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Computer-assisted anatomically placed double-bundle ACL reconstruction: An *in vitro* experiment with different tension angles for the AM and the PL graft

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ABSTRACT

Anterior cruciate ligament reconstruction techniques are evolving with innovations like double-bundle (DB) grafts and computer assistance. The current DB techniques do not appear to make the clinical difference yet. Insight in various techniques may lead to better results. In this study, the anterior laxity of a DB reconstruction with an anteromedial (AM) graft fixated in 90° of flexion and a posterolateral (PL) graft fixated in 20° and computer-assisted anatomically placed femoral attachments was compared to normal values and single-bundle grafts. In 8 fresh-frozen human cadaveric knees, the anterior laxity was tested from 0° to 90° flexion, with a 100 Newton (N) anterior tibial load in joints with (1) intact ACL, (2) torn ACL, (3) single-bundle (SB) graft tensed with 15 N in 20°, (4) anatomic AM graft tensed with 15 N in 90°, (5) anatomic PL graft tensed with 15 N in 20°, and (6) anatomic DB graft (4 + 5).

All reconstructions caused a posterior position of the tibia. Relative to the normal anterior laxity, the single-bundle techniques showed significantly increased laxities: The SB technique in 0° (+1.1 mm) and 15° (+1.7 mm); The AM reconstructions in 45° (+1.6 mm) and 90° (+1.5 mm); The PL reconstructions in all angles (from +1.4 to +2.3 mm), except in 0°. The anatomic DB technique showed no significantly increased laxities and restored normal laxity in all angles.

1. Introduction

The Anterior Cruciate Ligament (ACL) can be characterized by two functional bundles, the anteromedial (AM) and the posterolateral (PL) bundles [1,15]. Both bundles have different tension patterns in relation to the knee flexion angle, resulting in different contributions to determining the laxity of the joint. The AM bundle is rather tight over the entire range of motion, but mostly tensed in flexion. The PL fibers are tight at the lower flexion angles, near extension [1,13,25,33,37].

A reconstruction technique with two grafts, placed at the anatomical positions of the two functional bundles, combining the functions of both bundles, should theoretically result in a physiological behavior of the reconstruction, constraining anterior laxity over the complete range of motion [44,45]. Nevertheless, a systematic review of 4 patient studies employing this technique did not show a significantly better clinical outcome of double-bundle versus single-bundle reconstruction [29].

Improvement of the double-bundle technique could contribute to a better clinical outcome [9]. Since graft function is affected by graft tension and knee flexion angle at the moment of graft fixation [18,31,41,45], we hypothesized that tensioning the AM and PL bundles at the flexion angles at which they contribute most to anterior stability, may lead to a further optimization of ACL functioning. Hence, it is hypothesized that tensioning of the PL bundle is best done at 20° of flexion [31,33,41] whereas the AM bundle is preferably tensed in 90° of flexion [33,37,44].

The objective of this study was to measure the anterior laxity characteristics of a doublebundle reconstruction technique. The main goal was to address the ability to restore normal anterior laxities through a computer-assisted anatomically placed double-bundle quadriceps-bone reconstruction of the ACL. To assess the individual constraining capacity of the two grafts in this double-bundle reconstruction technique and the synergistic effects combining both, the relative contributions of the AM and PL bundles were also analysed. To place the results of the double-bundle

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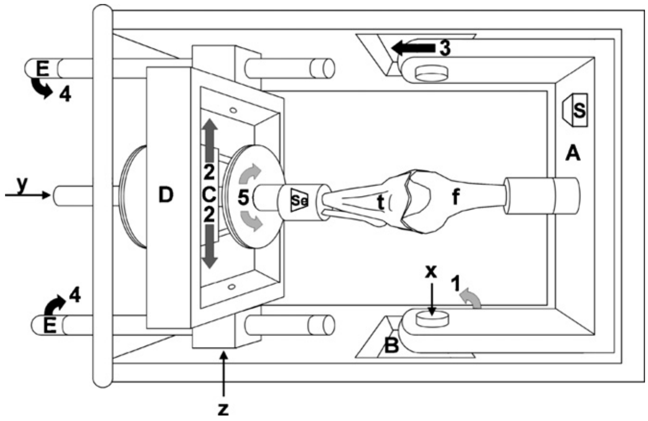

Fig. 1. The knee joint motion and loading apparatus from proximal. The femur (f) is mounted at bracket (A). Flexion (1) is achieved by manual rotation of bracket A around the joint in axis *x*. The tibia (t) is free tot move in varus-valgus rotation and medial–lateral translation, through translation (2) of block C in slot D. Proximal–distal translation of the femur, allowed through translation of bracket A in slot B, is forced into an axial compression towards the tibia (3) applying 25 N at both sides. Anterior–posterior translation of the tibia, allowed through block D around axis *z*, is forced towards anterior (5) applying 50 N at E (2×). Internal-external translation (5) around axis *y* is restrained to the rotation position of the normal knee in 0°. The source (S) of the Fastrak system is mounted onto bracket A; the sensor (Se) onto the tibia-cylinder.

technique in perspective, the anterior laxity of a normal knee, an ACL-deficient knee and a knee reconstructed with a single-bundle graft positioned at the femoral 11 or 1 o'clock position, was also determined.

The hypothesis tested in this study was that the anatomic double-bundle reconstruction, with the PL tensed at 20° and the AM at 90° of flexion, will approximate normal anterior translation, measured in six angles ranging from 0° till 90°.

2. Methods

Eight fresh cadaver knees, obtained from autopsy and kept frozen until the time of use, were screened for absence of abnormalities on radiographs. The age of the donors at the time of death ranged from 58 to 91 years. The bones were cut approximately 20 cm from the joint line. The knees were thawed overnight and the grafts were harvested: the Bone-Patellar tendon-Bone (BPB) graft for the single-bundle reconstructions. The quadriceps tendon with a bone block of the proximal patella was prepared for the double-bundle technique. This graft is very suitable to be used as a DB graft, since it has tendon tissue over the whole boneblock, which could be split into two slips. The quadriceps tendon has similar properties as the BPB graft [39]. Subsequently, all muscle tissue was removed; the medial and lateral capsule and ligament tissue of the knee joint were kept intact.

A knee loading system, in which knees could be subjected to different loads in various flexion angles, was used for the experiments (Fig. 1). This system was previously used and extensively described in an *in vitro* study [5] and based on an earlier developed motion and loading apparatus [6]. There was a special fixation method of the femoral and tibial bones in the system. The bones were embedded with polymethylmethacrylate (PMMA) in plastic cylinders, which were part of the apparatus. When the PMMA hardened, it was possible to repeatedly remove the specimen, locate and drill the femoral and tibial tunnels and replace the knee in exactly the same position in the cylinders of the apparatus again. Subsequently, the grafts were fixated. The position of the femur was fixed and the tibia was free to move in four degrees of freedom, i.e. anterior/posterior translation, medial/lateral translation, proximal/distal translation and varus/valgus rotation. Besides the flexion, axial internal and external rotation of the tibia was restrained to the rotation position of the normal intact knee in the corresponding flexion angles during the tests. This was done to prevent the influence of variable coupled axial rotations on the AP translation which may mask the true effects of the procedures on AP translation. Furthermore, an axial force of 50 N was applied. This force was applied along the tibial axis, to simulate a compressive force to the knee joint and avoid sub-luxation, particularly in the ACL-deficient knee. The non-metallic design of the system made it possible to record motions of the tibia with an electromagnetic 3Space Fastrak tracking system (Polhemus Navigation Sciences, Colchester, Vermont, USA). The source of the Fastrak system was attached to the part of the knee system were the femoral bone was fixed and the sensor to the tibial part. The anterior laxity of the knee resulting from an anterior force was measured, as explained later, at various flexion angles under 6 different conditions of the ACL: (1) intact; (2) ACL-deficient; (3) single-bundle (SB) reconstruction; (4) anatomic anteromedial bundle (AM) reconstruction; (5) anatomic posterolateral bundle (PL) reconstruction; and (6) anatomic double-bundle (DB) reconstruction.

(1) The first measurements were performed with an intact knee. After fixating the specimen in the apparatus, the axial force of 50 N was applied and the knee was moved 3 times over the complete range of motion to precondition the joint. Then the knee was positioned in 6 flexion angles (0°, 15°, 30°, 45°, 60° and 90°). At every angle the three-dimensional (3D) position of the unloaded tibia relative to the femur was recorded with the Fastrak system. The rotation positions of the knee in the various angles were noted, to be used in the following tests. The same recordings were performed after the tibia was loaded with an anterior force of 100 N to obtain the anterior translation.
(2) For the second condition, the ligament was cut and all ACL tissue was removed. After the 3 pre-conditioning cycles over the range of motion, the measurements with the tibia unloaded and loaded in anterior direction were performed in the 6 flexion angles, with the rotation fixed in the position as measured in the intact condition.
(3) The first reconstruction that was performed, was the SB reconstruction. Placement was achieved, outside the apparatus, by applying two commonly used drill guides to position the tibial and femoral tunnels, respectively. The tibial tunnel was positioned using the PCL Oriented Placement Marking Hook$^{\text{TM}}$ [Arthrex Inc., USA] and drilled with an 11 mm-drill. This guide places a tibial tunnel in the anatomical ACL attachment avoiding notch impingment [19,21,30,34,48]. The femoral tunnel was positioned with the transtibial femoral guide$^{\text{TM}}$ [Arthrex Inc., USA] with a 7 mm offset, placed in the over-the-top position at 11 o'clock. With this instrument a femoral tunnel is placed at the so-called 'isometric zone' [21,48]. An 11 mm-tunnel was drilled in the femur. Then the knee was repositioned in the motion- and loading apparatus and the BPB graft was positioned in both tunnels. In the femoral hole, the bone was located proximally, the tendon distally. The bone in the tibial tunnel was lateral and the tendon medial. Before tensioning the graft, the tibia was translated posteriorly and manually held in that position. Then the graft was tensioned with 15 N on a pretensioning spring device in 20° of knee flexion [21]. With that initial tension, the graft was preconditioned with 3 motion cycles of the knee. It was observed that the tension measured on the spring device, varied with knee flexion, during the loading cycles. However, at 20°, the pretension of 15 N was regained. Subsequently, the graft was fixated with interference screws in the drill holes, while care was taken to maintain the pretension on the graft. Finally, all measurements were performed and

recorded. After the recordings of all tests, the whole BPB-graft was removed.

(4) For the AM reconstruction, the quadriceps tendon bone graft (QTB) with the bone block was prepared by dividing the tendon into two slips which ends were sutured to make a solid fixation possible. The anatomical position of the femoral tunnel was determined with a computer-assisted system (CAS, SurgiGATE, Medivision, Switzerland). Since the QTB graft had one bone block, only one tunnel had to be made. Using the specifically developed 3D femoral template [24], incorporated in the ACL-module (MEM Institute for Biomechanics, Switzerland), the tunnel was positioned at the anatomical center of the ACL. Therefore the surface of the notch and the posterior joint cartilage edge at the medial wall in the lateral notch were digitized. With these data the computer template, with the centers of the AM and PL bundles and the ACL, was displayed in the notch. The ACL center position was marked with a computer-tracked awl and an 11 mm-tunnel was drilled using a K-wire. This tunnel never overlapped the tunnel of the SB reconstruction. It did overlap the positions of the AM and PL anatomic centers. Subsequently, the bone block was positioned in the femoral tunnel. Then CAS was used to determine the correct position relative to the AM center, since the template also contained the anatomical AM center location, visible at the monitor. After digitizing the center of the AM tendon slip at the bone block, it was rotated until the bone mark was at the same position as the AM template mark. The knee was repositioned in the knee motion- and loading apparatus. A titanium interference screw was used to fixate the block at the femoral site. The tendon slip at the anatomical AM position was guided with the sutured end through the tibial tunnel at the medial side [16,23]. The graft was tensioned in 90° of flexion with 15 N, with the tibia translated posteriorly. Then the graft was preconditioned with 3 motion cycles of the knee. Finally it was fixed with the sutures around a screw, which was placed medial from the exit of the tibial tunnel at the tibial surface. Finally, all measurements were performed and recorded.

(5) To test the anatomic PL-reconstruction, the PL tendon was fixated. It was positioned at the lateral side of the tibial tunnel and tensioned in 20° flexion with 15 N. After the 3 conditioning cycles, the tendon was fixated in 20° flexion, through the sutures at a screw placed laterally relative to the tibial tunnel exit, with the tibia manually placed in a posteriorly translated position. Finally, all measurements were performed and recorded.

(6) For the measurements of the knees with the anatomic DB technique, both the AM and PL grafts were fixated as described above. The measurements were performed and recorded.

To define a coordinate system relative to which rotations and translations were calculated, the sensor of the Fastrak system was mounted upon a stylus after the experiments. With this 3D digitizer, the point posterior of the tibial anterior cruciate insertion site at the tibial plateau was recorded. Next, the point 15 mm proximal to this recorded point was defined in the software as the origin of the tibial coordinate system [6]. Then the position along the anterior–posterior axis of the unloaded tibia in the intact knee, was calculated for all flexion angles (Fig. 2). The same was done for the condition in which the tibia was loaded with 100 N anterior force. The difference between the positions in anterior–posterior (AP) direction of the unloaded – and 100 N-loaded tibia was defined as the anterior laxity of the knee throughout the range of motion. In all reconstruction techniques, the tibia translated in posterior direction during tensioning and fixation of the graft. This led to a more posterior tibia position in the unloaded reconstructed knee relative to the position of the unloaded tibia of the intact knee. This posterior translation is referred to as the AP-error of the tibia.

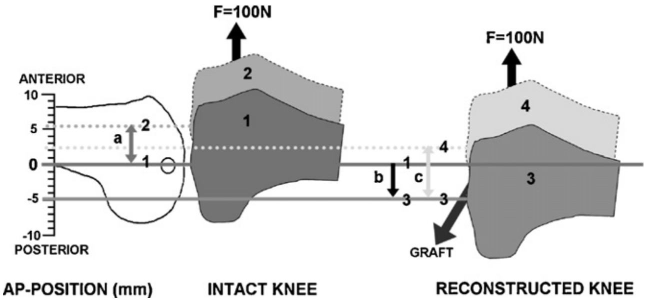

Fig. 2. Lateral view of a fixed femur and a moving tibia. (1) The initial anatomic AP-position of the unloaded tibia relative to the fixed femur in the intact knee is defined as 0 mm. (2) An anterior force (100 N) applied to the tibia causes an anterior shift relative to the anatomic AP-position, which represents (a) the normal anterior laxity ($a = 2-1$). (3) During graft fixation, the tibia is repositioned resulting in a new position of the unloaded tibia in the reconstructed knee: AP-position after ACL reconstruction. The difference in AP-position between the intact and reconstructed unloaded knee is defined as (b) the AP-error ($b = 1-3$). (4) An anterior force (100 N) applied to the tibia in the reconstructed knee, causes an anterior shift relative to the AP-position, which represents (c) the anterior laxity of the reconstructed knee ($c = 4-3$).

Statistical analysis was performed using SPSS® (12.0.1 for Windows, SPSS Inc., Chicago, IL). For all conditions, the mean anterior laxity in all 6 flexion angles was calculated as an average of all knees. Normal quantile plots were performed and data was tested for normality with the Shapiro Wilk test, significance was set at $P < 0.05$. The laxities of all separate reconstruction techniques were compared with the laxity of the intact knee with the non-parametric Wilcoxon Signed Rank test. The same was done for the AP-errors of the reconstructed knees to determine if these were significantly different from zero. This study was powered to detect a 1-mm difference in anterior laxity ($\alpha = 0.05$). To detect differences between the 4 reconstruction techniques, the laxity and AP-error from each reconstruction were also compared to each of the other techniques with the non-parametric Wilcoxon Signed Rank test. Finally, the Friedman Rank Test was performed to determine which technique had the best laxity results over all specimens for a given flexion angle. In each individual knee, the laxity results of all four reconstruction techniques in that flexion angle were ranked, with the smallest laxity value nominated as the best result. This ranking was done for all knees, resulting in an average ranking value for each reconstruction technique in that flexion angle. This procedure was repeated for each of the 6 flexion angles considered.

3. Results

The laxity of the knees with an intact ACL showed a typical pattern as function of flexion, with an increasing anterior laxity from 0° of flexion up to 30° of flexion after which the laxity decreased again (Table 1; Fig. 3). The mean laxity in 90° flexion was the smallest over the range of motion tested. However, the effect of flexion angle on the anterior laxity was not statistically significant ($P > 0.05$).

In knees with the ACL cut, the tibia translated anteriorly in the unloaded condition. The anterior laxity was significantly increased by a factor of two relative to the intact knee in all flexion angles (P-values ranged between 0.012 and 0.025) (Table 1; Fig. 4).

The increased anterior laxity after cutting the ACL, was significantly reduced by all reconstruction techniques (Fig. 4). The laxity patterns of the reconstructed knees were similar to those of the intact knee. The outcome of the Friedman Rank Test showed that the knees with the double-bundle technique had the smallest anterior laxity in the lower flexion angles: in 0°, 15°, 30° and 45°. The

Table 1
Anterior laxity of the tibia in response to 100 N anterior tibial load (mean ± SD in mm).

Flexion angle	ACL-reconstructions					
	ACL intact	ACL #	AM	PL	ADB	SB
0°	4.9 ± 0.6	8.7 ± 1.8*	5.5 ± 1.5	5.5 ± 2.0	4.7 ± 2.1	6.0 ± 1.0*
15°	6.3 ± 1.5	12.7 ± 3.6*	7.8 ± 1.6	8.0 ± 1.4*,†	7.0 ± 1.1‡	8.0 ± 1.4*,†
30°	6.9 ± 2.2	14.2 ± 4.1*	7.7 ± 1.6	8.3 ± 2.0*,†	7.2 ± 1.5	7.7 ± 1.8
45°	5.5 ± 2.1	11.0 ± 5.4*	7.1 ± 1.3*	7.8 ± 1.7*†,‡	6.5 ± 1.1	6.8 ± 2.3
60°	4.7 ± 2.4	10.4 ± 4.1*	6.2 ± 1.5	7.1 ± 2.8*	5.6 ± 1.2	5.9 ± 2.1
90°	3.8 ± 2.3	7.1 ± 3.5*	5.4 ± 2.6*	5.9 ± 2.6*,‡	5.2 ± 1.6	4.8 ± 1.8

ACL intact: knee with the intact ACL; ACL #: knee with deficient ACL; AM: anatomic single-bundle reconstruction of the anteromedial graft; PL: Anatomic single-bundle reconstruction of the posterolateral graft; ADB: anatomic double-bundle reconstruction with quadriceps tendon bone graft; SB: single-bundle reconstruction with bone-patellar tendon-bone graft.

[*] $P < 0.05$ compared with ACL intact.

[†] $P < 0.05$ compared with ADB.

[‡] $P < 0.05$ compared with ISB.

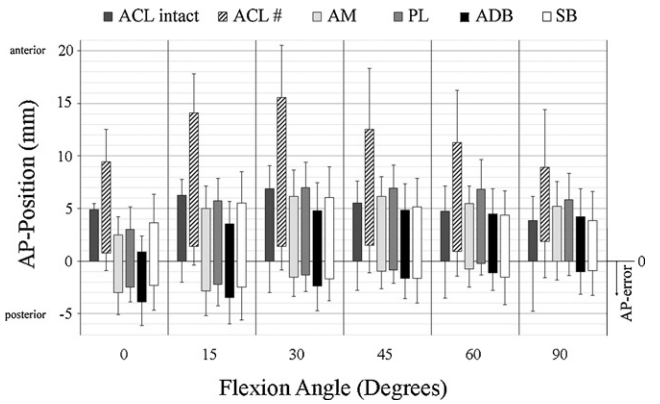

Fig. 3. The mean (±SD) anterior laxity (mm) of the knees ($N = 8$) under 6 conditions in various knee flexion angles. The initial anatomic AP-position of the unloaded tibia in the knees with the intact ACL served as the starting position (0 mm). The lower limit of each bar represents the mean AP-positions (−SD) of the unloaded tibia. The upper limit of each bar represents the mean AP-positions (+SD) of the 100N-loaded tibia. The difference between these two tibial positions, i.e. the length of the bar, is the anterior laxity. The difference between the AP-position of the unloaded intact tibia and the posterior tibial position in the unloaded reconstructed knees, the negative part of the bar, is the AP-error. ACL intact: knees with intact ACL; ACL #: deficient ACL; AM: anteromedial graft; PL: posterolateral graft; ADB: anatomic double-bundle reconstruction; SB: single-bundle reconstruction.

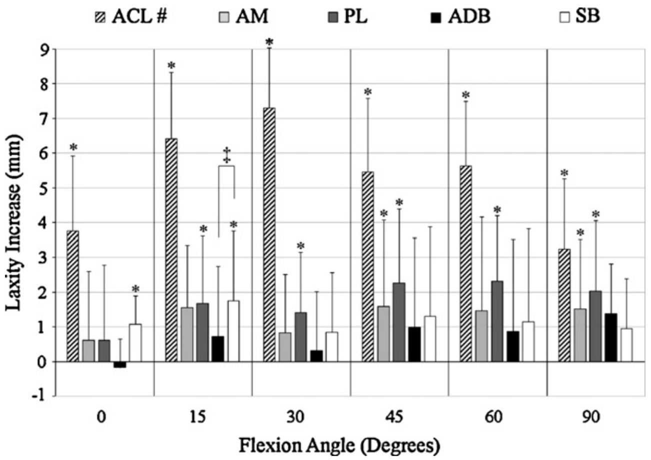

Fig. 4. The mean (+SD) anterior laxity increase (in mm) of the tibia of the ACL deficient knees ($N = 8$) and knees with the 4 ACL-reconstructions, relative to the knees with intact ACL, in various knee flexion angles. ACL #: deficient ACL; AM: anteromedial graft; PL: posterolateral graft; ADB: anatomic double-bundle reconstruction; SB: single-bundle reconstruction; *$P < 0.05$ compared with intact knee; ‡$P = 0.016$ ADB compared with SB.

SB technique showed the smallest laxity data in the higher flexion angles 60° and 90°.

The anterior laxity values of the SB reconstructions were higher than in the intact knees. In the positions near extension (0° and 15°), the laxity (1.1 mm and 1.7 mm) was significantly higher than the normal laxity ($P = 0.007$ and $P = 0.045$ respectively). The differences in the higher flexion range (30–90°) were small and not significant. In 15°, the laxity of the SB was also significantly higher (1 mm, $P = 0.016$) than the laxity of the DB in 15°.

In the knees with the anatomical AM reconstructions, the anterior laxity of 1.6 mm in 45° and 90° of flexion were statistically significantly ($P = 0.038$ and $P = 0.030$ respectively) higher compared to the intact knees. The anterior laxity increases at 0°, 15°, 30° and 60°, ranging between 0.6 and 1.5 mm, were not statistically different from the intact laxity.

The anatomic PL reconstructions restored the anterior laxity in 0°; the increase, on average 0.6 mm, did not differ significantly from the laxity of the intact knees ($P = 0.410$). In all other angles the laxities were significantly higher than the normal laxity, with an increase ranging between 1.4 and 2.4 mm (60°) (P-values ranged between 0.023 and 0.049).

The anatomic DB reconstructions normalized the anterior laxity of the intact knees best over the complete range of motion. In 0° the laxity of the DB was, on average smaller than normal (4.7 mm the DB technique vs. 4.9 mm for the intact ACL), however the difference was not significantly different from zero. In the other angles the DB laxity differed from normal laxity with values between 0.3 mm and 1.4 mm (90°), but the total laxity was not statistically significant different from the intact-ACL laxities.

After every reconstruction, the tibia had a posterior position in the unloaded condition, compared to the intact knee. This AP-error, caused by the fixation of the graft, arose especially in the lower flexion angles, with maximal values for knee extension (Table 2; Fig. 3). All techniques caused significant AP-errors in 0° and 15° flexion (P-values ranged between 0.012 and 0.036). The anatomic DB and the SB also had a significant AP-error in 30° ($P = 0.017$ and $P = 0.042$ respectively), the DB also in 45° ($P = 0.045$). The AP-errors of the DB technique seemed larger than those of the SB technique (0.7–1.6 mm), but did not differ significantly.

4. Discussion

In this study the anterior laxity in normal knees and in knees with several differently placed grafts was evaluated. With this experiment, the hypothesis was tested that a double-bundle reconstruction with two grafts positioned and tensed at both its anatomical attachment centers, thus combining the functionality of both bundles, would be able to mimic the intact ACL functioning over the complete range of motion.

Table 2
Posterior translation of the tibia caused by manual repositioning during fixation (mean ± SD in mm).

Flexion angle	ACL-reconstructions					
	ACL intact	ACL #	AM	PL	ADB	SB
0°	0	−0.8 ± 1.7	3.0 ± 2.1*	2.5 ± 1.4*	3.9 ± 2.2*	2.3 ± 2.4*
15°	0	−1.4 ± 1.8	2.8 ± 2.4*	2.2 ± 2.0*	3.5 ± 2.5*	2.5 ± 3.1
30°	0	−1.4 ± 2.2	1.5 ± 1.8	1.3 ± 1.6	2.4 ± 2.4*	1.7 ± 2.1
45°	0	−1.5 ± 2.7	1.0 ± 1.7	0.8 ± 1.3	1.7 ± 2.0*	1.7 ± 2.4
60°	0	−0.9 ± 2.3	0.7 ± 1.8	0.2 ± 1.1	1.1 ± 1.7	1.5 ± 2.6
90°	0	−1.8 ± 3.5	0.1 ± 2.0	0.0 ± 1.4	1.1 ± 1.0	0.9 ± 2.3

ACL #: deficient ACL; AM: anteromedial graft; PL: posterolateral graft; ADB: anatomic double-bundle reconstruction; SB: single-bundle reconstruction.

* $P < 0.05$ compared with ACL intact.

The results of this study were in line with those of other studies [22,42,44]. The intact knee was most stable in extension and in 90° of flexion and most lax at a flexion angle of 30° [18,35,42,44,45]. In knees where the ACL was cut, anterior laxity was significantly increased. The amount of increase was somewhat smaller, ca. 35%, than in other studies, most likely caused by the use of a lower anterior load (100 N) compared to the other studies (134 N) [22,42]. The anatomically placed DB reconstruction showed anterior laxity values closest to those observed in the intact knee. In contrast, none of the single-bundle grafts, SB, AM or PL, were capable of restoring the anterior laxity in all flexion angles [35,45]. The AM reconstructions did not restore the normal anterior laxity in 45° and 90° flexion [22], and the PL reconstructions failed in restoring the normal values at higher flexion angles [33,45]. The SB reconstructions could not normalize the anterior laxity in 0° and 15° flexion [18,42,44].

The testing methodology revealed a posterior translation of the unloaded tibia in all reconstructed knees relative to the tibial position in intact knees. This AP-error has previously been reported in other *in vitro* reconstruction studies [7,11,14,26–28]. In agreement with those studies, the reconstructed knees showed the largest AP-errors in extension. In the higher flexion angles the AP-error was smaller since the posterior cruciate ligament restrained the posterior tibial translation [26]. The AP-error can be explained by the graft forces generated during graft tensioning and subsequent fixation. The clinical consequences are unknown. In only one clinical study, the tibial position relative to the femur was measured at different post-operative times relative to the pre-operative ACL-deficient condition [40]. This study showed that the tibia may considerably shift anteriorly during the post-operative time. It was not clear what the influence of this anterior repositioning was on the clinical anterior laxity results or physiological joint motion. Further *in vivo* studies should be performed to determine the consequences of intra-operative AP-errors on postoperative function after the ligament remodeling period. In the meantime, it is important to be aware that tension protocols can cause an AP-error, which places the tibia in a non-anatomic position relative to the femur. Both flexion angle and graft tension influence the tibial positioning [7,14,26,28]. Besides that, the relative preoperative anterior position of the tibia and the reduction of the subluxation before graft tensioning plays a role. Höher proposed a standardized force of reduction since this force influences the laxity outcomes [18]. In conclusion, one can apply different strategies to control the intra-operative AP-error.

The AM graft was fixated in 90° with 15 N. It was observed during the conditioning cycles that the tension registered at the pretension spring device, in the grafts increased near extension. This tension increase in an AM graft, when moving the knee towards extension was also reported by others [12,31,48] and may explain the normalized laxity values in the lower flexion angles. The applied tension protocol was not sufficient to normalize the laxity in the higher angles. Increasing the tension does not seem to be the solution as Mae et al. found that graft fixation with 44 N in 90° resulted in laxity results smaller than normal, accompanied with a very high in situ force and a large tibial posterior displacement [27]. Hence, it appears that 90° of flexion is not the optimal knee angle for tensioning the graft. In addition, Miura also reported the overload of the AM graft near extension if the graft was fixated in 60° of flexion [31]. Vercillo found that fixation in 15° knee flexion resulted in lower forces compared to the forces in the intact AM bundle over the complete range of motion [41]. Hence, it appears to be difficult to establish an adequate tensioning protocol which is perhaps caused by the finding in this study that ACL-reconstructive forces are affected not only by flexion angle and tension force but also by tibial–femoral AP-errors which are ignored in most contemporary tensioning protocols.

The PL graft normalized the laxity only for knee extension, despite the fixation in 15° knee flexion which seems to be the most appropriate fixation angle [31,41]. The initial graft tension was somewhat low compared to other studies [31,41,45]. Since the tension on PL grafts increases towards extension [4,31,46], our tension protocol was sufficient to restore laxity for knee extension. A higher tensile force at 15° knee flexion can thus be advocated, which will result in laxity values closer to normal in 15° and 30°.

Obviously there are several limitations to the current study. It is an *in vitro* study with specimens of donors of relatively high age. Furthermore, some questions remain unanswered in this study, because we measured the anterior laxity with the rotation fixed, although functional stability also includes a rotational component, as is seen in pivot-shift tests and dynamic analyses [36]. However, by fixation of the internal–external rotation to a preset value, we were able to solely measure effects on anterior laxity, without interference of changes in axial rotations. We accepted that this went at a cost relative to anatomical reality. From other studies, it is clear that there is a contribution of the PL graft in restoring the stability in rotational direction [13,20,43–45,47]. One of the study aims was to show that the PL, tensed in 20° of flexion, also contributed significantly to the anterior laxity results in the lower flexion angles. The results were in line with others [22,45].

5. Conclusion

Although a PL reconstruction tensed with 15 N in 20° restored normal anterior laxity only in 0° and an AM reconstruction tensed with 15 N in 90° failed in restoring normal anterior laxity in 45° and 90°, the anatomic double-bundle technique, positioned with CAS, produced anterior laxity values close tot normal over the complete range of motion. However, this was accompanied with a posterior tibial–femoral AP-position. Therefore, additional studies are required to further improve the tensioning protocol of anatomic double-bundle reconstructions, which considers the tension force and flexion angle, but also the tibial–femoral AP-position.

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Conflict of interest

The authors declare that there are no conflicts of interest.

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