Panoramic Measurement and Analysis of Strain Distribution in the Human ACL Using a Photoelastic Coating Method*

Shunji HIROKAWA**, Kouji YAMAMOTO***
and Takashi KAWADA****

Large and highly variable deformations of the ACL cannot be adequately quantified by one-dimensional and/or localized measurements. Since the complex anatomy of the ACL makes uniform loading of all fiber bundles almost impossible, strains on specific portions being tested are considerably altered during knee movement. To observe the ACL's entire surface, we propose a photoelastic coating method. A simulator jig was used to allow a natural motion of the knee whose medial and lateral femoral bone parts were removed in order to expose the ACL for observation. The simulator jig with the knee was mounted on a universal stand which allows tilt and swivel rotations, so that the exposed ACL might be viewed from any direction. Measurements were performed on the strain distributions over the ACL at various knee angles. The panoramic images of the photoelastic fringe patterns yielded significant results. Special attention was paid for insight into the relation between strain distribution and the directions of fiber run.

Key Words: Biomechanics, Measurement, Sensor, Anterior Cruciate Ligament (ACL), Photoelastic Measurement, Knee Motion Simulator Jig, Strain Distribution, Panoramic Observation

1. Introduction

Although studies measuring strain on the Anterior Cruciate Ligament (ACL) in association with knee motion are extensive⁽¹⁾⁻⁽⁶⁾, the length patterns for fiber bundles in the ACL remain controversial issues. This may account for that the strain peak moves on the ACL surface according as the knee flexes⁽⁷⁾, thereby introducing the various strain values depending upon which site is measured. It is well known that

during knee motion, the ACL does not function as a simple band of fibers under constant tension⁽⁴⁾, however there have been no studies measuring strain distributions over the entire surface of an ACL. Recently, a system has been devised in which dye markers on a ligament under a uni-axial tensile test were traced by a VDA (Video Dimension Analysis) system, and has been applied to measuring strain distribution on the patellar tendon and the medial collateral ligament (MCL) of the rabbit^{(8),(9)}. However, the VDA system cannot measure strain over the entire surface of an intra-articular ligament such as the ACL; As a matter of fact, most have either measured local strain at a single well-defined site or utilized a point-by-point system of measurement to determine the average strain on the ACL.

Considering the above circumstances, we used the photoelastic coating method to determine the strain distribution over the surface of an ACL in a cadaver knee⁽¹⁰⁾. In this method, when a polyurethane film of linear photoelastic material adheres to the ACL; the strains on the ACL surface can be measured by the fringe order appearing on the film. A special apparatus, designated a knee motion simulator jig was

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** Department of Intelligent Machinery and Systems, Faculty of Engineering, Kyushu University, 4-2-1 Ropponmatsu, Chuo-ku, Fukuoka, Fukuoka 810-8560, Japan. E-mail: shunhiro@rc.kyushu-u.ac.jp

*** Department of Mechanical Engineering, Kurume Institute of Technology, 2228 Kamitsu, Kurume, Fukuoka 830-0052, Japan. E-mail: kouji@cc.kurume-it.ac.jp

**** Department of Orthopaedic Surgery, Faculty of Medicine, Kurume University, 67 Asahi Machi, Kurume, Fukuoka 830-0011, Japan

designed, which allows to simulate the natural motion of a knee from which the femoral condyles had been removed to expose the ACL.

To determine strain distributions on the ACL, we use the following information from the photoelastic fringes; they are 1) variations of fringe order, 2) deformations of fringe patterns and 3) movements of fringe positions. When conducting the previous study however, we found that the ACL's complex configuration presented difficulties for measuring strain distributions precisely using data from medial and lateral views only. Since the fiber bundles in the ACL run in a spiral fashion between both the tibial and femoral insertions, strain distributions along these bundles cannot be obtained unless the ACL is viewed from all directions around its longitudinal axis. Thus we need the information about 1) through 3) to be those viewed from all directions. In this study, we performed extensive analyses on the strain distribution over the ACL surface by employing a panoramic measurement.

2. Measurement Experiments

Since the details of measurement experiment have been described elsewhere⁽¹⁰⁾, whose outlines will be summarized here. We used a specific polyurethane film (NIPPORAN 5230, Nihon Polyurethane Co., Japan) for its optically high fringe-sensitivity, excellent elongation and a close affinity with biological soft tissues. In our first study, jointly using a Differential Variable Reluctance Transducer (Micro Strain Inc., USA), we found that the average coefficient of correlation between the photoelastic fringe order and strain value for the film was 0.999, indicating an excellent linear relation, and this linear relation continued up to 45% of strain. Later on, the relationship was used to calculate the strain value on the ACL from the fringe order. Next, we performed a preliminary study on human fascia-lata ligaments and rabbit medial collateral ligaments, to determine if this method was practical. We found that it accurately reflected large and highly variable strains of the soft tissues with negligible effect on the tissues' properties. The tangent modulus of the polyurethane film itself was 3 ± 0.7 MPa, almost negligible compared to the value for the ligaments, for example 460 ± 27 MPa for the human fascia-lata.

Three fresh frozen right cadaver knees (specimens A, B, C) obtained from 67-70-year-old males were used for the measurements. To reproduce natural knee motion with the condyles removed, we designed a special apparatus, designated a knee motion simulator jig (Fig. 1). The jig can make six axes' movements, namely three transverses and three

Fig. 1 A view of the knee mounted on the knee motion simulator jig with the ACL exposed

rotations, and we can read variations of six movements by the scale indices when we loose all the screws used to lock the six axes' movements. After the knee was fixed in the simulator jig, two orthopaedic surgeons each moved the knee by hand through a range of flexion-extension (from 0° to 140°). A palpation check was made to confirm that the correct relationship was being maintained between opposing articulating surfaces during free motion of the knee. The five scale indices were read and recorded at 10° intervals. Five kinds of knee motion are internal-external rotation, valgus-varus motion, anterior-posterior displacement and compression-distraction between the tibia and the femur, all are accompanied by flexion-extension of the knee. Each surgeon repeated the process by ten times, then using twenty sets of data, each of the variations of five kinds' motion was described respectively with five regression curves as a function of flexion-extension angles. Later, the five regression curves were used to reproduce the six degree of freedom for natural passive motion characteristics of a knee whose femoral condyles have been removed.

After this was done, all soft tissues and the medial and lateral condyles were removed leaving the intact ACL exposed to view. Figure 1 shows the knee on the jig after preparation. The ACL is reported to experience maximum retraction at about 10° to 30° of knee flexion⁽¹¹⁾, and it retains a virtually flat shape at knee angles from 0° to 10° . Thus for convenience, the polyurethane monomer was applied to a thickness of 0.4 mm while the knee was at 10° flexion; this angle was taken as an arbitrary zero reference of strain. After the polyurethane film became dry, the simulator jig containing the prepared knee was set on a stand. The apparatus was put into the photoelastic observation apparatus as shown in Fig. 2. When the simulator jig was rotated around the vertical axis of the univer-

Fig. 2 A schematic drawing of the photoelastic observation apparatus

sal stand to view the ACL around its longitudinal axis, the tilt angle of the stand was adjusted so that the ACL surface was perpendicular to the polariscope ray. The arrangement of the photoelastic observation apparatus shown in Fig. 2 is to obtain isochromatics. To obtain the isoclinics, two quarter-wave plates are removed, and the following technique is used. A polarizer and an analyzer are rotated on their axes simultaneously through a series of incremental angles, so as to obtain multiple images, namely the isoclinics, and thus determine the principal stress directions by tracking the locations of the highest fringe intensity from one image to another.

We reproduce the natural passive motion characteristics of a knee whose femoral condyles have been removed as follows; Using the previously obtained five regression curves, we flex the knee with the corresponding five types of movement being simulated, and then tighten all axis screws to maintain the chosen position. At each stage of knee flexion during the experiment, the stand was rotated round with the isoclinics and isochromatics over the ACL's surface being recorded with a video camera. The direction of the observation from the anterior side was defined as $\beta=0^\circ$; the directions for the medial, posterior and lateral sides are defined as $\beta=90^\circ, 180^\circ, 270^\circ$. As most parts of the apparatus were made of transparent acrylic material, the ACL could be seen from the lateral direction ($\beta=270^\circ$) as well. From all the video pictures recorded, we chose the following for analysis: those images in which the knee angle θ was altered in increments of 15° the stand angle β was

Fig. 3 Isoclinics of the medial view ($\beta=90^\circ$) at 90° of knee flexion (subject A)

Fig. 4 Isoclinics of the lateral view ($\beta=315^\circ$) at 90° of knee flexion (subject A)

altered in increments of 45° , and the polarizer and analyzer angles α were rotated at intervals of 5° .

3. Results

For the limited space, we will present one set of data from each specimen in Figs. 3 through 7, instead of presenting all the results from all three specimens. Yet it should be mentioned that the results from all three specimens matched each other closely.

3.1 Isoclinic fringes

Figure 3 (a) shows the photographs of isoclinic shade stripes viewed from the medial direction ($\beta=90^\circ$) at 90° of knee flexion. In the figure, α is the rotation angle of the polarizer from the vertical in a clockwise direction; the $\oplus$ symbols show the principal axes of polarizer and analyzer, both the axes are aligned to be orthogonal with each other. Figure 3 (b) shows the principal strain diagrams and the principal strain diagrams derived from the photographs (a). The solid lines indicate the maximum principal strain lines ϵ_1 and the broken lines the minimum principal strain lines ϵ_2 . The isoclinic diagrams (the first four images from left to right) were drawn from the shade stripes and the polarizer's positions. The principal strain diagram (the far right image in (b)) was created by superimposing 37 isoclinic diagrams obtained at polarizer angles from 0° to 180° at 5° intervals.

Figure 4 (a) and (b) show respectively the same

Fig. 5 Isochromatics at 90° of knee flexion viewed from various directions (subject B)

results as Fig. 3 (a) and (b) viewed from the lateral direction ($\beta=315^\circ$). From 296 isoclinic shade stripe images (37 images $\times$ 8 directions), the principal strain diagrams viewed from 8 directions were drawn. Figure 3 (b) and Fig. 4 (b) show that the maximum principal strain lines are in parallel with each other and with the longitudinal outlines of the ACL; This held good for the principal strain diagrams at every knee flexion angles and view directions. We found the maximum principal strain lines are drawn closely along the macroscopically observed fiber bundles. We may conclude that the fiber bundles are aligned along the principal strain lines at a stretched state.

3.2 Isochromatic fringes

When two quarter-wave plates are inserted in the course of light as already shown in Fig. 2, a plane polariscope light turns to a circular one, and shade strips (isochromatics) appear on the ACL surface in proportion to the difference between two principal strain values on it (two principal stress values if the material is isotropic). Figure 5 presents the isochromatic fringes produced at 90° of knee flexion. The images in Fig. 5(a) are eight isochromatic photographs taken from 8 directions at intervals of 45°; and those in (b) are isochromatic diagrams made by tracing each photograph in (a) and adding the fringe orders. The nomograph between fringe order and strain value obtained in our preliminary study was applied to all isochromatics in this one. Although the isochromatic fringe order is proportional to the principal strain difference ($\epsilon_1 - \epsilon_2$), for a strongly anisotropic material such as a ligament, it is possible to assume that the minimum strain value, when compared with the maximum value, is small enough to ignore. That is, ($\epsilon_1 - \epsilon_2$) can be assumed to be nearly equal to ϵ_1 , and therefore the isochromatic order can be assumed as representing the strain values

along the fiber direction. In Fig. 5(b), 2.8% of strain (the second order fringe) is observed on the anterior-medial side near the femoral insertion. This number indicates the maximum strain value generated on the ACL surface at 90° of knee flexion. The following should be noted; First, strained portion spreads in an area, not only toward the longitudinal direction but also the transverse direction. Secondly, the bundles we defined with strain distribution patterns do not necessary coincide with the anatomically determined bundles. And thirdly, strain varies even along the fiber run.

3.3 Panoramic display of the ACL with the isochromatic fringes and the principal strain lines

For brevity's sake, we showed the principal strain and isochromatic diagrams only for 90° of knee flexion in Figs. 3 through 5. Here, Fig. 6 presents panoramic views of the principal strain and isochromatic diagrams from a variety of knee flexion angles. The columns are the views from eight directions, and the rows are the angles of knee flexion. Figure 6 well depicts successive deformations of the ACL and variations in strain distribution on it according to knee flexion. By comparing eight pictures one after another, we were able to determine the isochromatic fringe order with a good degree of accuracy. Attention should be paid to the fringe patterns obtained from the posterior aspect ($\beta=180^\circ$). On the posterior side, the second order fringe (2.8% strain) appears on the central portion of the substance at 0° of knee flexion. Theoretically, the photoelastic fringe order is proportional both to elongation and compressive strains. In this case, as is analogized from the medial picture ($\beta=90^\circ$) where another fringe with the second order appears on the anterior side, the postero-lateral bundle can be considered as being under tension when

Fig. 6 Photoelastic fringe patterns and principal strain lines at various knee angles viewed from various directions (subject C)

the knee is in full extension. This finding was further supported by a circumferential trace of fringe patterns about the ligament's longitudinal axis. On the antero-medial side ($\beta=45^\circ$), the strain peak of the second order fringe (2.8% strain) appears near the femoral insertion at 90° of knee flexion. At 120° of knee flexion, the strain peak moves distally to the middle portion of that bundle and increases the fringe order to the third (4.2% strain). We found the strain distributions vary widely according as a knee flexes.

3.4 Strain distribution along the principal strain lines

As already mentioned the isochromatic fringe order is virtually in proportion to the principal strain value, we know strain values along the principal strain lines from the pictures of principal strain lines with isochromatic fringes shown in Fig. 6. Also we found that the directions of principal strain are representing the fiber directions. In the sequel, we are able to obtain strain values along the fiber run. Figure 7 represents the three-dimensional views of strain distribution along the macroscopically determined four typical fiber lines at various knee angles. Elongation strains moving outward from the fiber line are represented by bands of solid, horizontal lines; com-

pressive strains moving inward are denoted by bands of dots. Figure 7 demonstrates that during knee flexion from 0° to 120° , strains along the anterior and posterior bundles increase and decrease in reciprocal fashion. Compressive strain (the second order fringe) is seen along the anterior bundle at 0° of knee flexion. Yet we notice that the anterior bundle is deflected and actually retracted at this stage. At 60° of knee flexion, strain along the bundle changes to elongation strain, continues as elongation strain, and after 90° of knee flexion, an elongation strain of 3% appears on the substance near the femoral insertion. At 120° of knee flexion, a strain reaches as much as 4% and this most stretched area spreads in a trapezoid shape. An elongation strain of 3% is seen on the substance along the posterior bundle at 0° of knee flexion, which gradually decreases to become compressive strain at 60° of knee flexion. Although compressive strain occurs as the knee flexes further, the compressive strain value does not increase; the posterior bundle becomes wrinkled instead.

The medial and the lateral lines show strain behaviors similar to those of the posterior and the anterior lines respectively. Especially the lateral line shows strain behavior quite similar to that of the

Fig. 7 Three-dimensional representations of strain distributions along the four typical fiber bundles at various knee angles (subject C)

anterior line, whose strain value is nearly half of the anterior's. It should be noticed that at 60° of knee flexion, tension and compression coexist along the medial bundle. Also it should be noticed that the posterior and the anterior bundles form an arc in shape even at the maximum strain at respectively 0° and 120° of knee flexion.

4. Discussion

In an earlier study, we used such novel technique as a photoelastic coating method for the measurement and analysis of strain distribution on the ACL. We found that it was indispensable for the ACL to be viewed from all directions around its longitudinal axis for the precise measurement and analysis. Thus we devised the apparatus for the present study to allow us to obtain the panoramic images of the photoelastic fringe patterns, which yielded significant information about strain distribution on the ACL.

4.1 Characteristics of the photoelastic measurement

We used the following information for the photoelastic fringes to determine strain distributions on the ACL; 1) variations of fringe order, 2) deformations of fringe patterns, 3) movements of fringe positions and 4) views from all directions about 1) through 3). They are summarized below.

4.1.1 Variations of fringe order We determined the photoelastic fringe order in accordance with the number of fringes from the ACL's insertion

border, starting with the 0-th order. Since the fringes are a measure of strain gradient, our photoelastic method is good to measure not only strain but also strain distribution, while several sensors reported in the literature could measure strain values only. We found that the fringe order varied when that fringe deformed or moved, but the order did not vary as long as the fringe stayed on the same position. We are the first to confirm the Pioletti et al.'s⁽⁷⁾ notion in a visible way. That is the most tense portion moves around over the ACL surface according as the knee flexes. Our photoelastic measurement brought us relative strain values at various knee angles as compared to those at 10° of knee flexion. Nevertheless we could infer absolute strain values through the following way. We found that the fringe order did not increase significantly in the case of compressive strain because the ACL, being an incompressive tissue, wrinkled after the elongation became zero. This phenomenon provided us with a reasonable measure for a zero strain judgment and consequently relative strain values could be converted into absolute strain values.

4.1.2 Deformation of fringe patterns Since deformation of fringe patterns was mainly accountable for deformation of the ACL rather than variation of strain value, it did not provide much information about strain distribution on the ACL. In the same reason we consider the above-mentioned VDA system^{(8),(9)} with many dye markers on a ligament cannot

measure ligament's strain precisely unless the ligament is flat in shape. As an alternative way, we measured the area surrounded by a colored fringe under a white light. Then we attempted to assess the area in tense on the ACL, however the results gave us qualitative information only.

4.1.3 Movement of fringe positions One of the advantages with our photoelastic method over other techniques is to be able to track fringe positions, in other words strain peak positions. One-dimensional/localized measurements at the specific portion are potentially misleading; If the strain peak moves its position slightly along a bundle, an excessive increase or decrease in strain would be recorded at the portion where the sensor is located, thereby creating the impression that the total length of that bundle changes that much, when in fact it does not. Vice versa, attention should be paid that even when the bundle does not change the total length, the peak strain could appear locally and move around, thereby causing ligament's failure. We believe tracking to fringe movement is crucial for insight into strain behaviour over the ACL surface.

4.1.4 Views from all directions A fringe pattern varied much when viewed from different directions as if it was not the identical fringe. Thus the fringe order was frequently misdetermined as long as the measurements were made from the medial and lateral views only⁽¹⁰⁾. The measurements in this study made it possible to identify each fringe and its order correctly by a circumferential trace of fringe patterns about the ligament's longitudinal axis. The literature present the graphs of fiber bundles' elongations as a function of knee flexion or rotation angles. Such graphs bring us difficulties to see in what configuration the fiber bundles are bearing strains, and to predict what kind of movements the knee should make in order to decrease strain on the ACL. The panoramic display of the ACL with strain distribution patterns on it yielded significant information for understanding how the strain changes along the fiber bundles in association with knee motion, and enabled us to check if the obtained strain values are correct.

4.2 Clinical significance of the results from the present study

4.2.1 Reciprocal functioning between the anterior and posterior bundles Several studies have concluded that the antero-medial bundle and the postero-lateral bundle of the ACL function reciprocally from extension through flexion of the knee⁽¹⁾⁻⁽⁵⁾. However, some researchers⁽⁶⁾ have disagreed with the reciprocal function theory and it has been reported that there is no histological evidence for dividing the ACL into two groups⁽¹¹⁾. The results in Fig. 7 clearly

demonstrate that both the anterior and the posterior bundles, function reciprocally from extension through flexion of the knee.

4.2.2 Initial strain Bach et al.⁽⁴⁾ were the first to measure the absolute strain values on the ACL using a tubular strain gauge filled with liquid metal, called LMSG (liquid metal strain gauge). They identified the zero strain state with the inflection point along the voltage-strain curve of the gauge output. They reported that as much as 7% initial strain was generated in the postero-lateral bundle of the ACL at full knee extension. Although our photoelastic method could only measure relative strain values, we could infer absolute strain values by referring relative strain values to that of the presumed zero strain state where variation of fringe order stagnated. Then we obtained the result that 3% initial strain existed in the postero-lateral bundle. The result was supported by a circumferential trace of fringe patterns about the ligament's longitudinal axis, and well agreement with the Bach et al.'s result.

4.2.3 Difference in strains during active and passive knee motion Beynnon et al.⁽⁵⁾ have reported through their *in vivo* measurement experiment that strain on the ACL caused by active knee motion with weight bearing and thigh muscles' contraction is quite different from that caused by passive knee motion. However, it should be noted that loads applied through body weight and thigh muscles' contraction are borne mainly on the joint articulating surfaces and little on the ACL. It should also be noted that increases or decreases in loads on the ACL are caused by the shifts of one insertion relative to the other insertion, but are never caused by an application of body weight or thigh muscles' contraction. Our method of measurement using the knee motion simulator jig enabled us to test this assertion. Therefore, using our knee motion simulator jig, we made anterior/posterior displacements in increments of 2 mm and internal/external rotations in increments of 3° in the tibia relative to the femur, and observed the consequent changes in isochromatic fringe patterns (specimen A). We found no significant changes in the fringe order. However, we did observe fluctuations in the location, shape and size of the fringe patterns. We found that the fringe moved proximally or distally along an identical fiber. We conclude that the difference in strains on the ACL caused by active and passive knee motions may not be as large as those reported previously in the literature. Our assertion should be confirmed through the measurement of strain distributions in the ACL under active knee motion. Also the measurement will be necessary under anterior-posterior displacement and/or inter-

nal-external rotation of the tibia relative to the femur.

5. Conclusion

In this study, we performed photoelastic measurement of strain distribution on the ACL using panoramic views from eight directions, and reached the following conclusions

(1) Reciprocal functioning between the anterior and the posterior bundles from extension to flexion of the knee does occur.

(2) A 3% initial strain exists in the postero-lateral bundle of the ACL at full knee extension.

(3) The fiber bundles are aligned along the principal strain lines at a stretched state.

(4) The maximum strain value over the entire surface of the ACL through the whole range of knee motion was 4.2%. This strain peak appeared on the middle portion of the anterior-medial bundle at 120° of knee flexion.

(5) Making the center of the substance a border, we found that at 60° of knee flexion, the femoral side of the medial bundle was under tension while the tibial side of the same bundle was in relaxation. We conclude that strain distribution was not uniform even along the same bundle.

(6) The panoramic display of deformation over the ACL's surface is effective in studying how the strain distribution of fiber bundles changes in association with knee motion.

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