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Strain Measurement at the Knee Ligament Insertion Sites

Dehnungsmessung der Kniegelenksbänder an deren knöchernen Insertionsstellen

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Key words: Ligament tension measurement – strain gauge – knee joint

We describe the modification of an existing method of ligament strain measurement at the knee joint in detail. At ten fresh joint specimens we used that technique where strain gauges are attached to the ligamentous insertions and origins. We both improved the preparation of the attachment site and the application of the strain gauges. In a special apparatus the specimens were moved from 0° extension to 100° flexion while simulating muscle strength and axial force. Testing was performed at the posterior cruciate ligament with both intact and transsected anterior cruciate ligament. In contrast to other existing techniques it does not affect the motion of the joint or the integrity and the function of the ligaments. Unlike the original description of that method we could register a loading behaviour of the posterior cruciate ligament that is similar to those reported in the literature.

Schlüsselwörter: Banddehnungsmessung, Dehnungsmeßstreifen, Kniegelenk

Die Modifikation einer existierenden Methode zur Banddehnungsmessung am Kniegelenk wird im Detail beschrieben. An zehn frischen Kniegelenkspräparaten verwendeten wir diese Technik, bei der Dehnungsmeßstreifen an die knöchernen Ansätze und Ursprünge der Ligamente appliziert werden. Wir verbesserten sowohl die Präparation der Applikationsstellen als auch die Fixierung der Dehnungsmeßstreifen. In einem speziell konzipierten Kniegelenkskinemator wurden die Präparate unter Simulation von Muskelkraft und Axialkraft von 0° Extension bis 100° Flexion durchbewegt. Die Messungen wurden am hinteren Kreuzband durchgeführt bei primär intaktem und später durchtrenntem vorderem Kreuzband. Im Gegensatz zu den meisten existierenden Meßmethoden werden durch diese Technik die Bewegung des Gelenks und die Integrität und Funktion der Ligamente nicht beeinflußt. Im Gegensatz zur initialen Beschreibung dieser Meßmethode konnten wir nun am hinteren Kreuzband ein Dehnungsverhalten registrieren, das mit den Literaturangaben weitestgehend übereinstimmt.

1 Introduction

There are several techniques for ligament tension measurement at the knee joint. Most of them have the disadvantage that they do affect the function either of the special ligament or of the whole joint. Therefore we generally modified and thus improved an existing method that leaves the ligament structure and the joint function untouched.

Among the most commonly cited techniques the so called indirect methods measure a changing amperage or voltage that can be correlated with the ligament tension. Some of these techniques are based on strain gauges like the Omega transducer (Dürselen et al., 1995), the buckle transducer (Lewis et al., 1998) and the tendon force transducer (An et al., 1990). Other indirect methods are the mercury strain transducer (Hull et al., 1996) and the Hall effect transducer (Fleming et al., 1993). On the other hand there are direct methods where the value is equated with the effective change of ligament length. They measure the separation distances of marked fibers of the ligaments (Wang et al., 1973), replace the fibers by threads (Hoogland and Hillen, 1984) or use a load cell/bone plug construct (Markolf et al., 1990).

In contrast to the mentioned techniques we looked for a method for ligament strain measurement at the knee joint which leaves the integrity and flexibility of the ligaments untouched. This requirement lead us to use a very special indirect technique where the strain gauges are attached directly to the bony ligament insertion sites.

This technique is based on the fact that the stress of a ligament or tendon at its bony insertion site correlates with the strain of the ligament or tendon itself [Cooper and Misol, 1970; Goble, 1980]. Accordingly the strain gauges can be placed close to the area where defined parts of ligaments insert into the bone [France et al., 1983].

Nevertheless, modifications to this formerly described technique by France et al. had to be made as we could not achieve reproducible results with the information in the mentioned literature. That was mainly due to problematic handling of the existing technique and missing technical details. These modifications merely concern the preparation of the measurement sites and the attachment of the strain gauges. In the following we will describe our modified technique of attaching strain gauges to ligament insertion sites and present measurement results we got with this method.

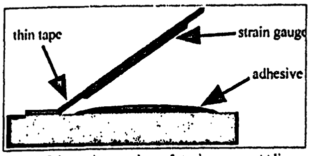

Fig. 1. Schematic procedure of strain gauge application – Step 1.

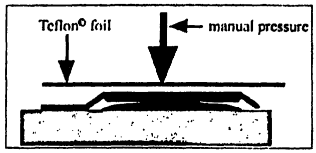

Fig. 2. Schematic procedure of strain gauge application – Step 2.

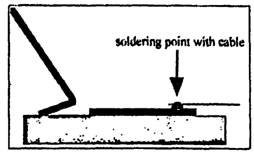

Fig. 3. Schematic procedure of strain gauge application – Step 3.

2 Materials and Methods

Strain Gauge Application Technique

At ten fresh human cadaver knee specimens the following procedures have proved to be reliable. The measurement sites were the femoral origins of the medial (anterior and posterior band) and lateral collateral ligament as well as the femoral and tibial attachment of the posterior cruciate ligament (anterolateral band and posteromedial band). After thorough removal of all soft tissue with the scalpel the application site is first smoothened with rough and then fine sandpaper. This area which needs to be approximately twice the size of the strain gauge is then cleaned with acetone for a few times. During that preparation a very thin cortical layer is removed and spongy bone comes out especially at the femoral origins of the posterior cruciate ligament and the medial collateral ligament. In order to prevent fat from oozing out of these cancellous pores and to create a smooth surface. The attachment site is covered by a thin layer of conventional adhesive for strain gauge attachment. The butylcyanoacrylat in that adhesive is very suitable for the application of strain gauges to native tissue [Küsswetter et al., 1978]. In contrast to the literature we made very good experiences with butylcyanoacrylat for closing the mentioned pores. It is very important to use a very small dose of that adhesive to create a thin covering. Too much adhesive can both cause problems as flexibility of the ligament fibers is concerned and impair the measurement results by stiffening the bone too much.

After this very thin first layer is dried the measurement site is again smoothened with sandpaper and fat is removed with acetone.

Now the strain gauge with the side containing the sensitive element and the soldered joint is placed onto a transparent thin tape. By means of the tape the strain gauge can be controlled and exactly placed where it is planned by means of attaching the gauges with their sensitive elements parallel to the ligament fibers. The tape must be slightly bigger than the gauge so that one end of the tape can be pressed next to the site. In the sense of a hinge it is possible to lift the tape and the strain gauge without changing its direction (Fig. 1). Then the application site is cleaned with acetone again and covered with a drop of adhesive. After moistening the accessible underside of the strain gauge it is clapped to the measuring site (Fig. 2). In order to push the strain gauge to the correct site for one or two minutes it is necessary to have a small Teflon® foil between the tape and the pressing finger. The non-adhesive Teflon® prevents a fixation of the finger with the underground due to cyanoacrylat at the edges of the strain gauge.

After pressing for two minutes (Fig. 3) the tape can be pulled away cautiously beginning at the edges of the gauge. Afterwards the two cables carrying the wires for each strain gauge (copper with PVC-isolation) can be soldered. That must be done very quickly as too long contact of the soldering iron with the soldering point at the strain gauge can lead to loosening of the fixed gauge due to heat. Finally the strain gauges are covered with polyurethane for thermal and chemical insulation. To prevent destabilizing lead wire stress the wires are fixed to the bone with some adhesive near the gauge.

The following figures show a schematic drawing and three in situ pictures of the femoral and tibial insertion of the posterior cruciate ligament after application and insulation of the strain gauges as well as soldering and fixation of the wires (Fig. 4–7).

Experimental Details

Ten fresh adult right cadaver knees were used for this study. Measurement sites were the femoral origin (anterolateral band) and tibial insertion (posteromedial band) of the posterior cruciate ligament. In order to achieve nearly physiological experimental movements the knee specimens were fixed in an apparatus designed and constructed in our laboratory. Using this apparatus it was possible to allow the knee joint all natural degrees of motion while it was moved by a motor. Movement of the joint in varus or valgus position was only marginally possible. At preparation the wiry insertions of the quadriceps, semimembranosus, bizeps femoris and gastrocnemius muscle were kept intact and little screws were placed at these insertion points. In order to simulate the muscle forces effective at the knee joint during a flexion movement from 0° to 100° weights were fastened at the mentioned screws via thin metal cords. The muscle forces which naturally change from one angle of flexion to another were changed at every position where a measurement was performed. That means that the apparatus was fixed in a certain position for the sake of manual modification of the appropriate weights. The angles of flexion of this quasistatic measurement were 0°, 20°, 40°, 60°, 80° and 100°. By means of another device axial pressure for the simulation of body weight could be exerted on the specimens during all mentioned positions.

The mentioned muscles as well as the weights were chosen according to an article published by Roehrle et

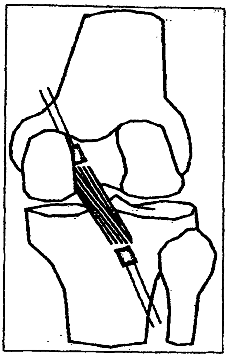

Fig. 4. Strain gauge application site at the bony insertion of the posterior cruciate ligament – schematic drawing.

Fig. 5. Strain gauge application site at the bony insertion of the posterior cruciate ligament – in situ picture of the complete posterior aspect of the knee.

Fig. 6. Strain gauge application site at the bony insertion of the posterior cruciate ligament – in situ picture of the tibial insertion in detail.

Fig. 7. Strain gauge application site at the bony insertion of the posterior cruciate ligament – in situ picture of femoral insertion in detail.

al. in 1984. While muscle strength and body weigth (axial force) was simulated strain of the mentioned ligaments was measured before and after transsection of the anterior cruciate ligament.

3 Results

The measuring results were registered at every angle of the quasistatic measurement and given by using the unit mV/V. Every reading was again the mean of a periodic measurement with the ratio 20/second lasting one second. Each measurement was repeatedly verified for the sake of reproducibility. The output voltages of the five strain gauges at the four different positions of the knee joint were recorded. Hoffmann (1987) showed that these output voltages are proportional to the mechanical strain of the examined ligaments. Thus we used the unit mV/V to express mechanical strain. The absolute ligament tension values were different from one knee specimen to another. In contrast the relative tension changes from one position to the following was very low and therefore negligible. Thus the mean values of the relative tension changes of all similar measurements of the ten knee specimens were calculated. The slight variations of the relative tension changes were documented and confirmed by the associated high percentage proportion of mean and standard deviation of the generated values. These mean values were the basis for the comparison and interpretation of the strain we measured at the mentioned ligaments before and after transsection of the anterior cruciate ligament.

We did not section the measured ligament and perform a calibration procedure as we think that the absolut force data is not more important for a conclusion than the raw data we got. Our data enables us to make a conclusion of clinical relevance like the tension change of a ligament or its parts in an intact knee compared to an anterior cruciate insufficient knee.

In the following diagrams (Fig. 8–9) you can therefore see the tension behaviour of the anterolateral band and posteromedial band of the posterior cruciate ligament in the status of an intact compared with a transsected anterior cruciate ligament. The values reflect the means of the relative tension changes in ten knee specimens.

The anterolateral band of the posterior cruciate ligament had its tension maximum in hyperextension, its minimum at 100° flexion. Transsection of the anterior cruciate ligament led to a continuous increase of tension.

The posteromedial portion of the posterior cruciate ligament was relaxed in 0° to 20° extension and showed its tension maximum at 100° flexion. Transsection of the anterior cruciate ligament produced reduction of tension from 0° extension to 60° flexion and a rise of tension from 60° to 100° flexion.

4 Discussion

All the techniques described in the introduction endanger the measured ligaments. Replacing the ligament fibers by threads or using a load cell/bone plug construct contains the danger of damaging the ligaments directly. Both the mercury strain transducer, the Hall effect transducer and the Omega transducer are based on suturing a foreign body onto the concerning ligament. By using the buckle transducer or the tendon force transducer the ligament is fixed in a little metal body. Although the different methods or devices mentioned in the introduction do not exceed 15 mm in length and 10 mm in breadth and height they all disturb the concerning ligament and joint by bringing in foreign material, partly stiffening the ligamentous tissue or changing its initial tension or its natural run.

In contrast the technique of applying the strain gauges to the bony insertions of the ligaments has the advantage that the integrity and flexibility of the examined ligament is nearly untouched. Furthermore strain gau-

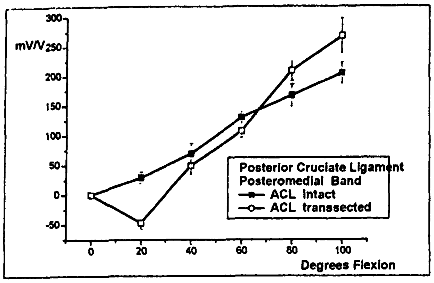

Fig. 9. Tension behaviour of the posteromedial band of the posterior cruciate ligament.

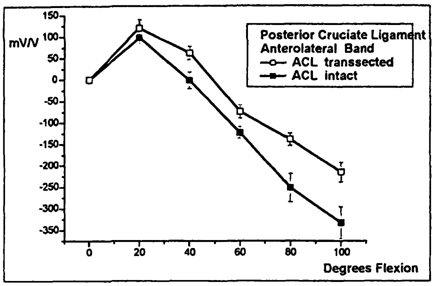

Fig. 8. Tension behaviour of the anterolateral band of the posterior cruciate ligament.

ge measurements generally show excellent linearity. Strain gauges are very small and their mass can almost be neglected. That involves the disadvantage of heating up. Nevertheless the great variety of strain gauges enables one to choose an object that perfectly fits to the tension behaviour and heating of the examined structure.

In our ten experiments the above mentioned procedure proved to be most reliable especially as far as filling the spongy bone for proper strain gauge attachment was concerned. The technique of strain gauge application (Fig. 1–3) was not described before. Nevertheless it was still very difficult to mount the strain gauges to exactly the same position at every knee joint. Therefore the ligament fibers and the sensitive elements of the strain gauges were probably not always parallel. That might explain a relative discrepancy of the absolute tension values we found. The high reproducibility of the experiments and the extremely low differences of the relative tension changes from one angle of the joint position to the following prove that the mentioned points of criticism can almost be neglected.

The improvement of the mentioned technique can also be seen in the fact that the measurement results of our experiment are similar to other experiments where at least muscle strength is simulated (Fuss, 1991; Friederich et al., 1992). Although there is an enormous range of literature about the topic of ligament tension measurement that we exemplary show for the posterior cruciate ligament most sources can not be compared as they are based on experiments without action of muscle strength and axial force. Kurosawa et al. (1991) did measurements before and after transsection of the anterior cruciate ligament and got very similar results for the posteromedial band of the posterior cruciate ligament.

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