Collateral ligament strains during knee joint laxity evaluation before and after TKA.

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ABSTRACT

Background :

Passive knee stability is provided by the soft tissue envelope which resists abnormal motion. There is a consensus amongst orthopedic surgeons that a good outcome in Total Knee Arthroplasty requires equal tension in the medial and the lateral compartment of the knee joint, as well as equal tension in the flexion and extension gap. The purpose of this study was to quantify the ligament laxity in the normal non-arthritic knee before and after standard Posterior-Stabilized Total Knee Arthroplasty. We hypothesized that the Medial Collateral Ligament and the Lateral Collateral Ligament will show minimal changes in length when measured directly by extensometers in the native human knee during varus/valgus laxity testing. We also hypothesized that due to differences in material properties and surface geometry, native laxity is difficult to be completely reconstructed using contemporary types of Posterior-Stabilized Total Knee Arthroplasty.

Methods :

A total of 6 specimens were used to perform this *in vitro* cadaver test using extensometers to provide numerical values for laxity and varus-valgus tilting in the frontal plane.

Findings :

This study enabled a very precise measurement of varus and valgus laxity as compared with the clinical assessment which is a subjective measure. The strains in both ligaments in the replaced knee were different from those in the native knee. Both ligaments were stretched in extension, in flexion the Medial Collateral Ligament tends to relax and the Lateral Collateral Ligament remains tight.

Interpretation :

As material properties and surface geometry of the replaced knee add stiffness to the joint, we recommend when using a this type of Posterior-Stabilized Total Knee Arthroplasty to avoid overstuffing the joint in order to obtain varus/valgus laxity close to the native joint.

Keywords: Total Knee Arthroplasty, posterior-stabilized prosthesis, ligament strain, laxity testing.

1. Introduction

Surgeons rely on ligament testing for many clinical conditions. Assessment of knee joint laxity in the case of injury for instance is used in the daily practice of many clinicians. Laxity testing is, however, usually performed in a qualitative fashion, controlling neither applied force nor resulting displacement (Heesterbeek et al., 2008; Van Damme, G. et al., 2005). Thus, the interpretation of such testing relies on the surgeons' experience and ability to compare the subjective assessment of a particular knee to an expectation of normal knee laxity.

During a Total Knee Arthroplasty (TKA), orthopedic surgeons evaluate ligamentous strains intra-operatively to decide, for instance, if and how a surgical release of the soft tissue envelope has to be performed. Also in this situation, laxity assessment is purely qualitative. Surgeons judge the stability of the knee joint during replacement and decide to either release the ligaments or tighten the joint by using a thicker tibial insert based on a combination of feeling and experience. Consequently, we can state that it is very difficult to evaluate and balance the soft tissues accurately or precise (Freeman, 1997). Many devices have been developed to evaluate knee laxity intra- and extraoperatively (Küpper et al.,2007) since adequate soft tissue balancing is a prerequisite for a successful total knee arthroplasty (Whiteside et al., 1987; Whiteside, 2002). From literature we know that medio-lateral instability is the most common cause of instability and a leading cause of early clinical failure (Fehring et al.,2001; Fehring and Valadie,1994; Sharkey et al., 2002). The objective of this paper is to document the levels of strain deviation in the collateral ligaments that can be expected during varus-valgus testing in the native and replaced knee, as compared with the varus-valgus tilting observed during the same test.

Furthermore, the implicit idea behind laxity testing is that the collateral ligaments act as passive mechanical restraints. We know that structural damage is occurring in the ligaments from 5.14%

strain levels (Provenzano et al., 2002). Based on a value of 60 N/mm for the stiffness of both medial and lateral collateral ligaments (Wilson et al., 2012) a quite simple mechanical analysis $\Delta x = F/k$ (where k is the stiffness of the ligament) shows that to obtain this level of strain, forces in the medial collateral (MCL, l0=100 mm)) and lateral collateral (LCL, l0=60 mm) ligaments of 300N and 190N respectively are needed. It is clear that ligament strains and forces should certainly remain below this level after TKA.

However, there is abundant literature showing that strains resulting from loads as small as 10 N result in firing of the afferent nerves from the receptors in the ligaments. This means that excessive forces are not needed to have clinical relevance (Sjölander et al.,1989; Khalsa et al.,1996; De Avilla et al.,1989; Zimny et al.,1991; Freeman and Wyke,1967; Yan et al.,2010; Johansson, 1991). Given their high sensitivity on the one hand and their limited strength on the other, it is in fact questionable whether the collateral ligaments really stabilize the knee joint (Arms et al., 1983). Their role might be more that of sensors which trigger the real knee joint stabilizers, i.e. the muscles (Barata et al., 1988). If this is true, we believe that soft tissue balancing should probably be performed in a far more accurate way than it is typically done nowadays.

To prevent the afferent nerves from firing, the maximum ligament deformation is $\Delta x = F/k = 10/60$ mm = 0.17 mm. This corresponds to strains of only 0.7%. Since there is no literature available on the effect of strains which exceed this level permanently, the precautionary principle commands to stay close to this level or not exceed it too much after TKA. We believe that ligament strains should certainly remain below 5.14% (structural damage level).

In summary, many believe that ligamentous strains after TKA should be similar or close to the native situation to be able to prevent patient discomfort as there is pain, stiffness and instability. However, due to the large differences in material properties and also the change in surface geometry we expect that the native laxity of the knee joint is difficult to be completely reconstructed after TKA. To measure the changes induced by TKA, we therefore performed an in vitro cadaver test using extensometers to provide numerical values for laxity in the medio-lateral plane. The purpose of this study was to quantify the ligament laxity in a normal non-arthritic knee before and after a standard total knee arthroplasty.

2. Materials and Methods

Six fresh frozen full leg cadavers with non-arthritic knees were used for this study. It has been demonstrated by Bellemans et al. that in arthritic knees with varus deformity who are a candidate for a TKA, soft tissue integrity is maintained until the deformity exceeds 10° (Bellemans et al., 2010). Therefore we assumed that non-arthritic knees could be used in this experiment.The age of the individuals at the time of death ranged from 76 to 95 years (mean: 84.3 years). There were 4 male and 2 females. All specimens consisted of complete limbs, disarticulated at the level of the hip. An MRI scan and full leg radiograph was made of the knee joint and specimen specific cutting blocks for a primary PS TKA (Genesis II, Smith & Nephew, Memphis, TN, USA) were designed based on the images (Visionaire protocol, Smith & Nephew, Memphis, TN, USA). Afterwards, frames with four reflective markers were fixed to femur and tibia and a CT scan of the full leg was made. The scan was then processed in Mimics (Materialise, Leuven, Belgium) to identify bone landmarks and ligament insertion points (Figure 1). Coordinate systems for femur and tibia were defined based on these landmarks and this information was then used to calculate flexion angles and varus-valgus deviation during laxity tests, using the Grood and Suntay convention (Grood and Suntay, 1983).

The specimens were thawed at room temperature for twenty-four hours prior to testing. After the macroscopic and clinical examination, the specimens were prepared in a standardized fashion (Victor et al., 2009) . Two calibrated extensometers (Type 634.12F-24, MTS, Eden Prairie, MN, USA) were firmly sutured to the lateral and medial superficial collateral ligaments with the knee unloaded and in full extension. A preliminary test of the fixation of the extensometers showed that strains could be detected with an accuracy of better than 1%.

The leg was fixed to the operating table with the proximal femur clamped in a vice (Figure 2). A rope was then looped around the ankle fixture at a distance of 30 cm from the joint line and slightly pulled with the dynamometer (FMI-220C5, Alluris, Freiburg, Germany) to the medial side (for varus testing) or to the lateral side (for valgus testing) till it was just tight without applying a measurable force. Then extensometer and Vicon camera data recording (Vicon, Oxford, UK) was started and the surgeon gently and slowly pulled the dynamometer until a force of 25 N was read from the display. After this maximal force was reached, the joint was allowed to come back to its unloaded position and the data recording was stopped. Strain was calculated using the engineering strain formula ϵ (in %)= $[(l - l_0)/ l_0] \times 100$ where l represents the instantaneous length of the ligament and l_0 the reference length, which was the length between the arms of the extensometers at full extension i.e. 25 mm.(Arms et al.,1983; Hull et al., 1996). The knee was sequentially flexed in approximately 0°, 45° or 90°, as measured with a digital protractor.

After testing the native knee, a PS TKA (Genesis II, Smith&Nephew, Memphis, TN, USA) was performed by the senior surgeon (HD) using a measured resection technique with the specimen specific cutting blocks and all tests were redone.

The knee was opened with the use of a standard medial parapatellar approach and a Genesis II cruciate-substituting total knee replacement (Smith & Nephew, Memphis, TN, USA) was performed without any releases. All implantations were performed with the use of patient-matched guides (Visionaire, Smith & Nephew, Memphis, TN, USA) and instrumentation provided by the implant manufacturer. Patellar resurfacing was not done. The implants were cemented in place and the arthrotomy was closed with a running suture. No ligament releases were performed in any case. The knees were examined for their stability as on the operating table by the senior surgeon in the classical way and were considered to be well balanced. The extensometers remained fixed to the collateral ligaments during the entire procedure. Then the same series of laxity tests was repeated with the total knee replacement in situ and with the same loads.

The marker trajectories of femur and tibia were processed to calculate position and orientation of femur and tibia during the laxity test. Based on the position of the landmarks with respect to the markers (as derived from the CT scan), exact flexion-extension, abduction-adduction and internal-external angles of the knee joint could then be derived. Flexion angle was used to control the approximate flexion angle obtained from the protractor. This showed that flexion angle was off on average 5° in most tests.

A paired t-test was performed to check significant differences between the intact closed joint and the neutral TKA for both initial strains and strain ranges during varus-valgus laxity testing in the three investigated flexion angles.

3. **Results**

3.1. Varus-valgus tilting

Initial and maximal varus-valgus tilting values of the tibia as measured with the Vicon system during the laxity tests are shown in Figure 3. Average tilt angles and standard deviations are reported in Tables I. On average, the knees are slightly in varus both before and after replacement and they tend to go slightly more in varus with increasing flexion. The intact knees show a little play of 2° at 40° and 85° of flexion. This play has disappeared after replacement in 40°, but not in 85° of flexion. Varus and valgus loading change varus angle by 2° (close to extension) to 3.5° (at higher flexion angles) in the intact knee and by similar, though slightly smaller, amounts in the replaced knee. Overall, varus-valgus tilting is quite similar before and after replacement. The only statistically significant difference is observed at 40° of flexion, during varus loading, when the maximal varus angle is smaller in the replaced knee than in the intact knee.

3.2. Collateral ligament strains

A typical result for the MCL and LCL strains during laxity testing is shown in Figure 4. Based on these data, initial and maximal strain values in MCL and LCL in different flexion angles during the laxity test were collected and are shown in Figures 5 and 6. Average strain values and standard deviations are reported in Tables II and III. Strain values (in %) can easily be converted to changes in length (in mm) by multiplying with 0.25 (based on the initial length between the extensometer arms). Standard deviations are quite high, which reflects the large interspecimen variability typically seen in biomechanical studies.

Initial strains in MCL and LCL near extension were close to zero, as expected because the starting situation for the laxity test was quite similar to the situation when the extensometers were mounted and which was used as the reference point for all following strain measurements. When the knee was flexed, the MCL tended to be stretched between 1% and 2% in 45° and up to 4% in 90°. The LCL remained isometric in 45° and relaxed in 90° (strain values between -3% and -4%). A small difference in initial strain values between valgus and varus testing was notable, indicating that there is some play present in the frontal plane in the native knee joint at all flexion angles.

Pulling the knee into valgus or varus with a force of 25N at the ankle led to lengthening or shortening of the MCL and vice versa for the LCL. The MCL showed changes in length of around 1% in 0° and 90° and of 2% in 45° in both directions. The LCL showed changes in length of approximately 2% in 0° and of 3% in 45° and 90°.

Replacement of the knee changed the strain behaviour of MCL and LCL during laxity testing to some extent. Both ligaments were stretched by almost 3% in extension, as can be clearly seen by the initial strain values in 0°. When the knee was flexed, the MCL tends to relax by about 1% in 45° and still further by another 6% in 90°, at which point the MCL is loose (initial strain between -3% and -4%). The LCL remains tight and stretches by another 1% in flexion The play which was initially present in the native knee has now completely disappeared. Length changes in MCL and LCL during valgus and varus testing are also smaller than in the native knee for all flexion angles.

Ligament testing of the native knee in full extension typically shows strains between 1.6-2.1 % , corresponding to ligament length changes of 0.4-0.5 mm. This corresponds with the results of Jeffcote et al. (2007). Testing at 45° of flexion almost doubles the strains. At 90° of flexion MCL shows more strain (5.2%) and LCL less (0.2%) or relative relaxation (see table 1). Figures 1 to 4 illustrate the strain range for the different flexion angles in varus/valgus in MCL and LCL for native and replaced knee. MCL is becoming tighter in the native knee but relaxes at 90° of flexion in the replaced knee. On the other hand, LCL relaxes in the native situation but becomes tighter in the replaced knee during flexion.

It was interesting to note that in the resting situation without force application, a gap or a little play of about 1% or 0.3 mm in both ligaments was noticed. This was consistent in 0°, 45° and at 90° of flexion, but disappeared after implantation of the TKA. After the insertion of a TKA in the neutral position we observed minimal increase in strain for both ligaments mainly in extension (0°).

4.**Discussion**

Clinical laxity testing in an intact native knee is a very subtle exercise. Even experienced surgeons will have difficulties to perform this clinical examination correctly and repeatedly and it is impossible to compare the results of the personal clinical feeling with other investigators.

On valgus and varus stress the length of the MCL changed by 0.5 and 0.275 mm respectively when measured in extension, 1.1 mm and 0.275 mm at 45° and 1.3 mm respectively 0.6 mm at 90° of flexion. In the LCL however, valgus and varus stress application changes the ligament length by -0.375 and 0.4 mm at 0°, -0.75 mm and 0.7 mm at 45°, and -1.6 mm and 0.05 mm at 90° of flexion. This demonstrates that the LCL in the native knee during flexion tightens minimally with varus stress and relaxes -1.6 mm with valgus stress. This is in agreement with the observations of Whiteside et al that the LCL normally is more lax, especially in flexion. Freeman also concluded that the LCL must be more lax during flexion to allow rotation. Overall these figures demonstrate an isometric behaviour of both collateral ligaments in the native situation.

However, after insertion of a TKA the MCL relaxes more than the native knee 6% with varus stress at 90° of flexion, giving the surgeon the “feel” of looseness , while LCL gives a more tight impression. However, when we used the Vicon data to measure the laxity angles rather similar angles were obtained for native and replaced knees at different degrees of flexion.

This reflects the difficulty for the surgeons to assess ligament laxity. Visually, clinical testing can give the surgeon a satisfactory impression, but extensometer measurements reveal subtle differences enough to trigger the mechanoreceptors of the soft tissue envelope.

Even varus-valgus angle measurements before and after TKA are almost identical in our experiment, however, insertion of a TKA in the neutral position increases the strain n extension in both ligaments from 0 to almost 3 %. The surgeon can assess this as a sign of stability. The patient however might experience stiffness due to the tightness of the joint, since the strain in ligaments clearly exceeds the 0.7% strain leading to firing of the afferent nerves.

Another striking observation was the presence of a slight play of about 1% or 0.3 mm of both ligaments in the native knee. This was consistent in 0°, 45° and at 90° of flexion. After insertion of the TKA this observation was always absent. Also when comparing our results with the literature (Heesterbeek et al.,2008; Okazaki et al.,2006; Markolf et al.1976; Tokuhara et al. 2004; Tokuhara et al., 2006) remarkable similarities can be observed despite the use of different measuring methods (x-ray). This can be explained through the loss of natural flexibility of the human structures (meniscus and cartilage) as they are replaced by stiffer materials (metal and polyethylene). The cartilage meniscal complex has a Young's modulus of 5 MPa compared with 700MPa for polyethylene.

Furthermore, we noticed the least level of laxity in extension (0°) for the native knee of about 3.7% or 0.9 mm with both varus and valgus forces added. However at 45° of flexion, the native knee showed an increase of strain in both sides, meaning a total of 7.4% (or 1.8 mm). This displacement at the level of the ankle joint is 1.5 cm, which corresponds well with our Vicon measurements. Maybe this deduction could be useful in the clinical practice.

At 90° of flexion the MCL showed again less laxity, back to -1.3% but LCL remained at 6% strain. This corresponded well with our clinical findings.

If we calculate the total strain (varus + valgus) for the native ligaments at extension (MCL 3.2% and LCL 3.1%)to this would equate to MCL 5.7% and LCL 6.0% in the replaced knee. At 45° this becomes respectively for the native knee 5.5% and 6.0% and for the replaced knee 3.5% and 8.1%. At 90° of flexion this was 7.6% and 6.6% for the native and 5.8% and 8.5% for the replaced knee.

This illustrates the isometric nature of both ligaments in the native knee at 0°, 45° and 90°, but also shows the changes after TKA with increasing strains in LCL and relative less strain in the MCL during flexion

The results by Van Damme et al (2005) who measured the medial joint-line opening on valgus and lateral joint-line opening on varus stress are quite larger than our results. This may be due to the measurement and calculation methods using a navigation system. They observed more joint-line opening as reported in this study. However after TKA implantation the laxity values were also a little less or more tight from those in the native knee especially for lateral laxity at 30° and 90° of flexion.

5. Conclusion

This study enables us a very precise measurement of varus and valgus laxity as compared to clinical assessment. The biomechanics of the ligaments in the replaced knee are quite different from those in the native knee. In the native knee, strain increases with flexion in the MCL, while the LCL relaxes in flexion. The differences are very subtle, never exceeding more than 2-3 mm (in terms of changes in length) or 2-3° (in terms of tibial tilting), and could potentially go unnoticed, even for an experienced surgeon. After insertion of a TKA, strain decreases in the MCL during flexion while increasing minimally in the LCL. However, since we tried to preserve the ligaments that act isometrically, it might be a good start to aim for a laxity that is within the range of the native knee.

As material properties and surface geometry of the replaced knee add stiffness to the joint we also recommend that the surgeons do not overstuff. It is known that patients prefer a slacker knee compared to a tighter one (Kuster et al., 2004). It is our recommendation to try to obtain laxity in varus and valgus between 2% and 3% (0.5 and 1.0 mm) for extension and between 3% and 5% (0.7 and 1.2 mm) for flexion.

For this study we concluded that the range of varus-valgus laxity in extension and flexion as measured passively in cadaver specimens are small and near isometric. More investigations are necessary to find out if the laxity data from this study after implantation of a contemporary PS-TKA can inform the surgeon on what to aim for in positioning the implant with respect to the mechanical axis.

Another way might be to accommodate the implant design to the soft tissue envelope. This is in fact done by customising the implant to each patient specifically.

During clinical testing subtle differences in ligament strain may remain undetectable. This is demonstrated when varus/valgus angles before and after TKA were compared as measured with the Vicon system. Nevertheless, we noticed differences in ligament strain before and after knee arthroplasty.

More investigations are necessary to find a relation between ligamentous strain on the one hand and tibiofemoral kinematics and contact forces on the other. Further work using a mathematical model taking into account joint geometry and material properties before and after TKA is recently initiated.

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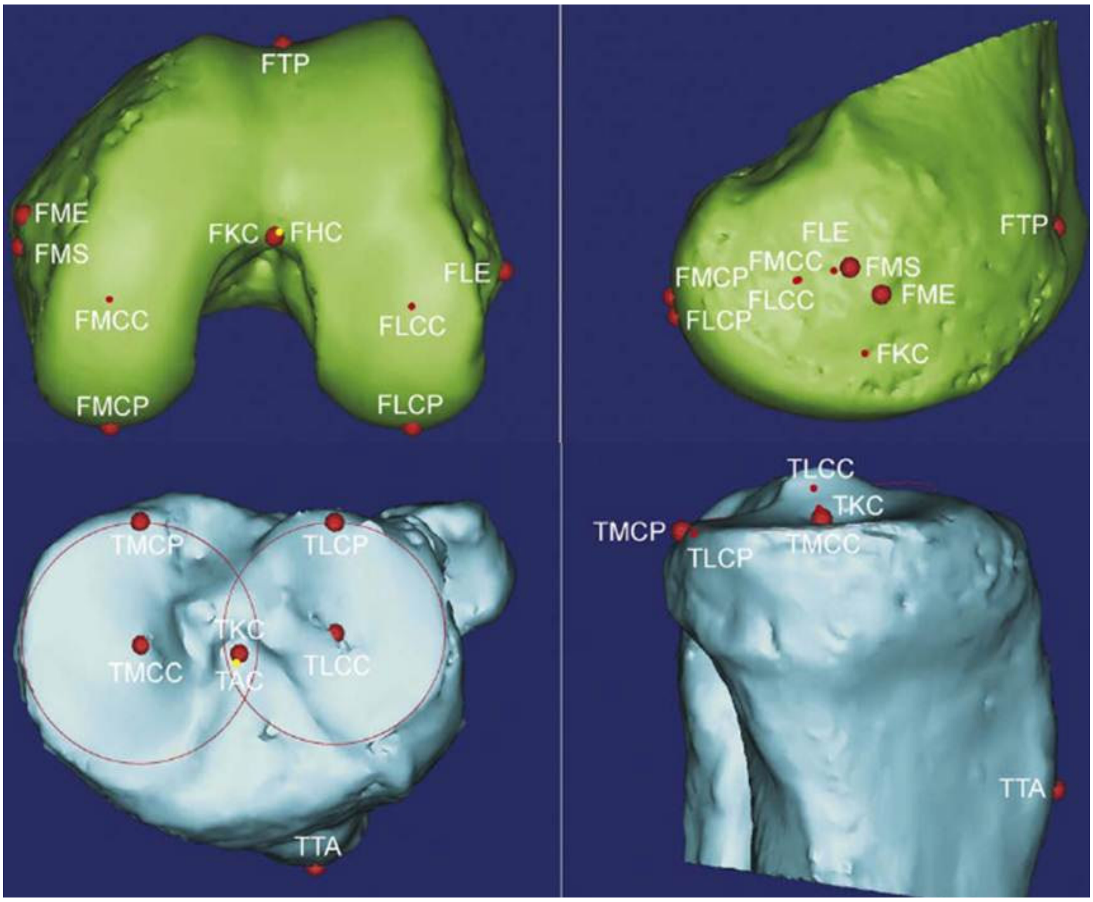
Table III: Average initial and maximal strain values in the LCL during valgus and varus laxity testing in different flexion angles. Standard deviations are given between brackets. Statistically significant differences between native and replaced knees are indicated with an asterisk.

Figures:



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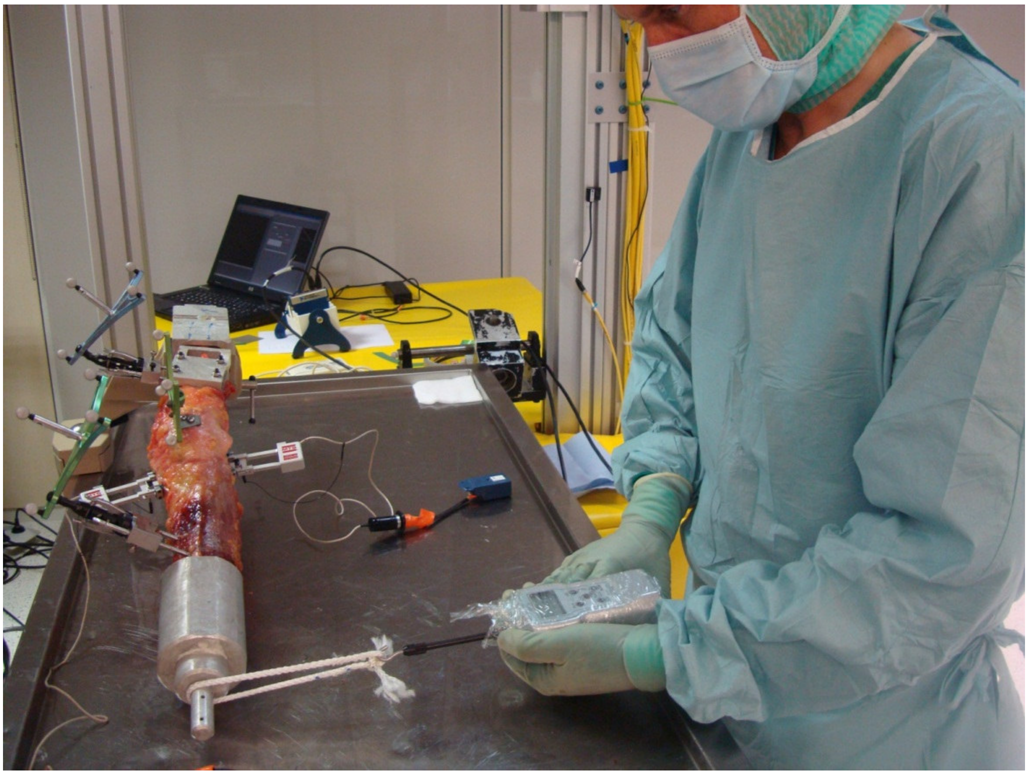

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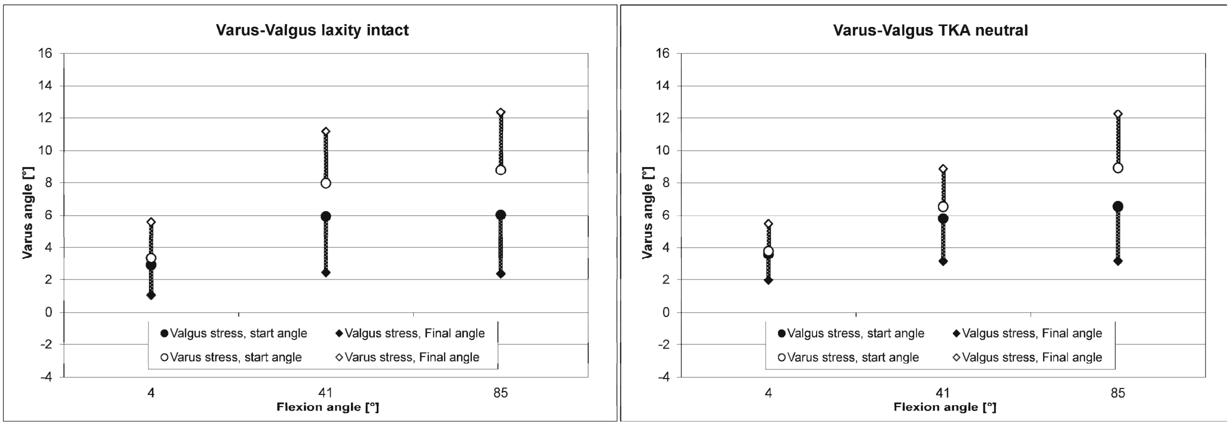

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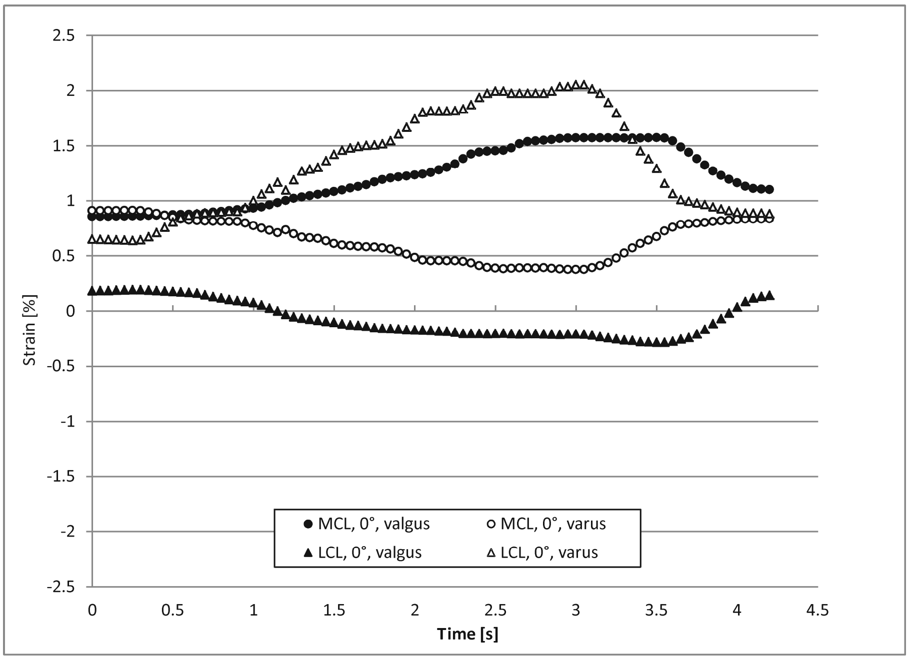
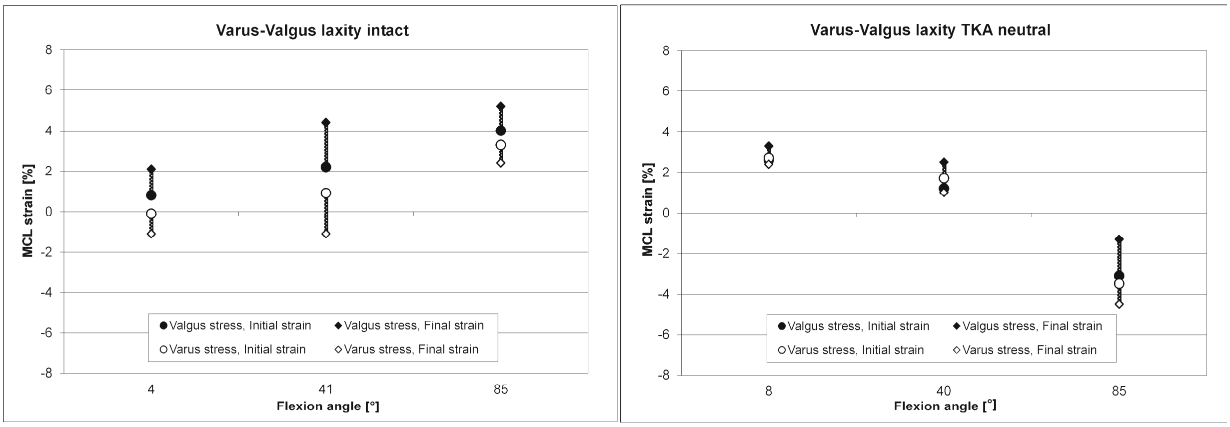
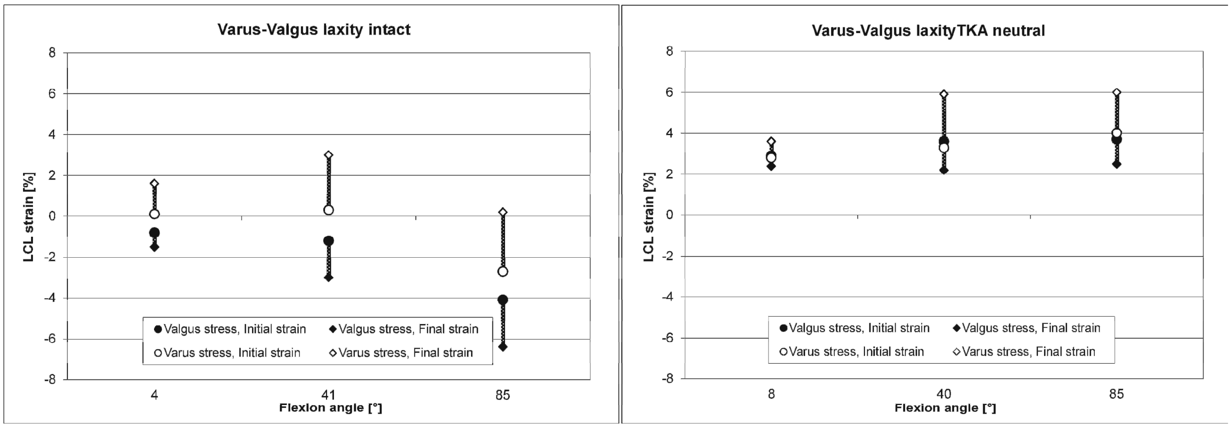


Figure 4: Typical result of the strains as function of time, recorded during the laxity test.



a b

Figure 5: Initial and maximal strain values in the MCL during valgus and varus laxity testing in different flexion angles. a: intact knee, b: replaced knee.



a b

Figure 6: Initial and maximal strain values in the LCL during valgus and varus laxity testing in different flexion angles. a: intact knee, b: replaced knee.

Tables:

Table I: Average initial and maximal varus angle during valgus and varus laxity testing in different flexion angles. Standard deviations are given between brackets. Statistically significant differences between native and replaced knees are indicated with an asterisk.

Test	Force [N]	Flexion angle [°]			Flexion angle [°]		
		4	41	85	8	40	85
Valgus	0	2.9 (1.38)	5.9 (4.37)	6.0 (6.35)	3.6 (2.74)	5.8 (4.26)	6.5 (6.12)
	25	1.1 (1.64)	2.5 (5.37)	2.4 (7.42)	2.0 (2.55)	3.1 (4.52)	3.2 (7.39)
Varus	0	3.3 (1.39)	8.0 (4.27)	8.8 (6.05)	3.8 (2.69)	6.5 (4.13)	8.9 (5.61)
	25	5.6 (1.74)	11.2 (4.16)	12.3 (5.58)	5.5 (3.45)	8.9 (4.30)*	12.2 (4.97)
		Intact knee			Replaced knee		

Table II: Average initial and maximal strain values in the MCL during valgus and varus laxity testing in different flexion angles. Standard deviations are given between brackets. Statistically significant differences between native and replaced knees are indicated with an asterisk.

Test	Force [N]	Flexion angle [°]			Flexion angle [°]		
		4	41	85	8	40	85
Valgus	0	0.8 (0.88)	2.2 (2.65)	4 (5.44)	2.6 (3.86)*	1.2 (5.97)	-3.1 (6.76)*
	25	2.1 (1.24)	4.4 (3.11)	5.2 (5.82)	3.3 (3.94)	2.5 (5.73)*	-1.3 (6.28)
Varus	0	-0.1 (0.66)	0.9 (2.3)	3.3 (5.69)	2.7 (3.7)*	1.7 (5.95)	-3.5 (6.84)*
	25	-1.1 (1.35)	-1.1 2.61)	2.4 (5.81)	2.4 (3.73)	1 (6.08)*	-4.5 (7.01)
		Intact knee			Replaced knee		

Table III: Average initial and maximal strain values in the LCL during valgus and varus laxity testing in different flexion angles. Standard deviations are given between brackets. Statistically significant differences between native and replaced knees are indicated with an asterisk.

Test	Force [N]	Flexion angle [°]			Flexion angle [°]		
		4	41	85	8	40	85
Valgus	0	-0.8 (1.79)	-1.2 (2.6)	-4.1 (5.87)	2.9 (4.38)*	3.6 (2.99)*	3.7 (4.02)*
	25	-1.5 (2.4)	-3 (2.51)	-6.4 (7.00)	2.4 (3.94)	2.2 (2.99)	2.5 (3.32)
Varus	0	0.1 (0.61)	0.3 (2.51)	-2.7 (5.72)	2.8 (4.75)*	3.3 (4.11)*	4 (5.55)*
	25	1.6 (0.63)	3 (3.49)	0.2 (6.38)	3.6 (4.78)*	5.9 (6.71)	6 (6.51)*
		Intact knee			Replaced knee		