MINI-SYMPOSIUM: COMPUTER AIDED/ROBOTIC ORTHOPAEDIC SURGERY

(iii) The anterior cruciate ligament and navigation

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Summary
Here, we describe the current status of navigation systems used in anterior cruciate ligament surgery. Various systems of navigation are available; we use the Orthopilot system and the Praxim system daily. The goal of navigation is to help the surgeon to place the tibial and femoral tunnels in the correct position before drilling takes place. Thus, the ultimate goal is better positioning and isometry of the ligament graft in order to decrease the risk of adverse outcomes.

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Introduction
Surgical navigation has been in clinical use for 10 years now and was pioneered in knee surgery. The first steps were taken with the works of Dessenne,\textsuperscript{1} Julliard,\textsuperscript{2} and Cinquin,\textsuperscript{3} following initial ideas from Julliard, who considered traditional techniques to be too operator dependant and insufficiently adapted to the local anatomy of the knee.

Let us first consider some definitions. A new word has appeared in our own language: the ‘surgeries’ of the anterior cruciate ligament. This word expresses the use of computer-assisted navigation on the one hand and robot-guided surgery on the other. We will not deal with robotics in this article, since this field is still experimental and is currently prohibitively expensive. We would point out that the robot presently contributes to the surgical process by drilling the tunnels taking into account the three-dimensional data from scans.

Navigation, however, supports the surgeon. It will facilitate correct placement of tunnels. This requires pre-operative imaging data (usually CT scan), pre-operative fluroscopy,\textsuperscript{4,5} or even pre-anatomic data acquisition. This last option is chosen by the users in the majority of cases. The surgeon is still the master of his procedure, but is guided by navigation as a driver is guided by an in-car global positioning system.

Of the different systems available today, two have already proven their utility. One is the system developed by Praxim and used by Juliard, Merloz and Plaweski while the other is the Orthopilot system used by Saragaglia and our team.\textsuperscript{6–8} We will explain the principles of each system with particular emphasis on the Orthopilot system, with which we are most familiar.

Why use navigation?

We are aware of the good results of ligament surgery, nevertheless there remains a failure rate of 5–20\%.\textsuperscript{9,10} The causes of failure are multifactorial. The graft type, its quality or its fixation can be the origin of failure. On the
other hand, ligament positioning, and therefore the localization of femoral and tibial tunnels, will directly influence the results. \(^\text{11,12}\) Elongation of the transplant between the maximum flexion and maximum extension will depend on tunnel positioning. The greater the graft length variation between flexion and extension, the greater the risk of the transplant failure. The goal of the reconstruction is to obtain perfect ligament isometry, i.e. an absence of graft elongation. Staubli and Sati \(^\text{13}\) have shown that in a series of failures, the tunnel position was poor in 40–60% of cases. Recently, the major factor identified in the analysis of failures was poor positioning of the graft.

There are numerous arthroscopic techniques for ACL reconstruction using specific portals and views. Most of the time, these are used independently and their positioning depends on anatomic criteria pre-defined for each method. The goal is to position the femoral or tibial tunnel at the native origin and insertion of the ACL. Gillquist and Odensten \(^\text{14}\) have shown that only the central fibre of the normal ACL is isometric and that anisometry could vary up to 10 mm according to the position of fibres. However, other authors \(^\text{15}\) have calculated that there is no perfect isometric position for the ACL and that the length variation of the central fibre is of the order of 6 mm. Friederich \(^\text{16}\) believes that the most anterior fibre is isometric. If we place our graft at the centre of tibial and femoral insertions, the isometry would be approximately 4 mm. \(^\text{17}\) In reality, perfect ligament isometry does not exist and we should speak of relative isometry. Isometry is considered acceptable in practical terms if the variation of ligament length between flexion and extension is \(< 2\) mm. The goal of surgery is therefore to position a ligament with the utmost isometry. Conventional surgery uses the anatomic insertion sites as the guide to drill the tunnels and experience shows that the results are not so bad!

However, if we return to basic ACL anatomy we know that there are two bundles, an antero-medial bundle and a postero-lateral bundle. These are difficult to identify in a normal ACL under arthroscopy, but very real. Over recent years, several teams have been thinking that rebuilding the two bundles is the ideal solution. \(^\text{18,19}\) In theory, this is a seductive solution but actually increases the complexity of the surgical procedure and consequently the risk of positioning errors. We reserve our interest in this research area to improve our results with those patients who have greater degrees of laxity with major instability and a strongly positive pivot shift test on clinical examination. With traditional surgery we essentially rebuild the antero-medial bundle alone. Increasingly the importance of the postero-lateral bundle is emerging, as it has a very significant influence on anterior translation at 30° flexion, a frequent position of the knee in sports activity.

Thus, navigation appears to be more important if we are to manage more and more complex procedures. With navigation we can position the ligament, respecting isometry and avoiding impingement in the intercondylar notch. Completion of the tibial and femoral tunnels is not independent. Navigation takes into account the local anatomy, particularly the intercondylar notch, and also knee kinematics. It is possible to achieve two femoral tunnels and two tibial tunnels, or even two femoral tunnels and one tibial tunnel, depending on the grafts used (patellar tendon or hamstring). With navigation, the surgeon can secure ideal positioning of the tunnels, respecting on one hand, the knee anatomy and on the other hand the ligament isometry before drilling the tunnels.

Reconstruction of the ACL using the Orthopilot system

The equipment

This technique requires the conventional equipment for this type of surgery plus specific additional materials (Figures 1 and 2):

- An optoelectronic infra-red camera.
- A computer with the proper software.
- Tibial and femoral specific sights.
- Palpers.
- Active or passive sensors directly fixed on the tibia and on the femur via pins, which are linked to the computer system through a wire.
- Passive sensors, which consist of a retro-reflecting system, alternatively fixed on the palpers, on the sights. This passive system is only visualized via the camera and is not linked to the computer system. It enables better flexibility of use in relation to the active system.
- Pins of 20/10 mm and their fixation system.

Surgical procedure

The operation begins with knee exploration and positioning of the sensors. Conventional arthroscopy is followed by the treatment of meniscal injuries and clearing of the

![Figure 1](instruments-necessary-for-navigation)
intercondylar notch. We then position the active sensors (rigid body) or passive (Figure 3) directly on the bone with two filleted bicortical pins of 20/10 mm diameter. The sensor is attached to the pins. We position a sensor on the antero-medial side of the tibia, 7 or 8 cm from the joint line, and a further sensor on the antero-medial aspect of the medial tibial condyle. The fixation pins can be replaced by a screw. The fixation of the sensors must be done very thoroughly to avoid any skin alteration on the one hand, and to obtain a sturdy construct on the other hand, which avoids disturbance of sensor position during navigation procedures.

We start the procedure by recording several extra-articular points with a passive sensor with 4 reflecting spheres (Figures 3 and 4). Thus, we palpate the anterior tibial tubercle, the tibial crest over the ankle, the centre of the medial tibial space and the lateral tibial space. Then, we record the exact position of the knee at 90° and with full extension. We end with a kinematic acquisition between full extension and 90° of flexion. A measure of anterior tibial translation is possible in extension, with various positions of flexion, or at 90° of flexion, as well as in various positions of rotation. Measurement of the pivot shift is also possible at the end of the intervention after graft fixation, when measurement of rotation can also be made. It is furthermore possible to compare translation and rotation before and after fixation of the graft. Next we complete the intra-articulation palpations. Firstly, we detect the anterior segment of the lateral meniscus, then the anterior tibial edge. Then, we acquire the pattern of the whole anterior edge of the intercondylar notch by recording approximately 15 points. We conclude by recording the femoral attachment site of the ACL. Two points are stored: one at the posterior part of Blumensaat’s line and the other at the back of the notch, at 11 o’clock for a right knee and at 1 o’clock for a left knee. These points are fundamental for the computer to determine the dimensions of the knee and identify possible sites of impingement. The whole procedure can be followed on the computer via the available consecutive displays.

The tibial view
The tibial tunnel is located thanks to a specific sight fitted with a passive sensor. This sight is similar to conventional arthroscopic drill guides and has the same stiffness. We place the needle of the sight with the pin at the centre of the intended tibial insertion. The computer then gives us several data. First of all, we see the projection of the intercondylar notch in the pre-spinal area and the conflict zones are marked out in red (Figures 5 and 6). Then, we observe the exact position of the tunnel described in percentage terms compared with the anteroposterior distance on one hand, and also compared to the knee width. At this stage, the surgeon is free to select
Once the ideal position is selected it can be drilled with a bit.

Femoral viewing

This is also determined using a specific sight (Figure 7). We have two possibilities: either a sight for the inside-out technique, introduced by the arthroscope antero-medially, or a sight for the outside-in technique, which requires a 1 cm external counter incision. The computer guides the surgeon in positioning this by relating to the posterior part of the intercondylar notch via two data: the distance of the tunnel centre compared with the position over the top, and the theoretical isometry of the ligament according to the position of the tibial tunnel and knee kinematics. Finally, the computer gives us information on the tunnel orientation in the frontal plane and of the possibility of conflicts (Figure 8). Once more the surgeon is free to make the final choice and drill the tunnel as soon as a satisfactory position of the pin is found.

Anterior tibial translation measurement

Once the graft is fixed, we can compare anterior tibial translation to the measurement made at the start of the procedure. This test is carried out manually, under the same conditions as it was at the start of surgery. It remains controversial, since the observer of the test is never impartial. Will we apply the same force to produce anterior translation? But at least this test exists and has an indicative value. We can similarly assess the effect of surgery on rotation.

Discussion

We can state that this navigation system has already shown itself to be efficient and very accurate. As with the majority of the current navigation systems, it is in constant development, and the software has regular upgrades. We have recently investigated the accuracy of this system in a survey of 50 cases. This survey enabled us to compare the position of the tunnels observed on X-rays with data stored in the computer during surgery. We were able to check tunnel positions against recommendations in the current literature. The results showed the system to be reliable and reproducible. This study also proved that it was difficult to compare data stored by computer with X-ray measurements.
It is particularly difficult to compare angular data from the computer, as the palpation criteria during surgery are not the values we are able to study on X-rays.

Finally, it is obvious that the system is dependent on the number of palpations made to acquire anatomic data and on the way these palpations are performed. That is why we now use ceramic palpation sensors, which are very stiff and which limit the risk of inaccuracy. The system must now evolve to simplify the system of palpation. We must streamline to a system with fewer palpations but all relevant palpations.

The Orthopilot system has numerous advantages in our eyes. The setting-up of the system and its use are simple. We have observed that the learning curve is short. After 10 uses, the extra time needed for surgery falls from 20 to 10 min. The computer displays are simple and readable. Securing the sensors to bone by 20/10 pins is easy and does not create secondary problems except for pinpoint scars.

This technique does not revolutionise the routine of the surgeon compared with conventional methods. It can be easily learned by a surgeon who is used to anterior cruciate ligament surgery. There are few inconveniences, though it requires considerable attention since the surgeon must remain the master of the procedure and must interpret carefully the predictions made by the computer. The study of Robert\textsuperscript{6} pinpoints an ideal position for the tibial tunnel, but identifies a femoral positioning which appears a little anterior on the femur. This fact must be considered. Actually, his results on isometry, laxity, and the control of rotation are quite convincing, as are the functional results.

Navigation is becoming an essential tool to be adapted to patient morphology. In conventional surgery our methods always position the femoral tunnel at the same point whatever the patient morphology and whatever the tibial tunnel position. This may be the limiting factor for conventional surgery. The advantage of navigation is this relationship between the two tunnels that we do not have with conventional surgery. The Orthopilot system enables us to create an ideal tibial tunnel, avoiding impingement in the notch.\textsuperscript{21} It enables us to proceed to a femoral tunnel that also has ideal isometry, with control of rotation. For the implementation of two femoral tunnels, navigation is particularly necessary for creating the postero-lateral tunnel. Actually, this does not have a reliable anatomic marker compared with the antero-medial tunnel easily achievable by reading from the posterior edge of the lateral condyle. The study of Ishibashi\textsuperscript{19} demonstrates the advantages of the Orthopilot system, employing double tunnels to create an anatomic reconstruction of the two ACL bundles.

Other systems

Surgigate system

This system used by the de Rycke\textsuperscript{7} team is very similar to the Orthopilot system. It is based on the same principle of fixing the active sensors on the femur and tibia, on the acquisition of the knee kinematics and on the digitization of anatomic markers. The different data are compared with points which are previously stored on simple X-rays.

In 2001, de Rycke\textsuperscript{7} completed 91 ACL reconstructions with this system. He believed the learning curve was long and the procedure was not for everybody. Wiese and Rosenthal,\textsuperscript{22} recommend the use of navigation in revision surgery. Around 100 cases have been published, with an additional operative time of 15 min per intervention. The authors have not shown any statistically significant differences compared to a control group of patients operated using conventional surgical methods when considering early subjective results and objective measurements of laxity. However, there was a statistically significant difference in the positioning of tunnels estimated by radiographic measures. The position and orientation of tunnels are better with navigation. Nevertheless, we must challenge the results of this study since it is very difficult to get an objective measure of proper radiographic positioning of the tunnels.

Praxim system

This method of navigation has been used since 1992 by Julliard.\textsuperscript{23–26} Like the Orthopilot system, it does not use the pre-operative imaging. The principle of this system is based on the relationship between the tibial insertion and the femoral insertion of the graft. For each dataset, the computer system reveals the ligament anisometry and the possible conflicts with the roof of the notch. The computer permanently computes the isometry of the central fibre of the transplant. Numerous intra-articulation markers are stored during the first stage of surgery: the so called ‘bone morphing’. This step pinpoints the zones of conflict with the notch and will lead the surgeon to reshape the notch or to modify the position of the graft by moving backwards the tibial insertion. The second step is ‘anatomometrics’, which aims to identify the best ligament isometry.

Several studies using this computer tool, ‘protocol ACL logics’ have already given interesting results. Paweski\textsuperscript{27} has recently observed better results with this technique in terms of laxity and on the rotation stability of the reconstruction using a single bundle of patellar tendon. In a series of 150 cases, he has shown better results in terms of rotational stability, 23% in average, and better results measured by anterior laxity, at 10.1 mm. Therefore, he has used this tool to position the ligament according to local morphology but also used it to measure antero-posterior and rotary laxity. This is an important breakthrough, enabling measurement of these different variables during surgery, facilitating, for example, the decision to use a two-bundle technique or an additional antero-external reconstruction. Robinson and Colombet,\textsuperscript{28} have also measured per-operatively the axial rotation and coupled antero-posterior translation, before and after reconstruction of two bundles. They have measured axial rotation during the pivot shift and found 29° for one translation of 17 mm in 10 patients. After reconstruction of the antero-medial bundle, the reduction in rotary data was 16.4° for a translation of 6 mm. The addition of a postero-lateral bundle has enabled reduction of axial rotation of 12.6° and decreased anterior tibial translation during the Lachmann test.

As we understand more and more about the role of navigation in the per-operative assessment of knee laxity we
are devising interpretations of the best techniques to correct abnormal findings.

**Navitrack system**

This technique of navigation has been used since 1999. The principle is based on the variation in magnetic fields emitted by sensors during position changes. This method employed the recording of markers on a pre-operative scan. Ellermann and Siebold have published experience of 16 cases. The difficulties encountered using this system have lead the authors to change to an optoelectronic system since 2001. Nevertheless, the measurements made with the scanner are still essential and the extra average time of the surgery is 20–30 min.

**Fluoroscopic systems**

This system of navigation appeared in 1998, described by Klos. This technique not only uses a navigation system, similar to those previously described, but also a display intensity amplifier. Klos has completed a study demonstrating the improvement in the positioning of tibial and femoral tunnels with virtual fluoroscopy when compared with conventional fluoroscopy (without any navigation system). This system is interesting but it requires extra equipment and ionizing radiations.

**Conclusion**

Navigation in ACL reconstruction is a modern technique in constant evolution. Our experiences point out that this technique improves graft positioning and limits conflicts with the intercondylar notch. Navigation gives the surgeon an assessment of the central fibre isometry of the proposed graft, even before the tunnel is drilled, according to the positioning of the pins representing the centre of each tunnel.

Some studies are starting to show the clinical impact of navigation. What is most important for the surgeon is to achieve a strong graft with reliable longevity. Several studies have pointed out the importance of tunnel positioning for long-term clinical results. If our conventional arthroscopic guides enable precision in tunnel positioning, navigation provides a more relevant positioning adapted to the anatomy of each knee, taking into account its kinematics. However, the nature and the quality of the graft are never taken into account in navigation, though the risks of ligamentoplasty.

To be useful in regular practice, the navigation system should not increase the extent of the surgical approach and should not be complex to use. It must not inordinately increase surgical time and above all it should be reproducible. The Orthopilot system and the Praxim system seem to meet these criteria. However, it is necessary to conduct prospective surveys to demonstrate the reliability of the systems in tunnel positioning. These studies should compare post-operative radiographic measures with per-operative computer data. The difficulty with this study will be to define the X-ray criteria to compare the orientation and the position of the tunnels with the computer data. However, the most interesting development is the ability to be able to assess the importance of laxity, rotation and pivot-shift during surgery. Thus, we are able to choose the best surgical method. Navigation is becoming more and more useful in the development of double bundle techniques. Indeed, this complex technique must be simplified by the use of navigation. The positioning of the femoral tunnels is facilitated by navigation, since the absence of a reliable anatomic marker for the posterolateral tunnel achievement is otherwise a source of error.

In conclusion, we can say that navigation in ACL reconstruction has three goals:

- to enable the surgeon to place the ligament according to the patient’s individual anatomy,
- to enable less experienced surgeons to avoid major mistakes in positioning, and
- to enable the experienced surgeon to evolve a more anatomic reconstruction using a two-bundle technique.

We must not forget, whatever system is used, that the surgeon must be the master of his acts.

**References**


