Knee Surg Sports Traumatol Arthrosc (2011) 19:1277–1286
DOI 10.1007/s00167-011-1405-4

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Intraoperative comparisons of knee kinematics of double-bundle versus single-bundle anterior cruciate ligament reconstruction

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Received: 30 August 2010 / Accepted: 13 January 2011 / Published online: 11 February 2011

Abstract
Purpose Based on biomechanical anatomical studies, double-bundle reconstruction of the anterior cruciate ligament (ACL) was introduced to achieve better stability in the knee, particularly in respect of rotatory loads. An in vivo, computer-assisted, double-bundle (DB) ACL reconstruction is superior to a single-bundle (SB) ACL reconstruction at reducing rotatory, and AP laxities of the tibia at 20 degrees of knee flexion and also during the pivot shift test.
Methods The data of 63 patients who had ACL reconstruction were prospectively collected. Thirty-two patients had single-bundle reconstruction (SB group), and 31 received double-bundle reconstruction (DB group). The per-operative navigation system (Praxim ACL surgetics System) helped to search for a minimal anisometry profile of the grafts, which was favorable (graft loosened with flexion) in the anatomic area of ACL insertion and preventing any conflict between the graft and the femoral notch. The system also evaluated anteroposterior (AP) rotational stabilities and pivot shift. The value of the pivot shift was calculated from the values of the maximum rotation and AP translation obtained when performing the manoeuver before and after ACL reconstruction, comparing SB and DB reconstruction.
Results The post-operative AP displacement of the lateral compartment during the Lachman test was statistically reduced in DB group in comparison with SB group (5.1 ± 4.4 mm vs. 7.1 ± 3.2 mm, $P = 0.04$), whereas the AP displacements of the medial compartment were also reduced (3.4 ± 3.7 mm vs. 4.5 ± 2.6 mm, $P = 0.15$) but with no statistical significance. Internal and external rotations at 20° of knee flexion were lower in the DB group than in SB group with statistical significance (respectively, 13.2 ± 4.9° vs. 17.5 ± 4.0°, $P < 0.001$ and 9.1 ± 3.6° vs. 11.5 ± 3.5°, $P = 0.01$). During the pivot shift test, the post-operative AP maximal translation was statistically different in both groups: 4.5 ± 2.1 mm in DB group and 6.3 ± 2.7 mm in SB group ($P = 0.01$)), whereas the maximal rotation was not statistically different: 3.8 ± 2.5° in DB group and 3.4 ± 1.2° in SB group (n.s.). Therefore, Colombet's index was similar in DB group and SB group (respectively, 0.21 ± 0.16 and 0.17 ± 0.06, (n.s.)).
Conclusions This study shows a significant intraoperative advantage in anterior and rotational stability for four-tunnel DB ACL reconstruction compared with SB ACL reconstruction.
Level of evidence II.

Keywords Anterior cruciate ligament · Double-bundle reconstruction · Computer-assisted · Navigation · Biomechanics · Hamstring

Introduction

The gold standard for ACL reconstruction is the arthroscopic single-bundle (SB) technique. However, anatomical and biomechanical studies have characterized the ACL as composed of two different bundles: the anteromedial (AM) bundle and the posterolateral (PL) bundle [37]. Current ACL reconstruction techniques have focused on reconstruction of only one portion of the ACL. However, a failure rate of 11–30% is reported in the literature [10, 22, 39] with persistent instability of the knee at follow-up, especially in rotational stability as revealed by a positive pivot shift test result [15, 35, 40].

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Progress made over recent years has led to a greater understanding of the ACL anatomy and its 2 bundles [9, 32, 34]. To mimic more closely the normal structure of the ACL, double-bundle reconstructions have been performed. Biomechanical studies have shown that double-bundle (DB) ACL reconstruction is advantageous in restoring anterior knee stability and rotational stability in an ACL-deficient knee compared with SB ACL reconstruction [2]. Rotational stability, in particular, increased significantly with the additional reconstruction of the PL bundle when compared with a SB ACL reconstruction. Surgeons are now more equipped to restore the native anatomy and knee kinematics than ever before [26, 34].

The important issue is the lack of instrumental tools to assess the complex kinematic ligament stability during knee rotation in vivo [42]. However, objective clinical measurements are essential to compare SB with DB ACL reconstruction. Computer-assisted ACL reconstruction has been used [24]. Besides being useful in increasing the precision of the surgical procedure (tunnel placement) [33], it could be very effective in evaluating the global performance of the reconstructed knee. It could provide very accurately the anteroposterior (AP) displacement and the internal rotation (IR) and external rotation (ER) of the tibia with respect to the femur in 3-dimensional planes of the joint motion [6]. There are very few studies evaluating quantification of in vivo knee laxity in the four-tunnel double-bundle ACL reconstruction with intraoperative inconsistent results on objective laxity: The computer was used to compare the values of the sagittal and rotational laxity obtained after different techniques of ACL reconstruction. Nevertheless, the software is not equivalent in their application processes, so the results are sometimes contradictory [3, 12, 36]. The software used in this current study allows to reconstruct the surfaces of anatomical ACL insertion with sub-millimeter accuracy and to determine realistic values of the envelope of laxity [13, 33].

Also, the hypothesis of this study was that four-tunnel DB ACL reconstruction can restore a better anterior and rotational stability than SB ACL reconstruction. Therefore, the purpose of our study was to evaluate the two patient groups in terms of anteroposterior and rotational stabilities as assessed by the Lachman and pivot shift tests using in vivo computer navigation to measure peak loads before and after ACL reconstruction.

Materials and methods

In a non-randomized controlled clinical trial, 62 patients underwent ACL reconstruction with four-strand semitendinosus and gracilis tendon autograft in a four-tunnel DB (DB group) or SB technique (SB group). Inclusion criteria were an ACL rupture without additional knee ligament injuries, no previous knee ligament surgery, no arthritic changes (joint space narrowing of more than 50% in any compartment), no meniscectomy or meniscal sutures, and no malalignment. The patient was excluded from the study when the examination under anesthesia or the intraoperative findings did not meet the above-mentioned inclusion criteria.

Sixty-two patients were included according to the prospective study design. All the patients gave their informed consent, and the ACL reconstruction technique to be used was decided with blind draw just before surgery. Time from injury to surgery was an average of 47 days (10–156). Thirty-two patients underwent computer-assisted SB ACL reconstruction, and thirty underwent computer-assisted DB ACL reconstruction, using four-stranded autologous hamstring tendons under general anesthesia or spinal anesthesia. All the per-operative data were collected and analyzed by one independent observer. Patient demographics and characteristics are outlined in Table 1.

Operative technique

All ACL reconstructions in the series were carried out by the same senior surgeon. The same skin incisions for both groups are used. The semitendinosus and gracilis tendons were harvested through an anteromedial horizontal tibial incision at the pes anserinus, and a length of tendon was harvested with a tendon stripper. The tendons were cleaned from soft tissue. For the four-tunnel DB ACL reconstructions, the semitendinosus tendon (for the AM bundle) and the gracilis tendon (for the PL bundle) were looped over a 20-mm (AM) and 15-mm (PL) EndoButton CL (Smith & Nephew Endoscopy, Mansfield, MA); for the SB ACL reconstruction, both tendons were looped over one single 25-mm EndoButton CL, and the direct bioabsorbable screw system BIORCI* (Smith & Nephew Endoscopy, Mansfield, MA) was used for the tibia to fix the graft in either SB or DB group. For both techniques, the distal free ends of the tendons were armed with No. 2 Ethibond sutures using a whipstitch technique. The tibial and femoral ACL footprints and the intercondylar notch were cleaned from soft tissue as much as necessary to enable the use of bone morphing® technology sites. A notchplasty was performed to recreate a Roman arch. All graft diameters were measured in 0.5-mm steps, and the tibial and femoral bone tunnels were drilled accordingly in 0.5-mm steps with a conventional reamer on the tibial side and with a headed reamer on the femoral side for DB and SB ACL reconstructions.

For navigated surgery, our department uses the Surgetics Station hardware, which has dedicated software for ACL

Table 1 Pre-surgery parameters

	SB group (n = 32)	DB group (n = 30)	P value
Demographic parameters			
Age (year), mean	34.3 ± 11.7	33.3 ± 11.0	n.s.
Female gender	13 (41.9)	11 (33.3)	n.s.
Side right	17 (53.1)	13 (39.4)	n.s.
Pre-operative laxities			
Lachman test			
Lateral compartment (mm)	15.2 ± 3.7	13.9 ± 4.1	n.s.
Medial compartment (mm)	11.7 ± 2.3	10.8 ± 2.6	n.s.
Rotations at 20° of knee flexion			
Internal rotation (°)	21.4 ± 5.2	20.4 ± 4.4	n.s.
External rotation (°)	14.3 ± 4.0	12.4 ± 5.5	n.s.
Pivot shift			
AP maximal translation (mm)	20.6 ± 4.1	18.7 ± 3.9	n.s.
Maximal rotation (°)	24.4 ± 5.3	22.3 ± 3.6	n.s.
Colombet's index	0.25 ± 0.11	0.20 ± 0.09	0.048

Values are expressed as mean ± standard deviation except for sex and operated side which are expressed as number (percent). Statistical difference between pre-operative parameters of single-bundle (*SB group*) and double-bundle (*DB group*) anterior cruciate ligament reconstruction was evaluated by the unpaired Student's t-test or χ^2 test where appropriate

procedures, the ACL Logics Julliard Protocol [33]. Hardware and software were both manufactured by Praxim Medivision (La Tronche, France). The 3D surfaces of the tibial plateau and femoral notch are digitized and reconstructed using Bone Morphing® technology [31] This process requires about 60 s per bone surface. Practically, it is performed using the pointer arthroscopically to digitize clouds of points in all crucial and relevant areas of tibia and femur. The surgeon sweeps the pointer on the investigated areas. On the tibia: tibial eminences and center of the tibial plateau (medial and lateral), tibial anterior median point. On the femur: anterior arch, complete notch and posterior cortical [6, 33]. Once Bone Morphing® has been performed, the surgeon recreates on the screen, a true 3D representation of the knee. The ACL Logics system recorded different anatomical acquisitions. Accuracy of bone morphing can easily be verified for each patient, by placing the tip of the pointer on the surface of the bone (pointer tip to bone actual distance is 0 mm) and read the calculated distance on the virtual 3D model displayed on the touch screen. The measured distance and calculated distance must be within 1 mm in the digitized areas.

Computer-assisted single-bundle ACL reconstruction

The system was used according to the following protocol.

1. Cleaning of debris was performed in a conventional way.
2. Systematically, the shape of the notch was checked by visual inspection. If the shape was estimated to be like an open "Roman arch," the notch was left intact. If it was narrow, remodeling of the notch was performed using the shaver to create a Roman arch shape.
3. The followed data were then collected:
   - For any pair of insertion sites F and T selected by the surgeon, the system computes and displays the obtained profile reflecting distances between F and T along a passive flexion–extension recorded at the beginning of surgery. This profile represents the chronicled distances between F and T, starting at maximum extension to the maximal flexion position. The profile is known as "anisometry profile", and the maximum recorded length variation is referred to as "anisometry". If the anisometry profile decreases with increased flexion, indicating that the graft loosens with flexion, this profile trend is said to be "favorable". Therefore, at any time, it is possible to measure the isometry of the insertion sites for any flexion angle according to various rotations or anterior drawer applied to the tibia.
   - For a given insertion site F on the femur, the system computes and displays the projection of the femoral notch onto the tibial plateau for the fully extended knee joint position.
   - For a given insertion site T on the tibia, the system computes and displays an anisometry map on the lateral side of the femoral notch, in the potential insertion area. This color map represents the anisometry value associated with each insertion point F on the femur (with an accuracy of 1 mm).

Note that there is always a crest line on the anisometry map that separates the posterior area, where anisometry will be favorable, and the anterior area, where anisometry will be unfavorable. This crest line plays an important role because it defines for each patient the border that should not be overtaken anteriorly if tightening of the graft with flexion is to be avoided.

– For any pair of insertion sites F and T selected by the surgeon, the system computes and displays a cylindrical envelope graft whose radius is adjustable on the touch screen. In extension positions, the system shows where a potential conflict between the graft and the notch is expected. The conflict penetration depth is displayed on the touch screen.

All data and measurements, including planning strategies and global results, can be recorded on a CD-ROM for each patient.

4. On the tibia, the surgeon searched for an insertion site that was the most anterior and medial possible inside the ACL native area and inside the projection of the femoral notch represented on the screen. A safety clearance of 2 mm was shown by the computer. The navigated tibial conventional guides were aimed at targeting this point. The tibial tunnel was drilled, and the exit of the real tunnel on the plateau was digitized with the pointer to compensate from any deflection of the K-wire. Given this point T, the system computes and displays the anisometry map on the femur.
5. The surgeon uses directly the conventional femoral guide (Acufex® aiming device (Smith Nephew, Andover, MA)) equipped with a navigated instrument and searches for an insertion site that was anatomometric (i.e., with a minimal anisometry, less than 3 mm and inside the native ACL area), but that is always "favorable" (i.e., an anisometry profile that either decreases with flexion or is flat) and always in the anatomical area of the native ligament.
6. The femoral tunnel was drilled in–out.

Computer-assisted double-bundle reconstruction (Fig. 1)

For the DB reconstruction, we used similar principles [5].

Navigation of femoral AM tunnel

The center of the attachment of the AM bundle on the tibia was identified, and the navigation software generated an "anisometry map" projected onto a digital image of the PL aspect of the intercondylar notch. Femoral AM tunnel position at the most isometric point was selected. Once the position was selected, the knee was slowly flexed to 120° to ensure proper orientation of the tunnel. The tunnel was drilled through the AM portal by use of the calibrated drill equipped with the navigation array.

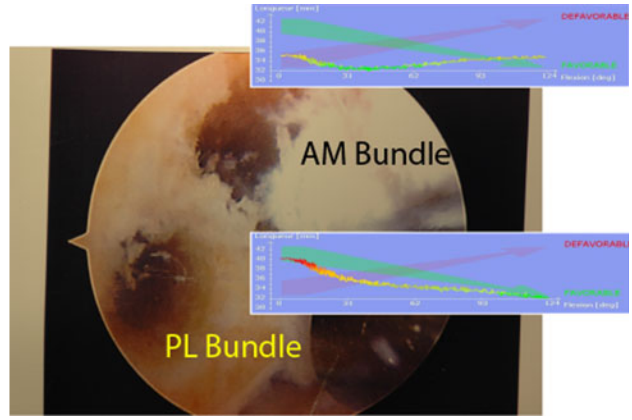

Fig. 1 Arthroscopic view of positioning of the AM and PL femoral tunnel inside native ACL area and with favorable anisometry

Navigation of femoral PL bundle tunnel

The center of the attachment of the PL bundle on the tibia was identified, and the navigation software generates an "anisometry map" projected onto a digital image of the PL aspect of the intercondylar notch. The navigation display also showed the position of the AM bundle tibial tunnel aperture so that the PL bundle position may be selected to maintain a bony bridge of approximately 2 mm between the apertures as they emerge into the joint. Once the position was selected, the knee was flexed back to 120° and the tunnel was drilled with a 4.5-mm drill, guided by the navigation array, through the AM portal. Care should be taken to observe the obliquity of the tunnel to ensure that the AM and PL femoral tunnels diverge at approximately 15°.

Navigation of tibial AM and PL bundle tunnel (Fig. 2)

The drill, equipped with the navigation array and calibrated 4.5-mm drill bit, was used for the AM bundle tunnel. The computer display guides was positioned by projecting a targeting circle onto the center of the anatomic attachment area of the native AM bundle (which was already identified and digitized, as described previously). The tibial PL bundle tunnel was similarly drilled. A 2- or 3-mm bony bridge between the tibial bundles must be maintained.

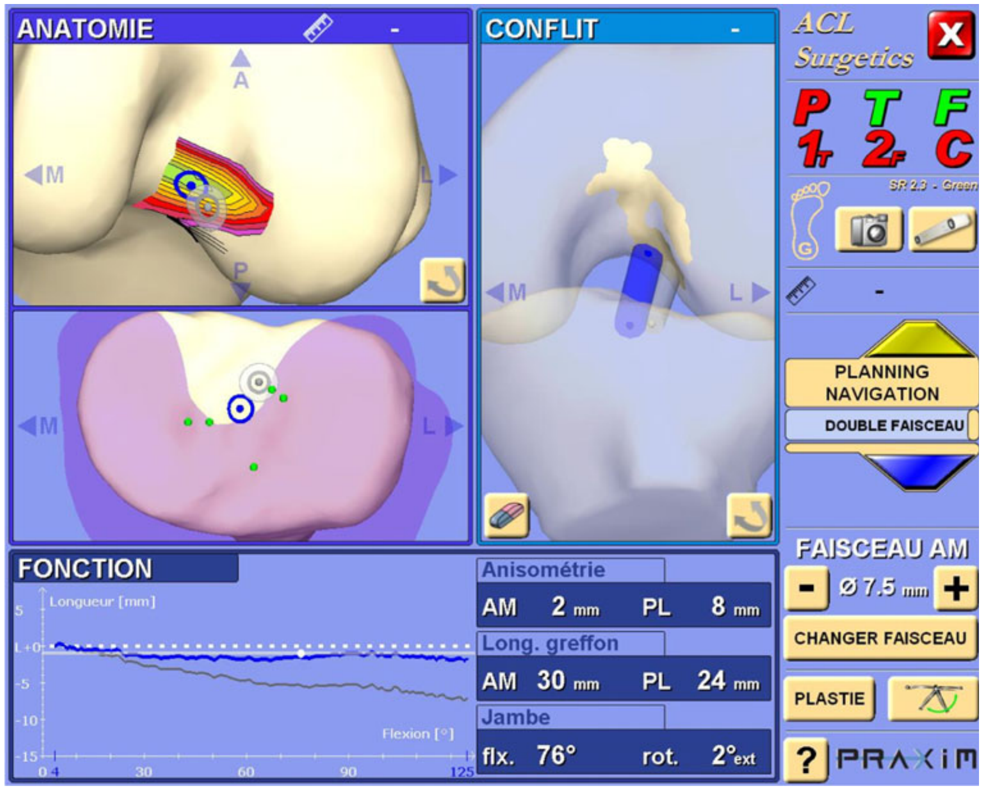

Fig. 2 Map of the AM and PL bundle with the values of isometry. The curve of AM bundle is almost horizontal (anisometry of 2 mm), and the curve of the PL bundle decreases between extension and flexion with favorable anisometry of 8 mm. On the tibial plateau, there is no conflict with the notch (projection of the arch in purple)

Intraoperative measurements

Real-time visualization of knee instabilities was quantified using the navigation system. Measurement accuracy of the data recorded by the computer was infra millimeter for the AP laxity and less than one degree for rotations.

- We assessed the following biomechanical parameters before (just before removing the remnants) and after reconstruction in both groups. The rotation was 0° when the knee did not undergo any rotational force (natural position to be neutral). The same operator applied a maximum force equal for all tests.
- Maximum internal (IR) and external rotation (ER) at 20° of knee flexion (Fig. 3).
- Anteroposterior tibial translation of lateral and medial compartments and rotatory laxities during the Lachman test (20° of knee flexion) (Fig. 3).
- Tibial internal/external rotation and anteroposterior tibial translation during the pivot shift test (Fig. 4).
- Colombet's index (translation/rotation during pivot shift test) [6].

The clinical laxity tests were manually performed at maximum force by the same operator. Test reliability was ensured by repeating each maneuver performed with a maximum force five times. The values used for the analysis were the maximum value recorded by the computer for each test. The repeatability of the manual clinical laxity tests at maximum force was evaluated in several previous studies [7, 8] and was found to have an accuracy less than 1 mm for translations and 1° for rotations. During the tests, the surgeon was able to verify, on the navigation system, the degree of limb flexion and rotation in order to standardize the initial position of the knee.

Statistical analysis

Measurements were expressed as mean ± standard deviation (SD). Statistical difference between DB and SB group (for the results) was evaluated by the unpaired Student's t-test (quantitative demographic parameters, laxities) or chi^2 test (nominal demographic parameters) where appropriate (Statview 5.0; SAS Institute, Marlow, UK). Differences with $P < 0.05$ were considered significant.

Results

The SB group comprised 32 patients (19 men/13 women), while the DB group comprised 30 patients (19 men/11 women). There were no significant differences in background factors regarding sex ratio or age between both groups (Table 1).

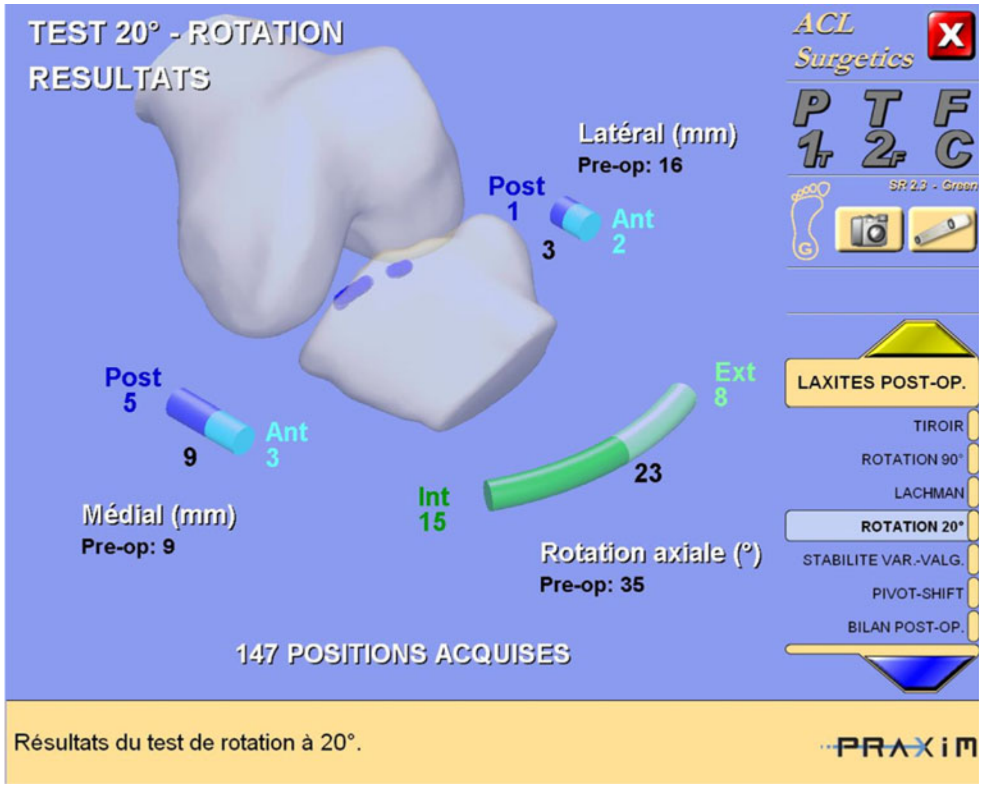

Fig. 3 View on the screen of post-operative maximum rotatory and AP laxity (with the pre-operative values)

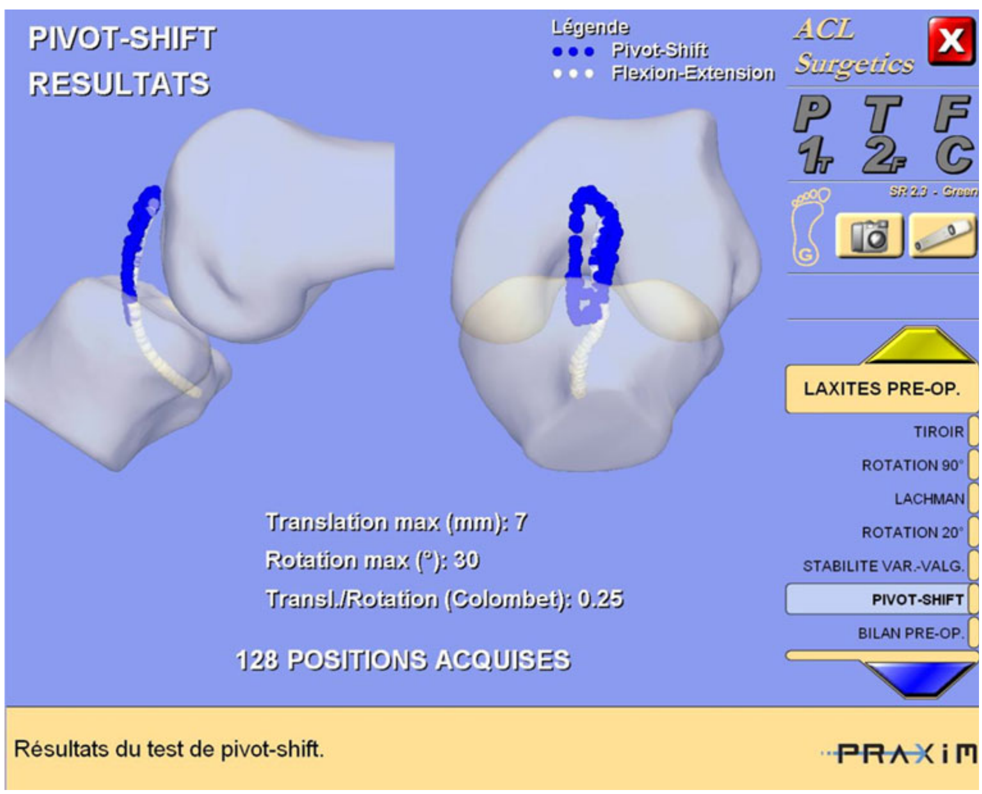

Fig. 4 post-operative values of the pivot shift test

Baseline laxity test

There was no statistical difference in pre-operative laxities between both groups (Table 1) except for Colombet's index, which was slightly higher in SB group than in DB group (0.25 ± 0.11 vs. 0.20 ± 0.09, $P = 0.05$).

Post-operative laxities

Post-operative laxities are summarized in Table 2. The post-operative anteroposterior displacement of the lateral compartment during the Lachman test was statistically significantly reduced in DB group in comparison with SB group (5.1 ± 4.3 mm vs. 7.1 ± 3.3 mm, $P < 0.05$), whereas the anteroposterior displacements of the medial compartment were not statistically different (3.4 ± 3.7 mm vs. 4.5 ± 2.6 mm). Maximum internal and external rotations at 20° of knee flexion were lower in the DB group than in the SB group (respectively, 13.2 ± 4.9° vs. 17.5 ± 4.0° (IR), $P < 0.01$ and 9.1 ± 3.6° vs. 11.5 ± 3.5° (ER), $P < 0.001$). Laxities during the pivot shift test were also different in both groups: the maximal translation was 4.5 ± 2.1 mm in DB group and 6.3 ± 2.7 mm in SB group ($P = 0.01$), whereas the maximal rotation was 3.8 ± 2.5° in DB group and 2.5 ± 1.2° in SB group ($P = 0.468$). However, Colombet's index was similar in DB group and SB group (respectively, 0.21 ± 0.16 and 0.17 ± 0.06, (n.s.)).

Discussion

The most important finding of the current study was that DB ACL reconstruction compared with SB improves the envelope of the rotatory laxity and also AP laxity. The aim was to compare the intraoperative results of navigated four-tunnel DB ACL reconstruction with hamstring tendons compared with navigated SB ACL reconstruction in a controlled clinical trial. The results showed less anterior tibial translation on the lateral compartment measured by the computer navigation in group DB ($P = 0.046$) compared with group SB. These findings may indicate that the additional reconstruction of the PL bundle does add to anterior lateral stability. We also noted a significant improvement in terms of internal and external rotational stability according to the computer navigation in the DB group compared with the SB group (respectively, $P < 0.001$ and $P < 0.01$).

In a controlled laboratory study, Tsai et al. [41] found that an all-inside double-bundle ACL reconstruction demonstrated significant improvement in restoring normal rotational knee motion during simulated pivot shift testing compared with single-bundle ACL reconstructions in vitro, with no significant differences in other knee loading conditions. Markolf et al. [27] in a cadaveric study found that adding a posterolateral graft to an anteromedial graft tended to reduce laxity and tibial rotation, but the reductions were accompanied by markedly higher forces in the posterolateral graft near 0 degrees that occasionally caused it to fail during tests with internal torque or anterior tibial force. In another cadaveric study by Ho et al. [16] found that single- and double-bundle ACL reconstructions are equally effective in restoring normal anterior translation to the knee under both anterior and rotational loads.

Moreover, the most important finding in the present study was to quantify the laxities of ACL-deficient knee and with ACL single-bundle or double-bundle reconstruction. If our results are consistent with previously published laboratory studies [14], very few in vivo studies have

Table 2 Post-surgery laxities

	SB group ($n = 32$)	DB group ($n = 30$)	P value
Lachman test			
Lateral compartment (mm)	7.1 ± 3.2	5.1 ± 4.4	0.046
Medial compartment (mm)	4.5 ± 2.6	3.4 ± 3.7	n.s.
Rotations at 20° of knee flexion			
Internal rotation (°)	17.5 ± 4.0	13.2 ± 4.9	<0.001
External rotation (°)	11.5 ± 3.5	9.1 ± 3.6	<0.01
Pivot shift			
AP Maximal translation (mm)	6.3 ± 2.7	4.5 ± 2.1	0.01
Maximal rotation (°)	3.4 ± 1.2	3.8 ± 2.5	n.s.
Colombet's index	0.17 ± 0.06	0.21 ± 0.16	n.s.

Values are expressed as mean ± standard deviation. Statistical difference between post-operative single-bundle (*SB group*) and double-bundle (*DB group*) anterior cruciate ligament reconstruction was evaluated by the unpaired Student's t-test. Differences with $P < 0.05$ were considered significant published values of maximum AP or rotational laxity of a knee. Comparing pre- and post-operative laxity after computer-navigated single- and double-bundle ACL reconstruction Hofbauer et al. [17] found equivalent values to those we have found for internal rotation and AP translation (Table 3).

Previous in vivo studies have compared SB versus DB ACL reconstruction. Seon et al. [38] evaluated the intra-operative stability during double-bundle anterior cruciate ligament (ACL) reconstructions using a navigation system and compared the results with those obtained from single-bundle reconstructions and suggest that a double-bundle ACL reconstruction restores greater knee stability with respect to the anteroposterior and rotational stability than a single-bundle reconstruction.

The benefit of adding a PL graft to the AM graft sustains the previous findings of Kanaya et al. [21] who placed the graft in single-bundle reconstruction more closely to the PL bundle. In an intraoperative prospectively randomized evaluation of anteroposterior and rotational stabilities in anterior cruciate ligament reconstruction, they [21] found that a lower femoral tunnel single-bundle reconstruction reproduced AP and rotational stability as well as a double-bundle reconstruction after reconstruction intraoperatively. With the same anatomical placement for single or double bundle as us, Ishibashi et al. [20] found that AP displacement, after double-bundle ACL reconstruction, was significantly improved compared with AP displacement after posterolateral bundle or anteromedial bundle fixation in an intraoperative evaluation with the OrthoPilot navigation system.

In this current study, laxities during the pivot shift test were different in both groups but only for the maximal translation: 4.5 ± 2.1 mm in DB group and 6.3 ± 2.7 mm in SB group ($P = 0.012$), whereas the maximal rotation was 3.8 ± 2.5° in DB group and 2.5 ± 1.2° in SB group (n.s.). In a cadaveric model, Markolf et al. [28] showed that a single-bundle reconstruction was sufficient to restore intact knee kinematics during a simulated pivot shift event. Colombet et al. [6] in an in vivo navigated study with the same system as us demonstrated that AM and PL bundles act differentially to stabilize the knee, particularly during the pivot shift. In this ACL Logics Praxim navigation system, the values defining the pivot shift were calculated from a reference area located near the center of rotation of the knee [36] and are probably far from a realistic mathematical definition of the pivot shift. Using another navigation system (Orthopilot), Ishibashi et al. [19] indicated that both the posterolateral and the anteromedial bundle similarly control both anterior translation and internal rotation during pivot shift testing.

The results of this current study seem not to be in agreement with the findings of Ferretti et al. [11, 12] who showed, in two computer-assisted in vivo studies with the Ortho pilot system, no differences between single-and double-bundle reconstruction techniques in reducing the AP displacement and the IR and ER of the tibia at 30° of knee flexion. Nevertheless, the first study included only 10 patients in each group, and also in our opinion, the navigation system used for these 2 studies (Orthopilot) does not include a sufficient set of anatomical points for mapping virtual reliable and realistic values for calculating the anisometry transplants.

Although the pathologic kinematics of the pivot shift are difficult to measure, recent technological advances have allowed more accurate and objective descriptions of the pivot shift, which have furthered our understanding of the complex motions involved [25]. These advances may lead to a method of quantifying the pivot shift for research purposes and, ultimately, to ACL reconstruction that is tailored specifically to each patient's objectively measured rotational instability [23, 31]. If navigation provides an opportunity to better analyze in vivo the motions that comprise the pivot shift and the kinematic changes that are inherent after ACL reconstruction [30, 31], also no navigation system gives a very accurate value for the pivot shift. This maneuver is dependent on the operator carrying out the pivot shift, and imprecise sub-maximal data can be compiled in all 3 planes. Recently, some studies introduce new tools to measure the acceleration during the pivot shift testing: Hoshino et al. [18] in vivo controlled laboratory study measured the pivot shift test in the anterior cruciate ligament deficient knee using an electromagnetic device and concluded that the increase in tibial anterior translation and acceleration of subsequent posterior translation could be detected in knees with a positive pivot shift result, and

Table 3 Pre- and post-operative laxity after computer-navigated single- and double-bundle ACL reconstruction

		AP laxity (mm)		Internal rotation (°)	
		Pre-operative AP	Post-operative AP	Pre-operative IR	Post-operative IR
Hofbauer (13)	SB	12.6 (±1.2)	5.8 (±1.9)	27.4 (±0.61)	20.3 (±0.2)
	DB	12.7 (±1.3)	5.4 (±1.6)	27.9 (±0.63	12.3 (±0.3)
Our study	SB	11.7 (±2.3)	4.5 (±2.6)	21.4 (±5.2)	17.5 (±4.0)
	DB	10.8 (±2.6)	3.4 (±3.7)	20.4 (±4.4)	13.2 (±4.9)

this increase was correlated to clinical grading. Musahl et al. [29] used a modified continuous passive motion machine (CPM) for measurements of AP translation and rotation during the pivot shift test. In the ACL-deficient knee, translation with manual pivot shift testing (11.7 ± 2.6 mm) was significantly higher than with mechanized pivot shift testing (7.4 ± 2.5 mm). Rotation with the manual pivot shift testing (18.6 ± 5.4°) was also significantly higher than with mechanized pivot shift testing (11.0 ± 2.3°). We also believe that the joint laxity has to be quantify through the range of knee flexion during the pivot shift test and thus could reflect more accurately the sensation felt by the patients and the motion observed by the surgeon during clinical pivot shift test [3].

There are some limitations to the current study. The results were limited by the fact that all tests were manually performed during surgery; therefore, there was no control of the forces acting on the limb; however, some studies in literature [7, 8] reported that tests performed with manual maximum force are as repeatable as tests performed with controlled force.

Computer navigation systems are not all the same and that they cannot be relied on independently.

New scientific studies in the future will include a more complete analysis of the graft insertion sites correlated with isometric envelope of the graft during all tests of laxity including pivot shift test and at different ranges of flexion of the knee. Optimal position for placement of the tunnels during ACL reconstruction remains controversial [4]. Navigation systems provide a powerful tool to obtain knee kinematics and anatomical landmarks during surgery. Future studies will present new predictive tools to guide tunnel placement in the femoral site for single- and double-bundle techniques by predicting the knee laxity after reconstruction based on kinematics data recorded before reconstruction by a navigation system.

Also, there were intraoperative data but no follow-up data. Future applications include non-invasive registration techniques to use navigation as a combined pre-operative, intraoperative and post-operative measurement tools [3, 23] correlated with clinical outcomes evaluated over 2 years [1, 17].

Conclusion

The results of this study showed a significant intraoperative advantage in anterior and rotational stability for navigated four-tunnel DB ACL reconstruction compared with navigated SB ACL reconstruction. So, computer-assisted ACL reconstruction technique helped us to perform an intraoperatively comprehensive knee laxity analysis, to optimize the placement of the grafts, and to evaluate objectively the biomechanical effect of the reconstruction.

References

1. Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N (2010) Comparison between single-and double-bundle anterior cruciate ligament reconstruction: a prospective, randomized, single-blinded clinical trial. Am J Sports Med 38:25–34
2. Belisle AL, Bicos J, Geaney L, Andersen MH, Obopilwe E, Rincon L, Nyland J, Morgan C, Caborn DN, Arciero RA (2007) Strain pattern comparison of double and single bundle anterior cruciate ligament reconstruction techniques with the nativ anterior cruciate ligament. Arthroscopy 23:1210–1217
3. Bignozzi S, Zaffagnini S, Lopomo N, Fu FH, Irrgang JJ, Marcacci M (2010) Clinical relevance of static and dynamic tests after anatomical double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 18:37–42
4. Brophy RH, Pearle AD (2009) Single-bundle anterior cruciate ligament reconstruction: a comparison of conventional, central, and horizontal single-bundle virtual graft positions. Am J Sports Med 37:1317–1323
5. Colombet P, Robinson J, Jambou S, Allard M, Bousquet V, de Lavigne C (2006) Two-bundle, four-tunnel anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 14: 629–636
6. Colombet P, Robinson J, Christel P, Franceschi JP, Djian P (2007) Using navigation to measure rotation kinematics during ACL reconstruction. Clin Orthop Relat Res 454:59–65
7. Daniel DM, Stone ML, Sachs R, Malcom L (1985) Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. Am J Sports Med 13:401–407
8. Edixhoven P, Huiskes R, de Graaf R, van Rens TJ, Slooff TJ (1987) Accuracy and reproducibility of instrumented knee-drawer tests. J Orthop Res 5:378–387
9. Edwards A, Bull AM, Amis AA (2008) The attachments of the anteromedial and posterolateral fibre bundles of the anterior cruciate ligament. Part 2: femoral attachment. Knee Surg Sports Traumatol Arthrosc 16:29–36
10. Eriksson E (1997) How good are the results of ACL reconstruction? Knee Surg Sports Traumatol Arthrosc 5:137
11. Ferretti A, Monaco E, Labianca L, Conteduca F, De Carli A (2008) Double- bundle anterior cruciate ligament reconstruction: a computer-assisted orthopaedic surgery study. Am J Sports Med 36:760–766
12. Ferretti A, Monaco E, Labianca L, De Carli A, Maestri B, Conteduca F (2009) Double-bundle anterior cruciate ligament reconstruction: a comprehensive kinematic study using navigation. Am J Sports Med 37:1548–1553
13. Fleute M, Lavallee S, Julliard R (1999) Incorporating a statistically based shape model into a system for computer assisted anterior cruciate ligament surgery. Med Image Anal 3:209–222
14. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE (2004) Distribution of in situ forces in the anterior cruciate ligament in response to rotatory loads. J Orthop Res 22:85–89
15. Galway H, MacIntosh DL (1980) The lateral pivot-shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
16. Ho JY, Gardiner A, Shah V, Steiner ME (2009) Equal kinematics between central anatomic single-bundle and double-bundle anterior cruciate ligament reconstructions. Arthroscopy 25:464–472

17. Hofbauer M, Valentin P, Kdolsky R, Ostermann RC, Graf A, Figl M, Aldrian S (2010) Rotational and translation laxity after computer-navigated single- and double-bundle anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc 18:1201–1207
18. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamagushi M, Muratsu H, Yoshiya S, Kurosaka M (2007) In vivo measurement of the pivot-shift test in the anterior cruciate ligament–deficient knee using an electromagnetic device. Am J Sports Med 35:1098–1104
19. Ishibashi Y, Tsuda E, Yamamoto Y, Tsukada H, Toh S (2009) Navigation evaluation of the pivot-shift phenomenon during double-bundle anterior cruciate ligament reconstruction: is the posterolateral bundle more important ? Arthroscopy 25:488–495
20. Ishibashi Y, Tsuda E, Tazawa K, Sato H, Toh S (2005) Intraoperative evaluation of the anatomical double-bundle anterior cruciate ligament reconstruction with OrthoPilot navigation system. Orthopedics 28(suppl 10):s1277–s1282
21. Kanaya A, Ochi M, Deie M, Adachi N, Nishimori M, Nakamae A (2009) Intraoperative evaluation of anteroposterior and rotational stabilities in anterior cruciate ligament reconstruction: lower femoral tunnel placed single-bundle versus double-bundle reconstruction. Knee Surg Sports Traumatol Arthrosc 17:907–913
22. Kaplan N, Wickiewicz TL, Warren RF (1990) Primary surgical treatment of anterior cruciate ligament ruptures: a long-term followup study. Am J Sports Med 18:354–358
23. Kendoff D, Citak M, Voos J, Pearle AD (2009) Surgical navigation in knee ligament reconstruction. Clin Sports Med 28:41–50
24. Koh J (2005) Computer-assisted navigation and anterior cruciate ligament reconstruction: accuracy and outcomes. Orthopedics 28(suppl 10):s1283–s1287
25. Lane CG, Warren RF, Stanford FC, Kendoff D, Pearle AD (2008) In vivo analysis of the pivot shift phenomenon during computer navigated ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 16:487–492
26. Lewis PB, Parameswaran AD, Rue JP, Bach BR Jr (2008) Systematic review of single-bundle anterior cruciate ligament reconstruction outcomes: a baseline assessment for consideration of double-bundle techniques. Am J Sports Med 36:2028–2036
27. Markolf KL, Park S, Jackson SR, McAllister DR (2009) Anterior-posterior and rotatory stability of single and double-bundle anterior cruciate ligament reconstructions. J Bone Joint Surg Am 91:107–118
28. Markolf KL, Park S, Jackson SR, McAllister DR (2008) Simulated pivot-shift testing with single and double-bundle anterior cruciate ligament reconstructions. J Bone Joint Surg Am 90: 1681–1689
29. Musahl V, Voos J, O'Loughlin PF, Stueber V, Kendoff D, Pearle AD (2010) Mechanized pivot shift test achieves greater accuracy than manual pivot shift test. Knee Surg Sports Traumatol Arthrosc 18:1208–1213
30. Pearle AD, Solomon DJ, Wanich T et al (2007) Reliability of navigated knee stability examination: a cadaveric evaluation. Am J Sports Med 35:1315–1320
31. Pearle AD, Kendoff D, Musahl V, Warren RF (2009) The pivot-shift phenomenon during computer-assisted anterior cruciate ligament reconstruction. J Bone Joint Surg Am 91:115–118
32. Petersen W, Zantop T (2007) Anatomy of the anterior cruciate ligament with regard to its two bundles. Clin Orthop Relat Res 454:35–47
33. Plaweski S, Cazal J, Rosell P, Merloz P (2006) Anterior cruciate ligament reconstruction using navigation: a comparative study on 60 patients. Am J Sports Med 34:542–552
34. Pombo MW, Shen W, Fu FH (2008) Anatomic double-bundle anterior cruciate ligament reconstruction: where are we today? Arthroscopy 24:1168–1177
35. Ristanis S, Stergiou N, Patras K, Vasiliadis HS, Giakas G, Georgoulis AD (2005) Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. Arthroscopy 21:1323–1329
36. Robinson J, Carrat L, Granchi C, Colombet P (2007) Influence of anterior cruciate ligament bundles on knee kinematics: clinical assessment using computer-assisted navigation. Am J Sports Med 35:2006–2013
37. Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res 15:285–293
38. Seon JK, Park SJ, Lee KB, Yoon TR, Seo HY, Song EK (2009) Stability comparison of anterior cruciate ligament between double- and single-bundle reconstructions. Int Orthop 33:425–429
39. Shelbourne KD, Gray T (1997) Anterior cruciate ligament reconstruction with autogenous patellar tendon graft followed by accelerated rehabilitation: a two- to nine-year follow-up. Am J Sports Med 25:786–795
40. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W (2004) Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. Am J Sports Med 32:975–983
41. Tsai AG, Wijdicks CA, Walsh MP, Laprade RF (2010) Comparative kinematic evaluation of all-inside single-bundle and double-bundle anterior cruciate ligament reconstruction: a biomechanical study. Am J Sports Med 38:263–272
42. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL (2002) Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. Am J Sports Med 30:660–666