

# Analysis of forces of ACL reconstructions at the tunnel entrance: is tunnel enlargement a biomechanical problem?

M. Jagodzinski<sup>a,\*</sup>, T. Foerstemann<sup>b</sup>, G. Mall<sup>c</sup>, C. Krettek<sup>a</sup>, U. Bosch<sup>d</sup>, H.H. Paessler<sup>e</sup>

<sup>a</sup>Department of Trauma Surgery, Hanover Medical School, Carl-Neuberg-Str. 1, 30625 Hanover, Germany

<sup>b</sup>Department of Bio- and Hospital-Engineering, Hanover Medical School, Carl-Neuberg-Str. 1, 30625 Hanover, Germany

<sup>c</sup>Department of Forensic Medicine, The Ludwig Maximilian University, Postfach 151023, D-80046 Munich, Germany

<sup>d</sup>Center of Orthopedics and Sports Traumatology of the INI, Alexis Carrel Str. 4, 30625 Hanover, Germany

<sup>e</sup>Atos-Clinic, Bismarckstr. 9-11, 69198 Heidelberg, Germany

Accepted 24 March 2004

## Abstract

Bone tunnel enlargement is a common phenomenon following reconstruction of the anterior cruciate ligament (ACL). Biomechanical and biological factors have been reported as potential causes of this problem. However, there is no analysis of forces between the graft and bone, as the graft changes direction at the bone tunnel entrance.

The purpose of this study was to study these 'redirecting forces'.

Magnetic resonance images of 10 patients with an ACL reconstruction (age:  $26 \pm 6.8$  years) were used to determine the angle between graft and drill holes. Vector analysis was used to calculate the direction and magnitude of the perpendicular component of the force between the bone tunnel and the graft at the entrance of the bone tunnel. Force components were projected into the radiographically important sagittal and coronal planes. Tension of ACL reconstructions was recorded during passive knee motion in 10 cadaveric knee experiments (age:  $28.9 \pm 10.6$  years) and the tension multiplied with the force component for each plane.

Results are reported for the coronal and sagittal planes, respectively: For  $-10^\circ$  of extension, the percentages of graft tension were determined to be  $17 \pm 7$  (max: 26; min: 7%) and  $26 \pm 9$  (max: 39; min: 16%) for the tibia. They were  $59 \pm 6$  (max: 66; min: 48%) and  $99 \pm 1$  (max: 1.00; min: 99%) for the femur. Force components were  $14.68 \pm 6.54$  and  $25.73 \pm 12.96$  N for the tibial tunnel. For the femoral tunnel, they were  $52.48 \pm 19.03$  and  $90.77 \pm 32.06$  N.

Percentages of graft tension and force components were significantly higher for the femoral tunnel compared with the tibial tunnel. Moreover, in the sagittal direction, force components for the femoral tunnel were significantly higher compared with the coronal plane (Wilcoxon test,  $p < 0.01$ ).

The differences in force components calculated in this study corresponds with the amount of tunnel enlargement in the radiographic planes in the literature providing evidence that biomechanical forces play a key role in postoperative tunnel expansion.

© 2004 Elsevier Ltd. All rights reserved.

**Keywords:** Knee; Anterior cruciate ligament; Bone tunnel enlargement; Hyperextension

## 1. Introduction

Bone tunnel enlargement has been observed following reconstruction of the anterior cruciate ligament (ACL) (Fink et al., 2001; Hoher et al., 1998; Jansson et al.,

1999; Webster et al., 2001). The increase in tunnel diameter over time is greatest in between 4 and 6 months after surgery and then decreases at 1 and 2 years follow-up (Buelow et al., 2002; Webster et al., 2001).

A study that investigated bone tunnel healing in rabbits showed that drill holes without grafts heal from the outside to the surface of the joint creating a conical-shaped tunnel (Berg et al., 2001). However, this observation does not explain the differences in tunnel width that have been observed between the sagittal and anteroposterior planes (Clatworthy et al., 1999; Fink

\*Corresponding author. Tel.: +49-511-532-2050; fax: +49-511-532-5877.

E-mail addresses: michael@jagodzinski.com (M. Jagodzinski), foerstemann.thorsten@mh-hannover.de (T. Foerstemann), gmall@rechts.med.uni-muenchen.de (G. Mall), office@bosch-ini-hannover.de (U. Bosch).

et al., 2001; Jansson et al., 1999; L'Insalata et al., 1997). Tunnel enlargement is more commonly found when pure tendon grafts are used compared with bone patellar tendon autografts (Clatworthy et al., 1999; Webster et al., 2001).

Numerous studies have conducted displacement (Beynon et al., 1992) or tension (Goss et al., 1997; Markolf et al., 1990; Goss et al., 1997) measurements of the ACLs or ACL substitutes. However, no study used the data to determine the redirecting forces that are caused by the angulation of the graft at the entrance of the bone tunnels.

The purpose of this study is to investigate the magnitude of redirecting forces at the articular side of the tibial and femoral drill holes following a reconstruction of the ACL. The results are compared with the amount of tunnel expansion that others have observed following ACL reconstruction.

## 2. Material and methods

### 2.1. Patient selection and surgical technique

Ten patients having had ACL reconstructions using a semitendinosus/gracilis graft were examined in between 6 and 12 weeks (mean:  $8.3 \pm 2.4$  weeks) after they had a primary ACL reconstruction. Patients who had associated grade 3 collateral ligament tears or associated lateral or posterior instability or partial resection of the meniscus were excluded. The group consisted of six female and four male patients, with an average age of  $26 \pm 6.8$  years (range: 18–42 years) at the time of surgery.

All procedures were performed by a single surgeon (H.H.P.) using a doubled semitendinosus and gracilis graft. Graft diameter averaged  $8.6 \pm 0.7$  mm (range: 7–10 mm). An endoscopic technique was used in all cases. The tibial tunnel was drilled with a drill guide (Richard Wolf GmbH, Knittlingen, Germany) with an angulation of  $40\text{--}45^\circ$ . The femoral tunnel was drilled through the anteromedial portal using a guide (Arthrex<sup>®</sup>, Naples, FL) with the knee flexed  $120^\circ$  in the 11 or 1 o'clock position in a region that has been determined being most isometric (Hefzy et al., 1989). Femoral fixation was performed using a bottle-like tunnel which enabled a press fit fixation (Paessler and Thermann, 2002). Tibial fixation of the graft was performed using Mersilene sutures no. 6 (Ethicon Inc., Somerville, NJ) and a bone bridge. All drill holes were in the regions recommended by Harner et al. (1994) for the location of the femoral and tibial tunnel.

### 2.2. Magnetic resonance imaging

Imaging was performed on a 0.18 T MR-unit (Artoscan<sup>®</sup>, ESAOTE BIOMEDICA, Genua, Italy). The low-

field-strength MRI is equipped with a variable heel rest that enables the knee to fully extend. The knees were positioned at  $0^\circ$  of external rotation. Knee extension was increased stepwise. For each examination position, two independent observers assessed knee extension with a technique previously described with high accuracy ( $R^2 = 0.83$ ; Jagodzinski et al., 2000b). Each step averaged approximately  $2.5^\circ$ . Images closest to each  $10^\circ$  increment of knee extension were subject to further analyses.

A three-dimensional (3D) T1-weighted flash sequence was chosen with a resolution of  $256 \times 256 \times 128$  voxels. A field of view of 14–16 cm was used, depending on knee size. Imaging time was 2:56 min per sequence. Time to echo was 250 ms and repetition time was 560 ms, thus providing T1-weighted images. The coronal plane was aligned with the posterior outline of the femoral condyles with the knee fully extended. The femoral position was not changed during knee flexion. The images were then reconstructed in the coronal, sagittal and axial planes and transferred to a personal computer for further analysis. The procedure was repeated after increasing knee extension step by step.

### 2.3. Determination of graft tunnel angulation

Measurements of the angles between the ACL graft and the femoral and tibial tunnel were determined after importing the images into Auto-CAD (Auto-CAD, Autodesk Inc., San Rafael, CA 94903, USA). The image slices were superimposed and the outline of the femoral and tibial tunnels and the ACL graft were marked by 'eyeballing' the locations. The center of the drill holes and the graft was obtained using a midline function of the software (Fig. 1), creating a vector triplet in the sagittal, coronal and axial planes. Angle measurement function was used to determine the angles between the femoral and tibial tunnel and the graft in each plane. The procedure was repeated for the data of all knee extension angles.

### 2.4. Vector analysis

Vector analysis was used to calculate the direction and magnitude of the perpendicular component of the force between the bone tunnel and the graft at the entrance of the bone tunnel. This force was then projected into the sagittal and coronal planes to determine the percentage of graft tension and relative magnitude of this force that acts in the radiographic planes.

The axis of the bone tunnels and their articular connection lines create two pairs of intersecting lines that define a graft–drill hole angle ( $\alpha$ ,  $\beta$ ). These were determined in the coronal (COR), sagittal (SAG) and axial (AX) planes (Fig. 2). They were transferred into

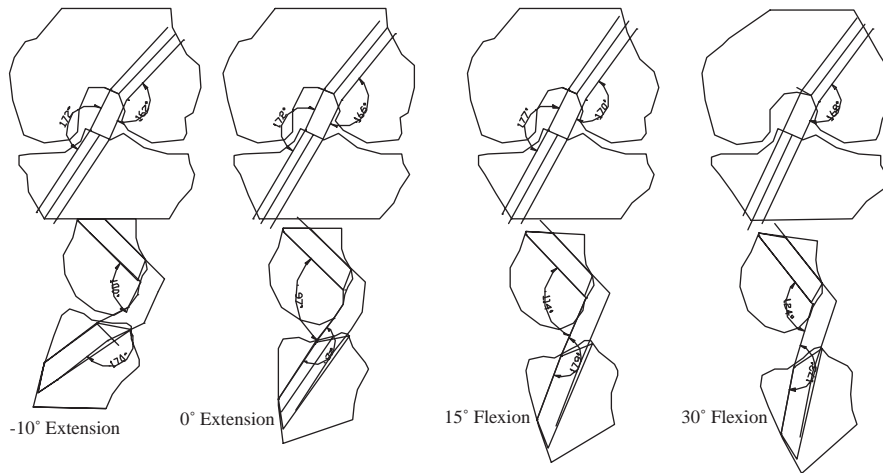


Fig. 1. MR images were obtained from reconstructions of 3D data in sagittal, coronal and axial planes and exported into a computer assisted design program. The outline of the bone tunnels was marked on each slice and the midpoints connected to obtain the tunnel projection. Angle measurement tool was used to determine corresponding tunnel-graft angles. The procedure was repeated for each knee extension angle.

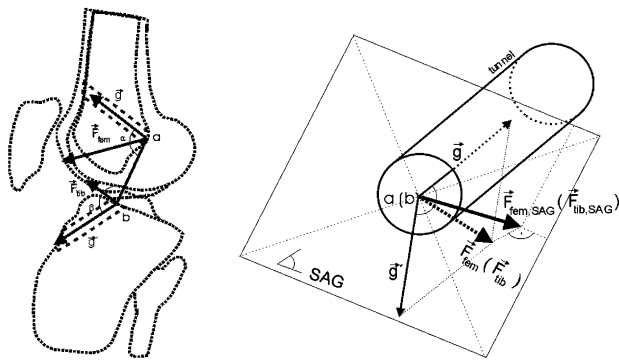


Fig. 2. Vectors parallel to the bone tunnels ( $\vec{g}$ ,  $\vec{g}'$ ) and the connection line between entrance point of femoral (a) and tibial tunnel (b) define vectors of redirecting forces ( $\vec{F}_{fem}$ ,  $\vec{F}_{tib}$ ; left). These vectors were projected in the sagittal and coronal planes (e.g. sagittal plane, right).

Cartesian coordinates  $\vec{a} = (a_x, a_y, a_z)$  using

$$\cos(\alpha) = \frac{\vec{a} \cdot \vec{b}}{|\vec{a}| |\vec{b}|}$$

After normal transformation of the vectors and their projections in the above-mentioned planes, a non-linear equation system with nine unknown variables (three vectors with three components each) has to be solved. As there can be no analytical solution to this problem, a residual function which includes the sum of the squared differences between observed and calculated angles was used. This residual function was minimized using random start vectors according to the Levenberg–Marquardt method (Meyer and Roth, 1972; Bronstein and Semendjajew, 1996). The numeric inaccuracies of the obtained minimal residuals are smaller than the ones that result from observing given angles from three different projections.

The calculated Cartesian coordinates of vectors parallel to the bone tunnels  $\vec{g}$ ,  $\vec{g}'$  and their intersecting

line  $[ab]$  can be used to determine the vectors for redirecting forces at the entrance of tibial and femoral bone tunnels ( $a$ ,  $b$ ,  $\vec{F}_{fem}$ ,  $\vec{F}_{tib}$ ; Fig. 2). The force vectors have to be projected into the plane which is perpendicular to the bone tunnel. In a second step, a projection into the sagittal and coronal planes was performed ( $\vec{F}_{fem,SAG}$ ,  $\vec{F}_{fem,COR}$ ,  $\vec{F}_{tib,SAG}$ ,  $\vec{F}_{tib,COR}$ ; Fig. 2), in order to assess the magnitude of force that may contribute to bone tunnel enlargement observed on sagittal and coronal radiographs/CT-scans.

The magnitude of the vectors projected in the sagittal and coronal planes can be simplified as percentages of graft tension  $f_{fem,SAG}$ ,  $f_{fem,COR}$ ,  $f_{tib,SAG}$ ,  $f_{tib,COR}$ .

The measured forces of the ACL reconstructions have to be multiplied with these percentages in order to obtain the magnitude of force in the corresponding planes that were obtained for various knee extension angles, for example

$$|\vec{F}_{fem,SAG(0^\circ)}| = f_{fem,SAG(0^\circ)} \times |\vec{g}_{(0^\circ)}|,$$

$|\vec{g}_{(0^\circ)}|$  is the magnitude of the vector parallel to the bone tunnel at an observed extension angle of  $0^\circ$ . These forces between the graft and bone, as the graft changes direction at the bone tunnel entrance, are referred to as ‘redirecting forces’.

### 2.5. Cadaver study

For tension measurements of the ACL reconstructions, the knees of 10 human cadavers were examined in the Department of Forensic Medicine of the Ludwig-Maximilian-University in Munich, Germany. The cadavers were matched with the patients with respect to sex, age ( $\pm 5$  years), knee laxity ( $\pm 2$  mm) and passive hyperextension capability ( $\pm 5^\circ$ ). The age was  $28.9 \pm 10.6$  (range 17–46) years. The examination took place an average  $2.1 \pm 1.2$  (range 0–3) days postmortem.

We used the legs of four men and six women, with a height of  $173.0 \pm 6.0$  (range 161–182) cm and a weight of  $72.9 \pm 15.4$  (range 55–106) kg. One knee showed a grade 3 osteochondral lesion of the medial femoral condyle and two specimens grade 2 lesions of the patellofemoral joint. However, no signs of ligament damage or meniscal injuries or general arthritis were observed.

## 2.6. Technical equipment

For tension measurements, a tension load cell (ELFS-T3, Entran Devices Inc., Fairfield, NJ) with a measurement range of 0–500 N (0.2% accuracy in relation to its measurement range) was connected to a external fixator with a calibration device. For the determination of knee extension, a precision long-arm goniometer that is equipped with molds of the greater trochanter and the anterior tibia was connected to a digital increment transducer that produces signals in steps of  $0.34^\circ$ . The accuracy of the device has been determined with 0.6% on a measurement range of  $180^\circ$  in a previously published investigation (Jagodzinski et al., 2000a). All sensors were connected to a central processing unit, both tension and pressure sensors were temperature compensated. Data were recorded on a random access memory chip and transferred to an IBM compatible notebook personal computer after each loading cycle.

## 2.7. Cadaver preparation and measurement technique

The knee and hip joints were passively moved through the full range of motion 20 times to reduce tissue stiffness caused by the rigor mortis. A central arthrotomy was used and the patella was dislocated laterally. The infrapatellar plica and parts of Hoffa's fat pad were resected to facilitate exposure of the cruciate ligaments. The precision goniometer was aligned with the axis of rotation of ankle, knee and hip.

An instrumented maximal manual Lachman test was measured with a knee arthrometer (Rolimeter<sup>®</sup>, Aircast Europa GmbH, Neubeuern, Germany) three times. The mean value was recorded. Lachman testing was performed by the same investigator consistently for each cadaver.

The preparation technique was the same as for the surgical technique described for the ACL reconstruction technique. Tunnel placement was checked using a fluoroscope. A sagittal X-ray was taken in order to correct tunnel placement according to published standards (Harner et al., 1994).

For the tibial tunnel, a 12 mm drill hole was established in the posterior section of the ACL footprint using an arthroscopic tibial drill guide (Sulzer AG, Winterthur, Switzerland). A poly-tetra fluor ethylene (PTFE) bushing with an external diameter of 12 mm and an internal diameter of 8 mm was inserted into the tibial

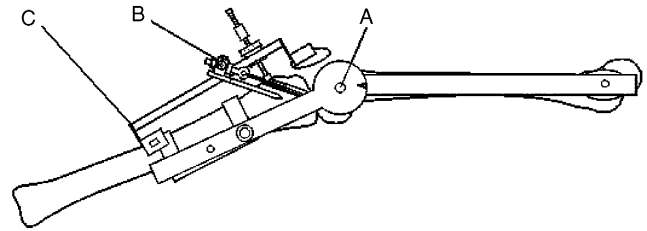


Fig. 3. A long-arm goniometer with molds of the greater trochanter and the anterior tibia was equipped with a digital incremental transducer (A) to obtain knee extension angles. The ACLs were reinserted through a tibial drill hole with a PTFE bushing and connected to a load cell (B). Tension was increased until preoperative laxity was restored. Knee laxity was determined with a Rolimeter<sup>®</sup> (C) and a maximum manual test.

tunnel. A self-drilling Steinmann nail was drilled parallel to the tibial tunnel distally.

The graft was inserted through the PTFE bushing. The tension measurement sensor with a custom made buckle was attached to the Steinmann pin and connected with the graft in front of the outlet of the tunnel (Fig. 3).

After initial fixation, the ACL graft was preconditioned applying 20 cycles through the full passive range of motion. Tension was adjusted until the maximal manual displacement was restored to the preoperative value. The maximum manual measurements of tibial translation were recorded three times. The standard deviation for intraobserver measurements was 0.8 mm. The maximal manual displacement was controlled after each testing cycle; if there was an increase, the measurements were repeated after readjusting graft tension.

The tension testing protocol started with three repeated measurements from full passive extension (foot on a heelrest) into full flexion. The tension levels were transferred to a notebook computer after each testing cycle.

## 2.8. Statistical analysis

All mean values are reported with standard deviations, such as minimum and maximum. Due to the small number of cases, we used a non-parametric, two-tailed Wilcoxon test (Bosch, 2002). A *P*-level of 0.05 was regarded significant. The procedures were performed using SPSS for Windows 10.0 (SPSS-company, Chicago, IL 60606, USA).

## 3. Results

### 3.1. Bone tunnel-graft angulations

The following data are reported for the sagittal, coronal and axial planes, respectively. The acutest

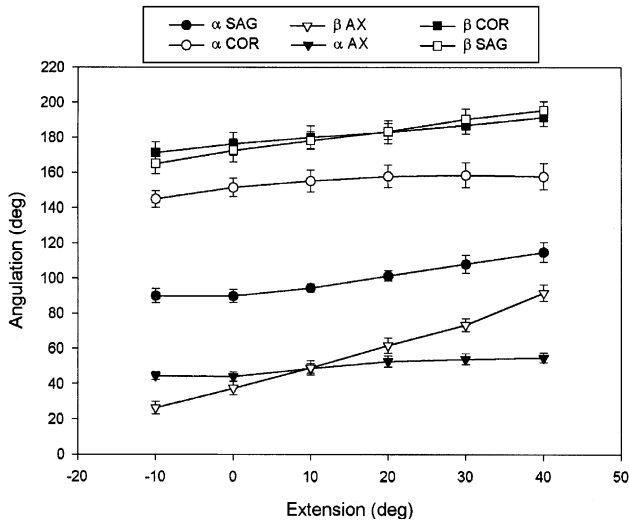


Fig. 4. Angulations between femoral ( $\alpha$ ) and tibial ( $\beta$ ) tunnel and ACL graft in the sagittal (SAG), coronal (COR) and axial (AX) planes as a function of knee extension.

femoral tunnel angles were observed for full extension. At  $-10^\circ$  hyperextension, tunnel graft angulation was  $90.1^\circ \pm 4.0^\circ$  (max  $95^\circ$ , min  $83^\circ$ ),  $145.1^\circ \pm 4.7^\circ$  (max  $154^\circ$ , min  $140^\circ$ ) and  $44.7^\circ \pm 2.2^\circ$  (max  $48^\circ$ , min  $40^\circ$ ). Angles increased with knee flexion.

For the tibial tunnel, angles in the sagittal and coronal planes were more obtuse than femoral tunnel angles. For  $-10^\circ$  hyperextension, they averaged  $165.1^\circ \pm 5.7^\circ$  (max  $173^\circ$ , min  $157^\circ$ ) and  $171.4^\circ \pm 5.9^\circ$  (max  $183^\circ$ , min  $165^\circ$ ). In the axial plane, angles were more acute and increased with knee flexion, being  $91.8^\circ \pm 4.8^\circ$  (max  $98^\circ$ , min  $81^\circ$ ) for  $40^\circ$  of knee flexion. The data are summarized in Fig. 4.

### 3.2. Percentages of graft tension

The mathematical calculation of the percentages of graft tension revealed that the highest percentages were found for the femoral tunnel in the sagittal plane (at  $-10^\circ$ :  $99 \pm 1\%$ ;  $88$ – $99\%$ ). They were significantly higher than in the coronal plane for all observed extension angles ( $p < 0.01$ ). Both were significantly higher than percentages for the tibial tunnel for all observed extension angles ( $p < 0.01$ ). For the tibial tunnel, the force percentage in the sagittal plane was only significantly higher for  $-10^\circ$  extension ( $p < 0.02$ ). Data for the entire range of motion in between  $-10^\circ$  and  $40^\circ$  of knee extension are summarized in Fig. 5.

### 3.3. Knee extension and stability parameters

Maximum extension of all 10 knees combined was  $-7.9 \pm 2.4^\circ$  ( $-14.0^\circ$  to  $-6.2^\circ$ ). Extension increased to  $-8.2 \pm 5.7^\circ$  ( $-16.0^\circ$  to  $-5.0^\circ$ ) after resection of the ACL

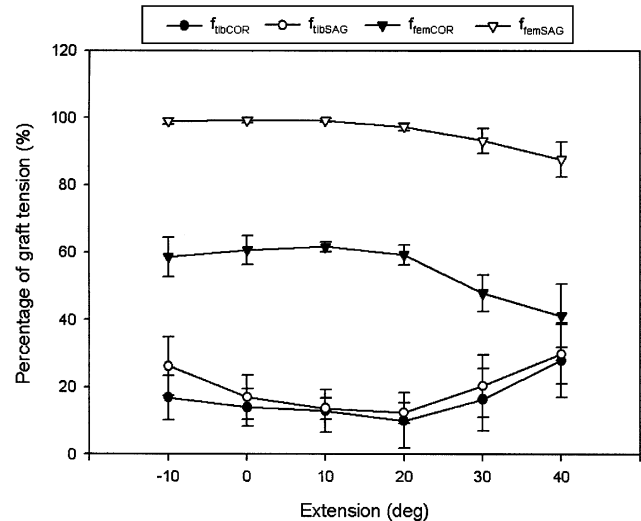


Fig. 5. Force percentages ( $f$ ) for the redirecting forces of ACL grafts at the entry of tibial and femoral tunnels to the joint in the sagittal (SAG) and coronal (COR) planes as a function of knee extension.

and was restored after reconstruction of the ACL to  $-7.6 \pm 2.2^\circ$  ( $-13.0$ – $5.0^\circ$ ).

Maximal manual displacement of the tibia was  $6.2 \pm 1.7$  mm ( $4.0$ – $10.0$  mm) preoperatively, increasing to  $12.8 \pm 1.5$  mm ( $10.0$ – $15.0$  mm) in the ACL insufficient knees. Preoperative maximal manual displacement values could be restored in all cases.

### 3.4. Anterior cruciate ligament graft tension

We observed a continuous increase in tension of the ACL grafts from flexion until full passive extension. Tension of the ACL reconstructions was determined with  $101.9 \pm 38.4$  N ( $40.5$ – $166.0$  N) for  $-10^\circ$  hyperextension and  $64.1 \pm 19.9$  N ( $28.5$ – $91.7$  N) at zero degrees of extension (Fig. 6). The Data were used to determine the force components.

### 3.5. Force components

With the force percentages calculated, the force components were highest in full extension. The components were significantly higher for the femoral tunnel in the sagittal plane ( $90.77 \pm 32.06$  N;  $49.87$ – $131.99$  N) compared with the coronal plane ( $52.48 \pm 19.03$  N;  $27.77$ – $9.763$  N) and with the tibial tunnel in both sagittal ( $25.73 \pm 12.96$  N;  $7.83$ – $43.09$  N) and coronal planes ( $14.68 \pm 6.54$  N;  $7.11$ – $27.56$  N) in between  $-10^\circ$  and  $30^\circ$  (Table 1). For the tibial tunnel, there was a significant difference between the sagittal and the coronal force components at  $-10^\circ$  extension ( $p < 0.02$ ). The complete data for the force components are shown in Figs. 6 and 7.

4. Discussion

Tunnel widening has been observed by many authors following reconstruction of the ACL (Hogervorst et al., 2000; Jansson et al., 1999; Webster et al., 2001). Although there is no correlation between tunnel enlargement and short-term follow-up (Jansson et al., 1999; Nebelung et al., 1998; Segawa et al., 2001), there are clinical problems associated with this phenomenon: Wide tunnels alter the direction of the graft within the joint. If a revision surgery is necessary, the enlarged tunnels must be filled up with bone before a new transplant can be inserted (Brown and Carson, 1999).

The reasons for bone tunnel enlargement are still not fully understood. Biomechanical stress of the graft could be the main contributing factor.

This study was conducted in order to examine ACL graft redirecting forces in patients who underwent a reconstruction of the ACL.

In order to assess the tension of the reconstructions, tunnel angulation was simulated in cadavers that matched the reconstruction group.

Although this may have caused some error from the true tension that occurs during flexion/extension in vivo,

the results of the cadaver experiments were very close to the ones obtained from in vivo measurements. In their investigation of active flexion–extension, Beynnon et al. (1992, 1997) found an increase of ACL strain up to 3–4% from 30° to 10° of extension (this study was limited to +10° of knee extension due to impingement of the sensor). The analysis of ACL tension with a load transducer reports 118 (50–240 N) for knee extension of –5° (Markolf et al., 1990). There is an exponential increase in ligament tension during the final 20° of knee extension in this study. This tension is increased by quadriceps tendon pull and contraction of both quadriceps and hamstring tendons (Markolf et al., 1990; Beynnon et al., 1997). Hence, the absolute magnitudes of tension determined in this study, may be underestimated. The occurrence of high forces during the last 30 degrees of full extension is consistent with all the above-mentioned studies. Proportions of the graft magnitudes are only a subject to changes of graft–tunnel angles and knee kinematics; these parameters were determined from in vivo magnetic resonance images.

The redirecting forces determined in this investigation with the ACL reconstruction technique chosen resulted

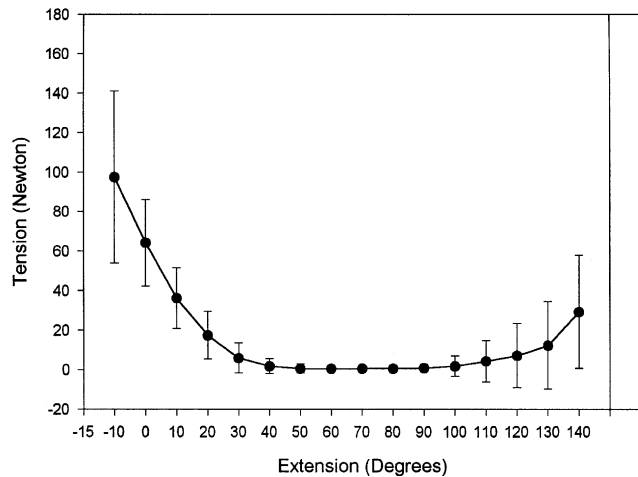


Fig. 6. Tension of ACL grafts obtained from the cadaveric experiments as a function of knee extension.

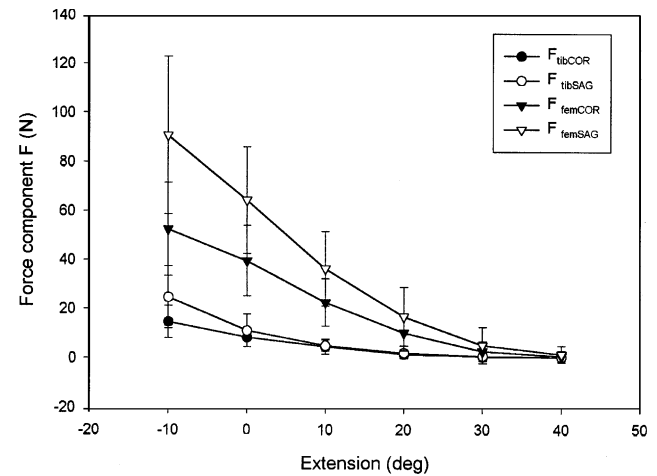


Fig. 7. Predictions of redirecting forces ( $|F_{fem}|, |F_{tib}|$ ) obtained from combined in vivo and experimental in vitro data in the sagittal and coronal planes as a function of knee extension.

Table 1  
Significance levels for the different force components (F) in the observed planes (two-tailed Wilcoxon test)

| Extension (deg) | tib_SAG<br>tib_COR | fem_SAG<br>fem_COR | fem_COR<br>tib_COR | fem_SAG<br>tib_SAG | fem_SAG<br>tib_COR | fem_COR<br>tib_SAG |
|-----------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| -10             | <b>0.018</b>       | <b>0.018</b>       | <b>0.018</b>       | <b>0.018</b>       | <b>0.018</b>       | <b>0.018</b>       |
| 0               | 0.221              | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       |
| 10              | 0.445              | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       |
| 20              | 0.169              | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       | <b>0.005</b>       |
| 30              | 0.233              | <b>0.022</b>       | <b>0.028</b>       | <b>0.022</b>       | <b>0.022</b>       | <b>0.028</b>       |
| 40              | 0.483              | 0.059              | 0.236              | 0.092              | 0.092              | 0.269              |

tib: tibial tunnel; fem: femoral tunnel; COR: coronal plane; SAG: sagittal plane. Bold: significance ≤ 0.05.

in significantly higher redirecting forces at the articular entrance of femoral than of tibial tunnels. There was a significant difference between the sagittal and the coronal plane for both the femoral ( $-10$ – $30^\circ$ ) and tibial tunnel (at  $-10^\circ$ ). These findings correspond with the reports of tunnel widening in the literature (Table 2). Throughout all reports, there is more tunnel enlargement evident for the femoral than for the tibial tunnel. All cited references show more tunnel widening for the tibial tunnel in the sagittal compared with the coronal plane. However, there is not enough data published in order to perform a regression analysis.

Biologic factors contributing to bone tunnel enlargement are discussed in the literature: Soft tissue grafts are more likely to develop bone tunnel enlargement than bone tendon bone grafts (Webster et al., 2001). Bone density of the drill hole wall and synovial fluid that enters the drill holes are also accused (Hoher et al., 1998).

Movement of the graft within the tunnel has been demonstrated to enlarge the tunnels significantly (Buelow et al., 2002). Two ways of motion have been defined: Along ('bungee effect') and perpendicular to the axis of the tunnel ('windshield wiper effect') (Hoher et al., 1998). Movement leads to a soft tissue interface between bone and graft and promotes 'degloving' of the reconstruction (Weiler et al., 2000). Both forms of graft motion are caused by the vectors investigated in this study.

Perren (1979) described in his 'Interfragmentary Strain Theory' that the transformation of tissue type is a function of gap distance and gap motion. Both are influenced by the force magnitude and direction investigated in this study. If the gap becomes too large, non-union or delayed union may occur even with adequate fixation. Reduction of the gap occurs when a press fit fixation close to the tunnel entrance and a limitation of redirecting forces are established.

Graft fixation close to the articular entrance of the tunnels does influence graft–bone tunnel pressure: an interference screw positioned on the side of the tunnel that faces the direction of the force vector can exert an opposite force on the graft. Close to tunnel fixation

limits graft migration in the direction of the force vector (Hoher et al., 1998). To our knowledge, there is no in vivo study that has investigated if graft motion within the bone tunnels stops as a response to healing. Weiler et al. (2002) have demonstrated in an animal model, that with a close to tunnel fixation, a mature intratunnel tendon–bone junction with a zone of fibrocartilage is found at 9–12 weeks.

As a magnetic resonance imaging system was used to acquire the 3D data of the knees, this study could not determine graft tunnel angles and redirecting forces for knee flexion beyond  $50^\circ$ . However, the tension data for ACL grafts show (similar to Markolf et al., 1990) that there is limited tension for the range of motion in between  $50^\circ$  and  $110^\circ$ .

Redirecting forces may be an important factor that causes bone tunnel widening as the reconstruction is stressed mechanically. The magnitude of redirecting forces depends on graft tunnel angle and intraligament tension. The tunnel angle for the femoral tunnel in most reconstruction techniques used today is steeper in the extended knee. Since this and other studies found the highest graft tension levels in extension, redirecting forces are higher in the femoral bone tunnel, especially in the sagittal plane. Possible solutions to this problem can be to reduce the tunnel angulation (especially the femoral tunnel angle). Rigid close to tunnel fixation is another key that may prevent redirecting forces to cause tunnel widening. Immobilization would certainly diminish redirecting forces but has been shown to compromise postoperative results. However, instead of immobilization, we would recommend repeated uncontrolled exercising in the range of motion that has been shown to cause redirecting forces to occur ( $15^\circ$  of flexion to full hyperextension). The effects of such a modified rehabilitation protocol in terms of tunnel widening have to be studied. Interestingly, a recent study has shown that aggressive rehabilitation is correlated with bone tunnel enlargement (Paessler and Mastrokalos, 2003). To our knowledge, there has been no study that examines the time dependence of tunnel migration. It certainly depends on the type of fixation used. When using a rigid close to tunnel fixation, Weiler et al. demonstrated

Table 2  
Comparison of bone tunnel enlargement in four studies

| Author                      | Fink et al. (2001) | Jansson et al. (1999)           | L'Insalata et al. (1997)        | L'Insalata et al. (1997) |
|-----------------------------|--------------------|---------------------------------|---------------------------------|--------------------------|
| Graft                       | Patellar tendon    | Semitendinosus/gracilis tendons | Semitendinosus/gracilis tendons | Patellar tendon          |
| Imaging method              | CT-scan            | Radiograph                      | Radiograph                      | Radiograph               |
| Time after surgery (months) | 24                 | 24                              | 6–12                            | 9–22                     |
| Tibia coronal               | 16.4%              | 31%                             | $20.9 \pm 13.4\%$               | $9.7 \pm 14.7\%$         |
| Tibia sagittal              | 30.6%              | 42%                             | $25.5 \pm 16.7\%$               | $14.4 \pm 16.1\%$        |
| Femoral coronal             | —                  | 48%                             | $30.2 \pm 17.2\%$               | —                        |
| Femoral sagittal            | —                  | na                              | $28.1 \pm 14.7\%$               | —                        |

Note: The percentage of tunnel diameter increase is consistently larger for the sagittal plane of the tibia compared with the coronal plane (na = not analyzed).

in a sheep model that Sharpey-like fibers develop at the tunnel outlet within 6 weeks.

There are also important biological factors that contribute to bone tunnel enlargement. The most prominent one is the choice of graft. Tendons show more tunnel widening than bone blocks (L'Insalata et al., 1997; Webster et al., 2001). However, discrepancies between the amount of tunnel enlargement can be observed between the anteroposterior and sagittal planes in various studies (Buelow et al., 2002; Clatworthy et al., 1999; Hogervorst et al., 2000; Jansson et al., 1999; Webster et al., 2001).

Further investigations that examine the impact of biomechanical stress (rehabilitation programs with limitation of extension versus full active and passive hyperextension) are necessary to assess if there is a biological response to redirecting forces in ACL reconstructions.

## Acknowledgements

We want to express our special thanks to H. Klein and his team at the Department of Forensic Medicine for the support of this study. Further we wish to thank Prof. Dr.-Ing. C. Hartung, for assistance in the vector analysis of the data, and to Albrecht GmbH, Neu-beuern, Germany, for supporting this investigation.

## References

- Berg, E.E., Pollard, M.E., Kang, Q., 2001. Interarticular bone tunnel healing. *Arthroscopy* 17, 189–195.
- Beynon, B., Howe, J.G., Pope, M.H., Johnson, R.J., Fleming, B.C., 1992. The measurement of anterior cruciate ligament strain in vivo. *International Orthopaedics* 16, 1–12.
- Beynon, B.D., Johnson, R.J., Fleming, B.C., Stankewich, C.J., Renstrom, P.A., Nichols, C.E., 1997. The strain behavior of the anterior cruciate ligament during squatting and active flexion–extension. A comparison of an open and a closed kinetic chain exercise [see comments]. *American Journal of Sports Medicine* 25, 823–829.
- Bosch, K., 2002. *Statistik-Taschenbuch*. Oldenburg Verlag, Munich, Vienna, Oldenburg.
- Bronstein, I.N., Semendjajew, K.A., 1996. *Taschenbuch der Mathematik*. Teubner, Stuttgart.
- Brown Jr., C.H., Carson, E.W., 1999. Revision anterior cruciate ligament surgery. *Clinics in Sports Medicine* 18, 109–171.
- Buelow, J.U., Siebold, R., Ellermann, A., 2002. A prospective evaluation of tunnel enlargement in anterior cruciate ligament reconstruction with hamstrings: extracortical versus anatomical fixation. *Knee Surgery Sports Traumatology Arthroscopy* 10, 80–85.
- Clatworthy, M.G., Annear, P., Bulow, J.U., Bartlett, R.J., 1999. Tunnel widening in anterior cruciate ligament reconstruction: a prospective evaluation of hamstring and patella tendon grafts. *Knee Surgery Sports Traumatology Arthroscopy* 7, 138–145.
- Fink, C., Zapp, M., Benedetto, K.P., Hackl, W., Hoser, C., Rieger, M., 2001. Tibial tunnel enlargement following anterior cruciate ligament reconstruction with patellar tendon autograft. *Arthroscopy* 17, 138–143.
- Goss, B.C., Hull, M.L., Howell, S.M., 1997. Contact pressure and tension in anterior cruciate ligament grafts subjected to roof impingement during passive extension. *Journal of Orthopaedic Research* 15, 263–268.
- Harner, C.D., Marks, P.H., Fu, F.H., Irrgang, J.J., Silby, M.B., Mengato, R., 1994. Anterior cruciate ligament reconstruction: endoscopic versus two-incision technique. *Arthroscopy* 10, 502–512.
- Hefzy, M.S., Grood, E.S., Noyes, F.R., 1989. Factors affecting the region of most isometric femoral attachments. Part II: the anterior cruciate ligament. *American Journal of Sports Medicine* 17, 208–216.
- Hogervorst, T., van der Hart, C.P., Pels Rijcken, T.H., Taconis, W.K., 2000. Abnormal bone scans of the tibial tunnel 2 years after patella ligament anterior cruciate ligament reconstruction: correlation with tunnel enlargement and tibial graft length. *Knee Surgery Sports Traumatology Arthroscopy* 8, 322–328.
- Hoher, J., Moller, H.D., Fu, F.H., 1998. Bone tunnel enlargement after anterior cruciate ligament reconstruction: fact or fiction? *Knee Surgery Sports Traumatology Arthroscopy* 6, 231–240.
- Jagodzinski, M., Kleemann, V., Schoenhaar, V., Iselborn, K.W., Mall, G., Nerlich, M., 2000a. Experimental and clinical analysis of the accuracy of knee extension measurement techniques. *Knee Surgery Sports Traumatology Arthroscopy* 8, 329–336.
- Jagodzinski, M., Richter, G.M., Passler, H.H., 2000b. Biomechanical analysis of knee hyperextension and of the impingement of the anterior cruciate ligament: a cinematographic MRI study with impact on tibial tunnel positioning in anterior cruciate ligament reconstruction. *Knee Surgery Sports Traumatology Arthroscopy* 8, 11–19.
- Jansson, K.A., Harilainen, A., Sandelin, J., Karjalainen, P.T., Aronen, H.J., Tallroth, K., 1999. Bone tunnel enlargement after anterior cruciate ligament reconstruction with the hamstring autograft and endobutton fixation technique. A clinical, radiographic and magnetic resonance imaging study with 2 years follow-up. *Knee Surgery Sports Traumatology Arthroscopy* 7, 290–295.
- L'Insalata, J.C., Klatt, B., Fu, F.H., Harner, C.D., 1997. Tunnel expansion following anterior cruciate ligament reconstruction: a comparison of hamstring and patellar tendon autografts. *Knee Surgery Sports Traumatology Arthroscopy* 5, 234–238.
- Markolf, K.L., Gorek, J.F., Kabo, J.M., Shapiro, M.S., 1990. Direct measurement of resultant forces in the anterior cruciate ligament. An in vitro study performed with a new experimental technique. *Journal of Bone and Joint Surgery [American]* 72, 557–567.
- Meyer, R.R., Roth, P.M., 1972. Modified damped least squares: an algorithm for nonlinear estimation. *Journal of Mathematics and its Applications* 9, 218–233.
- Nebelung, W., Becker, R., Merkel, M., Ropke, M., 1998. Bone tunnel enlargement after anterior cruciate ligament reconstruction with semitendinosus tendon using endobutton fixation on the femoral side. *Arthroscopy* 14, 810–815.
- Paessler, H.H., Mastrokalos, D.S., 2003. Anterior cruciate ligament reconstruction using semitendinosus and gracilis tendons, bone patellar tendon, or quadriceps tendon-graft with press-fit fixation without hardware. A new and innovative procedure. *Orthopedic Clinics of North America* 34, 49–64.
- Paessler, H.H., Thermann, H., 2002. *The anterior cruciate ligament: state of the art 2000*. Barth Verlag, Heidelberg (Ref Type: Generic).
- Perren, S.M., 1979. Physical and biological aspects of fracture healing with special reference to internal fixation. *Clinical Orthopaedics and Related Research* 138, 175–196.
- Segawa, H., Omori, G., Tomita, S., Koga, Y., 2001. Bone tunnel enlargement after anterior cruciate ligament reconstruction using

- hamstring tendons. *Knee Surgery Sports Traumatology Arthroscopy* 9, 206–210.
- Webster, K.E., Feller, J.A., Hameister, K.A., 2001. Bone tunnel enlargement following anterior cruciate ligament reconstruction: a randomised comparison of hamstring and patellar tendon grafts with 2-year follow-up. *Knee Surgery Sports Traumatology Arthroscopy* 9, 86–91.
- Weiler, A., Hoffmann, R.F., Stahelin, A.C., Helling, H.J., Sudkamp, N.P., 2000. Biodegradable implants in sports medicine: the biological base. *Arthroscopy* 16, 305–321.
- Weiler, A., Hoffmann, R.F., Bail, H.J., Rehm, O., Sudkamp, N.P., 2002. Tendon healing in a bone tunnel. Part II: histologic analysis after biodegradable interference fit fixation in a model of anterior cruciate ligament reconstruction in sheep. *Arthroscopy* 18, 124–135.