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Computer-Assisted Anterior Cruciate Ligament Reconstruction: An Evidence-Based Approach of the First 15 Years

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Abstract: In the last 15 years, computer-assisted surgery (CAS) has been used for many purposes during anterior cruciate ligament (ACL) reconstruction, such as tunnel positioning, joint laxity evaluation, and biomechanical studies. This article is an evidence-based literature review of the contribution of such technology to ACL surgery. A search of the PubMed and Medline databases was performed. Articles were classified according to the study design and to the research topic: anatomy, laxity, kinematics, and comparison of surgical techniques. An evidence-based approach was used to verify the clinical usefulness of CAS to ACL surgery. The use of CAS for research purposes was also evaluated. CAS was shown to improve femoral tunnel positioning, even if clinical outcomes showed no differences compared with manual techniques. CAS technology was found to be useful for research purposes in terms of providing a better comprehension of the effect of different ACL reconstructions and of the different bundles on joint laxity, as well as describing tunnel positioning in relation to native ACL insertion. CAS in ACL surgery can improve results at time 0 and can improve knowledge about ACL anatomy and kinematics. Its application remains limited mostly to research purposes because of the invasiveness of the system and the absence of improved clinical results at follow-up. **Key Words:** Anterior cruciate ligament—Computer-assisted surgery—Evidence-based results.

Computer-assisted surgery (CAS) in anterior cruciate ligament (ACL) reconstruction has now reached 15 years of research. The first publications started during the 1990s.[1] A main goal of navigated procedures was to improve the correct positioning of the graft, with anatomic references and graft isometry during range of motion being taken into consideration. Research in this field was conducted given that 70% to 80% of the complications were a result of 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 provided by computer-based ACL reconstruction was evaluated in clinical use. Dessenne et al.[1] and Bernsmann et al.[3] showed the feasibility of image-less navigation in routine clinical setup.

These studies, however, have not increased the interest of the orthopaedic community in 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 ACL reconstruction, and the correct positioning of graft insertions is still a matter of debate.[4] In addition, the

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

Thanks to more surgeon-friendly systems and to the evolution of software for computer-based ACL surgery, recently, there has been an increased interest in this field. This development permits us to perform stability testing, including rotational and translational measurements or decomposition of complex clinical tests such as the pivot-shift test,[5] allowing us to better evaluate the effect of different surgical procedures on the stability of the knee and to better describe a patient's specific laxity. The augmented performance of navigation systems allowed the use of this methodology to assess the performance of new reconstructive surgical techniques such as double-bundle (DB) reconstruction. In fact, starting in 2005, a large number of articles on navigated ACL as well as on anatomic DB reconstruction techniques have been published (Fig 1).

The purpose of this article is to provide an evidence-based literature overview of the current state of computer-assisted techniques for ACL reconstruction, highlighting the current concept of navigation and the future perspectives in this field.

METHODS

Our search of the PubMed and Medline databases in May 2009 with the query "anterior cruciate ligament" AND ("computer assisted" OR "navigation") found 213 articles. Of these, 84 were related to the topic. The following types of studies were excluded: studies on the use of medical imaging to evaluate joint kinematics in a laboratory setup, studies of bone or graft structural properties, studies on animals, studies of the ACL ligament in total knee arthroplasty or unicomarmental knee arthroplasty, reviews on ACL surgical techniques where navigation was cited but not described, and Level V studies.

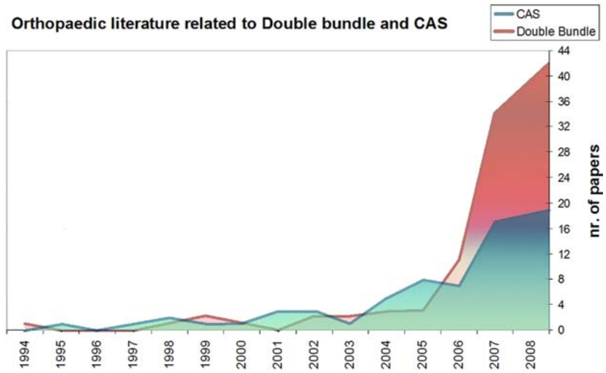


FIGURE 1. Publications, found in Medline and PubMed databases, about DB and CAS ACL reconstruction in the last 15 years.

TABLE 1. *Classification of Publications According to Type of Study*

Study Design*	Level of Evidence I	II	III	IV	Total No. of Articles
Time series	2	6	20	3	31
Review	0	3	7	2	12
Comparative study	2	16	1	0	19
Laboratory	0	16	6	0	22
Total	4	41	34	5	84

*Time series indicates a longitudinal study about the effect of ACL reconstruction on 1 population before and after treatment. Review indicates a review article. Comparative study indicates a longitudinal study where 2 cohorts with different ACL reconstruction methods are compared. Laboratory indicates a controlled laboratory study.

Most of the articles presented case series in vivo or controlled laboratory studies; more recently, comparative and review studies were published. The Level of Evidence was I in 4 of the 84 articles, II in 41, III in 34, and IV in 5 (Table 1).

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

The main topics of the articles were uniformly distributed, with similar numbers of anatomic studies (including ligament insertion, tunnel positioning, and graft isometry) and kinematic studies. There were also similar numbers of comparison publications (different CAS techniques or conventional surgery) and descriptive publications. Only 3 articles presented clinical follow-up. It is interesting to note that the number of in vivo studies, kinematic studies, and studies comparing surgical techniques has increased in recent years whereas the number of in vitro, validation, and anatomic studies has decreased (Table 2).

The literature about CAS in ACL reconstruction presents a variety of topics and methods. All the aspects of surgery have been covered in the studies, from anatomic to kinematic considerations and from technical to clinical aspects. Between the late 1990s and the early 2000s, navigation was used to find the most appropriate graft attachments for a single-bundle

TABLE 2. *Classification of Articles, According to Topic, Divided per Year of Publication*

		Subjects				Comparison			
Year of Publication	No. of Articles	In Vitro	In Vivo	Anatomy	Kinematics	Surgical Techniques	Manual *v* Navigated	Descriptive/ Validation	Follow-up
2009	14	2	10	2	10	8	3	1	0
2008	17	6	10	6	6	4	1	3	0
2007	19	6	9	7	10	4	5	9	1
2006	7	1	6	5	3	0	3	2	1
2005	8	3	3	3	2	0	1	4	1
2004	5	0	2	3	0	0	0	3	0
2003 or Earlier	14	7	5	11	3	1	4	11	0
Total	84	25	45	37	34	17	17	33	3

reconstruction considering isometry[1,6-9] or according to tibia and femur anatomy.[1,3,6-16] Mauch et al.,[17] Burkart et al.,[18] and Schep et al.[19] found no significant differences between CAS and manual placement by an experienced surgeon. In contrast, Klos et al.[20] and Degenhart[21] found improved accuracy with a computer-assisted system based on radiographs and computer simulation.

The use of navigation for kinematic evaluation of translational and rotational uniplanar joint laxities under stress has only been reported since 2006.[22-24] Zaffagnini et al.[25] and Martelli et al.[26,27] validated an in vivo setup showing high intersurgeon and intrasurgeon repeatability of the maneuvers.[26] Pearle et al.,[22] in an in vitro study, showed the reliability of the measurements compared with a robotic manipulator.

In conclusion, navigation was found to be reliable in terms of clinical setup and for femoral placement, with most of the articles showing improved positioning in the navigated ACL compared with the manual technique; however, the clinical efficacy of CAS compared with conventional techniques has not been proved.[8,28,29]

NAVIGATION IN RESEARCH

Because of intrinsic precision of the systems and the possibility of evaluating 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 in 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 examining native ligament insertions.
2. Laxity measurement—studies that evaluate the usability of CAS in measuring anteroposterior (AP) knee laxity compared with conventional arthrometer measurements.
3. Kinematics—studies that evaluate joint kinematics by use of different clinical stress tests such as pivot shift or primary rotation.
4. Individualized surgery—studies that evaluate the effect of different surgical strategies on joint laxity.

Drill Hole Placement

One of the most critical factors for a 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.[30] CAS systems for ACL reconstruction have focused on isometry and graft elongation[7-10,16,23] or on impingement-free placement.[1,8,10,17,19,31,32] Most of the articles highlighted the versatility of the systems for different surgical techniques, indicating that CAS is a useful tool in reducing surgical errors.[7,10,21]

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.[10,19,20] Graft orientation was not correlated clinically with a better result.[29] Burkart et al.,[18] using a robotic system, showed that the drill hole placement of even experienced surgeons is not consistent. Systems use different tools to help surgeons in tibial insertion navigation. These can be related to the notch contour or AP measurement.

Studies partly failed to show advantages of navigated over non-navigated ACL reconstructions.[28] 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.[13,33]

Femoral Placement: In femoral placement most studies show improved positioning in navigated ACL reconstruction using radiographic data.[10,11,20] Because many studies are still defining the position of the ACL at the femoral site, there is no clear optimal aiming point. The position in the femur is nevertheless related to kinematic outcome in the laboratory setting.[34-37] The recent interest in DB reconstruction has again opened the discussion on where to anatomically position the drill holes[16,38,39]; the second step would be to relate this position to the aiming point as determined radiographically and by navigation.

In conclusion, most of studies on tunnel placement suggest that, for tibial placement, an experienced surgeon can achieve comparable results with or without navigation,[10,17-19,29,40] whereas only a few authors have shown an improvement in tibial drill hole placement with navigation.[8,20] In contrast, for femoral placement, most of articles show improved positioning in the navigated ACL compared with the manual technique.[10,11,20]

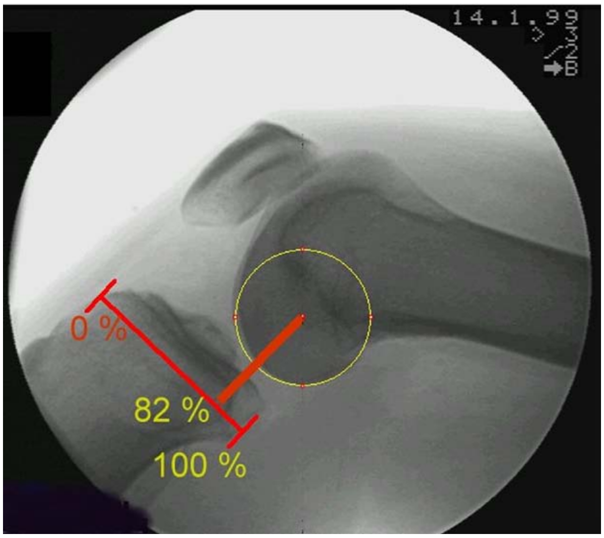


FIGURE 2. Radiographic measurement tool used to evaluate anterior tibial displacement by use of a circle (data from reference[51]). The red line (AP line, tibial AP direction) is a line on the proximal tibia, parallel to the tibial plateau, joining the anterior and posterior cortices (tibial landmark). The yellow circle is a circle fitting the posterior and inferior contours of the femoral condyles (femoral landmark), as proposed by Amis. The orange line is the projection of the condylar circle to the AP line.

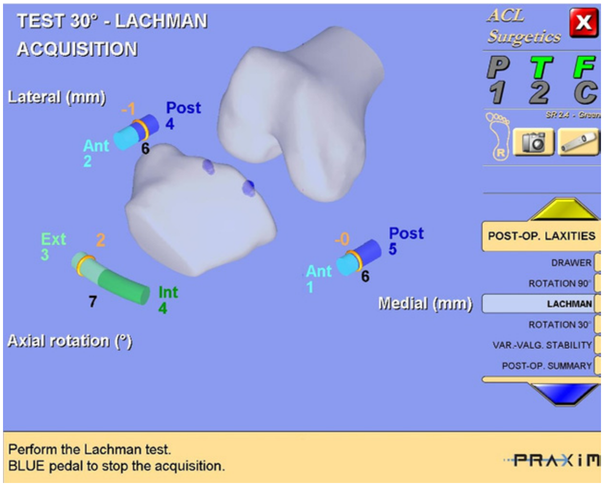
Laxity

One of the most important goals in ACL reconstruction is restoring the normal AP laxity of the knee. For this reason, joint laxity–measuring devices, such as the KT-1000/KT-2000 (MEDmetric, San Diego, CA) and the Rolimeter (Aircast [DJO], Vista, CA), have been developed and used preoperatively and postoperatively to assess joint laxity, and they are now also available for intraoperative use.[41-43] A number of studies have been conducted to assess the accuracy and reliability of the main devices. Zaffagnini et al.[25] and Valentin et al.[29] compared intraoperative kinematic data with laxity data reported in the literature acquired with instrumented testing devices, such as the KT-1000 or Rolimeter. The results obtained were in accordance with previous results and showed that navigation can reliably measure a significant reduction in all knee laxities after ACL reconstruction. More recently, Monaco et al.[44] and Lopomo et al.[45] used a navigation system to evaluate the reliability of the Rolimeter used intraoperatively.

Several other methods for instrumented measurements have been introduced over the years. AP laxity was evaluated in the 1990s with stress radiography in scientific articles,[30,46] using the posterior aspects of the proximal tibia and femoral condyles as landmarks for determining relative translations. However, the use of these measurement tools seems too complicated for routine application, 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. Klos et al.,[47,48] using the condylar contour technique (Fig 2), found superior reproducibility in aligning the measurement with full AP positioning on the proximal tibia; other alignment lines have been used for the tibia,[49] but recently, Doi et al.[50] once again suggested the use of the AP tibia line.

Kinematics: Since the beginning of CAS ACL reconstruction, the possibility of evaluating knee laxity at time 0 has been explored by surgeons. This technology allows evaluation of not only the anterior posterior translation during the Lachman or drawer test (Fig 3) but also internal-external and varus-valgus rotations of tibia under different stress test conditions at fixed flexion angles. Several studies have been published, in particular after 2000, reporting the quantification of the effect of ACL reconstruction in controlling knee laxity.

The possibility of exploring different laxities was widely examined in DB ACL reconstruction, to quan-



Perform the Lachman test.
BLUE pedal to stop the acquisition.

Figure 3. Execution of Lachman test with Praxim Medivision Surgetics system (Praxim, La Tronche, France). Motion of the tibia is shown in real time. The coupled internal tibial rotation (4°) occurring with anterior translation is clearly shown. The anterior translation of the medial and lateral tibial condyles is also shown (1 mm and 2 mm, respectively).

tify the effect of each bundle in controlling knee rotational instabilities, but studies have reported contradictory results.

Ishibashi et al.[52] evaluated the effect in controlling knee laxity of the anteromedial (AM) and posterolateral (PL) bundles in DB ACL reconstruction in 32 patients. They noted that the PL bundle has an important role near extension whereas the AM bundle has an important role throughout the flexion range in controlling AP laxity. However, they found no effect in controlling tibial rotation for both bundles.

Steckel et al.[53] evaluated DB ACL reconstruction in cadavers; AP translation data showed that the DB technique and AM bundle technique could restore AP stability comparably to the intact state. For internal-external laxity, the DB technique showed overcorrection. The anterior drawer and manual Lachman knee laxity tests showed improved stability for the DB technique compared with the AM bundle technique. Similar results were also found in vivo by Zaffagnini et al.[54] and Ferretti et al.[55] at 30° of flexion.

Pivot Shift: Although the primary control of the native ACL and of the reconstructed graft in AP laxity of the knee has been shown to be effective, the controversial results obtained with internal-external 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. Results shown by Steckel et al.[56] on the contribution of AM and PL bundles in vitro of the native ACL in controlling tibial translation and rotation highlighted that current clinical knee laxity measurements may not be suited for detecting subtle changes such as PL bundle deficiency in the ACL anatomy.

Recently, Bull et al.[57] reported that these specific clinical procedures allow assessing 2 different types of joint instability: (1) static and (2) dynamic. The static measurement is in general associated with uniplanar laxity tests. On the other hand, 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.

Amis and colleagues,[5] Colombet et al.,[38] and Ishibashi et al.[58] described the envelope of passive motion of the tibia during a pivot-shift test before and after ACL reconstruction, finding consistent reductions during the pivot shift as a combination of external tibial rotation and posterior tibial translation.

Hoshino et al.,[59] in an office setup, and Lane et al.,[60] intraoperatively, found 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 this increase was correlated with clinical grading. Similar experiences with an electromagnetic tracking system were reported by Kubo et al.[61]

In conclusion, the CAS evaluation of knee kinematics has highlighted how primary uniplanar laxity evaluation may not be sufficient to describe the effect of ACL reconstruction in controlling secondary laxities.[56] This fact led to the evaluation of more complex tests, such as the pivot shift, which seems to be more related to a patient's subjective status and to the clinical outcome.[60] ACL insufficiency can be documented clinically with the pivot-shift maneuver with navigation (Fig 4).

Individualized Surgery: Some studies have recently compared 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 surgeons to improve the surgical outcome, considering the patient-specific laxity.

Monaco et al.[62] evaluated the effect of a lateral extra-articular reconstruction in addition to a standard single-bundle ACL reconstruction with hamstring tendon graft compared with an anatomic DB ACL recon-

TABLE 3. *Advantages and Disadvantages of Current Navigation Systems for ACL Reconstruction*

Advantages	Disadvantages
6 *df*	Expensive
Reliable	Invasive
High precision	No contralateral evaluation
Intraoperative use	No office setup

Abbreviation: *df*, degrees of freedom evaluation.

FIGURE 4. Execution of pivot-shift test with Klee system (Orthokey, Lewes, DE). The screen shows antero-posterior (AP) translation during the pivot-shift maneuver. On the left, it is possible to read the value of peak laxity around 30° (15.5° preoperatively and 4.0° postoperatively); in the graph it is possible to evaluate the envelope of passive motion of the tibia (red, preoperatively; green, postoperatively).

struction. They found that the addition of a lateral plasty is more effective in reducing the internal rotation of the tibia at 30° of knee flexion. Similar results were found by Bignozzi et al.[63] studying a lateral plasty added to a single-bundle over-the-top graft.

Ishibashi et al.[64] compared hamstring DB and patellar tendon graft techniques.[65] The results showed that both techniques similarly improved knee laxity. In the DB reconstruction the 2 grafts showed contrasting behavior. The PL bundle restrained tibial displacement mainly in knee extension, whereas the AM bundle restrained it more in the knee flexion position. The PL bundle has a more important role in controlling rotation of the tibia than the AM bundle.

Kanaya et al.[66] evaluated knee laxity in 26 patients, with a custom device, under regular loads before and after ACL reconstruction, comparing DB reconstruction and single-bundle reconstruction with a lower femoral tunnel. No significant differences were found between the 2 groups, and the findings affirmed that a lower femoral tunnel placed with single-bundle reconstruction reproduced AP and rotational stability as well as DB reconstruction. Similar results were found by Ho et al.[67] and Seon et al.[68] in 2 cohorts of patients operated on with central anatomic single-bundle and anatomic DB reconstructions. Zaffagnini et al.[69] 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° of flexion and that the reconstruction was not able to fully restore laxity in flexion, raising the question of how to address the medial collateral ligament when a grade II strain is found.

In conclusion, quantification of joint laxity may also be helpful in starting to define a translational quantification of different surgical techniques, as well as different associated pathologies. These data can be useful to define what has recently been called "on demand" surgery.[16,35] With this improvement, it may be possible to address a patient's pathology

TABLE 4. *Possible Evolution of CAS Systems for ACL Reconstruction*

Generation of CAS System	Main Feature	Advantages
Present status	Invasive reference arrays	Anatomic mapping for DB Kinematic in vivo data
Future direction step 1	Noninvasive reference arrays	Laxity data comparing injured with uninjured sites In-sport kinematic recording Kinematic follow-up
Future direction step 2	Force control during kinematic tests	Observer-independent data Data set according to different surgical techniques
Future direction step 3	Intraoperative decision-making software	Normal data for rotation/translation on different lesions Evaluation of contribution of other structures (menisci, cartilage, posterior cruciate ligament)

according to its specific kinematic and anatomic features, thus resulting in the most appropriate surgical technique being chosen.

CONCLUSIONS

As Lord Kelvin stated in the 19th century, "If you cannot measure it, you cannot improve it." This philosophy fully adapts to the concept of navigation. With the help of less invasive and image-free systems in the last 15 years, our knowledge about the anatomy and kinematics of the ACL has improved dramatically. However, the use of surgical navigation for tunnel placement has remained limited because the targets and tolerances for optimal graft positioning are still poorly understood. With the introduction of kinematic evaluation, however, it became possible to quantify at time 0 the effect of surgery in controlling knee laxity.

The greatest challenge, however, of navigation remains the tracking technology: accurate tracking of knee motion is predicated on the use of rigid osseous fixation of trackers. Navigation still remains an invasive technique; therefore it adds potential risks to surgery, and comparative examinations of the contralateral limb or at follow-up are difficult. Furthermore, application of standardized loads during stability testing in vivo remains a challenge (Table 3).

These data begin to 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 level, where quantitative data can help refine tracking of surgical outcome.

At present, the first-generation systems allow 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 of the operating room (Table 4). That will allow researchers to compare kinematic data with the contralateral limb or during postoperative rehabilitation without the use of radiologic techniques. Further improvement will allow the possibility of standardize kinematic tests and therefore the beginning of a collection of a global data set that may be used on navigation systems, where real-time feedback, together with intraoperative decision-making software, will provide an effective aid to the surgeon.

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