XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

SOME IDEAS OF THE LIGAMENT CONFIGURATIONS' EFFECT ON STRAIN CONCENTRATIONS

K. Yamamoto, S. Hirokawa**, and T. Kawada****
*Deptment of Mechanical Engineering,
Faculty of Engineering, Kurume Institute of Technology, 2228 kamitsu, Kurume, Fukuoka 8300052 Japan
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Abstract: A photoelastic coating method was applied for ligament surface strain measurement on the flat-shape MCL and the irregular-shape ACL. Strain measurement for the MCL using VDA system [1] *found that the strain values were higher on both the tibial and femoral insertions than on the midsubstance* [2]. *In the ACL however, higher strains were observed only on the femoral insertion, but not on the tibial insertion. Similar results were found form our photoelastic measurements subject to the coronal models of MCL and ACL, as well as the actual MCL and ACL. Therefore the strain along the fiber line may vary according to the morphologies of the ligaments.*

keywords: photoelastic method, strain concentration, ligament configuration

1. INTRODUCTION

Photoelastic coating method was applied for surfaces of human ACL and rabbit MCL. The ligament strain were measuremed along the fiber line. On the MCL, the strain concentration occures at both the insertion. On the ACL it was at only the tibial insertion.

It seems to be true that the concentration does not occure only due to the high water content[2] but also due to the configuration espacially at the insertion areas.

To clarify the reason why these differences could be found, several experiments were performed.

2 MATERIALS AND METHODS

Two sets of experiments were done. One was the photoelastic method for coronal section model of ACL and MCL. The other was the application of photocoating method to the actual ligaments of human and rabbit.

2.1 Photoelastic model method on coronal section

The photoelastic model observation was done using the models of coronal section of ACL and MCL as shown in Figure 1. The ACL and MCL coronal planes have insertion configurations respectively in **a-b** and **a-a**. The models were made with a I mm thick sheet of the photoelastic coating material.

Figure 1 Coronal section cinfigurations of ACL and MCL

2.2 Photocoating method on actual knee ligament

The ACLs of human cadaver knees (aged from 67 to 75) were used for the measurement. The knee specimens were mounted on a specially designed Knee Motion Simulator Jig as shown in Figure 2. The jig can record the passive knee motion data. After recording knee motion, the condylectomy operation was done while the knee was set on the jig. This exposed the ACL for all around observation. During the measurement, the motion recorded with the intact knee could be reproduced even after the condylectomy.

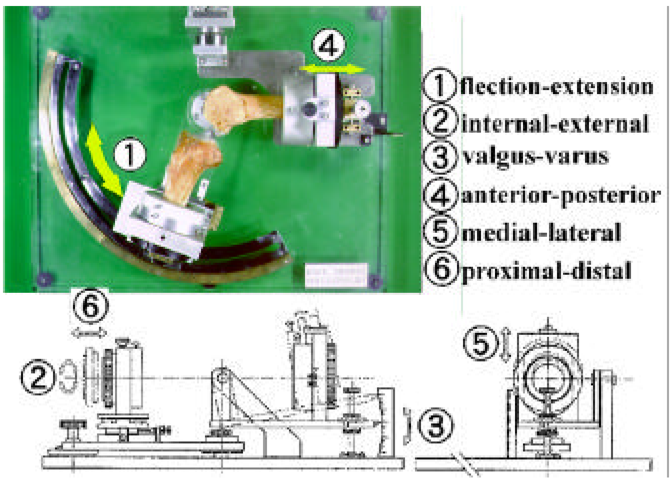


Figure 2 Knee Motion Simulator Jig

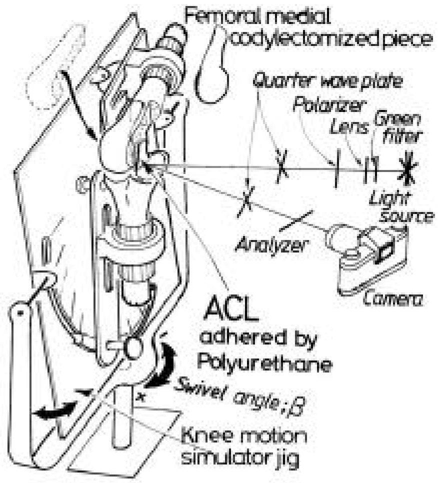


Figure 3 Experimental setup

A photoelastic coating film of polyurethane was adhered all around the exposed ACL surface in 0.4mm thick, when the knee was fixed on the jig at 10 flexion: most relaxed state[3]. The jig with the knee specimen was mounted on a specially designed universal stand. All the set was put into the polar ray field as shown in Figure 3. Then the fringe observation was carried out during knee motion.

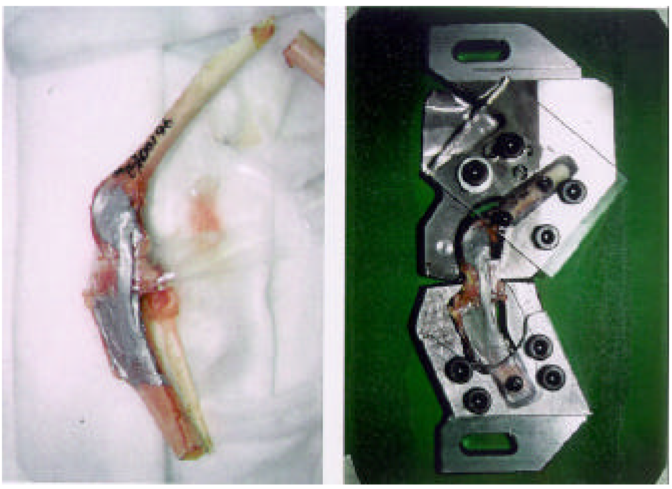


Figure 4 Rabbit's Femur-MCL-Tibia complex and chucks

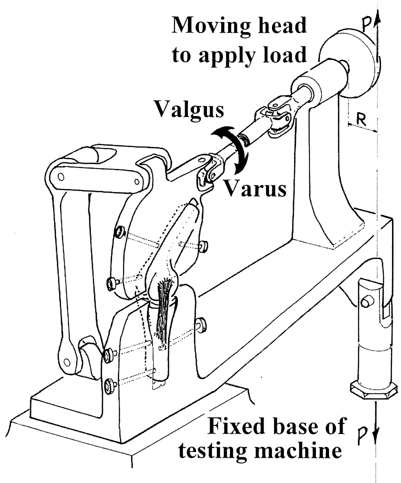


Figure 5 Valgus moment application apparatus.

Next, photocoated MCLs on the femur-MCL-tibia complex of mature Japanese white rabbits (mail, body weight 30±2N) were used as the specimens. The distal and proximal bone ends were griped tightly on the specially made chucks as shown in Figure 4. The upper and the lower chucks had groves duplicating respectively the femoral and tibial antero-medial sections. By these chucks, the tensile load or the valgus moment was applied under the photoelastic observations as shown in Figure 5.

3 RESULTS

3.1 Strain Concentration on Coronal Section Model of ACL and MCL

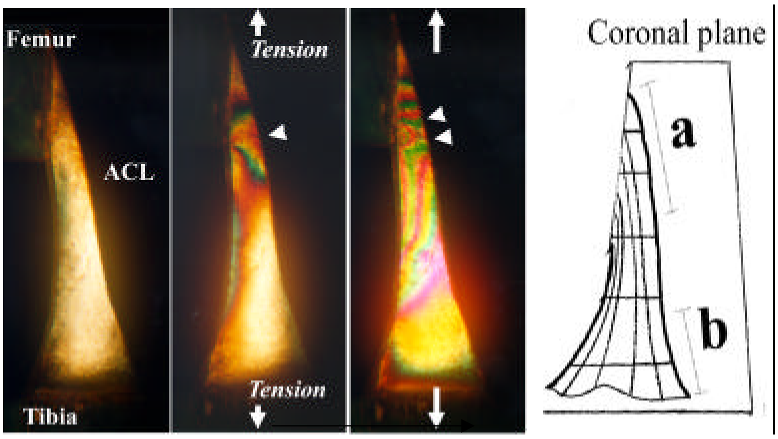


Figure 6 Isochromatic fringes on ACL coronal section model under tension and the shape of coronal section

Figure 6 shows fringe concentration under tension at the ACL's coronal section model. The concentration was seen in the femoral insertion. Where the cross sectional area is reducing to zero indicated by **a** in the schematic drawing of coronal section shape. The fibers are expressed in the longitudinal lines [4]. The femoral insertion has non-uniform length fibers. Therefore the fringe concentration occurs near the side **a**, especially on the shorter fiber side opposite to the triangular indicates.

On the tibial side as **b,** the insertion has perpendicularly oriented fibers. Therefore the shape is like a mild fillet, which being able to reduce stresses. Therefore there is no concentration at the tibial insertion side.

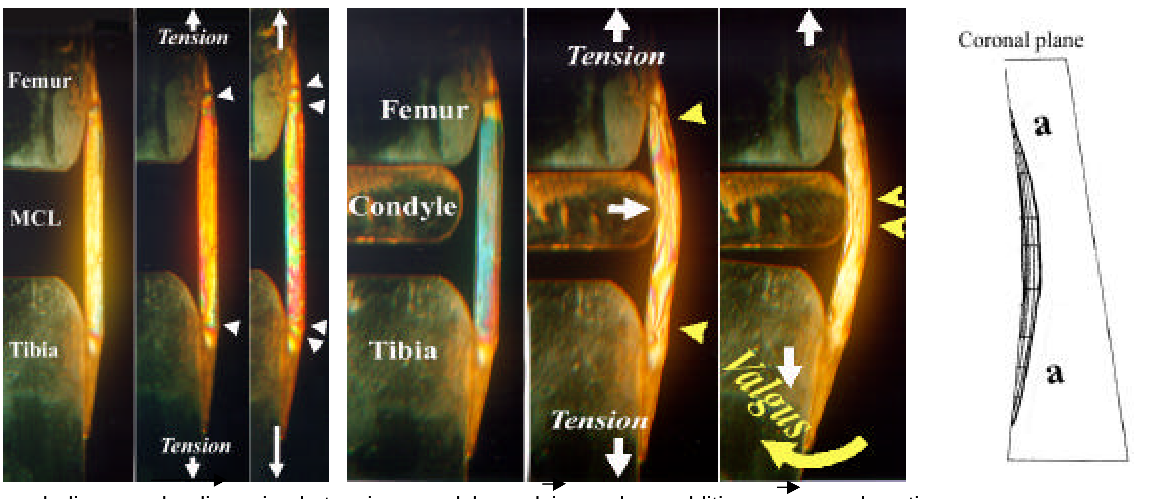


Figure 7 MCL fringe concentration under uniaxial tension (shown in left three photos); condyle applying to push the midsubstance of MCL, in addition with the valgus case (shown in middle three photos); and coronal section shape (right)

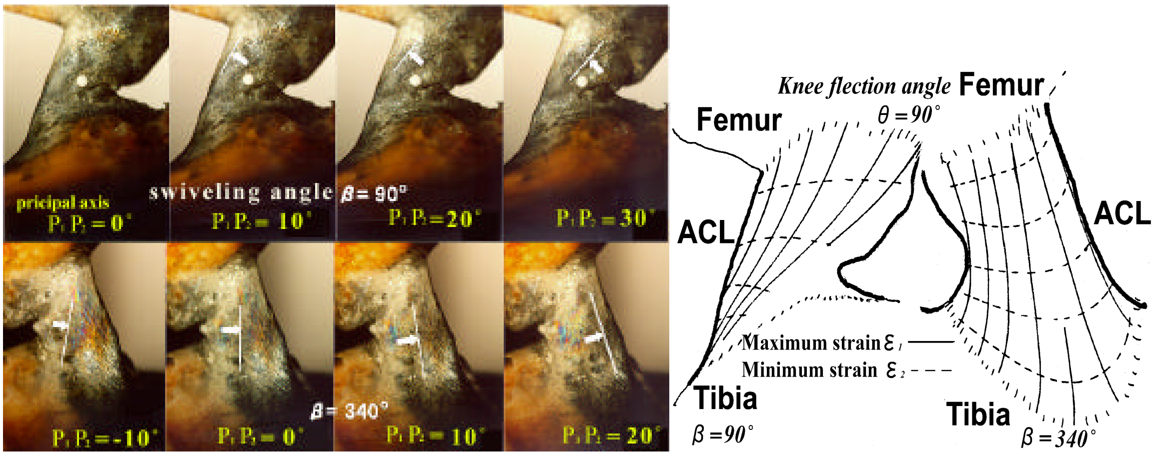
Figure 7 shows photoealstic fringe concentration on the model of MCL coronal section. The concentrations occur in both the insertion. Because both the insertion have non-uniformally arranged fibers, as shown **a**. In the same manner as the ACL's femoral insertion site, the higher fringe begins to appear on the shorter fiber side.

In the middle of the photos, the fringe concentration was seen due to external force of the condyle to midsubstanace. Especially in the case of further application of valgus movement, the concentration disappear at both the insertion area and highly remains only at the condyle contacting area. This evidence may conduct the MCL's natural role to provide for valgus moment. The longer fiber in outside and shorter fiber in inside are the exact and neat length for the warping when valgus rotation occurs. Therefore the simple tension applying against the MCL should cause a mechanically extra-ordinal situation.

These model fringe behavior will coincide to actual ligament strain behavior.

3.2 Strain concentration on photocoated

Relative strains on the ligament surface were measured along the fiber line. Preliminarily in a test of pure tension using a photocoated human Fascia lata. The calibration curves between strain values and Isochromatic fringe order have obtained[4]. Instead of the general kind of strain analyses which is needed to divide the principal strains into maximum and minimum, the authors have find first the fiber direction as the principal strain line on the ligament surface. Along the fiber line which is maximum principal strain line, the strain can be easily valuated from the calibration. Since the action of fiber is effective only on the tension as in the pure tension test.



(a) **(b)**

Figure 8 (a) Isochlinics of various principal axis angles P_1P_2 and swivel angles β of universal stand. **(b)** Principal strain trajectories drawn from the isoclinics (a) at the 90 knee flexion.

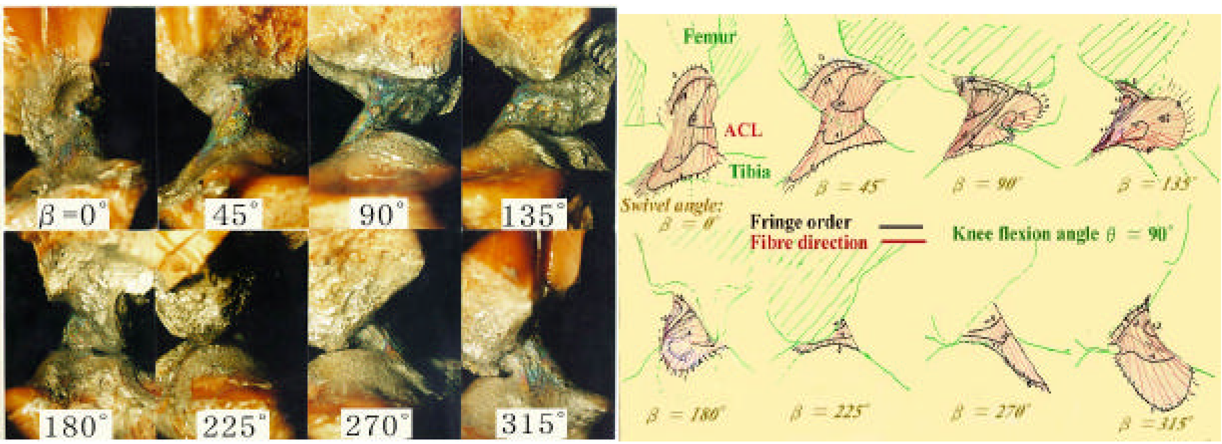
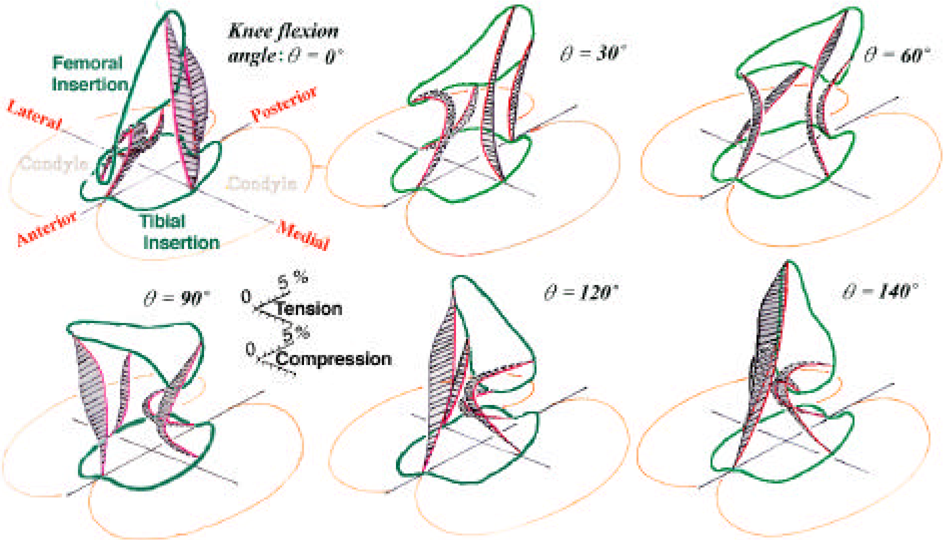


Figure 9 Isochromatic fringe patterns(left) and the sketchs(right) with fringe order(black line) along fiber direction(red line).

Principal strain trajectories obtained by isoclinics as shown in Figure 8(a) of knee flexion angle 90 , were drawn like Figure 8(b). The maximum principal lines seem to be laminated. Also they bundle to the outline of ACL shape. Therefore it was found that bundling the fibers is laminating the fibers, so the trajectory elucidate the fiber direction. Also isochromatic fringe values along the fiber lines can elucidate the fiber's strain distribution.

Figure 8 shows typical fringe patterns also its sketches with fringe orders and fiber lines at 90 knee flexion. From these sketches for all knee flexion 0 to 140 , the strain distribution along the fiber line were obtained.



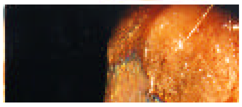
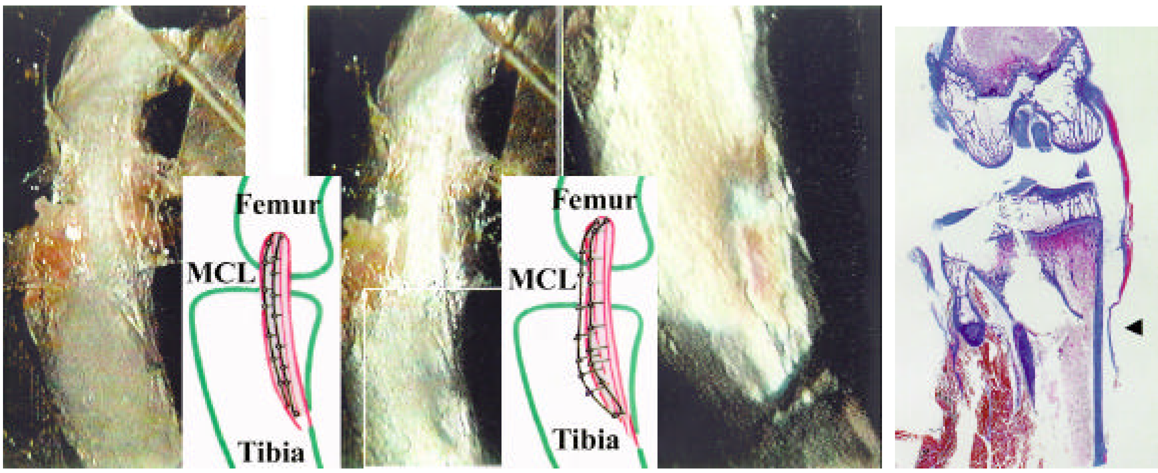


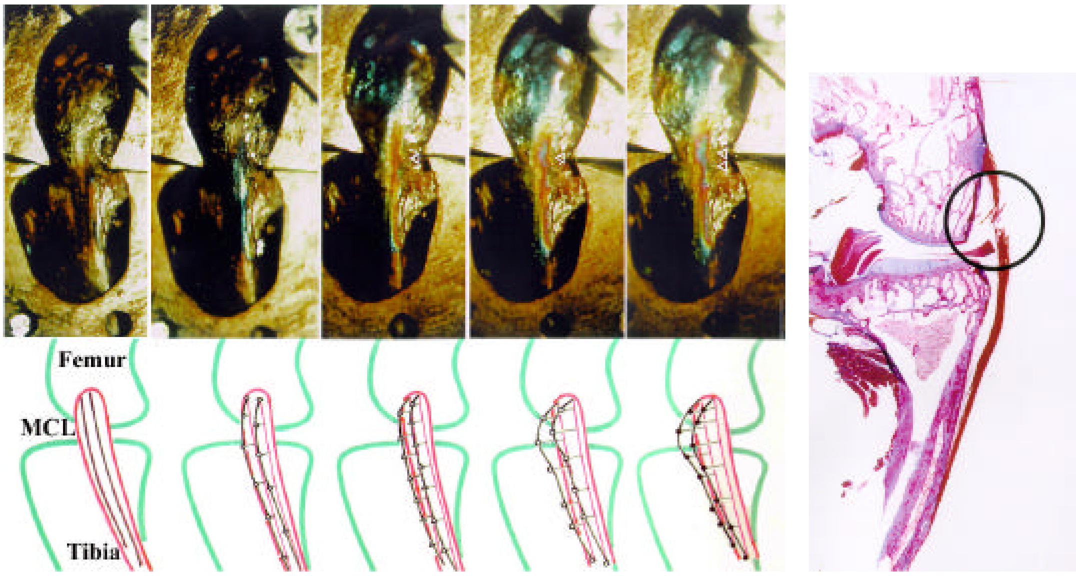
Figure 10 shows strain distributions along typical fiber with the ligament configuration during knee flexion angle from 0 to 140 . The strain at the anterior fiber and the posterior fiber are reciprocally changing with the knee flexion. In the ultimate state on 140 flexion, the anterior fiber strain is tensioned most. The strain concentration occurs only on the femoral insertion area up to 4%. As shown in the case **b** of Figure 6, the ACL's tibial insertion has moderate-fillet effect, and does not cause the concentration.



no loading → loading enlarged tibial site micro-photograph of tibial avulsion

Figure 11 MCL fringe patterns and strain distribution (black bold) along the fiber line(red) under the tensile load. The microscopic photograph was taken from the dyed bone and soft tissue after the tensile test to detect the injury site.

Figure 11 is the MCL's fringe with the strain distribution along the fiber line, shows from no loading state to loading state. The strain concentration is observed on both the insertions in the loading state. These concentrations are due to the decrease in the cross sectional area as shown in the model case of Figure 7 as **a.** So the avulsion occurs in the insertion site. The shown situation is a tibial avulsion. The avulsion is possible to begin earlier in the tensile test. It can be considered that the higher fringe at the tibial insertion area is caused by the avulsion. Because the higher fringe order excess some times more than strain value 4% which is the ultimate value in the case of ACL, even if the mechanical properties of MCL are different from them of ACL.



no loading → loading micro photograph of the midsubstance injury

Figure 12 MCL fringe pattern under valgus moment with strain distribution (black bold) along the fiber line(red). Micro-photograph to detect the injury site.

Figure 12 shows the MCL's strain distribution under valgus moment from no loading state to loading state. The midsubstance strain is higher rather than insertion, because the condyle is impinging the midsubstace. This strain concentration is caused by the same reason as told before in the case of valgus rotation at coronal section model shown in Figure 7. Therefore in the same manner, the stress concentration does not occur at insertion area. This evidence can elucidate for the stress concentration to injure the midsubstance of MCL.

5. CONCLUSIONS

1) Strains on the surface of ACL and MCL were measured by photocoating method.
2) The strain concentrations around the insertion areas were different between ACL and MCL.
3) The difference could be elucidated by the morphologies; This was clearly demonstrated by the experimental results with the coronal section model.

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AUTHORS: Univ. Ass. Prof. *Kouji L. Yamamoto, Kurume Institute of Technology, 2228 Kamitsu, Kurume, Fukuoka 830-0052 Japan, Phone Int. +81+942 22 2345 ext.276, Fax Int.+81+942 22 7119, E-mail: kouji@cc.kurume-it.ac.jp;
Univ. Prof. Dr. **Shunji Hirokawa, Graduate School of Engineering Department of Intelligent Machinery and Systems Kyushu University, 4-2-1 Roppon-matsu Chuo-ku Fukuoka 810-8560 Japan, Phone & Fax Int. +81+92-726-4796 (direct), E-mail : shunhiro@rc.kyushu-u.ac.jp;
Med. Dr. ***Takashi Kawada, Department of Orthopaedic Surgery, School of Medicine, Kurume Univ. 1 Asahi-machi, Kurume, Fukuoka 830-0011 Japan, Phone Int. +81+942-31-7568, Fax Int. +81+942-35-0709