RESEARCH ARTICLE

# Rotational Stability of the Knee in a Comparative Study of Anterior Cruciate Ligament Reconstruction Using the Double-Bundle and Single-Bundle Techniques

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## Abstract

**Background:** The purpsose of this study was to evaluate the biomechanical outcomes of patients who underwent ACL reconstruction either with the DB or SB technique. We hypothesized that the DB technique would provide better rotation control of the knee following ACL reconstruction.

**Methods:** The study included seventy-five participants (26 DB, 22 SB, and 27 healthy volunteers). Only cases with at least one year of postoperative follow-up were included. The participants performed three different demand tasks: walk task, walk and change direction, and stair descent and change direction, which was tracked using a three-dimensional 4-camera optoelectronic system. The following kinematic data were analyzed: tibial rotation amplitude and maximal internal and external rotation. Knees with ACL reconstruction were compared to contralateral knees with intact ACL and healthy knees. Clinical outcomes were determined using the subjective and objective International Knee Documentation Committee (IKDC) questionnaire and a manual arthrometer (KT 1000).

**Results:** Both surgical groups exhibited similar clinical outcomes (mean subjective IKDC 91 SB vs. 90 DB, *P=0.815*; KT 1000 difference: 2mm in both groups, *P=0.772*). The vertical component of the ground force reaction revealed no differences between the surgical and control groups (*P>0.05*). Tibial rotation amplitude and maximal internal and external rotation were similar between the control, SB, and DB groups in all three different demand tasks (*P>0.05*).

**Conclusion:** ACL reconstruction using either the SB or DB technique can restore rotational control to the level of a healthy knee. No clinical or functional differences were found between the SB and DB surgical options.

**Level of evidence:** II

**Keywords:** Anterior cruciate ligament, Anatomy, Anterior cruciate ligament reconstruction, Biomechanical phenomena

## Introduction

The anterior cruciate ligament (ACL) has been one of the most studied structures in the musculoskeletal system in the past 25 years. Its anatomy, biomechanics, function, epidemiology, injury mechanisms, and clinical treatment outcomes have been extensively studied. ACL injuries are relatively

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frequent, with an estimated incidence in the general population of 1/3000 individuals per year, with 70% of cases occurring during sports practice. Isolated ACL injuries represent almost 50% of all knee ligament injuries.[1,2]

Early or premature osteoarthritis (OA) that tends to occur following ACL injury is one of the most important complications however, its exact pathophysiology remains to be understood completely.[1,3,4] Patients were classified as high, moderate, or low risk using preinjury sports participation and knee laxity measurements. Early anterior cruciate ligament reconstruction (within 3 months of injury). It has been suggested that a lack of rotational control between the tibia and femur after the single-bundle (SB) ACL reconstruction technique changes the contact pressure between these surfaces, leading to cartilage wear, impaired chondrogenesis, and ultimately, late OA.[2] Several *in vitro* and *in vivo* studies have found that ACL reconstruction with the SB technique cannot reestablish rotational control of the tibia to normal levels.[1,2,5–7] Patients were classified as high, moderate, or low risk using preinjury sports participation and knee laxity measurements. Early anterior cruciate ligament reconstruction (within 3 months of injury).

The ACL is formed by the anteromedial (AM) and posterolateral (PL) bundles. Historically, when SB ACL reconstruction that maintains the ligament length or SB AM bundle reconstruction is performed, the anatomy of the ACL may not be restored.[8] However, the AM and PL bundles play different but essential roles in controlling the rotational stability of the knee joint.[9,10] Changes in integrity, length, and in situ forces in each bundle reveal that both bundles stabilize knee rotation.[11–13] The AM bundle is the main stabilizer against the anterior translation of the tibia when the knee is flexed, whereas the PL bundle acts mainly when the knee is extended.[14,15] Both bundles are equally important during a combined anterior and rotational force to the tibia.[16–18] Surgical and biomechanical studies in humans demonstrated that double-bundle (DB) ACL reconstruction could restore knee rotational stability better than SB reconstruction.[19–22] However, although significant improvement in pivot shift tests after DB reconstruction has been reported, functional superiority has not been demonstrated.[23,24] The literature regarding in vivo knee kinematics after DB ACL reconstruction still presents conflicting results.[25–28]

This study aimed to assess the in vivo rotational stability of the knee after ACL reconstruction using the SB and DB techniques. The hypothesis was that DB ACL reconstruction would be more effective than SB ACL in enhancing the rotational stability of the knee during dynamic motions.

## Materials and Methods

This study was approved by the Institutional Review Board and followed all ethical guidelines regarding human research. Informed consent was obtained from all individuals who agreed to participate in the study and met the inclusion criteria.

### *Design*

This cross-sectional, comparative, controlled, biomechanical single-center study included patients who underwent ACL reconstruction.

### *Participants*

A pilot study was performed with six patients to estimate the number of patients required for 80% power and 5% significance to detect a mean difference of 5° in tibial rotation amplitude (TRA) between the SB and DB groups, and the third group as a control, assuming a standard deviation of 5. Using a sample calculation for analysis of variance (ANOVA), considering two-tailed tests, a sample size of 21 individuals per group was determined.

The inclusion criteria for the control group were as follows: understand the informed consent form and agree to participate in the study, absence of neurological or musculoskeletal impairments, and no history of injury to the lower limbs. The inclusion criteria for the ACL reconstruction groups were as follows: patients with an isolated ACL rupture reconstructed using either the SB or DB technique at least ten months before the start of the study and no ACL re-rupture or active symptoms in the operated knee.

The patients were enrolled consecutively to reach the target sample size. Seventy-five participants were enrolled, with 27 in the control group, 22 in the SB group, and 26 in the DB group. There was no significant difference in age (*P=0.951*) and height (*P=0.531*) between the three groups. However, weight (*P=0.027*) and body mass index (*P=0.015*) were greater in the DB group than in the control group but similar when compared to those in the SB group [Table 1A].

The patients were tested for a mean period of 15 ± 2 months postoperatively. Before biomechanical testing, all patients were subjected to a new clinical evaluation, and objective and subjective International Knee Documentation Committee (IKDC) scores were assessed [Table 1].[29]

### *Surgical procedure*

All surgical procedures were performed or directly supervised by a single surgeon (C.D.). SB ACL reconstruction was performed according to the description by Pinczewski et al., and DB ACL reconstruction was performed following the technique described by Jarvela et al. and Zelle et al.[21,22,30-32] We harvested ipsilateral semitendinosus and gracilis autografts from all patients. In the SB and DB techniques, grafts were fixed with bioabsorbable interference screws (Mega Fix®, Karl-Storz, Tuttlingen, Germany) in the femur and tibia.

### *Biomechanical evaluation*

Biomechanical evaluations were conducted by a single senior evaluator. All participants performed three tasks with different biomechanical demands and an increasing load progression. The first was the walking task (WT), in which the patient walked (4–6 m) at a comfortable speed and stepped on the force

**Table 1A. Anthropometric characteristics of the groups**

| | Control (n=27) | SB (n=22) | DB (n=26) | *P value* |
|---|---|---|---|---|
| **Age (years)** | 27 ± 5 | 27 ± 8 | 27 ± 7 | 0.951 |
| **Height (cm)** | 173 ± 10 | 175 ± 9 | 176 ± 10 | 0.531 |
| **Mass (kg)** | 69 ± 11 | 76 ± 9 | 78 ± 15* | 0.027 |
| **BMI (kg/m²)** | 23.14 ± 2.57 | 24.87 ± 2.05 | 25.19 ± 2.94* | 0.015 |

SB: single bundle; DB: double bundle; BMI: Body mass index; Data presented as average ±SD; * Comparison of DB Group Vs. Group control, *P<0.05*; Anova, teste *post-hoc* Bonferroni.

**Table 1. Surgical and clinical parameters from the surgical groups**

| | SB (n=22) | DB (n=26) | *P value* |
|---|---|---|---|
| **Time to evaluation (months)** | 16 ± 2 | 15 ± 2 | 0.264 |
| **Operated side (R: L) #** | 13:9 | 16:10 | 0.863 |
| **Dominance (R: L) &** | 18:4 | 22:4 | 0.946 |
| **Subjective IKDC** | 91 ± 5 | 90 ± 5 | 0.815 |
| **IKDC target (A: B) #** | 10:12 | 15:11 | 0.398 |
| **KT 1000 difference (mm)** | 2 ± 1 | 2 ± 1 | 0.772 |

SB: single bound; DB: double bound; R, right; L, left. Data presented as average ± SD. # Comparison of the distribution of qualitative variables between groups; Chi-square test. & Comparison of the distribution of the qualitative variable between the groups; Verissimilitude ratio test.

plate with the limb to be analyzed. The second task was walk and change direction (WT&CD), in which the individual walked at a comfortable pace and performed a 90° change of direction on the support foot when it touched the force plate (clockwise if on the right leg and counter-clockwise if on the left leg).[33] The third was stair descent and change direction (SD&CD), in which the participant descended a four-step stair and, after the support foot touched the power plate, made a 90° change of direction (clockwise if on the right leg and counter-clockwise if on the left leg).[34] In the second and third tasks, participants were instructed to: raise their arms above the waist to not cover the markers (described next) on the thigh; to point the foot forward when it first touched the force plate, and not to touch the swinging foot on the ground before finishing to change the movement direction. After performing the pivot, the participants walked about three steps toward a reference point located 90 degrees from the original trajectory. The WT&CD and SD&CD tasks are illustrated in Figure 1.

The anatomical system calibration technique was adopted for the kinematic analysis, and retro-reflective markers were positioned according to Figure 2.[35] Data were captured using a 4-camera system (Vicon 460, Oxford Metrics, Oxford, UK) to assess the lower limb and pelvis position, and ultimately, the three-dimensional movement was analyzed. A force plate (OR6-2000, AMTI Inc., Watertown, MA, USA) embedded in the floor and connected to a computer was used to calculate the ground reaction force (GRF), as described previously.[26]

Tibial internal-external rotation during the dynamic tasks was calculated concerning the femur using Euler angles as the third rotation of a Cardan sequence, as proposed by Grood and Suntay.[36] Thus, it corresponds to the angular displacement around an axis. It passes midway between the two femoral epicondyles and through the center of the ankle (midway between the two malleoli). TRA was defined as the maximum

**Figure 1. Positioning of the femoral tunnel in the single-bundle (SB) group. A) Computed tomography scan in the sagittal plane highlighting the femoral tunnel location. B) Representative illustration (green) of the femoral tunnel region in the SB group.**

**Figure 2. Walk and change direction (WT&CD) and stair descent and change direction (SD&CD) tasks. The top images illustrate WT&CD, a task of intermediate complexity. The bottom images illustrate SD&CD, a highly complex task.**

internal rotation angle, represented by positive values (Max-IR), subtracted from the maximum external rotation angle, represented by negative values (Max-ER). Tibial rotation was plotted against gait time during the support phase period to test if there was any difference between the groups.

All patients were instructed how to perform the tasks and had an opportunity to practice and adapt accordingly. The average between three to five trials was calculated for each task and both sides for all participants for the following variables: (A) TRA and (B) vertical impulse component of GRF.

During the support phase period, the rotation angles and the vertical component of the GRF were used to calculate the average between the attempts for each side of the individual. These series of attempts were used to calculate the average between individuals for the operated and non-operated sides (OS and NOS, respectively) in the SB and DB groups and the left and right sides in the control group during the execution of the three tasks.

### *Statistical analysis*

Comparisons of symmetry between the right and left knees in the control group (assessed using the Student's t-test) revealed no difference between the sides (*P > 0.05*) [Table 2A]. The average biomechanical parameters between the left and right knees were used to represent the control group for further comparisons. The following variables were compared as continuous variables using repeated-measures ANOVA: vertical component of GRF normalized by body weight (Max-GRF), TRA, maximum internal rotation angle (Max-IR), and maximum external rotation angle (Max-ER). ANOVA was performed to compare Max-GRF, TRA, Max-RI, and maxRE between the control group and the OS of the patient groups (SB and DB). In the SB and DB groups, the OS and the NOS were compared for the same variables using repeated-measures ANOVA, with appropriate contrast tests to compare the differences between OS and NOS within each group (SB and DB). The level of significance was 0.05 in the analyses.

**Table 2A. Comparison between the left and right knees of the control group, regarding the variables of interest**

| | Left side | Right side | *P value* |
|---|---|---|---|
| **Max-GRF WT** | 1.17 ± 0.07 (n=27) | 1.18 ± 0.09 (n=27) | 0.883 |
| **Max-GRF WT&CD** | 1.24± 0.16 (n=25) | 1.24 ± 0.18 (n=25) | 0.850 |
| **Max-GRF SD&CD** | 1.72 ± 0.40 (n=27) | 1.71 ± 0.36 (n=27) | 0.786 |
| **TRA WT (º)** | 12 ± 4 (n=27) | 12 ± 4 (n=27) | 0.426 |
| **TRA WT&CD (º)** | 27 ± 5 (n=27) | 27 ± 5 (n=27) | 0.637 |
| **TRA SD&CD (º)** | 27 ± 5 (n=27) | 28 ± 5 (n=27) | 0.485 |
| **Max-IR WT (º)** | 5 ± 4 (n=27) | 4 ± 5 (n=27) | 0.436 |
| **Max-IR WT&CD (º)** | 17 ± 6 (n=27) | 17 ± 5 (n=27) | 0.816 |
| **Max-IR SD &CD (º)** | 20 ± 6 (n=27) | 19 ± 6 (n=27) | 0.755 |
| **Max-ER WT (º)** | -7± 6 (n=27) | -9 ± 5 (n=27) | 0.164 |
| **Max-ER WT&CD (º)** | -10 ± 7 (n=27) | -9 ± 6 (n=27) | 0.636 |
| **Max-ER SD&CD (º)** | -8 ± 6 (n=27) | -9 ± 7 (n=27) | 0.502 |

WT: Walk task; WT&CD: Walk and change direction; SD&CD: stair descent and change direction; Max-GRF: GRF vertical component normalized by body weight (parameter with no unit); TAR: Tibial Rotation Amplitude; Max–IR: maximum angle of internal rotation; maxER: maximum angle of external rotation; Data presented as average ± SD.

## Results

### *Maximum ground reaction force (Max-GFR)*

Max-GRF was greater in the OS than in the NOS in the SB and DB groups during WT (P = 0.026) and SD&CD (*P=0.001*) [Table 2].

### *Tibial rotation amplitude (TRA)*

The mean TRA curves of the three groups (C, SB, and DB) according to time during the tasks were analyzed [Figure 3]. The groups presented a similar pattern during the gait cycle support phase for all tasks (*P>0.05*). In terms of TRA, no significant difference was observed when comparing the control group vs. OS and OS vs. NOS in both the SB and DB groups during WT, WT&CD, and SD&CD [Tables 3; 4, Figure 4].

### *Maximum internal and external rotation angle*

There was no difference in Max-IR and Max-ER angles when comparing the control group to the OS in both the SB and DB groups during all tasks [Table 5].

**Table 2. Results of the comparative tests between the non-operated and operated knees of the SB and DB groups**

| | SB Group | | DB Group | | *P* value* | *P value#* |
|---|---|---|---|---|---|---|
| | NOS | OS | NOS | OS | | |
| **Max-GRF WT** | 1.21 ± 0.18 (n=19) | 1.24 ± 0.18 (n=19) | 1.17 ± 0.08 (n=25) | 1.18 ± 0.08 (n=25) | **0.026** | 0.226 |
| **Max-GRF WT&CD** | 1.20 ± 0.11 (n=18) | 1.22 ± 0.16 (n=18) | 1.19 ± 0.11 (n=25) | 1.21 ± 0.12 (n=25) | 0.139 | 0.863 |
| **Max-GRF SD&CD** | 1.67 ± 0.31 (n=20) | 1.79 ± 0.38 (n=20) | 1.54 ± 0.26 (n=25) | 1.69 ± 0.34 (n=25) | **0.001** | 0.217 |

SB: single bundle; DB: double bundle; NOS: non-operated side; OS: operated side; WT: Walk task; WT&CD: walk and change direction; SD&CD: stair descent and change direction; Max-GRF: vertical component of the ground force reaction normalized by body weight (no units). Data presented as average ± SD. ANOVA * comparison between sides within treated group; # comparison between OS among treated groups

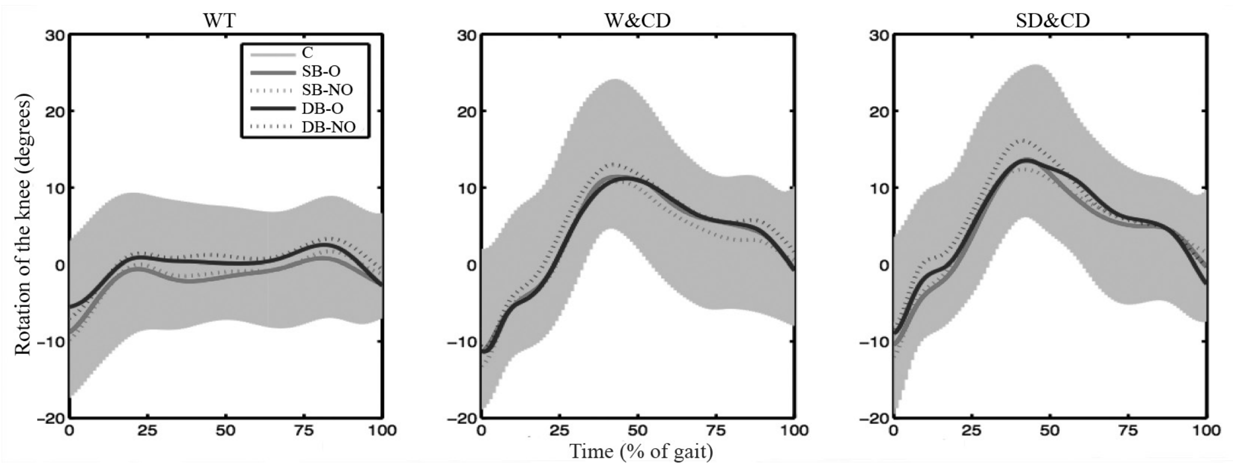


**Figure 3. Marker positioning in lateral and anterior views.**

**Table 3. Tibial Rotation Amplitude in control group and operated knees of SB and DB groups**

| | Control Group | SB Group OP | DB Group OP | *P value* |
|---|---|---|---|---|
| **TRA WT (º)** | 12 ± 3 (n=27) | 15 ± 7 (n=22) | 14 ± 4 (n=26) | 0.155 |
| **TRA WT&CD (º)** | 27 ± 5 (n=27) | 29 ± 6 (n=22) | 29 ± 5 (n=26) | 0.753 |
| **TRA SD&CD (º)** | 28 ± 4 (n=27) | 28 ± 5 (n=22) | 29 ± 5 (n=26) | 0.930 |

SB: single bundle; DB: double bundle; OP: operated side; WT: Walk task; WT&CD: walk and change direction; SD&CD: stair descent and change direction; TRA: Tibial Rotation Amplitude; Data presented as average ± SD; ANOVA. The average of the two knees of the people in the control group was used.

**Table 4. Tibial Rotation Amplitude in operated and non-operated knees of the SB and DB groups**

| | SB Group | | DB Group | | *P* value* | *P* value# |
|---|---|---|---|---|---|---|
| | NOS | OS | NOS | OS | | |
| **TRA WT (º)** | 15 ± 7 (n=22) | 15 ± 7 (n=22) | 13 ± 4 (n=26) | 14 ± 4 (n=26) | 0.307 | 0.462 |
| **TRA WT&CD (º)** | 28 ± 6 (n=22) | 29 ± 6 (n=22) | 28 ± 5 (n=26) | 29 ± 5 (n=26) | 0.345 | 0.936 |
| **TRA SD&CD (º)** | 27 ± 5 (n=22) | 28 ± 5 (n=22) | 28 ± 5 (n=26) | 29 ± 5 (n=26) | 0.229 | 0.482 |

SB: single bundle; DB: double bundle; NOS: non-operated side; OS: operated side; WT: Walk task; WT&CD: walk and change direction; SD&CD: stair descent and change direction; TRA: Tibial Rotation Amplitude. Data presented as average ± SD. ANOVA * comparison between sides within treated group; # comparison between OS among treated groups

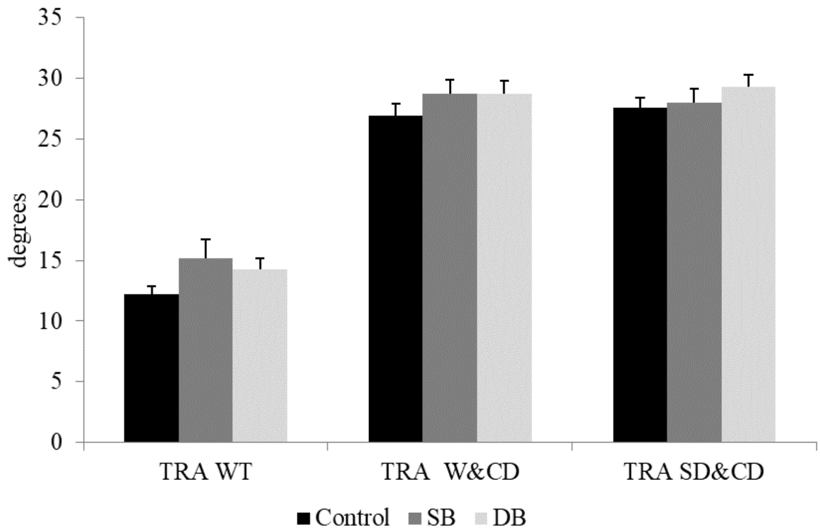


**Figure 4. Tibial rotation amplitude (TRA) during the support phase of the gait cycle in the three groups: Control (C), Single-Bundle (SB), and Double-Bundle (DB). Blue and red lines represent the SB and DB groups, respectively. The solid and dotted lines represent the operated knee (O) and the contralateral non-operated knee (NO), respectively. The line represents mean values; the gray area represents the control group (mean ± standard deviation).**

**Table 5. Maximum internal and external rotation in control group and operated side of the SB and DB groups**

| | Control Group | SB Group OP | DB Group OP | *P value* |
|---|---|---|---|---|
| Max-IR WT (º) | 4 ± 4 (n=27) | 8 ± 9 (n=22) | 4 ± 6 (n=26) | 0.090 |
| Max-IR WT&CD (º) | 17 ± 5 (n=27) | 16 ± 7 (n=22) | 15 ± 6 (n=26) | 0.355 |
| Max-IR SD&CD (º) | 19 ± 5 (n=27) | 19 ± 6 (n=22) | 17 ± 7 (n=26) | 0.367 |
| Max-ER WT (º) | -8 ± 5 (n=27) | -7 ± 6 (n=22) | -10 ± 6 (n=26) | 0.164 |
| Max-ER WT&CD (º) | -10 ± 6 (n=27) | -13 ± 10 (n=22) | -14 ± 7 (n=26) | 0.130 |
| Max-ER SD&CD (º) | -8 ± 6 (n=27) | -9 ± 6 (n=22) | -13 ± 8 (n=26) | 0.066 |

SB: single bundle; DB: double bundle; OP: operated side; WT: Walk task; WT&CD: walk and change direction; SD&CD: stair descent and change direction; Max-GRF: GRF vertical component normalized by body weight (without units); ART: Tibial Rotation Amplitude (values expressed in degrees); max-RI: maximum angle of internal rotation (values expressed in degrees); Max-ER: maximum angle of external rotation (values expressed in degrees); Data presented as mean ± SD; ANOVA. # The average of the two knees of the people in the control group was used.

## Discussion

It has been hypothesized that the rotational stability of the knee following ACL reconstruction is of paramount importance in the development of late OA. However, which surgical technique results in greater rotational stability is yet to be determined. This study aimed to assess the in vivo rotational stability of the knee after ACL reconstruction, comparing a control group with patients undergoing reconstruction using the SB and DB techniques. Previous studies have not demonstrated robust evidence of clinical superiority between the two ACL reconstruction techniques.[24,37–40] Our current findings corroborate biomechanical studies that have not demonstrated differences in rotational control between the SB and DB techniques.[41] Systematic reviews still bring divergent results regarding knee stability, clinical function, graft failure rate, and OA changes.[39,42–45]

The external "load" applied to the knee during any task is a crucial aspect when evaluating the knee's angles (TRA, Max-IR, and Max-ER). To control this "load" and consequently the intensity of the tasks, we measured the GRF and calculated the vertical component of the impulse.

There was no association between TRA and Max-GRF, indicating that all the participants performed the three tasks with a similar "load" on both sides. With that information, other parameters could be analyzed more reliably.

The outcome of knee kinematics after DB ACL reconstruction is not well established. Previous studies have demonstrated that SB ACL reconstruction could not restore normal knee kinematics.[2,5,6,46–51] Georgoulis et al. demonstrated an increase in the maximal angle of internal rotation in knees after ACL rupture, during gait, and when examined 7.6 ± 4.3 weeks after injury.[5] The article published by Ristanis et al. used an optoelectronic system for measurement. They found an increase in TRA in clinically stable knees after SB ACL reconstruction during the change of direction phase after stair descent compared with the NOS and a control group.[6] Similarly, using a dynamic radiographic system in a treadmill running task, Tashman et al. detected an abnormal rotational control of the knees subjected to SB ACL reconstruction.[52] They demonstrated that operated knees presented greater angles of Max-ER and adduction than the contralateral knee.

Tsarouhas et al. evaluated tibial rotation and rotational momentum during a change of direction task. They did not observe differences in TRA when they compared SB and DB ACL reconstruction.[27] However, they observed a smaller rotational moment in knees subjected to ACL reconstruction than in the controls. Conversely, Hemmerich et al. did not observe differences in TRA using a similar technique.[25] However, the SB group demonstrated a change in the rotational pattern, presenting greater external rotation, whereas the rotational pattern in the DB group was similar to that in the control group. Misonoo et al. demonstrated a reduction in TRA in both SB and DB compared with healthy knees, with no differences between the surgical groups.[26] They suggested a possible overcorrection of the tibial rotational control following surgery. The results of the present study, in some aspects, corroborate the results of these and other studies, such as that by Tsarouhas et al., in which no difference in rotational control was found between knees reconstructed using the DB technique and knees without injury.[27] The present study had some limitations. One limitation is the use of skin markers, which may generate an error because of the relative movement between the skin and bony structures.[23] In addition, the identification of anatomical landmarks can be challenging. To minimize such errors, we adopted the calibrated anatomical systems technique.[53] In this technique, the number of markers positioned directly on the skin is reduced. In addition, a unique evaluator places the markers and acquires the data. Alexander et al. tested the accuracy of this system based on skin markers, comparing them with markers placed on an Ilizarov fixator rigidly attached to the bone.[54] They obtained better results using the method in question, which was less than 3 mm for translation and less than 3° for rotation, compared with markers fixed to the bone. In other words, they obtained a smaller error than that of older methods for analyzing human movement.[23] The study was not designed to evaluate clinical results after ACL reconstruction (SB or DB) but was a biomechanical study that exclusively evaluated the rotational control of the knee.

The results and conclusions of this study should be considered within the applied methodology, and extrapolation to situations and groups of patients different from those in our study should be sensibly performed. Among the strengths of this study, the knees were evaluated in three distinct tasks with further biomechanical demands/complexity. In contrast, in most other studies, the knee was assessed using a single task or tasks with similar biomechanical demands.[26,27]

No differences in TRA, Max-IR, and Max-ER were noted after ACL reconstruction when the operated knees were compared with the contralateral healthy knees or those of a control group. No differences were found between patients subjected to SB or DB. Reconstruction of the ACL using the SB or the DB techniques can similarly restore rotational control of the knee.

***Conflict of Interest:*** Author WC is a paid consultant for DePuy Synthes. All other authors declare that they have no potential conflict of interest.

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