysis of the patellar mechanism. *J Orthop Res*, **5:**69-85.

Banks, S.A. and Hodge, W.A. (1996) Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy. IEEE Transactions on Biomedical Engineering, **43(6):** 638-649.

Breen, A., Allen, R and Morris, A. (1989) A digital video-fluoroscopic technique for spine kinematics. *J. Med. Engng & Tech.*, **13:**109-113.

Buff, H.U., Jones, L.C. and Hungerford, D.S. (1988) Experimental determination of forces transmitted through the patello-femoral joint. *J Biomech*, **21:**17-23.

Cheng, C.K., Yao, N.K. and Liu, H.C. (1995) Surgery simulation analysis of anterior advancement of the tibial tuberosity. *Clin. Biomech.*, **10:**115-121.

Cheng, C.K., Yao, N.K., Liu, H.C. and Lee, K.S. (1996) Influences of configuration changes of the patella on the knee extensor mechanism. *Clin. Biomech.*, **11:**116-120.

Cholewicki, J. and McGill, S.M. (1991) Lumbar spine kinematics obtained from videofluoroscopy. Book of Abstract, pp. 501-502, XIIIth International Congress on Biomechanics, Perth, Australia.

Cox, G.G., Templeton, A.W., McMillan, J.H., Wetzel, L.H. and Lee, K.R.(1990) Digital fluoroscopy and radiography system: technical description and clinical examples. *Radiographics*, **10:**491-498.

Duke, R.P., Somerest, J.H., Blacharski, P. and Murray D.G. (1977) Some investigations of the accuracy of the knee joint kinematics. *J Biomech.*, **10:**659-673.

Koh, T.J., Grabiner, M.D. and DeSwart, R.J.(1992) In vivo tracking of the human patella. *J Biomech.*, **25:**637-643.

Nisell, R. (1985) Mechanics of the knee. *Acta Orthop. Scand. (Suppl.)*, **216:**1-41.

Panjabi, M.M. (1979) Centers and angles of rotation of body joint: a study of errors and optimization. *J Biomech*, **12:**911-920.

Panjabi, M.M., Goel,V.K. and Walter, S.D. (1982) Errors in Kinematic parameters of a planar joint: guidelines for optimal experimental design. *J Biomech*, **15**:537-544.

Soudan, K., Audekercke, R.V. and Martens, M. (1979) Methods, difficulties and inaccuracies in the study of human joint kinematics and pathokinematics by the instant axis concepts. *J Biomech*, **12**:27-33.

Spiegelman, J.J. and Woo, S.L.-Y. (1987) A rigid-body method for finding centers of rotation and angular displacements of planar joint motion. *J. Biomech.*, **20**:715-721.

Star, M.J., Karfman, K.R., Irby, S.E. and Colwell, C.W. (1996) The effects of patellar thickness of patellofemoral forces after resurfacing. *Clinical Orthopaedics and Related Research*, **322**:279-285.

Stiehl, J.B., Komistek, R.D., Dennis, D.A., Paxson, R.D. and Hoff, W.A. (1995) Fluoroscopic analysis of kinematics after posterior-cruciate-retaining knee arthroplasty. *Journal of Bone and Joint Surgery*, **77(B)**:884-889.

Wallace, W.A. and Johnson, F. (1981) Detection and correction of geometrical distortion in X-ray fluoroscopic images. *J Biomech*, **14**:123-125.

Yao, N.K., Cheng, C.K. and Liu, H.C. (1992) Dynamic analysis of the human knee joint. Biomedical Engineering-Application, *Basis & Communication*, **4**:41-52. (in Chinese)

以活體之連續性X光攝影法研究承重對膝關節接觸運動之影響

鄭誠功 * ・ 姚南光 ** ・ 劉華昌 ***

* 國立陽明大學醫學工程研究所
** 國立台灣大學電機工程研究所
*** 國立台灣大學附設醫院骨科

摘　要

爲了要瞭解人體承重對膝關節接觸運動之影響，十二位正常成人被等分成兩組在膝關節承重與不承重的狀況下接受活體數位化連續性X光攝影，以獲得其膝關節伸直／彎曲的情形，這些連續性X光影像被進一步數據化得到膝關節的幾何資料及三個參數，這三個參數分別是旋轉半徑、旋轉弧長及股脛骨關節的接觸點，由這三個參數便可以求得膝關節當時接觸運動是滑動、轉動亦或是滾動，研究結果顯示，在承重組的膝關節滑動率是不承重組的四倍，且滑動最常發生於膝關節彎曲角度小於30度，在不承重時膝關節接觸運動較承重時有較多的轉動發生率及較少的滾動發生率，較大的轉動發生率都發生在膝關節彎曲角度大於60度時，所以本研究之結論爲自體承重足以影響膝關節之接觸運動。