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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

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Abstract This study analyzed the interaction between the anterior cruciate ligament (ACL) and the intercondylar notch roof (INR) in hyperextension of the knee using magnetic resonance cinematography. Cinematographic image series of 15 knees were investigated. Two independent observers identified the image that displayed the beginning of contact between the ACL and the INR. They determined knee extension on this image and on the image that displayed maximum hyperextension of the knee. Correlations between a variable representing impingement and the inclination angle of the INR, the anterior laxity of the knee, and full hyperextension were examined. Theoretical, impingement-free tibial tunnel positions for the knees were calculated as a percentage of the anteroposterior tibial width. All ACLs of the knees in this study made contact with the INR. The average extension angle at

the beginning of impingement was $-6.3 \pm 3.8^\circ$. There were significant correlations between impingement and maximum manual displacement as measured with the arthrometer ($r = 0.77$; $P < 0.001$), maximum hyperextension ($r = 0.67$; $P = 0.007$), and notch roof angle ($r = -0.73$; $P = 0.002$). There were biomechanically acceptable tunnel positions for all knees but one. Hyperextension is physiologically associated with impingement of the ACL. In uninjured knees there was a correlation between ACL impingement and hyperextension, inclination of the INR, and maximum manual displacement of the tibia. Impingement free tibial tunnel positioning is possible in most knees without notchplasty.

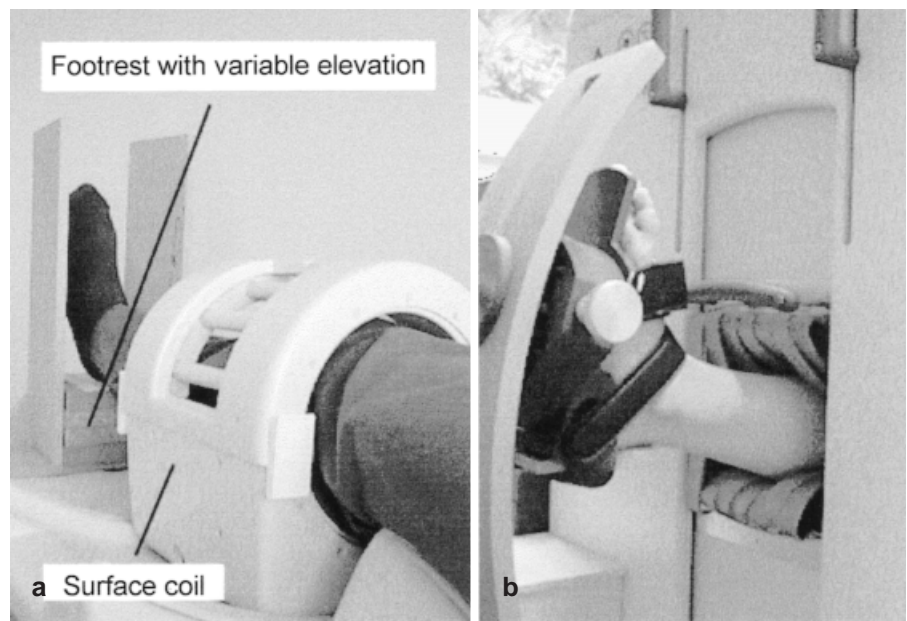
Key words Cinematography · Anterior cruciate ligament · Impingement · Notchplasty · Hyperextension

Introduction

The term roof impingement refers to contact between an anterior cruciate ligament (ACL) graft and the intercondylar notch roof (INR) [11–17]. Numerous authors have pointed out the importance of avoiding impingement in ACL reconstruction [7, 11–18, 23, 25, 32, 34, 36, 37]. Impingement is considered harmful for a graft and can lead to loss of extension, postoperative pain, graft deterioration, and the so-called “cyclops syndrome” [4, 27, 36]. Little is known about the interaction between the ACL

and the INR in the uninjured knee. According to Howell and Barad [13] the knee is able to hyperextend up to an average $-10 \pm 5.7^\circ$, and studies emphasize unimpaired postoperative side-to-side extension [31, 32] after reconstruction of the ACL; despite this, however, few biomechanical studies of the knee ligaments examine hyperextension [6, 10, 23, 26]. Friedman and Feagin [5] studied the anatomy of two frozen cadavers and found that the roof of the intercondylar fossa (notch) is V-shaped, impinges in hyperextension, and ruptures the ACL when the knee is forced into hyperextension. Howell and colleagues [17] have described the orientation of the ACL in

Fig. 1 a, b Positioning in the 1.0-T (a) and in the 0.18-T MRI (b)



terminal extension as vertical to the articular surface of the tibial plateau; the possibility of contact with the INR is not in their work. Beynnon and coworkers [2] investigated the stress behavior of the ACL using a hall effect transducer; however, the measurement of forces in hyperextension could not be determined due to impingement of the sensor. From the radiological point of view, magnetic resonance imaging (MRI) demonstrates a parallel alignment of ACL fibers with Blumensaat's line in hyperextension; no direct relationship with the INR has been reported [21]. Thus at present an exact analysis of hyperextension with regard to roof impingement is lacking.

High accuracy has been reported for MRI in detecting ruptures of the ACL [19, 28, 29]. The appearance of reconstructed ACLs subjected to roof impingement has been evaluated by MRI [14], and cinematographic MRI has been used to describe the biomechanics of the temporomandibular and patellofemoral joints [33]. This study examined the interaction between the ACL and the INR using cinematographic MRI. Differences in knee biomechanics and correlations between anatomical and biomechanical knee parameters were investigated, and theoretical positions of impingement free tibial tunnels were calculated.

Materials and methods

A total of 20 volunteers with a varying ability to hyperextend their knee were examined by cinematographic MRI. Five were excluded because of a lack of display of the ACL on parts of the image series. The remaining 15 subjects (9 women and 6 men) were aged between 17 and 42 years (mean 28 ± 6.37), none of whom had experienced injury to the knee. Clinical examination showed stable knee conditions; subjects with congenital laxity in both knees were not excluded.

Table 1 Scan parameters in the 0.18-T and the 1.0-T MRI

	Artoscan	Gyrosan
Type of sequence	Cinematography	T1-weighted turboflash echo
Image planning	Axial	Axial
Slice orientation	Sagittal oblique	Sagittal oblique
TR (ms)	200	16
TE (ms)	24	7.5
Flip angle (degrees)	–	75
Matrix	192×160	128×256
Slice thickness (mm)	5	5
Examination time (min)	1:06	0:23

MRI technique

Ten series were performed on a 0.18-T MRI unit (Artoscan, Esaote Biomedica, Genoa, Italy) using a variable heel rest; the remaining five patients were examined on a 1.0-T superconducting magnet (Gyrosan, Philips, Amsterdam, Netherlands) with a dedicated surface receiver coil. Knee extension could be modified stepwise by about 2.5° ; this was accomplished by increasing the foot support (Fig. 1). The low field strength MRI is equipped with a variable heel rest that was modified to enable full hyperextension of the knee (Fig. 1). The knees were positioned in 0° of external rotation. All patients were asked to relax the extremity.

The efficacy of current high and middle field strength MRI units in diagnosing ACL tears has been reported [35]; the same accuracy can be achieved when lower field strength is compensated by increasing imaging time. Regarding the parameters displayed in Table 1, images were similar in quality (matrix, signal to noise ratio, quality factor). To display the ACL in its full intra-articular pathway an axial scout was taken for image planning. The proper alignment of the ACL on a sagittal image was provided by a slight angulation (between 5° and 8°) depending on the planning image. The slice thickness was mounted to 5 mm to ensure display of the ACL with the variation of extension. All knees were brought into full passive hyperextension. Extension was decreased about 2.5°

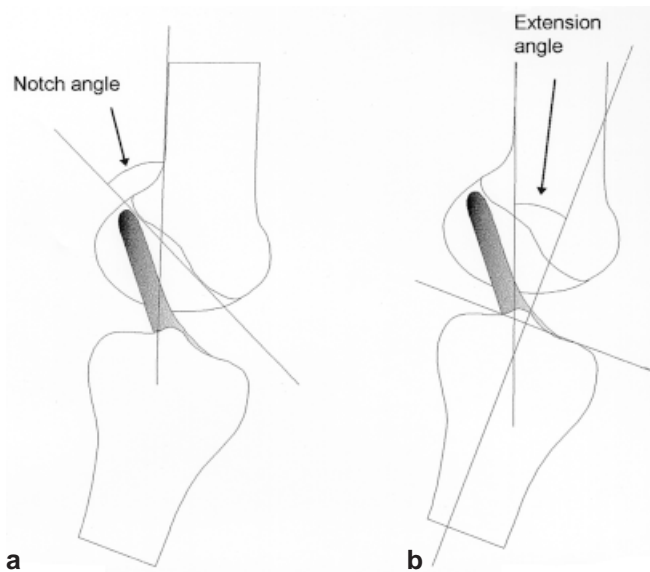


Fig. 2 **a** The slope of the intercondylar roof was determined by the intersection of the lines drawn parallel to the posterior cortex of the femur and Blumensaat's line. **b** Knee extension angles were measured with lines drawn parallel to the posterior cortex of the femur and a line drawn perpendicular to the tibial plateau on sagittal MRI

per scan until there was an obvious gap between the ACL and the INR. Inclination of the INR and extension angles were measured on a precisely sagittal scan through the middle of the joint.

Interpretation of MR images

Cinematography was used to determine whether the ACL made contact with the articular surface of the INR. This is enabled by a software function that creates a moving-picture from a series of MR images. Knee extension was determined by the line drawn parallel to the posterior cortex of the femur and a line drawn perpendicular to the tibial plateau (Fig. 2). A goniometer was used for the measurements. Two independent, blinded observers constructed two different angles; first, knee extension on the image that displayed the beginning of contact between the ACL and the INR was measured, and then maximum extension of the individual knee was determined. Three measurements of each extension angle were made by each observer; the mean value was recorded. Impingement laxity was defined as the difference in extension between contact of the ACL with the INR and maximum extension of the knee. This variable represents the impingement observed with the cinematographic analysis. Measurements of the inclination of the INR have reached high accuracy on X-rays [13]. In this study the measurement was performed by sagittal MRI in analogy (Fig. 2).

Measurement of the maximum manual displacement of the tibia in the Lachman position

The maximum manual displacement of the tibia in 30° of flexion of the knee was used to obtain a variable representing knee laxity (KT-1000, MedMetric, San Diego, Calif., USA). The measurement was performed by one of two independent assistant physicians during office hours before the patient was asked to participate in this study. The procedure was performed in accordance with published guidelines [3]. A side-to-side difference of more than 2 mm resulted in exclusion from the study.

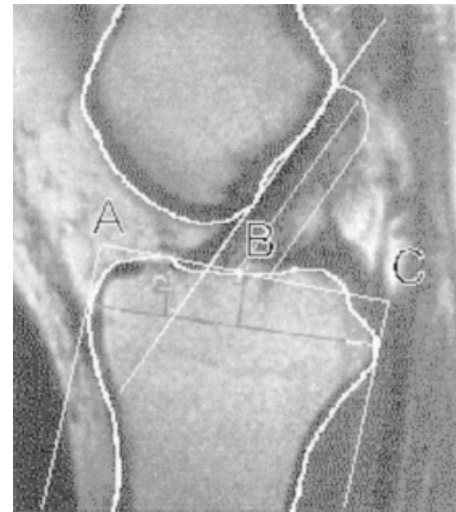


Fig. 3 Theoretical position of an impingement-free tibial tunnel modified according to Howell and Barad [15] on sagittal MRI of the knee in full hyperextension. The joint line is constructed vertical to a parallel of the posterior cortex of the tibia. *A*, *C* Are defined as the intersections of lines drawn perpendicular to the tibial plateau running through the most anterior (*A*) and posterior (*C*) points of the tibial cortex. *B* Is the intersection of a central line of a 10-mm tibial tunnel, located posterior to Blumensaat's line, and the tibial plateau. The percentage of the distance of *B* from *A* compared with the width of the tibial plateau *AC* was used to express the position of an impingement-free tibial tunnel

Theoretical position of impingement free tibial drill holes

A tibial drill hole can be regarded as impingement free if Blumensaat's line cuts the tibial plateau anterior to the tibial outlet of the graft on a sagittal image of the knee in the fully extended position. The theoretical positions of impingement-free tibial drill holes were calculated by the method of Howell and Barad [13]. The distance from the middle of the tibial drill hole to the anterior edge of the tibial plateau on sagittal MRI was divided by the total width of the tibial plateau in the sagittal plane (Fig. 3). The value is reported as a percentage.

Statistical analysis

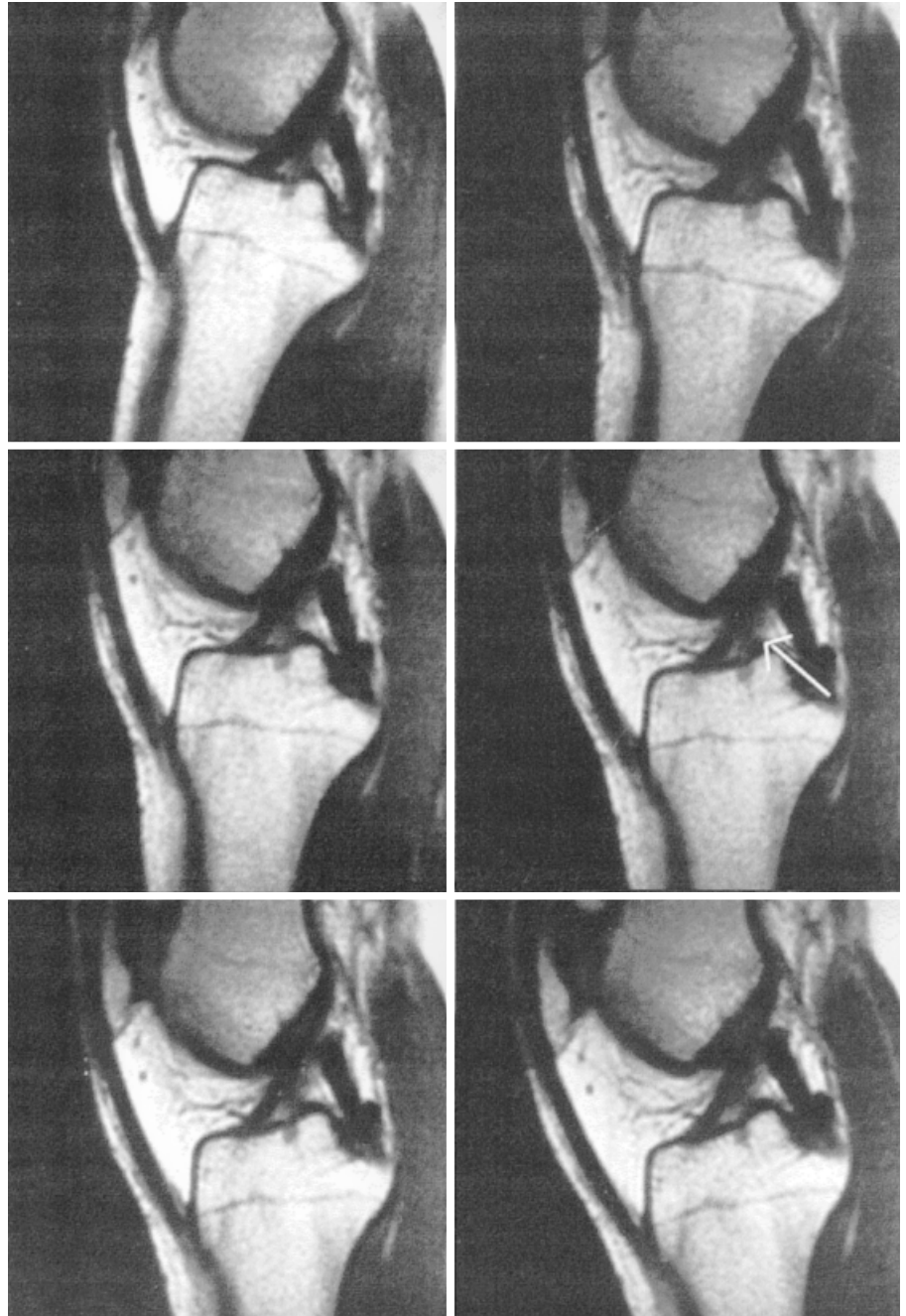
Descriptive analysis of the data includes maximum and minimum, mean, and standard deviation. Simple regression analysis was used to determine interobserver reliability in measuring knee extension angles. Since all data in this study are numeric, we used Pearson's correlation coefficient [9]. A *P* value below 0.05 was considered as significant and one below 0.001 as strongly significant. Fisher's transformation was used to obtain a 95% confidence interval for the correlation coefficient in a larger population [20]. All calculations were performed on an IBM-compatible computer using SPSS for Windows 6.1.3. and Excel for Windows 7.0.

Results

Measurement reliability

All 15 knees made contact with the articular surface of the intercondylar notch. A typical series of images for a knee

Fig.4 All knees in this study made contact with the intercondylar roof (*arrow*) before reaching maximal extension



in this study is shown in Fig. 4. One knee had only a minimum of hyperextension. Both observers decided that there was a contact of the ACL with the notch in this instance; however, no bending of the ACL could be seen. In all other knees the ACL stretched out in extension, contacted the notch, and then curved increasingly around the anterior lip of the notch roof until the knee reached terminal hyperextension. Regression analysis of the measurements of the two examiners revealed that knee extension ($r = 0.91$; $P < 0.001$) and the extension angle at the con-

tact of the ACL with the INR ($r = 0.84$; $P < 0.001$) were reliably measured (Figs. 5, 6). The mean values of both observers were used for further analysis.

Distribution of hyperextension, notch angle, and KT-1000 measurement

The mean maximum hyperextension ranged between -5.5° and -21.5° (mean $-15.37 \pm 4.51^\circ$). The notch angle

Fig.5 Interobserver reliability of measuring knee extension ($r = 0.91$; $P < 0.001$)

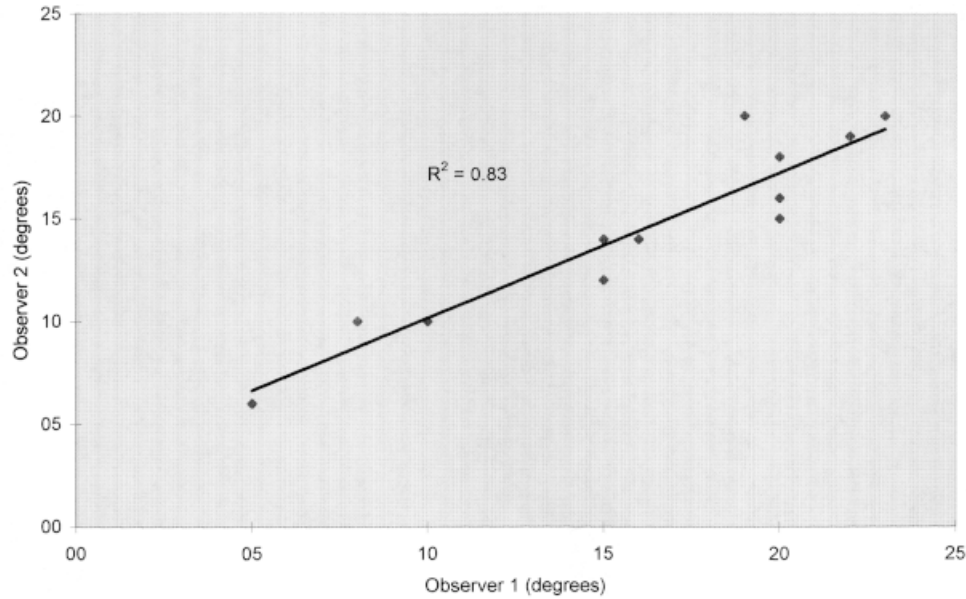
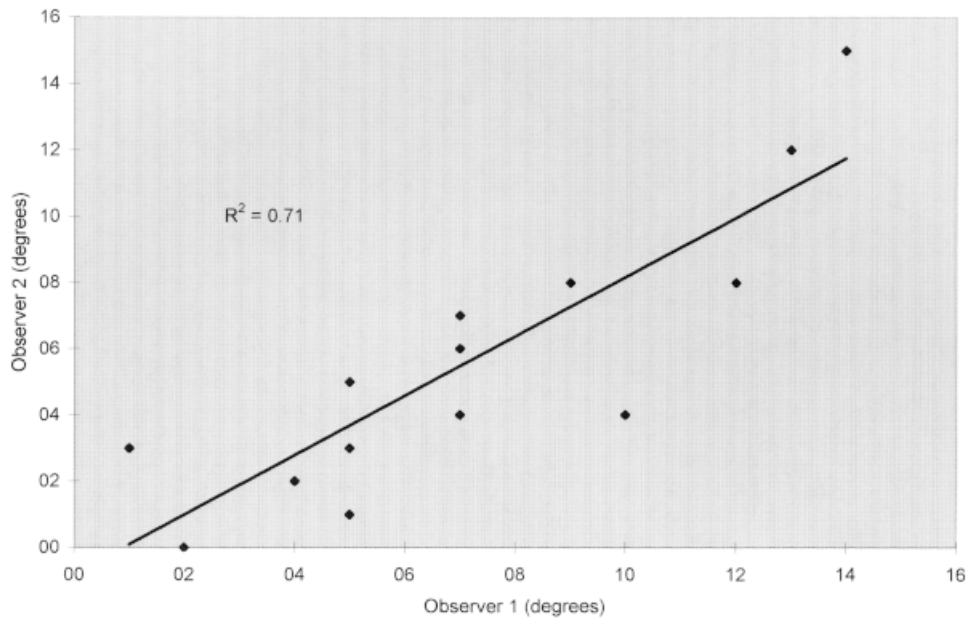


Fig.6 Interobserver reliability of measuring extension at the beginning of contact of the ACL with the intercondylar roof ($r = 0.84$; $P < 0.001$)



on sagittal MRI varied between 30° and 45° (mean 37.73 ± 4.80). The arthrometric measurement of knee laxity showed a maximum tibial displacement of 13 mm and a minimum of 3 mm (mean 8.03 ± 2.35).

Impingement

Mean contact of the ACL with the INR was 6.3 ± 3.8° of hyperextension (range 1–14.5°). Mean impingement laxity was 9.00 ± 4.82° (range 0.5–19.5°).

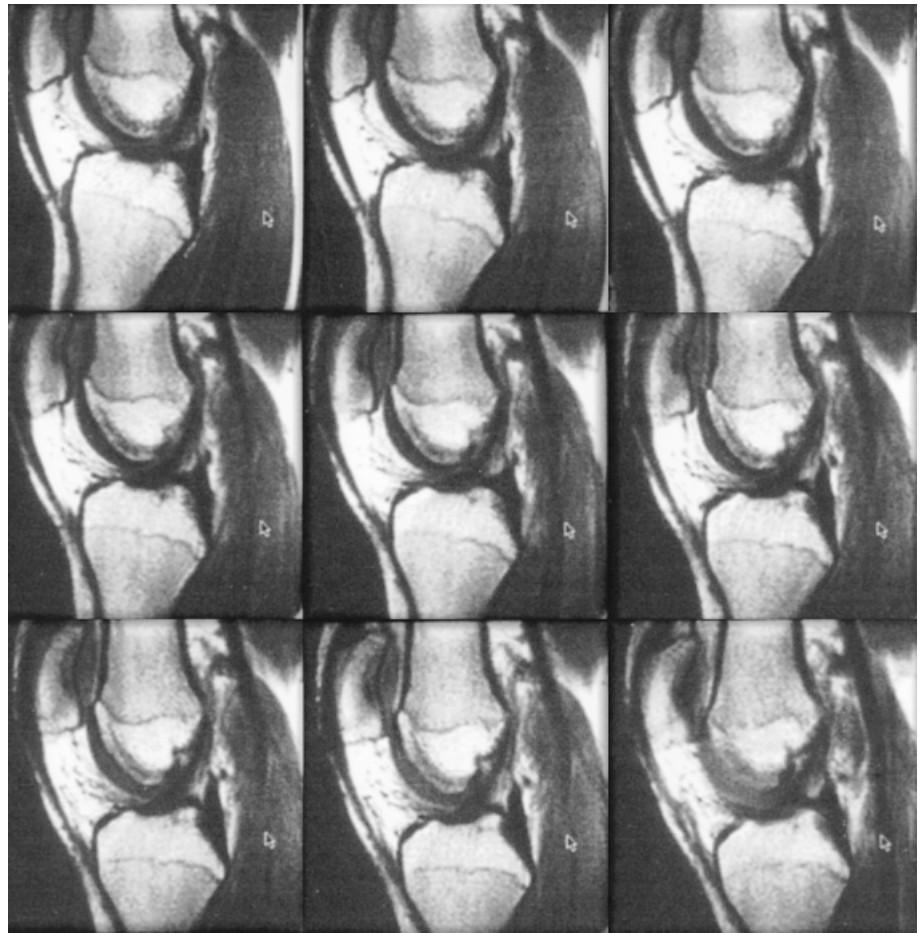
Relationship with the impingement laxity

There was a strong positive correlation of the radiographic measurement of impingement laxity with KT-1000 measurement of the anterior tibial displacement ($r = 0.77$; $P = 0.001$; 95% CI with Fisher’s transformation: 0.42–0.92) and the degree of maximum hyperextension ($r = 0.67$; $P = 0.006$; 95% CI with Fisher’s transformation: 0.24–0.88), and a negative correlation with the steepness of the notch angle ($r = -0.73$; $P = 0.002$; 95% CI with Fisher’s transformation: 0.34–0.90).

Table 2 Pearson's correlation coefficients for the variables in this study and significance levels (*parentheses* 95% confidence intervals for *r* yielded by Fisher's transformation)

Variable	KT-1000	Impingement	Hyperextension	Notch angle
KT-1000	–	0.77 <i>P</i> = 0.001 (0.42–0.92)	0.78 <i>P</i> = 0.008 (0.45–0.92)	–0.64 <i>P</i> = 0.010 (0.19–0.87)
Impingement	0.77 <i>P</i> = 0.001 (0.42–0.92)	–	0.67 <i>P</i> = 0.006 (0.24–0.88)	–0.73 <i>P</i> = 0.002 (0.34–0.90)
Hyperextension	0.78 <i>P</i> = 0.008 (0.45–0.92)	0.67 <i>P</i> = 0.006 (0.24–0.88)	–	–0.66 <i>P</i> = 0.006 (0.23–0.88)
Notch angle	–0.64 <i>P</i> = 0.010 (0.19–0.87)	–0.73 <i>P</i> = 0.002 (0.34–0.90)	–0.66 <i>P</i> = 0.006 (0.23–0.88)	–

Fig. 7 There was one case with a steep notch angle (30°), high laxity of the knee (13 mm on KT-1000 measurement), and impingement (19.5°) and thus a theoretical tunnel position of 62%



Correlations with other variables

There was a significant correlation between the degree of hyperextension and the notch angle ($r = -0.66$; $P = 0.006$; 95% CI with Fisher's transformation: 0.23–0.88; Table 2) and with maximal manual displacement as measured with the arthrometer ($r = 0.78$; $P = 0.008$; 95% CI with Fisher's transformation: 0.45–0.92; Table 2). KT-1000 values were also correlated with the notch angle ($r = -0.64$; $P = 0.010$; 95% CI with Fisher's transformation: 0.19–0.87; Table 2).

Position of theoretical impingement free tibial drill holes

The position of impingement-free tibial drill holes varied between 36% and 62% of the anteroposterior tibial depth (mean 43.20 ± 6.18). There was one case with the combination of a steep notch angle (30°), high laxity of the knee (13 mm on KT-1000 measurement), and impingement laxity (19.5°) and thus a theoretical tunnel position of 62%. Figure 7 shows the impingement series of this knee.

Discussion

ACL grafts that impinge are likely to sustain damage from the contact pressure of the INR in extension [8]. However, little is known about the biomechanics of the ACL in the uninjured knee in hyperextension. The material of our series is not representative of the average knee but was selected as a subpopulation of patients with ACL injuries who are able to hyperextend the uninjured knee. Problems occur among such patients in the case of a reconstruction of the ACL, especially when the ability of hyperextension is combined with a steep roof angle [13]. In a normal population mean knee extension has been reported as 10° of hyperextension with a 95% confidence interval of 8° – 12° [13]; our study population had a mean $15.37 \pm 4.51^\circ$ of hyperextension. Scuderi [30] reported a mean INR angle of $35^\circ \pm 4.7^\circ$ in a population of 115 knees, but the mean in our study was $37.73 \pm 4.8^\circ$. A relationship of $r = -0.46$ ($P = 0.008$) between knee extension and inclination of the notch angle has previously been reported in a series of 33 knees [13]. This is consistent with the 95% confidence interval given by the Fisher transformation for the $r = -0.66$ ($P = 0.006$) of this smaller population (range from -0.23 to -0.88).

Cinematographic analysis proved to be a reliable means for evaluating both knee extension and contact of the ACL with the INR. Contact of the ACL with the INR was observed in all individuals of this study. This impingement of the uninjured ACL varied with the amount of hyperextension of the knee. Cinematography can be used to determine whether there is impingement in an ACL reconstructed knee. Furthermore, the extension angle at the beginning of contact with the notch roof can be accurately measured. According to the results of this study, impingement occurs at $6.3^\circ \pm 3.8^\circ$ of hyperextension. Until now the detection of impingement in full passive hyperextension in an ACL reconstruction has been regarded pathological, as grafts with impingement have been associated with loss of extension and changes in graft appearance [12–18]. However, this evidence is based mainly upon cases with little potential for hyperextension of the knee. On the basis of our results we conclude that an ACL reconstruction in patients with hyperextension can tolerate impingement without damage. However, the beginning of contact between graft and INR should simulate the biomechanical behavior of the uninjured knee. Impingement that can be detected in an ACL reconstruction before reaching 5° of flexion is beyond the 99% interval for healthy individuals of this study and can be considered as predisposing to deterioration of the graft. It remains unclear how much impingement is tolerated by an ACL graft in hyperextension. None of today's reconstruction techniques can copy the bending of the ACL around the anterior lip of the intercondylar notch that we observed in this study.

We found a relationship between impingement, hyperextension, and maximum tibial displacement in uninjured



Fig. 8 Three-dimensional MRI of the ACL reconstruction of a knee with the combination of a steep notch roof angle and large hyperextension of the contralateral side. The patellar tendon graft fits precisely in the intercondylar notch and allows a minimum of impingement without damaging the reconstruction, thus enabling full hyperextension

knees. Accordingly, one can assume that a decrease in graft tensioning or an elastic graft material in an ACL reconstruction would facilitate full hyperextension by contributing to a minimum of impingement. Thus the antero-posterior displacement of the tibia in the Lachman test would increase. Both can be achieved by using either the semitendinosus tendon or tensioning of the graft in full hyperextension when using the patellar tendon. The correlations between impingement and hyperextension and the notch roof angle show that congenital laxity of the knee is associated with impingement of the ACL. In these knees one is likely to find the combination of a steep notch angle, large hyperextension, and anterior displacement in the Lachman test.

While the exact representativeness of correlations found in this study should not be overestimated due to the small number of cases, they were well within the 95%

confidence intervals for the r statistic yielded by Fisher's transformation. In this study population impingement-free tibial tunnels were located in 14 of 15 cases in the area recommended by several authors [1, 34] and that has been proven to be nearly isometric [22]. As a consequence of our findings, with increasing ability of hyperextension, the tibial tunnel should be placed further posterior to avoid impingement. In one instance the impingement-free tunnel position was found far posterior. Figure 7 shows the impingement series of this knee. One can see that after making contact with the INR the ACL bends increasingly around the anterior intercondylar roof. Knees with a steep notch angle, hyperextension, and a high risk of impingement in cases of ACL reconstruction have been reported as "unforgiving" [13, 18], because a reconstruction of the ACL is more likely to sustain damage from impingement of the INR. In such cases the surgeon must decide whether to simulate the biomechanics of the contralateral knee (which means steep notch angle and high laxity), or to establish conditions similar to those in knees without hyperextension (i.e., correction of the notch angle and decrease laxity in the reconstructed knee). Since problems with the patellofemoral joint and recurrent notch expansion have been reported after notch roofplasty [13] and correspond to our experience, we prefer simulating the biomechanics of healthy individuals with hyperextension.

The volunteer with the "unforgiving knee" in this study had undergone ACL reconstruction of the contralat-

eral knee. The operation was performed without notch roof resection but with special emphasis on fitting the patellar tendon graft precisely into the intercondylar notch in hyperextension [24]. This was achieved by a tibial tunnel positioned far posterior (2 mm distance from the PCL [22]) and tensioning the graft in full hyperextension. Post-operative three-dimensional MRI of the reconstructed knee shows that this procedure allows full hyperextension with a minimum of impingement (Fig. 8). This study of the relationship of the uninjured ACL and the INR underlines the necessity of intraoperative control of tibial tunnel placement with regard to roof impingement. After ensuring impingement-free ACL graft implantation, physiological individual hyperextension in respect to the uninjured knee can be encouraged.

In rehabilitation following ACL surgery we place special emphasis on achieving the same extension as in the contralateral side. For this reason we use a functional knee brace that enables knee hyperextension of up to -15° (Aircast-Hypex, Aircast Europa, Neubeuern, Germany). Further investigation is needed to determine the impingement forces in hyperextension of the normal knee and to ascertain whether impingement is tolerated by an ACL substitute in hyperextension.

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