The Role of Navigation Systems in ACL Reconstruction

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Fact Boxes

- *Navigation in ACL surgery is an important tool improving tunnel placement and laxity evaluation of injured knees.*
- *The navigation system can improve clinical outcomes and decrease the failure rate of ACL reconstruction.*

41.1 History of Computer-Assisted Orthopedic Surgery for ACL Reconstruction

Computer-assisted orthopedic surgery (CAOS) began in the 1990s. Its first application was used in spinal surgery to minimize the risk of damaging neurovascular structures when pedicle screws were inserted into the vertebra [40]. Development of CAOS then expanded into hip and knee arthroplasty in order to improve the positioning of the implant [1]. CAOS, particularly in conjunction with a navigation system, has also been applied to anterior cruciate ligament (ACL) reconstruction since the mid-1990s [8]. Failure of ACL reconstruction was often due to technical errors, such as inappropriate tunnel position of the graft. Navigation system was introduced in ACL reconstruction to reduce such errors and was focused on improving the accuracy and reproducibility of the tunnel placement. Since the 2000s, navigation systems have been used increasingly as a quantitative measurement tool to assess ACL graft obliquity or for visualization of the pivot shift (PS) phenomenon [21]. Not only can the surgeon confirm the virtual tunnel position, but they can also decipher important information such as the risk of graft impingement, graft isometricity, and accurate assessment of laxity patterns intraoperatively on the navigation display. Thus, navigation systems have the potential to improve outcomes after ACL reconstruction by reducing variability in tunnel positions and improving their accuracy. To that end, a number of investigators have reported their experience with navigation-assisted ACL reconstruction; we discuss some of their findings in this chapter.

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Table 41.1 Randomized control trials of ACL reconstruction with or without navigation system

Author	Publication year	Number of patients		Average age (range)	Male/female	Navigation system	Average follow-up (months)
		Navigation group	Conventional group				
Plaweski et al.	2006	30	30	30 (16–50)	40:20	Image-free (surgetics)	24
Mauch et al.	2007	29	24	34 (18–49)	17:36	Image-free (OrthoPilot)	NS
Chouteau et al.	2008	37	36	27 (14–53)	46:27	Image-based (original system)	26.4
Hart et al.	2008	40	40	29.4 (16–39)	64:16	Image-free (OrthoPilot)	28
Meuffels et al.	2012	49	51	NS (>18)	24:76	Image-based (VectorVision)	NS

NS not stated

41.2 Navigation Types for ACL Reconstruction

There are two types of navigation systems for ACL reconstruction: image-based (e.g., VectorVision ACL 1.0, Brainlab, Heimstetten, Germany; Stealth Station iON, Medtronic, Louisville, USA) and image-free (e.g., BLU-IGS, Orthokey, Lewes, Delaware, USA; OrthoPilot, B. Braun Aesculap, Tuttlingen, Germany; Medivision Surgelics System, Praxim, La Trouche, France). Image-based systems require anatomical reference data obtained from intraoperative fluoroscopy imaging. Image-free systems require no preoperative data, as they are able to acquire anatomical landmark and knee kinematics information. Image-free systems have been used for ACL reconstruction for more than 10 years. This system uses infrared cameras and transmitters with reflective markers attached to the femur and tibia to register the precise location of the instruments in three-dimensional (3D) space. The cameras can track the position of the instruments to within <1 mm and <1° with assistance from a computer [7, 54]. At the first step of registration, bony landmarks (consisting of the tibial tuberosity, anterior edge of the tibia, and the medial and lateral points of the tibial plateau) and knee kinematics (consisting of the knee position at 0° and 90° of knee flexion and consecutive knee positions between 0° and 90°) are registered (Fig. 41.1).

Next, the navigation computer builds a three-dimensional model of the knee joint. The intra-articular landmarks (consisting of the anterior horn of lateral meniscus, tibial and femoral footprint of the ACL, anterior notch outlet, etc.) are necessary for the computation of the tibial and femoral tunnel aperture. Surgeons can visualize the tibial and femoral tunnel position on the navigation display, as well as other valuable parameters necessary for creating a suitable tunnel such as the angle of the tibial tunnel in the sagittal and coronal planes, distance to the PCL anterior edge, distance to the posterior cartilage border of the lateral femoral condyle, distance between tunnels in the double-bundle technique, etc. (Fig. 41.2).

Additionally, knee stability test can be performed before and after graft fixation, to quantify surgical results, including the pivot shift (PS) test (Fig. 41.3). In our experience, the additional time required for navigation surgery is approximately 5–10 min.

Fig. 41.1 Transmitters with reflective markers were fixed to the femur and tibia via a pin fixator. The *straight pointer* attached to another transmitter is used to register the intra- and extra-articular landmarks

Fig. 41.2 Screenshot showing the navigation of the tibial drill tunnel (*Left*) and the navigation of the femoral drill tunnel (*Right*)

Fig. 41.3 Quantification of the PS test before and after ACL reconstruction

41.3 Accuracy of Tunnel Placement in ACL Reconstruction

The main object of using the navigation system for ACL reconstruction is to improve the precision of the femoral and tibial tunnel position. Several studies compared the accuracy of the tunnel position between navigation surgery and manual surgery. Regarding the tibial tunnel position, the mean position is not altered by the navigation systems but the deviation is significantly decreased [22, 47]. As for femoral tunnel placement, most studies show improved positioning in navigation-assisted ACL reconstruction on radiographic evaluation [22, 42, 46, 48]. Schep et al. studied intersurgeon variance during computer-assisted planning of ACL reconstruction and showed that the tunnel position was not associated with the experience level of the surgeon when using the computer-assisted surgical system [47].

There are few studies on the use of navigation systems in revision surgery [37, 51]. In revision surgery for failed ACL reconstruction, there are several types of problems including bone defects, primary tunnel malposition, and preexisting hardware. Creating an adequate new femoral tunnel is difficult in revision ACL surgery because of the existence of the primary tunnel. Taketomi et al. reported that 3D fluoroscopy-based navigation systems are especially helpful in this regard, because they enable visualization of the entire previous tunnel or any preexisting hardware inside the femoral tunnel that is not visible arthroscopically [51].

Recently, preservation of the ACL remnant has been a focus of ACL reconstruction. Remnant preservation is expected to accelerate graft maturation. However, it is difficult to confirm the ACL femoral footprint because of abundant remnant tissue. In such situations, navigation systems may be utilized for confirming the ACL footprint of the intercondylar lateral wall and for creating an adequate tunnel in the ACL footprint. Taketomi et al. described the femoral socket locations that were considered to be an anatomical footprint in accordance with previous cadaveric studies in remnant-preserving ACL reconstruction using 3D fluoroscopy-based navigation systems [52].

41.4 Knee Laxity and Kinematics Measurement

Another important feature of navigation systems in ACL reconstruction surgery is the capability to perform intraoperative kinematic evaluation of the knee joint during ACL reconstruction.

CAOS system for translational and rotational joint laxities evaluation under stress has only been reported since 2005. Zaffagnini et al. [56] and Martelli et al. [31] used the navigation for an in vivo setup with a high intersurgeon and intrasurgeon repeatability of the maneuvers.

With this system, many tests can be performed and measured for evaluating both static and dynamic instability at the operating room, before and after ACL reconstruction.

The static stability corresponds with uniplanar laxity (translation or rotation) at determined degree of flexion, for example, anteroposterior translation at 30° and 90° (Lachman and anterior drawer test, respectively), while dynamic corresponds to a complex combination of translation and rotation during the range of motion.

Since the development of new and easier navigation systems, the interest in computer-assisted procedures for clinical outcomes and research was increased. Many studies have been published since the 2000s to describe knee kinematics to enhance the knowledge about it and the effect of different techniques achieving static and dynamic stability.

Today, the most important clinical exam evaluating dynamic instability of the knee is the pivot shift test. For this reason, interest in navigating the PS was increased in the last years. Such test has been decomposed in many parameters; the most important are related with the translation, rotation, and acceleration of the lateral tibial plateau when the pivot shift maneuver is performed [28].

Some authors have used the navigation system in order to document the pre-operatory status and compared it with the surgical results of different techniques in ACL reconstruction surgery. Signorelli et al. in 2013 have shown the importance of preoperative measurements, especially in very unstable knees, in order to suspect secondary restraint lesions. In fact, higher level of preoperative laxities can underline complex injuries, where the isolated ACL reconstruction is not able to restore normal kinematics, and the addition of others procedures may be necessary to gain a better stabilization [49].

Others have used this system to assess physiological contralateral knee stability before ACL reconstruction. In the 2009, Miura and colleagues were the first to perform an in vivo study comparing both contralateral uninjured knee and ACL-injured knee [34].

More recently, Imbert et al. evaluated 32 patients who underwent ACL reconstruction surgery. They also compared with the contralateral uninjured joint. In clinical practice, both knees have always been evaluated, but in a qualitative way. These studies concluded that is important to evaluate objectively the healthy knee before surgery. Quantifying patient's physiological stability is very helpful for a better surgical approach [15].

41.5 Intraoperative Protocol

Usually navigation system is moved into the operating room and is placed about 2 m away from the operating table, after sterile field is prepared. Surgery is performed as usual, and only after graft is harvested, the tracking systems are fixed into the bones (tibia and femur) and then anatomical landmarks are acquired.

After that, different maneuvers are performed. Software used for kinematic acquisition (KLEE; Orhokey, Lewes, Delaware, USA) evaluates AP

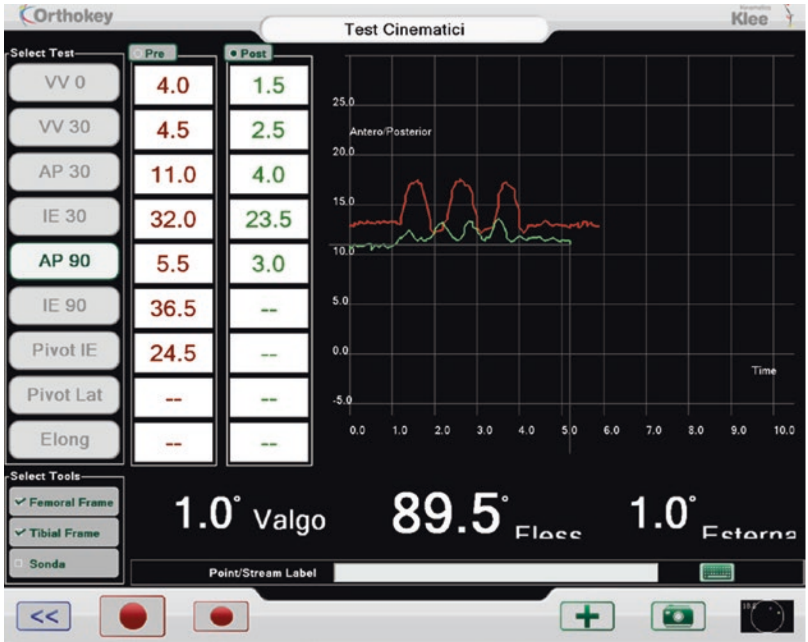

Fig. 41.4 Software interface (Klee, Orthokey) for intraoperative laxity evaluation. *Red curves* correspond with preoperative values and *green* with postoperative measures

translation at 30° and 90° (Lachman and anterior drawer test), VV (varus-valgus) rotation at 0° and 30°, IE (internal-external) rotation at 30° and 90°, and the pivot shift test. Maneuvers are performed and measured twice, before and after graft fixation (Fig. 41.4).

Finally when data is collected, the tracking frames are removed and surgery continues normally. Measurements displayed on screen are valuable information for the surgeon about the stabilizer effect of the surgical technique just performed (Fig. 41.5).

It is well known that the anteroposterior translation can be controlled by many different techniques, but achieving it hasn't to be the main objective in ACL surgeries, because rotational instability may persist [53, 57, 59].

Literature has shown for many years that the rotational stabilization is the principal goal when we face to unstable knees. In fact the presence of a positive pivot shift test can predict the failure of surgery [19, 23, 25, 45].

Concerning research applications, the navigation system allows to evaluate different reconstruction techniques.

Most of the studies reported the stabilizing effect of double-bundle ACL reconstruction, functionality of each bundle in the reconstructed ACL, quantification of the pivot shift phenomenon, and biomechanical function of ACL remnants, using a navigation system [4, 10, 14, 16–18, 20, 24, 26, 27, 29, 30, 34, 38, 39, 41, 44, 50, 55, 56, 60].

Ishibashi et al. reported that the posterolateral bundle (PLB) plays an important role in the extension position of the knee and that the anterolateral bundle (AMB) is more important in the flexion position [16].

In a recent systematic review performed by Björnsson et al. [3], they have found an important number of navigated studies comparing the stability achieved between anatomic double bundle and anatomic single bundle. Seventeen studies have compared the results in sagittal plane and they didn't find significant differences between them.

For the rotational instability, navigated analysis was performed in 20 studies and that only has shown a tendency supporting that DB is superior to control rotational instability. Further, comparisons were performed between anatomic

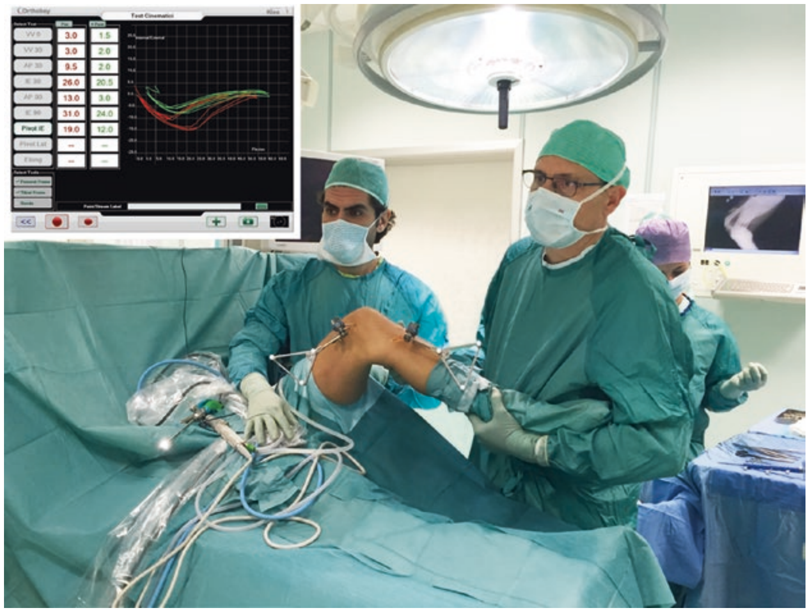

Fig. 41.5 Real-time pivot shift comparison between preoperative laxity and the achieved stability

and nonanatomic double-bundle techniques, and they found that nonanatomic double bundle has similar effect in controlling anteroposterior translation and the PS test than the anatomical technique [60].

Navigation was also used to evaluate the addition of a lateral extra-articular plasty (LEAP). This procedure has been proposed for better control dynamic instability, because it has better biomechanical properties in terms of rotational stabilization.

Colombet et al., Monaco et al., and Zaffagnini et al, using similar reconstruction techniques, analyzed the rotational controlling effect of the addition of LEAP to the intra-articular ACL reconstruction. They measured translation and rotation in different surgical times: before surgery, between the fixation of the intra-articular graft and the LEAP, and a last measure when the surgery had finished [2, 6, 36].

The studies comparing the addition of LEAP to the single-bundle techniques have shown an increased control in translation and rotation especially in the lateral compartment. There are statistically significant differences in the anterior translation of the lateral compartment at 90° of flexion and less lateral compartment opening in valgus at 0–30° of flexion when a LEAP was added.

Related with rotational stability, Zaffagnini et al. showed that single-bundle reconstruction with the addition of LEAP controls better the internal and the external rotation at 90° of flexion, whereas Monaco et al. only reported better results when measuring internal rotation, but no significant difference in external rotation [11, 35, 58].

That is confirmed by the systematic review performed this year by Hewison et al. [13] in which they analyzed the effect of LEAP in 29 articles. They also showed statistically significant reduction in pivot shift in favor of the combined procedure.

Despite all the studies performed, we are still having controversies about which is the best technique controlling dynamic instability of the injured knee.

Navigation is considered the gold standard for laxity quantification, and validation of new noninvasive devices must be related to it, because it has demonstrated to be highly precise and reliable quantifying knee laxity after ACL injury.

One of the main advantages is that it allows a real-time quantitative evaluation of the knee conditions at different moments of the surgical procedure, and therefore it allows surgeons to evaluate the knee status during kinematic maneuvers and, with this information given, perform a better and individualized approach.

However, navigation systems are difficult to use in clinical practice because of the invasive nature of the transmitter attachment. To gain wider acceptance of the navigation system in the clinic as a measurement tool of knee stability and kinematics, noninvasive surface markers and the development of dedicated software are also desirable.

41.6 Clinical Results of Navigation-Assisted ACL Reconstruction

The navigation system can improve clinical outcomes and decrease the failure rate of ACL reconstruction by reducing the variability of the tunnel position and creating more accurate femoral and tibial tunnels.

There were five randomized controlled studies that compared navigation-assisted and conventional ACL reconstruction [5, 12, 32, 33, 43] (Table 41.1).

Eggerding et al. [9] reviewed and combined the results of the above studies and did not find statistically or clinically significant differences between navigation-assisted and conventional surgery as determined by IKDC subjective score, Lysholm score, Tegner activity score, knee stability, tunnel placement, or complications. Apart from a significantly increased operative time for randomized participants using the navigation system (between 9.3 and 27 min longer), there was no difference in outcome of navigation versus conventional ACL reconstruction. They concluded that the currently available evidence does not indicate any improvement in clinical outcome when using navigation systems.

Conclusion

Experienced surgeons are skilled in accurate placement of bone tunnels into the native ACL footprint by using a variety of intra-articular landmarks (such as the resident's ridge) as reference points without employing navigation systems. Furthermore, randomized trials of ACL reconstruction with or without navigation systems have shown that the clinical outcomes were not significantly different between the two groups. When using the navigation system, it should be noted that placement of the reference markers requires additional incisions, and complications such as fracture, wound infection, and skin necrosis may occur. Therefore, some surgeons are of the opinion that the use of navigation in ACL reconstruction is not worthwhile. However, navigation systems can provide surgeons with a wide variety of data in real time that cannot be obtained under arthroscopic observation. Additionally, navigation systems are useful for the objective assessment of the tunnel position and for the measurement of knee stability and kinematics of pre- and postoperative surgery. They also serve as an educational tool for less experienced surgeons. Recent developments in computer technology will likely lead to further improvements in navigation systems. Because they allow a wide variety of intraoperative data to be collected, the utility of navigation systems in research is also expected to expand.

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