# Computer-assisted Anterior Cruciate Ligament Reconstruction. Four Generations of Development and Usage

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**Abstract:** The purpose of this paper is to review the literature about the contribution of navigation in anterior cruciate ligament (ACL) reconstruction. The evolution of computer-assisted surgery (CAS) for ACL reconstruction has undergone several steps. These steps were divided into 4 subsequent developments: (1) positioning of ACL graft placement; (2) laxity measurement of ACL reconstruction (quality control); (3) kinematic evaluation during ACL reconstruction (navigated pivot shift); (4) case-specific individual ACL reconstruction with adjustments and additional reconstruction options. CAS has shown to improve femoral tunnel positioning, even if clinical outcomes do not improve results of manual techniques. CAS technology has helped researchers better understand the effects of different ACL reconstruction techniques and bundles replacements on joint laxity and to describe tunnel positioning in relation to native ACL insertion. CAS in ACL surgery can improve results at time zero and can improve knowledge in this field.

**Key Words:** anterior cruciate ligament reconstruction, computer-assisted surgery, knee kinematics, instrumented pivot shift, quality controlled surgery, graft placement

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Computer-assisted surgery (CAS) in anterior cruciate ligament (ACL) reconstruction has now reached > 20 years of research. First publications started during the 1990s.[1] Main goals of the navigated procedures were to improve graft position and to better understand anatomic references and graft isometry during the range of motion. Research in this field was conducted considering that 70% to 80% of the complications were due to malpositioned tunnels.[2]

The purpose of these first systems was to augment the information given to the surgeon, to better identify the anatomic landmarks that could be difficult to be recognized in an arthroscopic setup. The efficacy of this enhanced information given by computer-based ACL reconstruction was evaluated in the clinical use. Dessenne et al[1] and Bernsmann et al[3] demonstrated the feasibility of imageless navigation in routine clinical setup.

These studies, however, have not increased the interest of the orthopedic community on this field for several years. The reason for this scarce interest in navigation was probably because of the unclear goal in tunnel placement and orientation during the ACL reconstruction, and the correct positioning of graft insertions is still a matter of debate.[4,5]

In addition, the costs and the time-consuming problems related to the use of these devices are still the major obstacles to the widespread use in clinical practice.

Because of more surgeon-friendly systems and because of the evolution of software for computer-based ACL surgery, recently, there has been an increased interest in this field. This development permits to perform stability testing, including rotational and translational measurements of complex clinical tests such as pivot shift.[6] It allows for better evaluation of the effect of different surgical procedures on the stability of the knee and to better describe patients' specific laxity. The augmented performance of navigation systems provided for this methodology to assess the performance of new reconstructive surgical techniques like double-bundle (DB). In fact, since 2005, there has been a large number of articles on navigated ACL and on anatomic DB reconstruction techniques.

The purpose of this article is to give a literature overview of current states in computer-assisted techniques for ACL reconstruction, highlighting the current concepts of navigation and the future perspectives in this field.

## MATERIALS AND METHODS

Pubmed and Medline research with query "anterior cruciate ligament" AND ("computer assisted" OR "navigation") provided 213 papers. Eighty-four papers were related to the topic. Exclusion criteria included: the use of medical imaging to study joint kinematics in a laboratory setup, bone or graft structural properties studies, studies on animals, study of ACL ligament in total or unicondylar knee arthroplasty, reviews on ACL surgical techniques in which navigation was cited but not described.

Because of intrinsic precision of the systems and because of the possibility to evaluate joint laxity and anatomy intraoperatively, navigation has been extensively used for research. A more structured analysis of the literature may help to understand the trends of research.

The literature can be divided into 4 different categories:

(1) Drill hole placement: studies that evaluate the usefulness of CAS in performing tunnel drilling or studying native ligament insertions.
(2) Laxity measurement: studies that evaluate the use of CAS in measuring anteroposterior (AP) knee laxity, comparing with conventional arthrometers.
(3) Kinematics: studies that evaluate joint kinematics under different clinical stress tests such as pivot shift or primary rotations.
(4) Individualized surgery: studies that evaluate the effect of different surgical strategies on joint laxity.

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## RESULTS

Most of the papers present case series in vivo or controlled laboratory studies; more recently, comparative and review studies were published. Of 84 papers 4 had a level of evidence of I; 41 had a level of evidence of II; 34 had a level of III; 5 had a level of IV.

There were more in vivo studies than in vitro; this may be related to the fact that navigation, with respect to other technologies like robotics, has been specifically designed for surgery. This provides for an easier setup despite a lower accuracy, therefore the possibility of in vivo evaluation was exploited by researchers.

Main topics of the papers were uniformly distributed; anatomic studies (including ligament insertions, tunnel positioning, and graft isometry) were similar to kinematic studies. Comparison (different CAS surgical techniques or conventional surgery) and descriptive papers had also similar number of publications. Only 3 papers presented clinical follow-up. It is interesting to note that there has been an increase in the number of in vivo, kinematic, and comparison studies between surgical techniques in the last years, whereas the number of in vitro, validation, and anatomy studies has decreased.

Literature concerning CAS in ACL reconstruction presents a variety of topics and methodologies. All the aspects of the surgery have been covered in studies, concerning anatomic, kinematic, technical, and clinical aspects. Between the late 1990s and beginning of 2000, navigation was used to find the most appropriate graft attachments in a single-bundle reconstruction. Measurements were aiming to isometry[1,7–10] or to tibia and femur anatomy.[1,3,7–17] Mauch et al,[18] Burkart et al,[19] and Schep et al[20] found no significant difference between CAS surgery and manual placement by an experienced surgeon. In contrast, Degenhart[21] and our group[22] found improved accuracy with a computer-assisted system on the basis of radiographs and computer simulation.

In the literature, navigation showed reliable results in femoral placement. Most of the papers showed improved positioning in navigated ACL compared with manual technique, but the clinical efficacy of CAS compared with conventional techniques has not been proved.[9,23–27]

## DISCUSSION

### Drill Hole Placement

One of the most critical factors for successful clinical outcome of ACL reconstruction is proper intra-articular positioning of the graft. There is general agreement that long-term results are significantly influenced by correct tunnel placement.[28] CAS systems for ACL reconstruction have focused on isometry and graft elongation[8–11,17,29] or on impingement free placement.[1,9,11,18,20,30,31] Most papers highlighted the versatility of the systems for different surgical techniques, indicating the CAS as a useful tool in reducing surgical errors (Fig. 1).[8,11,21]

### Tibial Placement

In tibial placement the mean position of tunnels is not altered by the use of navigated systems but the deviation is significantly decreased.[11,20,22] Graft orientation was not correlated to a better result clinically.[24] Burkart et al[19] showed with the use of a robotic system that the drill hole placement of even experienced surgeons is not consistent. Systems are using different tools for supporting surgeons to navigate the tibia insertion. The placement can be notch contour related or based on AP measurement.

Studies partly failed to show advantages of navigated over non-navigated ACL reconstructions.[23] The necessity of finding the correct graft positioning according to the surgical technique still remains a matter of debate. Guidelines for anatomic placement in DB reconstruction with the use of navigation systems are still under construction.[14,32]

### Femoral Placement

In femoral placement, most studies[11,12,22,33] show improved positioning in navigated ACL reconstruction using radiographic data. Because many studies are defining the position of ACL at the femoral site, there is no clear optimal aiming point.[5] The position in the femur is nevertheless related to kinematic outcome in the laboratory setting.[34–38] The recent interest in DB reconstruction has opened the discussion about the anatomic position of the drill holes.[17,39,40] The second step would be to relate this position to radiographic and navigating aiming points.

Most of the studies on tunnel placement suggest that, in tibial placement, an experienced surgeon can achieve comparable results with or without navigation[11,18–20,24,41]; only few authors have shown to improve tibial drill hole placement with navigation.[9,22] For femoral placement most of the papers[11,12,22] show improved positioning in navigated ACL compared with manual technique.

Measuring drill hole placement in postoperative X-ray is a challenge, which some authors address with computed tomography scan and X-ray measurement tools.[42]

### Laxity

One of the most important goals in ACL reconstruction is restoring the normal anterior/posterior laxity of the knee. For this reason joint laxity measuring devices, like the KT1000/2000 and the Rolimeter, have been developed and are used preoperatively and postoperatively to assess joint laxity, and are now also available for intraoperative use (Fig. 2).[43–45] A number of studies have been conducted to assess the accuracy and reliability of the main devices. Zaffagnini et al[46] and Valentin et al[24] compared intraoperative kinematic data with laxity data reported in literature acquired with instrumented testing devices, such as KT1000 or the Rolimeter. The results obtained were in accordance with previous results, and suggest that navigation can reliably measure a significant reduction of all knee laxities after ACL reconstruction. More recently, Monaco et al[47] and Lopomo et al[48] used a navigation system to evaluate reliability of Rolimeter used intraoperatively.

Several other methods of instrumented measurements are introduced over the years. AP laxity was evaluated in the 1990s with stress radiography in scientific papers,[28,49] using the posterior aspects of the proximal tibia and of the femoral condyles as landmarks for determining relative translations. However, the use of these measurement tools seems too complicated for routine use and the reproducibility of this method has not been reported. The introduction of computer-assisted techniques for stress radiography made the identification of anatomic landmarks easier. We could,[50,51] with the use of a condylar contour technique, find superior reproducibility in aligning the measurement with a full AP position on the proximal tibia. Other alignment lines[52] have been used for the tibia, but recently Doi et al[53] suggested to use the AP tibia line. New developments show advantages of navigated ACL in laxity control.[54,55]

The use of navigation for kinematic evaluation of translational and rotational uniplanar joint laxities under stress has been evaluated since 2000.[29,56,57] Zaffagnini et al[46] and Martelli et al[58,59] validated an in vivo setup demonstrating high intersurgeon and intrasurgeon repeatability of the maneuvers.[58] Pearle et al[56] demonstrated the reliability of the measurements compared with a robotic manipulator in vitro.

## Kinematics

Since the beginning of CAS ACL reconstruction, the possibility of evaluating knee laxity at time zero has been utilized by surgeons. This technology allows evaluating not only the anterior posterior translation during the Lachman or drawer test, but also internal-external (IE) and varus-valgus rotations of tibia under different stress tests at a fixed flexion angle. Several studies have been published since 2000, reporting the quantification of the effect of ACL reconstruction in controlling knee laxity.

The possibility to explore different laxities was widely used in DB ACL reconstruction, to quantify the effect of each bundle in controlling knee rotational instabilities, but studies reported contradictory results.

Ishibashi et al[60] evaluated in 32 patients the effect in controlling knee laxity of the anteromedial and posterolateral bundles in DB ACL reconstruction. He noted that the posterolateral bundle has an important role near extension, whereas the anteromedial bundle throughout the flexion range has a role in controlling AP laxity. They found no effect in controlling tibial rotation for both bundles.

Steckel et al[61] evaluated on cadavers the DB ACL reconstruction; AP translation data showed that the DB technique and the anteromedial bundle technique could restore AP stability comparable to the intact state. For IE laxity, the DB technique demonstrated overcorrection. The anterior drawer and manual Lachman knee laxity tests showed improved stability for the DB compared with the anteromedial bundle technique. Similar results were found in vivo by Zaffagnini et al[62] and Ferretti et al[63] at 30 degrees of flexion.

## Pivot Shift

Although the primary control of the native ACL and of the reconstructed graft in the AP laxity of the knee has

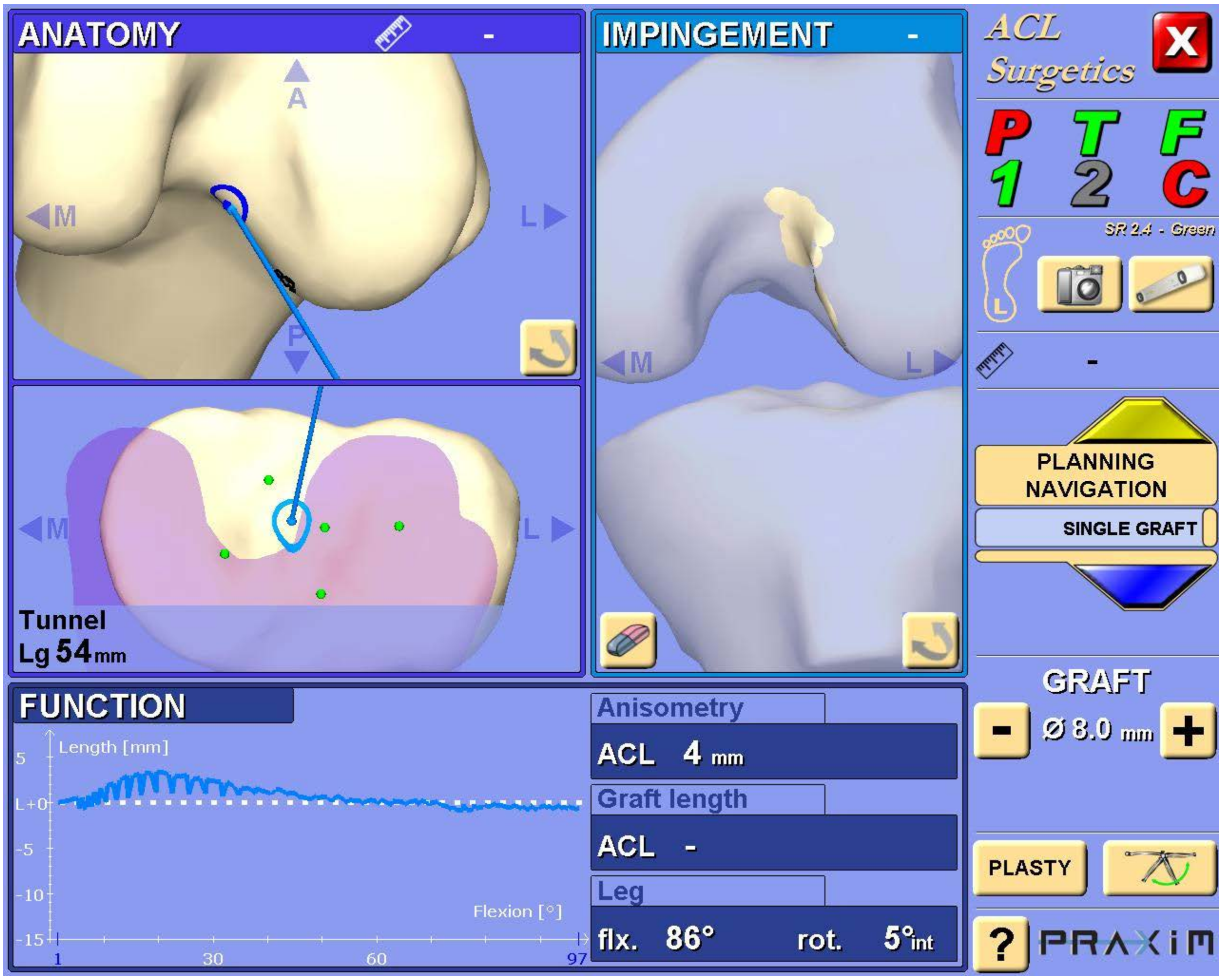


**FIGURE 1.** Drill hole placement with Praxim navigation. Green dots reflecting original ACL stump position. In purple projection of femoral contour recorded intra-operatively from patient bone contour data. Colors on femur target reflecting the position in relation to isometry point (green).

 

been demonstrated to be effective, the controversial results obtained with IE rotation may be related to the fact that the ACL has a secondary control for this laxity, or that other structures of the knee joint may be involved in the definition of the constitutional laxity of the patient. Steckel et al[64] explored the contribution of anteromedial and posterolateral bundles in vitro, in native ACL in controlling tibial translation and rotation, and stated that current clinical knee laxity measurements may not be suited for detecting subtle changes such as posterolateral bundle deficiency in the ACL anatomy.

Bull et al[65] reported that these specific clinical procedures allow the assessment of 2 different types of joint instability: (1) static and (2) dynamic instability. The static measurement is in general associated to uniplanar laxity tests. The dynamic instability of the knee is commonly presented as symptoms, thus clinical tests try to mimic these symptoms by controlling loads/movements of the joint. For this reason several authors have recently focused on the analysis of the pivot-shift test, trying to quantify and describe the dynamic laxity of the joint.

Bull et al,[6] Colombet et al,[39] and others[66,67] described the envelope of passive motion of the tibia during a pivot-shift test before and after ACL reconstruction founding consistent reductions during the pivot shift as a combination of external tibial rotation and posterior tibial translation.

Hoshino et al,[68] in an office setup, and Lane et al,[69] intraoperatively, found that the increase of tibial anterior translation and acceleration of subsequent posterior translation could be detected in knees with a positive pivot-shift result, and this increase was correlated to clinical grading. Similar experiences with the electromagnetic tracking system were reported by Kubo et al.[70]

The CAS evaluation of knee kinematics has shown that primary uniplanar laxity evaluation may not be sufficient to describe the effect of ACL reconstruction in controlling secondary laxities.[64,71] This fact leads to the evaluation of more complex tests, such as the pivot shift, which seems to be more related to patient's subjective status and to the clinical outcome.[67,69,72] ACL insufficiency can be documented clinically with the pivot-shift maneuver, with navigation (Fig. 3).

## Individualized Surgery

Some studies have compared, recently, the effect of different surgical techniques in controlling knee laxity. These studies are important to comprehend the effect of different surgical strategies on knee laxity and to help

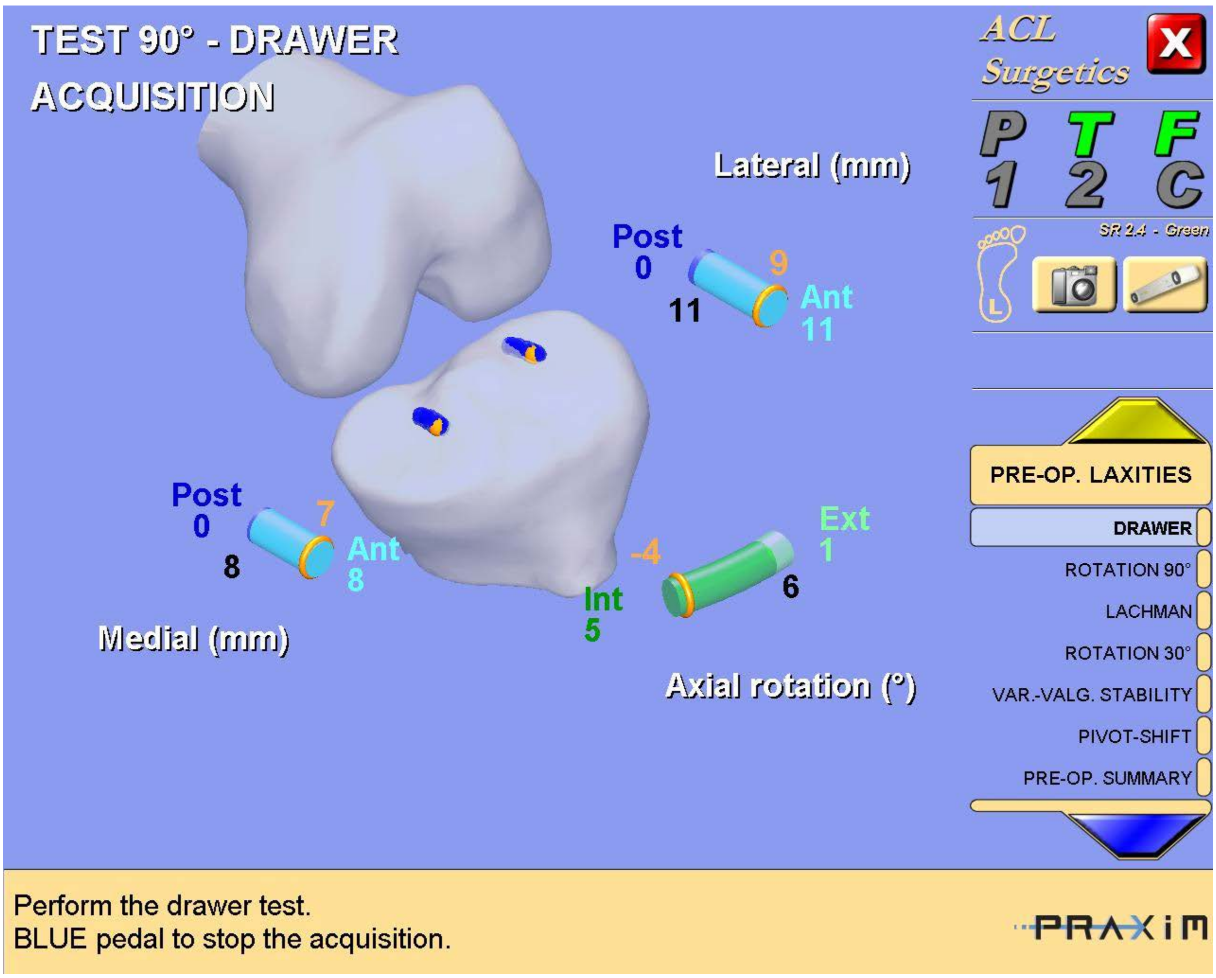


**FIGURE 2.** Laxity measurement in 90 degrees with maximal manual force preoperative laxity. Tests are performed before and after reconstruction.

surgeons improve the surgical outcome, considering the patient-specific laxity.

Monaco et al[73] evaluated the effect of a lateral extra-articular reconstruction in addition to a standard single bundle with hamstring tendons graft ACL reconstruction as compared with an anatomic DB ACL reconstruction. He found that the addition of a lateral tenodesis is more effective in reducing the internal rotation of the tibia at 30 degrees of knee flexion. Similar results were found by others[74–76] studying a lateral tenodesis added to a single bundle over the top graft.

Ishibashi et al[77] compared hamstring DB and patellar tendon graft techniques.[78] Results showed that both techniques improved knee laxity equally. In the DB reconstruction, the 2 grafts showed contrasting behavior. The posterolateral bundle restrained tibial displacement mainly in knee extension, whereas the anteromedial bundle restrained it more in the knee flexion position. The posterolateral bundle has a more important role in controlling rotation of the tibia than the anteromedial bundle.

Kanaya et al[79] evaluated knee laxity on 26 patients, with a custom device, under regular loads before and after ACL reconstruction, comparing DB and single bundle with lower more horizontal femoral tunnel reconstructions. No significant differences were found between the 2 groups and affirmed that a lower more horizontal femoral tunnel placed single-bundle reconstruction reproduced AP and rotational stability as well as DB reconstruction. Similar results were found by Ho et al[80] and Seon et al[81] in 2 cohorts of patients operated with central anatomic single-bundle and anatomic DB. Zaffagnini et al[82] evaluated the effect of an over-the-top DB technique, in reducing joint laxity, in patients with isolated ACL rupture compared with patients with associated grade II medial collateral ligament strain. They found different preoperative AP and varus-valgus laxities at 30 and 90 degrees of flexion and that the reconstruction was not able to fully restore laxity in flexion, raising the question for addressing the medial collateral ligament when a grade II strain is found (Fig. 4).

Quantification of joint laxity may also be helpful to start to define a translational quantification of different surgical techniques, and of different associated pathologies. These data can be useful to define what has been recently called as "on demand" surgery.[17,35] With this improvement the possibility of addressing patient's pathology according to its specific kinematic and anatomic features is achieved. Improvements are made in relating residual laxity to the contralateral side.[83]

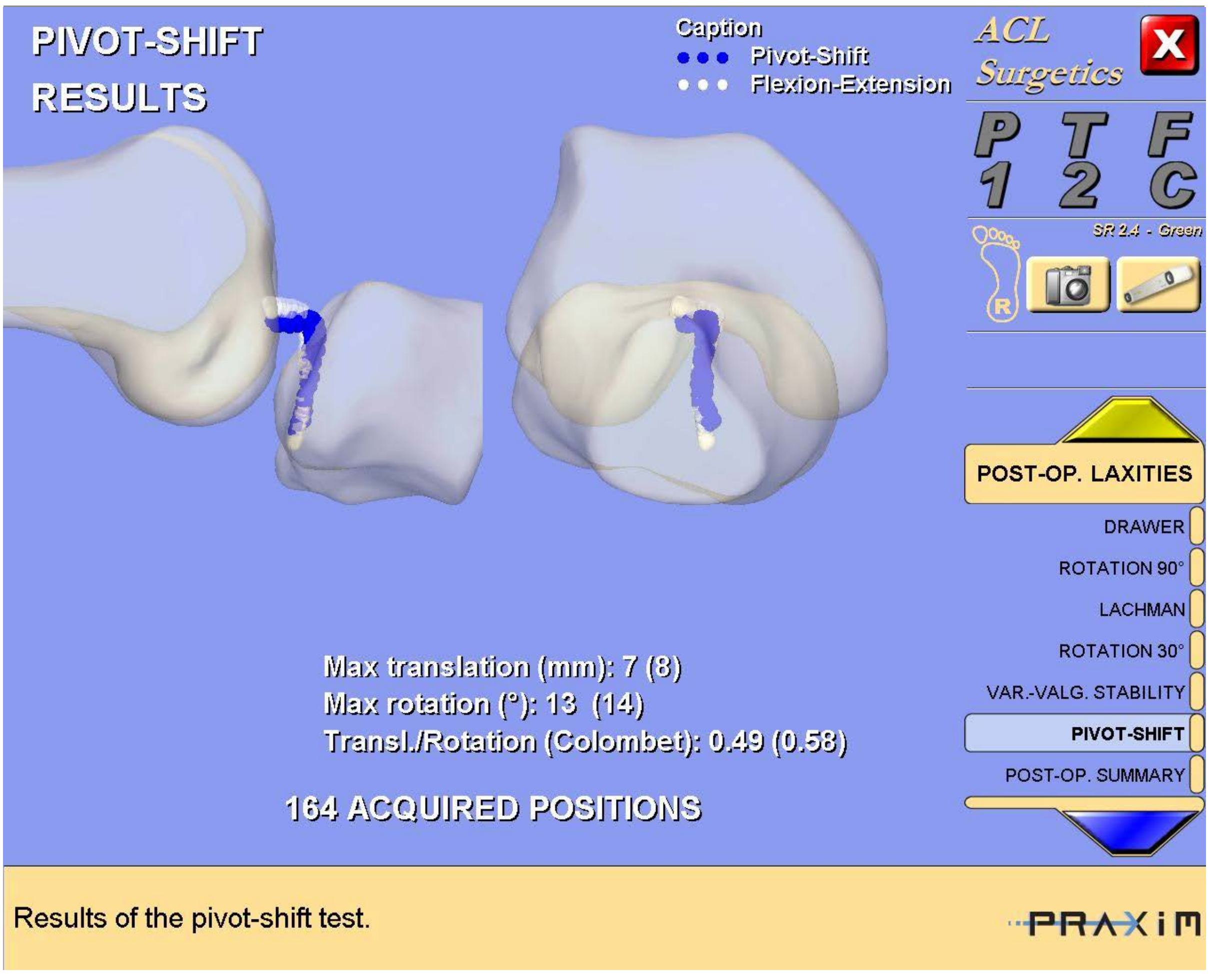


**FIGURE 3.** Pivot shift navigation, postoperative testing.

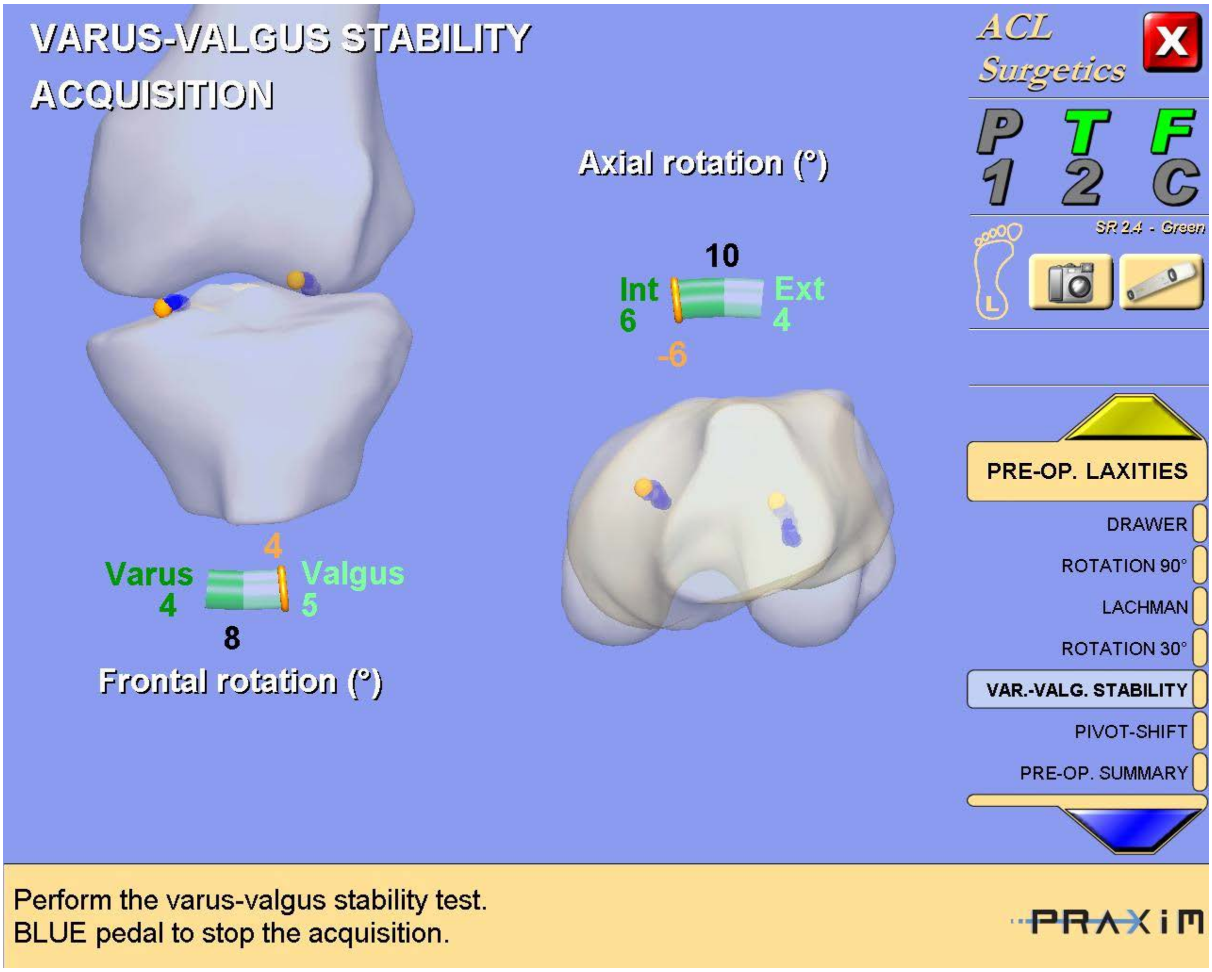


**FIGURE 4.** Varus valgus stability acquisition, testing performed before and after reconstruction. Collateral laxities can be found and monitored during surgery.

## CONCLUSIONS

The use of surgical navigation for tunnel placement remains limited because the targets and tolerances for this optimal graft positioning are under discussion. With the introduction of kinematic evaluation, it becomes possible to quantify at time zero the effect of the surgery in controlling knee laxity.

The biggest challenge, however, of navigation remains the tracking technology: accurate tracking of knee motion is predicated with use of rigid osseous fixation of trackers. Navigation remains an invasive technique; therefore, it adds potential risks to surgery, and comparative examinations of the contralateral limb or at follow-up are difficult. Further, application of standardized loads during stability testing in vivo remains a challenge.

These data establish requisite translational values for various types of ACL reconstructions. With this information available to the surgeon during surgery, it is now possible to think at the "on demand" individualized surgery, wherein quantitative data can help refine tracking of surgical outcome.

At present generation 1 of the system allows a complete intraoperative evaluation of the intervention, but with the evolution of technology, with noninvasive CAS systems, we will be able to increase knowledge about knee kinematics outside the operating room. This will allow researchers to compare kinematic data with contralateral limb, or in postoperative rehabilitation without the use of radiologic techniques. Further improvement will be the possibility of standardizing kinematic tests and starting the collection of a global data set that may be used on navigation systems. A real-time feedback, together with an intraoperative decision-making software, will provide an effective help to the surgeon.

The application remains limited mostly for research purposes because of the invasiveness of the system and because of the absence of improved clinical results at follow-up at this time.

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