ARTICLE IN PRESS

Journal of ISAKOS xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of ISAKOS

journal homepage: www.elsevier.com/locate/jisakos

State of the Art Review

Navigation in anterior cruciate ligament reconstruction: State of the art

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ARTICLE INFO

Keywords:
ACL
Navigation
CAS
Computer-assisted surgery
Anterior cruciate ligament

ABSTRACT

Computer navigation (CN) for anterior cruciate ligament (ACL) surgery has been used mainly for two purposes: to enhance the accuracy of tunnel position and to evaluate the kinematics of the ACL reconstruction (ACLR) and the stability achieved by different surgical techniques. Many studies have shown that navigation may improve the accuracy of anatomical tunnel orientation and position during ACL reconstructive surgery compared with normal arthroscopic tunnel placement, especially regarding the femoral side. At the same time, it has become the gold-standard method for intraoperative knee kinematic assessment, as it permits a quantitative multidirectional knee joint laxity evaluation.

CN in ACL surgery has been associated with diverse problems. First, in most optic systems additional skin incisions and drill holes in the femoral bone are required for fixation of a reference frame to the femur. Second, additional radiation exposure and extra medical cost to the patient for preoperative planning are usually needed. Third, CN, due to additional steps, has more opportunities for error during preoperative planning, intraoperative registration, and operation. Fourth, soft tissues, including the skin and subcutaneous tissues, are usually not considered during the preoperative planning, which can be a problem for kinematic and stability assessment.

Many studies have concluded that ACLR using a CN system is more expensive than conventional surgery, it adds extra time to the surgery and it is not mitigated by better clinical outcomes. This, combined with costs and invasiveness, has limited the use of CN to research-related cases. Future technology should prioritize less invasive intra-operative surgical navigation.

Introduction

Computer navigation (CN) in knee surgery represents the use of computer technology to determine a set of methods used for surgical planning, guiding or performing surgical interventions, and evaluating kinematics and stability after anterior cruciate ligament (ACL) reconstruction (ACLR). CN in ACLR was introduced by Dessenne et al. [1] in the mid-1990's as an intraoperative tool to assess knee kinematics after ACLR. Since then, many authors have used navigation systems predominantly for two purposes [2]: (1) to enhance the accuracy of tunnel position and (2) to evaluate the kinematic of the ACLR and the stability achieved by different surgical techniques.

Surgeon's opinion on the usefulness of CN for ACLR is divided [3]. While proponents of navigation systems argue that CN improves the positioning of the graft, leading to better clinical results by avoiding graft failure, those against highlight that these systems are associated with longer operating time and higher costs, without the justification of associated significant benefits when compared to conventional surgery, especially in high-volume surgeons [4,5]. These factors have limited the use of navigation systems to research-related cases (compared to total knee replacement, which started in 1998 [6], but expanded faster).

This narrative review will cover the history of CN in ACLR followed by the recent state-of-the-art advances in CN for ACLR; highlighting their current use and the potential future directions for routine application into surgical practice.

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https://doi.org/10.1016/j.jisako.2022.09.001
Received 12 May 2022; Received in revised form 15 August 2022; Accepted 17 September 2022
Available online xxxx

Types of CN in ACL surgery

There are two methods for navigation in ACLR (Table 1) [7]: image-based and image-free. The image-based method uses pre-operative computed tomography (CT) or intra-operative x-ray fluoroscopy in real-time during ACLR procedures, both exposing the patient to the ionizing radiation. The image-free method usually uses a preoperatively generated 3D model from CT or magnetic resonance imaging (MRI) plus intraoperative 3D bone morphing with an optical tracking system. The optical tracking system captures reference markers that are rigidly attached to the patient and the mapping is made using surgical tools (Fig. 1). Different systems have been named in the literature, the most common being Orthopilot [Braun, Germany], PRAXIM-Medivision [France], KneeNav [Pittsburgh, PA], and Vectorvision [BrainLab, Germany] among others. In some scenarios, especially regarding kinematic analysis, non-invasive (skin-mounted) inertial sensors for clinical practice (e.g. KiRA [Orthokey, Italy]) have been developed [2].

Guiding tunnel placement

The initial application of intraoperative navigation in arthroscopy was largely focused on tunnel positioning in ACL reconstruction to optimize graft kinematics and isometry. As ligament position varies significantly across individuals and, despite the substantial effort to limit variance and provide anatomic references to be used during surgery, correct tunnel placement is still a matter of experience with success rates varying broadly between low- and high-volume surgeons [8]. Tunnel malposition has a significant influence on ACLR graft failure, supporting the application of navigation to facilitate an increase in the accuracy of tunnel placement [4].

Many studies have shown that CN can improve the accuracy of anatomical tunnel orientation and position during ACLR surgery compared with normal arthroscopic tunnel placement [9–24]. Probably, the most important impact of CN in tunnel placement has been specifically on the femoral side [25–27]. In addition, there are studies that underlined how the use of a navigation system in ACLR could be useful for inexperienced surgeons to avoid poor tunnel orientation and positioning [28,29].

An example of where tunnel positioning could be difficult is when preserving remnants in ACL surgery, as these may affect a good visualization of the footprints, making it necessary to clean the footprint to achieve a correct tunnel positioning. In such situations, navigation systems might be used to confirm the ACL footprint position on the intercondylar lateral wall and to create an adequate tunnel using the native ACL footprint as a landmark [30]. Healing at the femoral aperture is slower than at the tibial aperture [31], which may in part be due to the extensive soft tissue clearance required to visualize the femoral tunnel position.

Another example where tunnel positioning is challenging is revision ACL surgery because of several issues surgeons have to deal with, including bone defects, primary tunnel malposition and pre-existing fixation devices, making adequate new tunnel positions fundamental for surgery outcomes. In this scenario, CN has shown to increase the possibility of creating optimal tunnel positions whilst avoiding these pre-existing issues [32–34].

Recent studies regarding navigation use for tunnel positioning in ACL surgery have mainly originated from Asia. In 2016, Lee et al. [35] using an intraoperative image-free navigation system (preoperative CT plus intraoperative optical tracking system) concluded that navigational femoral tunneling could make predictable tunnel position and orientation with high accuracy and reproducibility, and it could be used to improve safety, decrease the risk of a short femoral tunnel, and prevent posterior wall breakage. The cadaveric experimental results had tunnel lengths with deviations less than 1 mm in both the arthroscopic and navigational experiment groups. For the posterior wall margin, a large deviation with more than 4 mm was reported in the arthroscopic group, while better results were obtained in the experimental group with less than 1 mm error. However, it is important to note that the arthroscopic group consisted of only two cadavers, while the CN group consisted of 8 cadavers. The same group published another study the year later communicating similar results but with fewer (six) cadaveric specimens [7].

Cho et al. [36] in 2018 reported the development of an MRI-based surgical robot to create the femoral tunnel in ACLR with four sequential cadaveric experiments, each producing better accuracy compared to the previous one. The reported distances between the intra-articular points of the planned and the created tunnels were 7.78 mm in the first experiment and 1.47 mm in the last experiment. The difference in tunnel length was 4.62 mm in the first experiment and 0.99 mm in the last experiment. The investigators considered the latter results satisfactory.

Popkin et al. [37] in 2019 using 20 pediatric sawbone models (10 for CN (BrainLab, Germany) and 10 for fluoroscopic guidance) reported that the distance from the ideal tunnel placement using CN was 2.7 + 3.1 mm versus 6.4 + 4.2 mm for fluoroscopic guidance. The authors concluded that CN achieved a more accurate epiphyseal femoral ACL tunnel position but required more time to complete and had a higher effective radiation dose than fluoroscopic guidance.

The same year Raposo et al. [38] presented their proposition of a video-based navigation system for ACLR. Instead of using pin trackers far from the surgical site, this system used a marker being placed inside the joint (at an arbitrary point in the intercondylar surface). The results of their cadaveric study were defined as encouraging, obtaining a high accuracy and a relatively low increase in procedure time, avoiding the need for additional incisions or capital equipment.

Contrarily, regarding tibial tunnel location, Oshima et al. [39] in an in-vivo study of 35 patients, found that tibial tunnel location using fluoroscopy was more accurate than using an image-free navigation system, assessed by a postoperative 3D-CT. They considered that fluoroscopy provided consistent data on tunnel position intraoperatively and a good feedback system.

Kinematic evaluation

Navigation has become the gold-standard method for intraoperative knee kinematic assessment, as it permits a quantitative multidirectional knee joint laxity evaluation [2]. Since its appearance, it has provided a precise understanding of the different anatomical structures participating in knee stabilization in ACLR, and allowed the development of both in-vitro and in-vivo methodology to answer research questions in both native and reconstructed knee kinematics. Navigation has been employed to demonstrate the biomechanical difference between the two native ACL bundles [40–42] and the participation of secondary stabilizers such as the medial meniscus (for anteroposterior [AP] restraint and also rotational stabilization) [43–45] and the anterolateral capsule (or anterolateral ligament [ALL]) for rotational stability [46–48]. This improved knowledge of how knee structures influence knee kinematics has allowed investigators to study the implications after ACLR. Initially, there was interest in how navigation could compare a double-bundle (DB) and a single-bundle (SB) ACLR, followed by an increased interest in kinematic role of the anterolateral (AL) structures in an ACL deficient knee, and recently the kinematic properties of the ACL remnants.

It is common knowledge that the native ACL is a non-isometric structure: the anteromedial (AM) bundle is tense predominantly during knee flexion with a maximum at 45°–60°, whereas the posterolateral (PL) bundle is maximally taut with the knee in full extension [49]. Therefore, surgical techniques were developed to reconstruct the AM and PL bundles separately, as anatomically as possible. Different biomechanical studies have shown superior results to support a double-bundle (DB) reconstruction over a single-bundle (SB) reconstruction [50–52]. However, biomechanical studies do not always align with clinical in-vivo assessments. In a review of studies using navigation for kinematic

Table 1
Strengths and weaknesses for type of CN.

	Strengths	Weaknesses
Imaged-based CN	Additional check during the procedure (fluoroscopy)	Exposure to ionizing radiation
Image-free CN	No radiation exposure during the procedure	Additional incisions and drill holes for optic trackers

assessment, Zaffagnini et al. [2] reported that the majority of clinical studies do not show significant differences in controlling AP displacement (anterior drawer and Lachman tests) when comparing the SB and DB techniques. However, they stated that two systematic reviews reported that the DB technique was shown to be more effective for controlling rotational displacement (internal-external rotation and pivot shift test) [49,53]. It must be highlighted that initially, most studies compared an anatomic DB reconstruction against a transtibial (non-anatomic) SB technique. The meta-analysis by Desai et al. [49] included only anatomic reconstructions and found that anatomic DB ACLR was superior to anatomic SB reconstruction in terms of primarily AP laxity (KT-1000 test), and in contradiction to what Zaffagnini et al. [2] reported in their review, found no differences in rotation stability (pivot shift and navigation). By means of navigation, recent in-vivo studies have aimed to solve this controversy. Ikuta et al. [54] randomized 34 patients for anatomic SB and DB ACLR and performed intraoperative image-free kinematic evaluations before and immediately after ACL reconstruction at different knee range of motion angles. They found no significant difference in AP translation or tibial rotation between the two surgical techniques.

Pursuing the longer-term effect of a DB ACLR, Komzák et al. [55] reported a randomized trial with a two-year follow-up of 40 patients, including only isolated complete ACL injuries, and compared knee kinematics according to the healthy contralateral leg using passive trackers fixed to the thigh and leg with stripes. The authors found that anatomic DB ACLR restored the rotational stability of the knee joint after at least two years without any significant difference in comparison to the contralateral healthy knee, while the anatomic SB ACLR was not sufficient for restoring internal rotation. Despite this kinematic difference, a difference was not seen in patient-reported outcome measures, and AP translation was to the same extent for both techniques.

Considering that DB ACLR is more demanding and has shown to have a higher complication rate [56], a high interest has developed regarding the addition of an anterolateral (AL) tenodesis or reconstruction to augment a SB ACLR, increasing anterolateral rotational stability, restoring knee kinematics, and protecting the ACL graft whilst it heals and integrates. Navigation has demonstrated that AL supplementation provides an adequate rotatory restraint [2,57]. Moreover, clinical studies have shown superiority in controlling internal rotation of SB ACLR (non-anatomic) plus AL tenodesis technique versus an anatomic DB ACLR [47,58]. The question then arises whether an AL procedure is recommended for all SB ACLR, and if so which type of procedure. Based on biomechanical cadaveric studies using bone fixed markers for image-free navigation, it has been demonstrated that different AL procedures have different effects on kinematic control of anterolateral stability [59], with some subsequent concerns about an increase in lateral compartment pressures [60]. Select of appropriate patients for this additional procedure has interested many investigators, with recommendations for a patient-specific risk analysis [61,62]. The Anterolateral Ligament Expert Group consensus suggests that a patient who presents with a grade 2 or 3 pivot shift is a sufficient criterion for adding an AL supplementation [61]. However, the diverse reported sensitivity and specificity of the pivot shift examination [57,63] present a real challenge for this recommendation. As shown early on by Noyes et al. [64], the pivot shift is a subjective test, depending significantly on the examiner's hand. In this scenario, navigation could further aid in developing devices to create a reproducible and objective pivot shift assessment [2,57].

Navigation has provided the opportunity to evaluate the kinematic properties of different anatomical structures participating in knee stabilization, including ACL remnants. Nakamae et al. [65] using an intraoperative arthrometry with an image-free navigation system before and immediately after resection of the ACL remnant found that remnants up to one year from the initial injury that were bridged between the posterior cruciate ligament and the tibia or the intercondylar notch and the tibia, reduced AP translation at 30° of flexion, and had no rotational

Fig. 1. Example of the navigation system based on optical trackers mounted in the femur and tibia used in the study by Neri et al. [59].

implications. Contrarily, Nakase et al. [66] using the same intraoperative image-free navigation system and testing also before and immediately after remnant resection, found that ACL remnants may assist in both AP and rotational stability at 30° of knee flexion; however, the contribution to knee stability was only found in those complete remnants bridging from the anatomical origin on the medial wall of the lateral femoral condyle to the tibial insertion.

Limitations of CN

CN in ACL surgery has been associated with a wide variety of problems. First, in most optical tracking systems additional skin incisions and drill holes in the femoral bone are required for the fixation of an accurate reference frame. Second, additional radiation exposure and extra medical cost to the patient for preoperative planning are usually needed. Third, CN, due to additional steps, has a higher potential for error during preoperative planning, intraoperative registration, and technical operation. Fourth, soft tissues such as the skin and subcutaneous fat and muscle, are not usually considered during preoperative planning (e.g. when using skin-mounted sensors for kinematic assessment, subcutaneous tissue is fundamental as the distance between what we want to measure [knee laxity] from where we measure it, and can alter the results), and finally, most of the navigation systems require an anesthetized patient, meaning that a surgical setting is needed (which can be a limitation especially when wanting to measure joint laxity).

Alongside these four main limitations, a number of studies have also concluded that the increased expense of ACLR using a CN system, and the additional surgical time, are not mitigated by better clinical outcomes [7,8,67,68]. These factors have limited the use of navigation systems to research-related cases.

Future perspectives

As stated by Musahl et al., in 2012 [69], we agree that navigation can be a helpful tool for evaluating knee laxity, and we consider that it might be the key to answering when should an ACLR be augmented with an AL procedure. Future AL consensus should incorporate objective navigational pivot shift assessment into their recommendations.

Considering that navigation in ACLR permits a personalized kinematic evaluation of each patient, when focusing on a comparison between their preoperative and postoperative status and their healthy contralateral knee, navigation data could guide their rehabilitation protocol and aid in the decision of timing to return to sports. Only a few studies have employed intraoperative navigation systems for comparison between affected and unaffected knees [70,71], probably due to an increase in costs, surgical time, and radiation. Interestingly, Imbert et al. found that ACLR, with respect to the contralateral knee, intra-articular plus additional anterolateral reinforcement procedures do not restore normal joint laxity [70]. More studies are needed to discuss whether contralateral healthy knee biomechanical records are needed to obtain better clinical results. No studies were found specifically for navigation and ACL rehabilitation programs; nevertheless, 2D and 3D motion analysis methods have been created for knee kinematic evaluations of failure risk factors such as dynamic valgus [72]. Di Paolo et al. [73] have recently validated wearable sensor systems in multidirectional high-speed complex movements to evaluate the specific joint parameters commonly used in rehabilitation and return to sport assessment after ACL injury. Future investigations could include navigational data during the rehabilitation process to improve functional outcomes and accelerate the rehabilitation process while diminishing the graft failure rates after ACLR.

We believe that as technology continues to improve, navigation will provide objective kinematic parameters to assess knee-joint stability, helping not only to guide and personalize the correct surgical technique for ACLR and rehabilitation, but also to prevent an ACL injury. Tabori et al. [74] have recently published a machine-learning approach based on inertial sensors and optoelectronic bars to predict ACL injury risk in a female basketball player. Hopefully, future investigations using navigational data may reduce sport-related injuries.

Regarding tunnel positioning in ACLR, with the introduction of less invasive systems such as in Raposo et al. [38], navigational ACL surgery could be a possible choice in daily practice. There are cases that specifically would benefit from CN; a good example of this is multi-ligament knee surgery, where to our knowledge there are no studies published to this date. CN could help to guide faster, more accurate creation of the multiple tunnels required whilst avoiding tunnel collision, one of the biggest concerns in this type of surgery [75].

Compared to knee arthroplasty, where high dissatisfaction rates persist [76], ACLR has been a successful intervention over the last decades with high patient satisfaction rates. Thus, a remarkable improvement in clinical outcomes by navigation techniques might be hard to achieve and even harder to prove [77]. The use of surgical navigation for tunnel placement in ACL surgery remains inherently problematic because the optimal position for placement of ACL tunnels remains debatable [78,79]. Until today, the use of computer-assisted navigation systems has not correlated clinically with better results but led instead to increased concerns regarding the learning curve, higher costs, and time-consuming problems. Based on these factors, there are still major obstacles to the routine use of computer-assisted navigation systems in clinical practice.

Conclusions

CN is a developing technology in ACL surgery, which is currently mostly limited to research-related cases because current systems can require increased imaging radiation exposure, and are more invasive, more time consuming, and costly. In the contrary, regarding kinematic evaluation, it is considered the gold standard, thanks to the potential for in-vivo non-invasive skin-mounted monitoring, and the accuracy of results seen using in-vitro cadaveric biomechanical experiments. Future technology should prioritize less invasive intra-operative surgical navigation.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

1. Key articles

Dessenne et al. [1] reported the first use of CN in ACL surgery in 1995.
Zaffagnini [2] et al. published an historical review of CN in ACL surgery in 2016.
Raposo C [38] presented their proposition of a video-based navigation system for ACLR in 2019.
Ikuta et al. [54] and Komzák M et al. [55] reported biomechanical differences between SB and DB ACLR using navigation.
Neri et al. [59] and Neri et al. [60] analysed different AL procedures using image-free navigation.
Nakamae A et al. [65] and Nakase J et al. [66] did biomechanical evaluations of ACL remnants.
Di Paolo et al. [73] have validated navigational evaluation to specific joint parameters used in rehabilitation and return to sport after ACL injury.

2. Essential features of navigation in ACL surgery

There are two methods for navigation in ACLR: image-based and image-free

The image-based method uses pre-operative CT or intra-operative x-ray fluoroscopy in real-time during ACLR procedures, both exposing the patient to the ionizing radiation.

The image-free method usually uses a preoperatively generated 3D model from CT or MRI plus intraoperative 3D bone morphing with an optical tracking system.

In some scenarios, especially regarding kinematic analysis, non-invasive (skin-mounted) inertial sensors for clinical practice have been developed.

3. Major pitfalls

Most optic systems require additional skin incisions and drill holes for fixation of an accurate reference frame.

Additional radiation exposure and extra medical cost to the patient for preoperative planning are usually needed.

CN, due to additional steps, has a higher potential for error during preoperative planning, intraoperative registration, and technical operation.

The increased expense of ACLR using a CN system, and the additional surgical time, is not mitigated by better clinical outcomes

4. Future perspectives

Navigational data in ALCR could guide rehabilitation and aid in the decision of timing to return to sports.

Navigation could provide objective kinematic parameters to assess knee-joint stability, helping prevent an ACL injury in healthy individuals.

Regarding tunnel positioning in ACLR, with the introduction of less invasive systems, navigational ACL surgery could be a possible choice in daily practice.

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