EVALUATION OF PHOTO-ELASTIC MATERIALS FOR BIOLOGICAL SOFT TISSUES

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Abstract: The selection process for photo-elastic coating materials used in soft tissue strain measurement, and its application to Anterior Cruciate Ligaments, and Medial Collateral Ligaments are described in this paper.

Introduction

A better understanding of ligament strain distribution during knee motion is required to understand the mechanism of ligament injury more fully. Also, this information can be used by doctors during surgical operations. For Anterior Cruciate Ligament (ACL) reconstructions, it is necessary to use the isometric portion in areas where strain is not concentrated. And for rehabilitation after ACL surgery, it is necessary to avoid excessive stretching of the ligament where strain concentrations are located as well as knowing how high the concentrate ratio is. Unusual knee motion in the Medial Collateral Ligament (MCL), such as that encountered during hard sports, frequently gives us useful information [1] on the injury mechanism which is indicated by a higher strain concentration on the surface. In considering the above circumstances, we have developed a method to visualize this strain distribution on the entire surface of a ligament by using a photo-elastic-coating method [2]. Through experiments using this method, we have found that photo-elastic material selection is key for the success of obtaining 1) clear visibility of fringes, and 2) good affinity and adhesive properties to the biological soft tissue. Thus we experimented with five different kinds of materials on the ligament and determined the best material for our purposes. Finally we decided that the polyurethane resin was the best material to use with the photo-elastic-coating method on soft tissues.

Materials and Methods

Table 1 lists five photo-elastic coating materials and two soft biological tissues. The 1st and 2nd products are fibrin glues made from blood coagulation substances frequently used as tissue glues in surgical operations. These are chosen for their good affinity and adhesive properties on soft tissue. The 3rd is a mixture of fibrinogen and moderate thrombin from the 2nd and the 1st products respectively, in order to make the glue uniform. The 4th and 5th products are polyurethane synthetic resins. The 6th and 7th are biological soft tissues. The 6th is a Fascia lata ligament used as a test piece to calibrate the photo-elastic fringe order against the strain value during tensile testing. The 7th is an ACL used for strain measurement testing using a Polyurethane coated photo-coating film. The measurements were done on cadaver knee bones and ACL complexes. The ACL was exposed to both sagittal splitting condylectomies at the femur distal end. After exposure, the knee is maintained in an intact flexion and extension by means of a special knee motion simulator jig.

Table 1: Materials for Photocoating film, Soft Tissues and reflection layer.

	Item	*Components*	*Product*
	Fibrin glue of Biological adhesion made from blood product	Fibrinogen, Thrombin	Tisseel
2		Fibrinogen,Thrombin	Beriplast
3		Fibrinogen of Beriplast & moderate Thrombin of Tisseel	*Chimera glue of above two products coagulant*
4	Polyurethane Resin	Self setting type Polycarbonate diol	NIPPORAN 5120
5			NIPPORAN 5230
6	***Soft tissues***	Fascia lata	Cutting into a Strip test piece
7		Anterior cruciate Ligament	on both side condylectomized cadaver Knee bone & ACL complex
8	Reflector	Layer between coating film and tissue	Aluminum powder

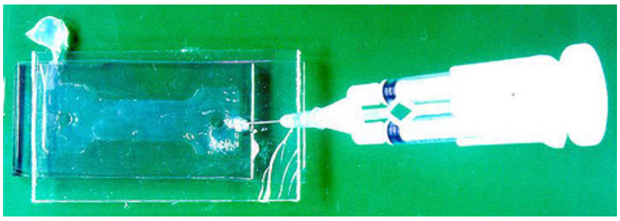

Figure 1: Mixing and injection to cast the glue test piece.

Figure 1 shows the two components' of the 1st, 2nd, and 3rd fibrin glues from Table 1 being injected with a double syringe equipped with a mixing tip and needle.

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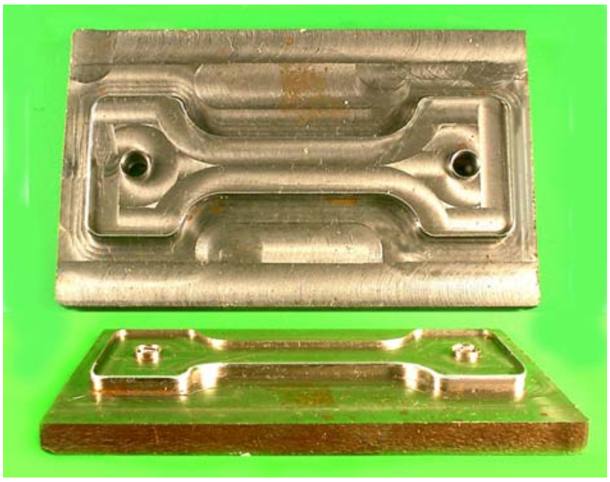
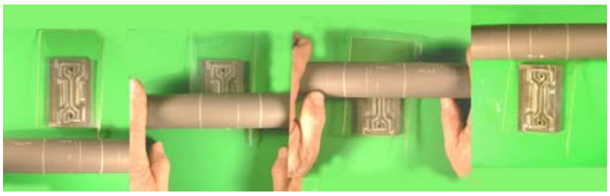
The test piece, 1mm thick with a tiny sprue, is cast onto a 4mm acryl plate using an injection mold apparatus with an acryl cover plate. The sprue is positioned far from the parallel portion of test piece to avoid mixing and pouring disturbances.



(a) Cutting die used for polyurethane sheet blanking



(b) Roll-cutting procedure

Figure 2: (a), A cutting die for Polyurethane sheet of 2mm thick into a tensile test specimen; (b), the roll cutting process to make sheet test pieces of polyurethane.

The Polyurethane was first made into 1 mm thick sheets by pouring the monomer liquid-state diol onto a flat 5 mm thick glass plate and allowed to cure for about 3 hours. Figure 2 (a) shows a formed cutter for blanking as shown in (b) as a roll-cutting procedure to make the test piece from a polyurethane sheet into the same figure as the fibrin glue test pieces.

Figure 3 shows a tensile testing apparatus used with the formed injection and blanking test pieces of fibrin glues and polyurethanes, respectively. An INSTRON type tensile testing machine, which had a double screw column driven cross head, was used. Using this apparatus, the first test was done to find the clear fringe visibility and high fringe-strain sensitivity of the coating materials by observing the birefringence fringes during tension.

The first test was conducted to determine the fringe clearness, the high strain resolution, and to calibrate the fringe-strain relationship using the best quality adhering film: Fascia lata strip.

Figure 4 shows the calibration test piece in the specially designed chuck, located in the polar ray field of the reflection type photo-elastic observation alignment.

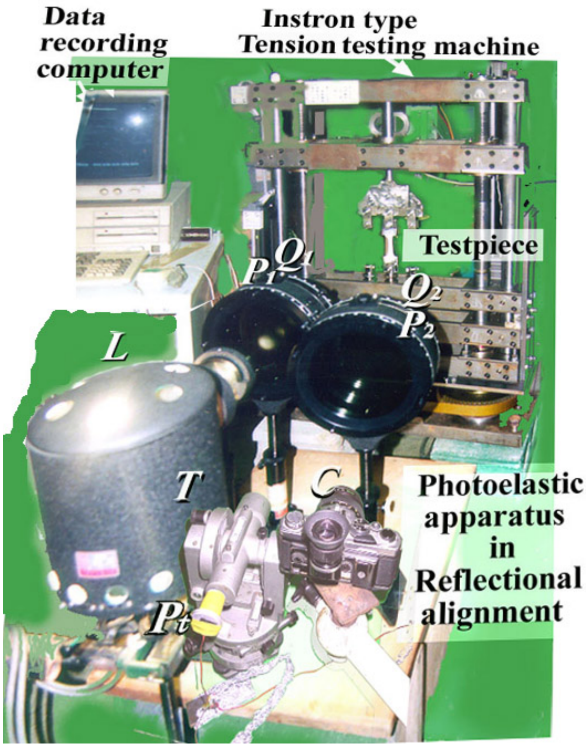


Figure 3: A tensile testing machine with a test piece in alignment with the reflection type photo-elastic polar ray field. The white letters indicate the following parts: L, light source; P_1, polarizer; Q_1, Q_2, quarter wave plate; P_2, analyzer; C, camera; T, telescope; P_t, phototransistor.

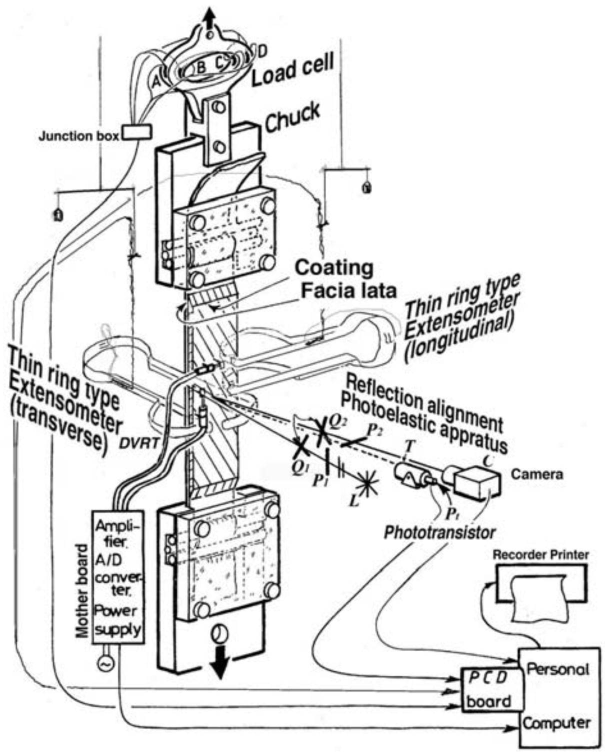


Figure 4: The Fascia lata strip with adhesion of polyurethane film in a 0.2 thick was held with special chucks and prepared for tensile testing to calibrate photo-elastic fringe order to the strain value.

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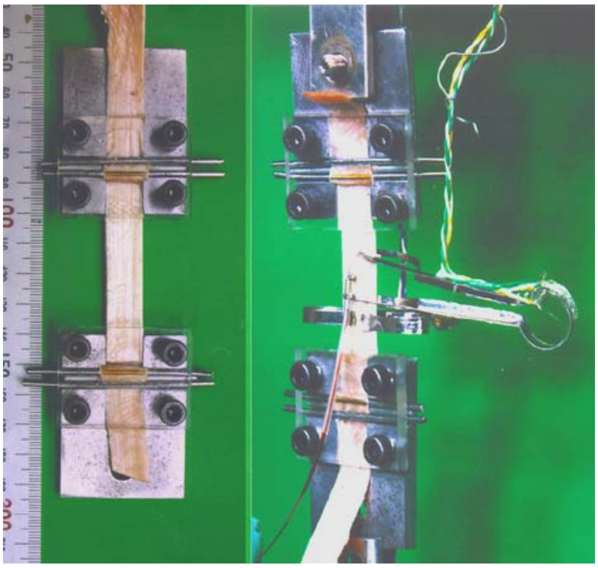
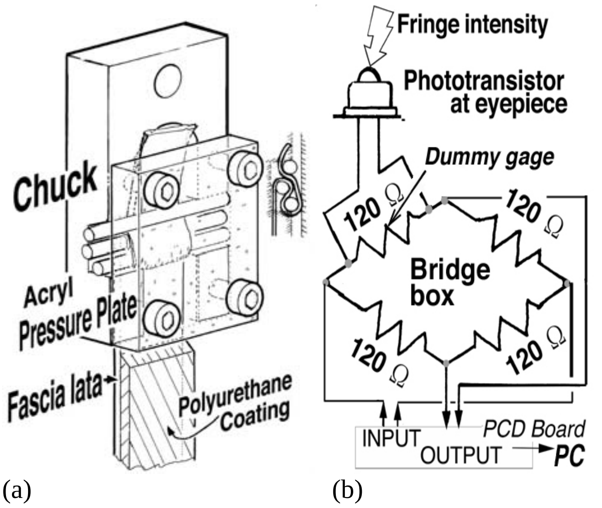


(a) (b)

Figure 5: Photos of the Fascia lata test piece (a) with a Photo coating held in the special chucks, and (b) two thin ring-caliper type extensometers mounted on the strip.

Figure 5 (a) shows a Fascia lata strip preparation for a tension test with adhesive photo-coating in the special chuck mount. The chucks allow the tissues to slip minimally against the load. The ligament is wound around three pins and held in a narrow slot as shown in Figure 6 (a). A detailed view of the holding pins is shown in the right upper.



(a) (b)

Figure 6: The special chuck (a), a fringe intensity detecting phototransistor in a strain gage bridge (b).

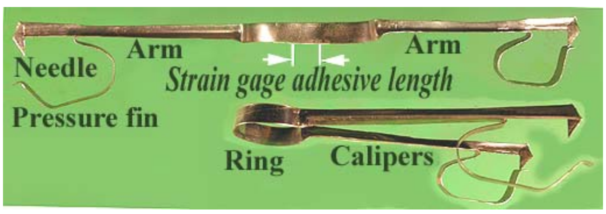


Figure 7: Thin-plate ring-caliper type extensometer.

Figure 7 shows an extensometer in the shape of ring-calipers made from a thin stainless steel plate, attached in longitudinal and transverse directions on the test piece as shown in Figure 5 (b).

It is hung lightly so that the influence on the soft tissues is quite low. In the gage length, the needles that are affixed to the tissue are not intrusive and contact is confirmed using pressure fins. The angle-bar-shaped caliper arms correspond with the end ring, so the elongations are well transmitted to the ring diameter deformation. Hence the strain gages in the mid area of the ring can measure the elongation of tissues and films.

Figure 6(b) shows an electric bridge circuit which detects the light and dark fringes. The phototransistor is inserted parallel to a dummy gage and closely attached to the eyepiece of a telescope. So the fringe intensity on the narrow test-piece area was transformed into electrical signals. Hence simultaneous measurement of both the elongation and the fringe intensity was accomplished.

Results

Figure 8 shows three fibrin glue test pieces curing in the injection mold. Tisseel has an opaque appearance and because of its flow properties it does not to reach the opposite end. The other two transparent pieces, Beriplast and Chimera glue, could be tensioned and their fringes were observed.

Figure 8: Fibrin glue test pieces injected into molds.

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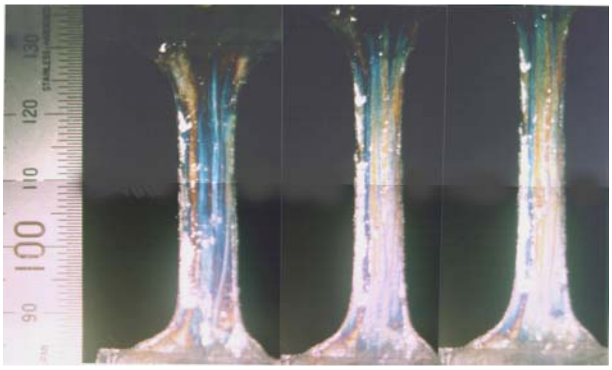

Figure 9: The Beriplast test piece has mottled fringes during the tensile test.

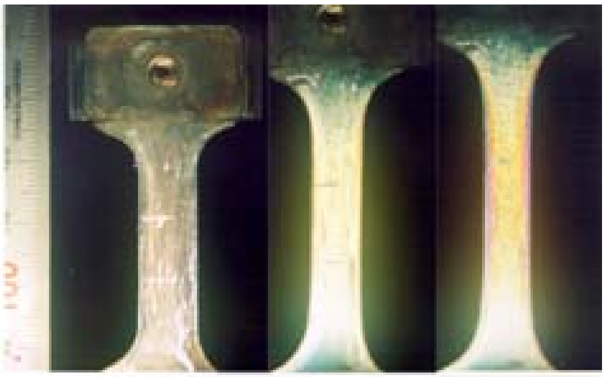

Figure 10: The Chimera glue piece has low sensitive and uniform fringes during the tensile test.

Figure 9, 10, and 11 shows the colour fringes from the Beriplast, the Chimera glue, and the polyurethane test pieces for the tension test for 0%, 15%, and 30% strain. The left side of Figure 11 shows the color isochromatic fringe scale and its corresponding comparison monochromatic fringe order.

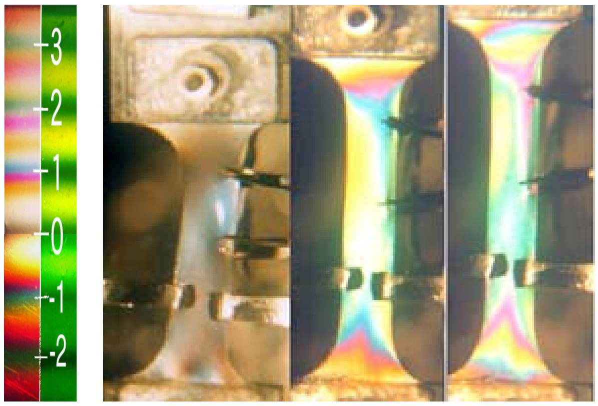

Figure 11: Polyurethane test pieces showing multi color fringes. Isochromatic color fringes are shown on the left side with its corresponding monochromatic fringes.

Mottled fringe patterns appear in the transparent Beriplast glue as shown in Figure 9. A quick coagulant component in the mixture at the tip of the double syringe, where mixing occurs, seems to have set faster than the rest of the test piece. Uniform, low sensitive fringes appear on the other transparent Chimera glue as shown in Figure 10. The thrombin in the Tisseel product seems to effectively except the quick coagulant, but the coloured fringes at most only reach one order when using the fringe translation scale. The polyurethane test piece shows multi colour fringes at its centre as shown in Figure 11. The colours indicate the presence of 2nd order fringes when using the scale on the left of Figure 11. So the next step is the fringe-strain calibration for the polyurethane.

Figure 12 shows a calibration test applied to the Fascia lata strip with the polyurethane photo coating. The colour fringes clearly change during the strip test-piece's lengthening.

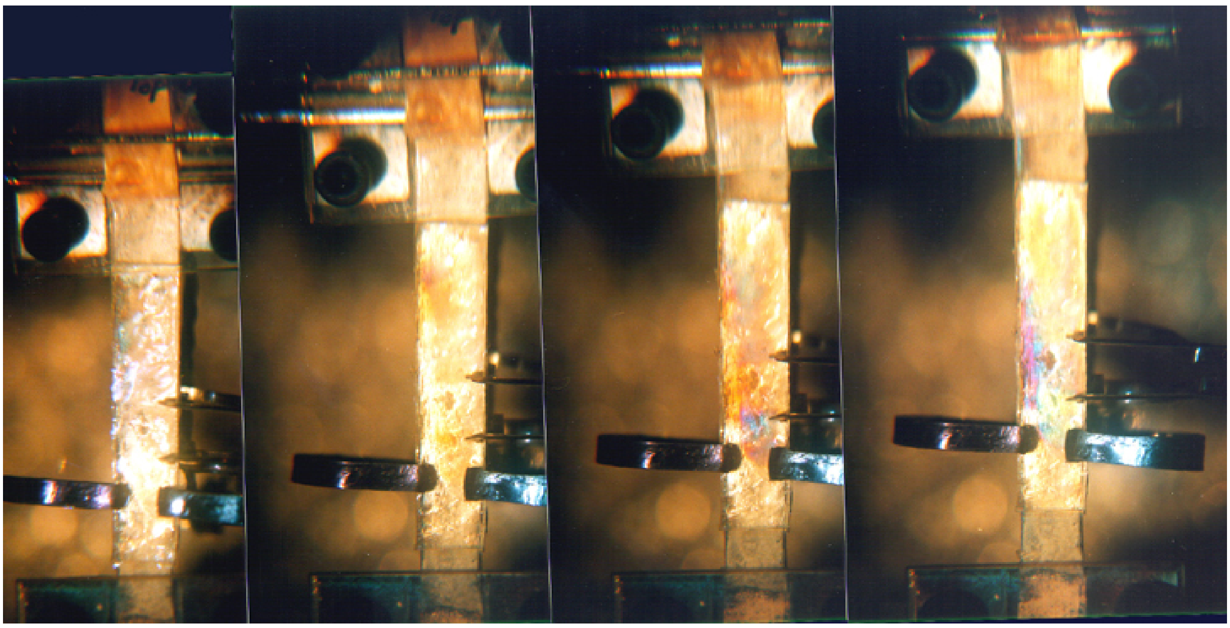

Figure 12: A Calibration test of fringe to strain using the Fascia lata strip using the polyurethane photo-coating.

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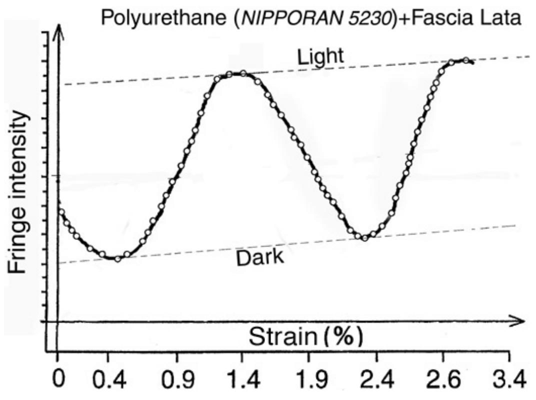


Figure 13: Relationship between the phototransistor fringe intensity and calculated strain taken from extensometer elongation

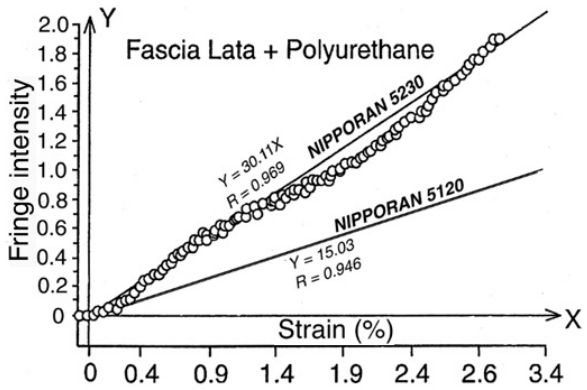


Figure 14: Fringe-strain sensitivity relation of the two kinds of polyurethanes: NIPPRAN 5230 and 5120.

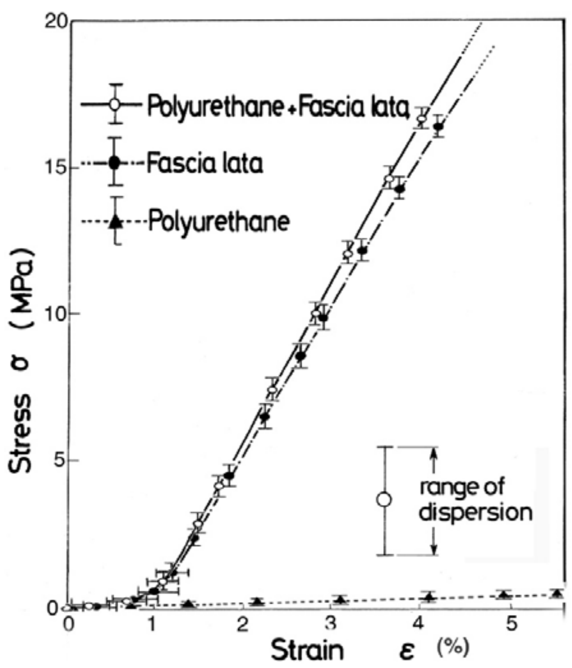


Figure 15: Characteristic curves of the Fascia lata proper, the proper with Polyurethane film complex, and the polyurethane.

The telescope eyepiece equipped with the phototransistor is aimed at the strip's mid-area where the longitudinal thin-plate ring-calliper type extensometer is attached by two needles. This allows fringe intensity and elongation to be recorded simultaneously. The fringe intensity was translated into fringe orders and elongation was translated into strain using the extensometer's two needles as the gage length in the unloaded state as shown in Figure 12 left.

Figure 13 shows the curve representing the fringe's dark areas and light areas obtained by the phototransistor on the telescope's eyepiece. Therefore, fringe orders translated from its intensity have the strain value relationship as shown in Figure 13.

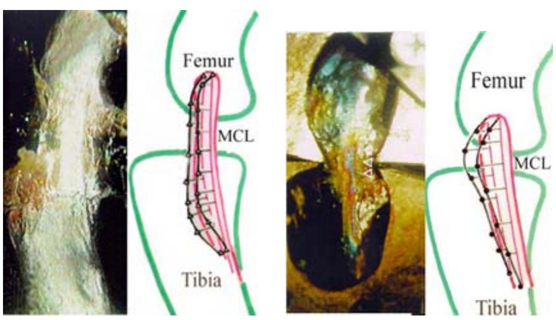
Figure 14 shows the photo-elastic fringe-strain sensitivities of the two kinds of polyurethane: NIPPORAN 5230 and NIPPORAN 5120, shown in the two lines respectively. The line inclinations express the coefficient of the fringe-strain sensitivity. The former sensitivity is higher than the latter one. Since polyurethane is more sensitive, it is a better choice for measuring ligament strain.

Figure 15 shows three mechanical characteristic curves. The upper curve is the Polyurethane NIPPORAN 5230 coated Fascia lata obtained from the calibration tension test as shown in Figure 12. The middle curve is Fascia lata, and the curve with the smallest slope is the Polyurethane which indicates a kind of elasticity. A toe-region near the origin is seen on the top and middle curves and typically indicates visco-elastic properties.

The vertical distance of discrepancy for the polyurethane+Facia lata and Fascia lata curves equals the distance between the x-axis and the Polyurethane curve. This distance also indicates the strengthening of the coating tissue by the coating. The strengthening is evaluated at about 10%. Against the range of measurement error dispersion, the strengthening range seems to be included in the error range so to be negligible for the use of photo coating on the soft tissue.

Discussion

The polycarbonate diol is a suitable photo-coating material for soft tissue. The NIPPORAN 5230 coating is suitable for ligament strain concentration examination as shown in Figure 16.



(a) (b)

Figure 16: A rabbit MCL's fringe and strain distribution in the tibial discrepancy (a), and in the valgus (b)

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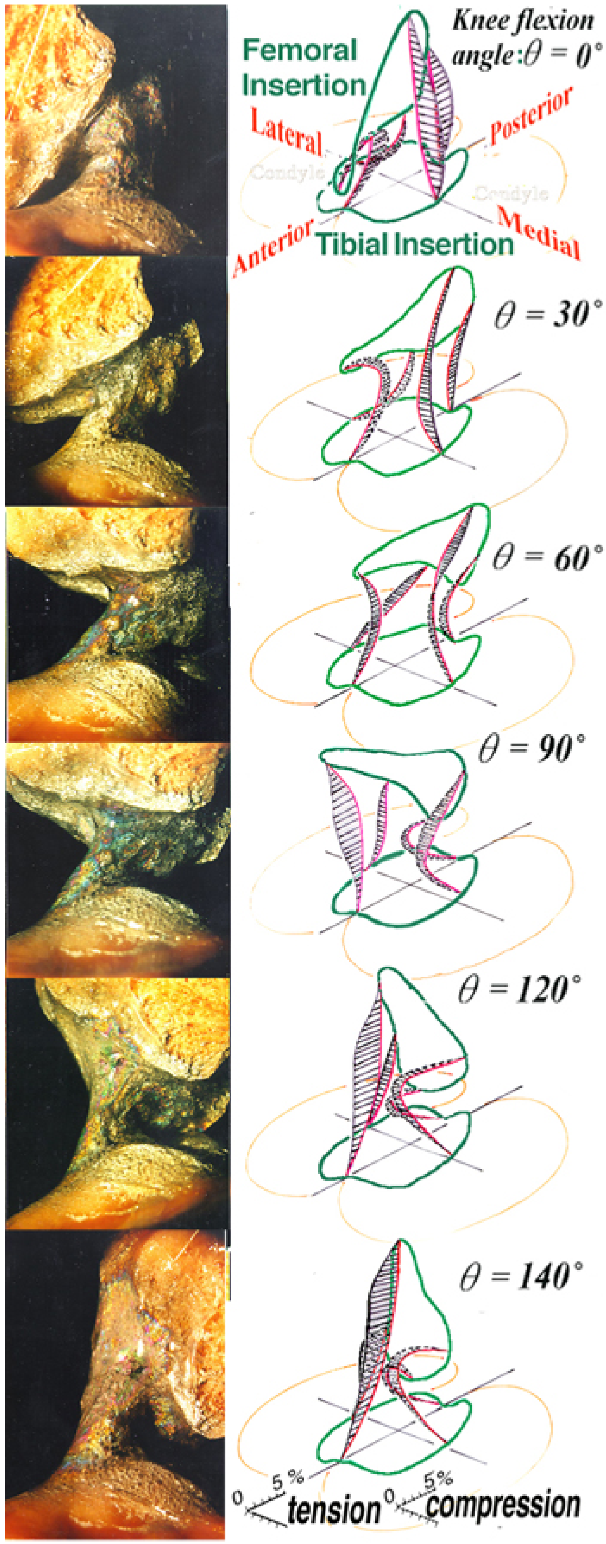

Figure 17: A cadaver knee with ACL's photo elastic fringe and the strain distributions along typical fiber runs.

Figure 17 shows a cadaver's ACL photoelastic fringes created by the coating film of the NIPPORAN 5230 during knee angle transition from 0 degrees to 140 degrees. The ACL is not a flat shape as with the MCL. Even so, the photo coating method can be applied evenly on the three-dimensionally shaped soft tissues. Figure 17 shows an example where we were able to determine the entire ACL surface strain distribution. Also the photo-elastic Isoclinic fringes can analyze the fiber run direction in the ligament. Other types of measurement methods found in the literature, such as using a Video Dimension Analyzer [3] or Differential Variable Reluctance Transducer [4], could not have performed as well as our method has.

Therefore *in-vitro* strain behavior during intact knee motion was analyzed on the entire surface of ACL along its fiber line. From the strain distributions along the fiber runs as shown in Figure 17 right. We can determine important information in these areas, such as knee angles and how high strain concentrations reach in the MCL and the ACL.

Conclusions

An excellent photo elastic coating film was successfully found in our experiments. The photo coating method which was applied to the ACL and MCL was effectively resolved as follows:

(1) The best photo coating material is polyurethane.
(2) The film fringes applied to the tissue can elucidate the strain distributions along fiber runs.
(3) The photo coating films on the soft tissue indicate strains concentrate regions effectively.

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