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Applications of computer navigation in sports medicine knee surgery: an evidence-based review

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Abstract Computer-assisted surgery (CAS) has been investigated in a number of sports medicine procedures in the knee. Current barriers to its widespread introduction include increased costs, duration, and invasiveness of surgery. Randomized trials on the use of CAS in anterior cruciate ligament reconstruction have failed to demonstrate a clinical benefit. Data on CAS use in high tibial osteotomy are more promising; however, long-term studies are lacking. CAS has a number of research applications in knee ligament surgery, and studies continue to explore its use in the treatment of osteochondral lesions. This article reviews the applications of CAS in sports medicine knee surgery and summarizes current literature on clinical outcomes.

Keywords Computer assisted surgery · CAS · Knee · Sports medicine · Anterior cruciate ligament · High tibial osteotomy

Introduction

Computer-assisted surgery (CAS) has become established in a number of areas of orthopaedic surgery, particularly in knee arthroplasty [1]. In sports surgery of the knee, the two main procedures for which clinical results have been published are anterior cruciate ligament (ACL) reconstruction and high tibial osteotomy (HTO). Navigation also has a number of research applications, and as navigation technology continues to advance, it has been used to aid less common procedures, such as retrograde drilling in osteochondritis dissecans (OCD) and osteochondral allograft implantation [2•, 3–5].

CAS aims to improve both the *accuracy* and *precision* of surgery [6]. Accuracy refers to the degree of closeness to the intended (ideal) target, and precision refers to the reproducibility or repeatability of obtaining this position. Increased precision should lead to reduced *outliers*, and this is an argument often used in favor of navigation systems [1]. It should be noted, however, that increased accuracy requires knowledge of what an *optimal* position or alignment is, which in sports surgery of the knee is often controversial [6, 7]. Additionally, the question remains whether improvements in accuracy and precision will lead to enhanced clinical outcomes [8]. Computer navigation systems universally increase the duration and cost of surgery [9], and justification for their use depends on such clinical improvements being demonstrated.

CAS also has other potential applications. It can be a valuable research tool, providing precise measurements on aspects, such as overall limb alignment, that normally require additional radiological procedures. It can also provide data previously confined to cadaver studies, such as real-time knee kinematics before and after ligament reconstruction. These data can then potentially be correlated with clinical outcomes, providing feedback as to which parameters are most important to success. It can also be a useful teaching tool, and there is evidence that computer navigation reduces or eliminates the effect of inexperience in instrument positioning [10], potentially shortening a surgeon's "learning curve."

Navigation in general

Navigation systems can broadly be divided into two groups. Image-based systems rely on either preoperative computed tomography (CT) scans [11] or intraoperative fluoroscopy [12]. Image-free systems use intraoperative data acquisition to build a computer model of the patient anatomy, which the surgeon then uses to guide the surgical procedure. Image-free

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systems have become popular because they eliminate the additional cost and delay of radiographic procedures and provide additional real-time kinematic data to the surgeon.

Data acquisition usually involves three steps: initial instrument calibration, bony fixation of a reference array, and registration of anatomical landmarks. Initial calibration ensures that the instruments are providing accurate positional information and no mechanical deformation of the instruments has occurred. Reference arrays are then attached independently to the bone of both the tibia and femur, often through separate incisions. These provide fixed reference points to the navigation computer. The reference arrays provide information to an optical tracker, through passive (markers with reflective coating) or active (infrared beams) means. This allows the tracker to localize their position in space and reference all other anatomical points to these markers. It is essential that these reference markers remain stable during the surgery, since even a small loss of position will compromise all other data points. The center of rotation of the hip joint is usually calculated digitally by extrapolation from a series of movements of the femur performed by the surgeon [13]. A pointer with an attached reference array is then used to mark out other anatomical landmarks, such as the ankle and knee joint surface. Using this system, any part of the leg can be localized by the navigation system relative to the reference arrays, and the computer can then build a three-dimensional (3-D) model of the knee joint. Accuracy can be checked by placing the pointer on any part of the bone surface, and the computer will display the calculated position in the 3-D model, allowing the surgeon to identify any discrepancy.

Once the model is generated, real-time information on alignment and kinematic data are available to the surgeon. Range of motion and the presence of fixed contractures can be identified, as well as accurate quantification of clinical tests such as anterior drawer and pivot shift [14]. Obtaining these data at the beginning and end of surgery allows the surgeon to assess the effect of a procedure on these parameters.

It should be noted that reference array placement adds to the invasiveness of a procedure and may require additional incisions. Complications related to this array placement, such as fracture and wound complications, have also been reported [15, 16].

Anterior cruciate ligament reconstruction

Anterior cruciate ligament (ACL) injuries are common, with an estimated 250,000 new ACL ruptures in the U.S. each year [17]. ACL reconstruction is one of the most common orthopaedic procedures in North America [18], and multiple studies have demonstrated that correct tunnel placement is a key factor for a successful clinical outcome [19–22]. Considerable variation in tunnel placement has been reported with conventional techniques [23, 24], and up to 80 % of complications are related to malpositioned tunnels [25]. CAS therefore has the potential to improve outcomes by reducing this variability and allowing more accurate tunnel placement.

Tunnel placement

CAS may allow for more accurate tunnel placement by improving the surgeon's ability to choose an "optimal" position. Different authors have proposed various CAS methods to attempt improvement of the accuracy of tunnel placement. Some systems use rules based on anatomical landmarks [6, 26], whereas other systems combine anatomical data with kinematic measurements to create *anatomometric* criteria [27, 28]. Anatomometry is a concept in which the graft isometry profile (variation of length from maximal flexion to extension) is optimized while anatomical factors, including graft impingement, are taken into account [29]. CAS allows the surgeon to intraoperatively assess the effect of "virtual" tunnel placements [30], and after defining the femoral and tibial attachment sides of the graft, the computer creates a virtual ACL between these points. During flexion and extension of the knee, the surgeon can then monitor graft impingement and isometry [31, 32]. Precise mapping of the intercondylar notch allows modification of tunnel position by real-time calculation, in which graft isometry is balanced against the risk of impingement. In theory, this allows the surgeon to increase accuracy by choosing more optimal tunnel positions. However while graft impingement has been associated with poorer clinical outcome [19], the effect of isometry is more controversial. Some authors recommend an isometric area for ACL placement, whereas others feel that graft isometry has little effect on clinical outcome [10, 33, 34]. Plaweski described an isometry *profile*, which, if the graft was seen to loosen in flexion, was thought to be favorable [28].

CAS may also help increase precision and improve intersurgeon variation. Schep [10] tested this hypothesis on three surgeons with various levels of experience performing CAS-assisted ACL reconstruction on 12 cadaveric knees. CAS planning reduced intersurgical variance, and the position of the virtual tunnels in both the tibia and femur was not related to the experience level of the surgeon. Klos [35] reported a consecutive series of ACL reconstructions by a single surgeon and found that graft placement variability was significantly reduced when an fluoroscopic-guided CAS system was used. Sati [36] reported on a CAS technique with six surgeons positioning an ACL in a cadaveric knee and found low variance in the positioning of both tunnels. Similarly, Picard [23] reported on differences between ideal tunnel placement and actual positioning for two experienced ACL surgeons in 20 foam knees and found improved precision with a CAS technique.

Clinical outcomes

Six randomized studies have compared clinical outcomes between CAS and conventional single bundle ACL reconstruction (Table 1). Plaweski randomized 60 patients [28] undergoing isolated ACL reconstruction 1–6 months postinjury to CAS or standard techniques. Tunnel position using the image-free CAS system followed the Julliard technique, aiming for a "favorable" isometry profile (graft loosening in flexion), with tunnels within the anatomical area of ACL insertion and without notch impingement [37]. No difference in IKDC or laxity outcomes was found between groups; however, the authors reported that variability of laxity and tibial tunnel position was reduced (i.e., precision was increased) in the CAS group.

Mauch randomized 53 patients to image-free CAS or conventional ACL reconstruction [38]. Conventional tibial tunnels were positioned 7 mm anterior to the posterior cruciate ligament (PCL) and the femoral tunnel at 1:30 or 10:30, using a clock face. CAS tunnels were positioned using an algorithm based on graft isometry and notch impingement. No differences in clinical outcome were found between groups. In contrast to previous findings, the CAS group had increased accuracy of tibial tunnel placement (closer to an "ideal" position of 44 % of the anteroposterior width of the tibia [39]), but precision (variability of tunnel position) was no different between groups. The authors attributed the high precision in the conventional group to the experienced nature of the surgeons involved.

Chouteau reported on 73 ACL patients randomized to a fluoroscopic-guided CAS system or conventional surgery [12]. CAS patients required 9.3 min extra surgery time. Femoral tunnel placement was according to the triangle method of Benareau [40], with a marker placed in the intended position and intraoperative fluoroscopy used to adjust this to the desired position. Tibial tunnels were positioned in a similar fashion aiming to avoid graft impingement with the intercondylar roof. Femoral tunnel placement was more accurate on postoperative radiographs, with the mean distance between the femoral tunnel and the ideal point of the triangle method being 2.5 mm with CAS and 7 mm with conventional techniques. CAS also allowed a more anterior tibial tunnel placement; however, no difference in clinical outcome scores or KT-1000 laxity tests was found between groups. Hart reported on 80 CAS patients randomized to an image-free CAS system or conventional surgery [41]. The CAS system used a combination of anatomical landmarks and isometry and impingement data to guide tunnel position. On postoperative radiographs, less variation was seen in femoral, but not tibial, tunnel position in the CAS group. Clinical outcome scores and knee laxity tests were similar between groups.

In 2009, Endele [42] published an updated report on tunnel position for 40 patients who were randomized in the previous study of Mauch et al. described above. MRI scans showed no difference in femoral or tibial tunnel positions and no difference in clinical outcomes at 2-year follow-up.

A Cochrane review combined the results of the above five studies and found no statistically or clinically significant differences in quality-of-life outcomes, objective knee function scores, knee stability, tunnel placement, or complications [8]. The report concluded that apart from a consistently increased operating time (from 9.3 to 26 min), a positive effect of CAS ACL reconstruction could neither be demonstrated nor refuted.

More recently, Meuffels published the largest RCT to date on 100 patients who were randomized to ACL reconstruction using a fluoroscopic-guided CAS system or conventional technique [6]. Tibial tunnel placement was aimed at 44 % of the anterior-to-posterior length of the tibial plateau as described by Staubli [43]. The femoral tunnel was positioned using the radiographic quadrant method of Bernard [44]. Postoperative CT scans showed no difference in accuracy or precision of tunnel position between groups. Clinical outcome data were not reported.

Summary

While basic science studies and early case series demonstrated improvement in both accuracy and precision of ACL

Table 1 Randomized controlled trials of CAS versus conventional ACL reconstruction

Author	Year	Country	No of patients		Navigation system	Graft type	Mean follow-up (months)
			Con	CAS			
Plaweski [28]	2006	France	30	30	Image-free (Surgitics)	HS	24
Mauch [38]	2007	Germany	24	29	Image-free (OrthPilot)	BPB	ns
Chouteau [12]	2008	France	36	37	Image Based (ns)	BPB	26
Hart [41]	2008	Czech Republic	40	40	Image-free (OrthPilot)	BPB	28
Endele [42]	2009	Germany	20	20	Image-free (OrthPilot)	BPB	24
Meuffels [6]	2012	Netherlands	51	49	Image Based (Brainlab)	HS	ns

Ns not stated, *Con* conventional, *CAS* computer-assisted surgery, *HS* hamstring, *BPB* bone-patella-bone tunnel placement with CAS techniques, these have not translated into improved clinical or radiological outcomes in randomized controlled trials. It should be noted that these trials involved experienced ACL surgeons, who may have less room for improvement with CAS use. Less experienced orthopaedic surgeons may derive more benefit from CAS technology possibly as a training intervention, but currently this has not been investigated. This is relevant because 80 % of all ACL reconstructions are performed by surgeons performing fewer than 20 ACL reconstructions per year [45]. Finally the controversy over “ideal” tunnel placement is illustrated by the varied positioning methods used in the above studies. The targets and tolerances for optimal graft positioning are still poorly understood; thus, better navigation is of limited use when the destination is unclear. Current surgical practice focuses on placing the bone tunnels within the anatomic insertion sites of the native ACL; thus, defining a universal optimal position may not be possible, and an individualized approach may be more appropriate [6].

Research applications in knee ligament surgery

CAS can provide data on intraoperative knee kinematics and multiplanar motion previously available only in biomechanical laboratories using cadavers. The accuracy of such data has been validated, with Monaco reporting no difference between intraoperative CAS and KT-1000 measurements of anterior tibial translation [14]. CAS measurement of the pivot shift has also been defined [46]. Similarly, Pearle [47] found that CAS can reliably register and collect multiplanar knee kinematic data during knee stability examination. Zaffagnini has used a CAS system to investigate static and dynamic laxity parameters following double-bundle ACL reconstruction [25, 48, 49].

These data could also be used to assess the effect of different surgical techniques on knee stability following other ligament reconstruction, including posterior cruciate ligament [50], medial collateral ligament [51], and posterolateral corner reconstructions [52]. CAS data have also been used to assess the effect of the different ACL bundles on knee kinematics in double-bundle reconstruction, but so far results are inconsistent [25, 53–55]. There is a subjective element to such tests, since it is difficult to standardize the amount of force applied, which may explain some of the variation in results [25].

Osteochondral lesions

Osteochondritis dissecans (OCD) is a variable condition, and surgery is indicated for unstable lesions and for stable lesions that have failed conservative measures. In the surgical treatment of stable OCD lesions, the aim is decompression to allow for revascularization of the defect. Retrograde drilling allows the surgeon to achieve this without violating the cartilage surface. This is typically achieved through intraoperative fluoroscopic guidance, which has the disadvantage of using two-dimensional imaging to guide 3-D positioning of the drill. A number of studies have investigated using MRI- or CT-based CAS systems to improve accuracy of the procedure, predominantly in the talus [56, 57]. Seebauer investigated an MRI-based CAS system in six cadaveric knees and found it was accurate to within 1.9 mm [58]. Muller compared an image-free CAS system for retrograde drilling in artificial knees to a fluoroscopic technique [59]. Interestingly he found a decreased surgical time with CAS use, mainly due to 100 % first-pass accuracy as compared with a mean 2.5 correction maneuvers required in the fluoroscopic group. While it is unclear whether operative times would improve in clinical use, a further advantage was the lack of radiation exposure. Similarly, Hoffman reported on a CAS system using electromagnetic navigation, and in a cadaveric setting, the CAS system showed improved accuracy and less operative time [3].

We are aware of only one report of the clinical use of CAS for retrograde drilling of OCD lesions in the knee. Gras [4] used an image-free CAS system in 8 patients with OCD lesions, 3 of which were in the knee. He reported a 93 % first-pass accuracy but noted a number of drawbacks, including cumbersome equipment and difficult and time-consuming workflows.

In detached OCD or other cartilage defects, grafting may be indicated. Recently two cadaveric studies used an image-free navigation system to guide harvesting and placement angles for osteochondral autograft transplantations (OATs) in the knee [2, 5]. Each transplanted plug must be harvested at a certain angle to match the local radius of articular surface curvature, and CAS has the potential to guide this. In both studies, significantly greater accuracy and precision were seen with the CAS versus the freehand technique. Currently, clinical data on CAS use for OATs are lacking.

High tibial osteotomy

Valgus-producing HTO is an effective procedure in patients with medial compartment osteoarthritis or other medial pathology of the knee, particularly in younger patients [60]. Early techniques focused on a closing wedge osteotomy that maximized initial stability; however, with the advent of modern fixation techniques, opening wedge HTO has gained popularity, particularly since it allows simple adjustments to the degree of correction. Postoperative alignment is crucial to the outcome of the procedure [61], with undercorrection leading to poor clinical outcomes [62•] and progression of medial osteoarthritis [63]. While the influence of overcorrection is more controversial [64], it may lead to early failure secondary to lateral compartment overload [65], patellar subluxation, and medial joint opening [66]. CAS systems that accurately provide limb alignment are well established in knee arthroplasty [67] and are easily adapted to osteotomy procedures. Registration of intraarticular knee landmarks is performed through either the addition of arthroscopy or the substitution of surface skin landmarks [7].

Ideal alignment

Most studies have found that correction to a slight valgus alignment following HTO optimizes clinical outcome [68, 69]. In 1979, Fujisawa reported on arthroscopic analysis of 54 patients following closing wedge HTO, reporting that medial cartilage regeneration occurred when the mechanical axis passed through the lateral 30 %–40 % of the tibial plateau, where 0 % represents its midpoint [70]. This corresponds to 65 %–70 % of the width of the entire plateau and became known as the Fujisawa point. This is similar to the suggestion of Dugsdale and Noyes, who empirically selected a target of 62 % of the plateau width [66] as measured from the medial cortex [71, 72]. Hernigou [61] expressed the ideal alignment in angular terms, aiming for a hip–knee–ankle angle of 183°–186°. Jakob suggested that the ideal postoperative alignment depended on the amount of medial compartment arthrosis, with greater valgus desirable in more severe disease [73].

While the proposed "ideal" postoperative alignments above differ slightly, there is general agreement that correction into slight valgus optimizes clinical outcome of HTO. Conventional techniques can lead to final alignments outside the desired range up to 50 % of the time [74]; therefore, CAS has the potential to increase the accuracy and precision of the surgery. Cadaveric studies support this, with Hankemeier et al. reporting improved accuracy and reduced variability of a fluoroscopy-based CAS system, as compared with the *cable method*, in 20 knees [75]. Similarly, Lutzner et al. found that the mean deviation from the target alignment was 1 % using a CAS system and 9 % using conventional surgery in 19 cadavers [76]. Like conventional techniques, current CAS protocols are not reliable or accurate in monitoring sagittal (i.e., tibial slope) and axial (rotational) alignment of the lower limb [7].

Clinical outcomes

Five retrospective studies comparing outcomes between CAS and conventional HTO (Table 2) have been reported. Currently no prospective or randomized studies exist.

Saragaglia [77] compared 28 CAS opening wedge HTOs with a historical control group of 28 conventional patients matched for age, sex, and degree of arthrosis. The goal of a final mechanical alignment of 184°±2° was achieved in 96 % of the CAS patients, as compared with 71 % in the conventional group ($p<.01$). Clinical outcome data were not reported. Maurer [78] reported on 67 opening wedge HTOs, the first 23 of which were performed using conventional surgery and the next 44 using an imageless CAS system. CAS resulted in higher accuracy of the postoperative mechanical leg axis within the stated objective of 3° to 5° valgus with fewer outliers. Operative time was increased by 10 min. No clinical outcomes were reported.

Kim [79] retrospectively reviewed 1 year follow-up data on 47 CAS and 43 conventional opening wedge HTOs. The two groups were similar in terms of age, BMI, and preoperative alignment and clinical scores. Allograft was used in the CAS group and autograft in the conventional group, and the stated goal was to achieve a weight-bearing line passing though 62 % of the medial tibial plateau. Final alignment films showed this line passing through a mean of 62.3 %± 2.9 % of the tibial plateau in the CAS group versus 58.7 %± 6.6 % in the conventional group. Mean Lysholm (85 vs. 83) and HHS (84 vs. 79) outcome scores were also better in the CAS group. These differences were statistically significant.

Bae [80] reported the only comparative CAS study on closing wedge HTO, prospectively evaluating 50 CAS procedures and comparing the results with an historical control group of 50 conventional HTOs. The surgical goal for both

Table 2 Comparative studies of CAS versus conventional HTO

Author	Year	Country	No of patients		Type of osteotomy	Navigation system	Mean follow-up (months)
			Con	CAS			
Saragaglia [77]	2005	France	28	28	Opening	Orthopilot	ns
Maurer [78]	2006	Germany	23	44	Opening	Orthopilot	ns
Kim [79]	2009	Korea	43	47	Opening	Orthopilot	12
Bae [80]	2009	Korea	50	50	Closing	Vectorvision	ns
Akamatsu [63]	2012	Japan	28	31	Opening	Orthopilot	12

Ns not stated, *Con* conventional, *CAS* computer-assisted surgery groups was a mechanical axis percentage of 62 %. Postoperative radiographs showed that the CAS surgery was more accurate (mean 59 % vs. 47 %, $p<.002$) and more precise (variability 2.3° vs. 3.7°, $p=.012$) than that for the conventional group. Weaknesses of this study include a lack of clinical outcome data and a retrospective control group that differed in some aspects, such as preoperative alignment, and the potential confounding effect of learning curve, with the CAS procedures being performed after the traditional technique cases. Akamatsu et al. [63] compared the results from a sequential series of 28 conventional and then 31 CAS-assisted HTOs. They found that CAS surgery was more accurate in achieving desired alignment and reduced the risk of undercorrection; however, no differences in Lysholm (95 vs. 96) or other functional outcome scores were found between groups. Of note, increased surgical time with navigation in the above studies ranged from 10 to 30 min [9].

Summary

HTO appears to be well suited to CAS since it has a clinically relevant technical goal with known tolerances. Conventional techniques result in significant variability in final alignment [74], and ”outliers” are known to have poorer clinical outcomes [81]. Comparative studies appear to show that CAS increases both accuracy and precision, but there is a lack of prospective data demonstrating that this leads to improved short- or long-term clinical outcomes. Further prospective studies are needed to confirm that the use of CAS is justified, since it increases surgical duration and navigation equipment comes at significant additional cost. Computer navigation may also have a role in aiding more complex osteotomies, such as following femoral malunion [82] or combined femoral and tibial osteotomies for severe genu varum [83].

Conclusion

Randomized trials into the use of CAS in anterior cruciate ligament reconstruction have failed to demonstrate a clinical benefit. Data on CAS use in high tibial osteotomy are more promising; however, clinical outcome data and long-term studies are lacking. CAS has a number of research applications in knee ligament surgery, and studies continue to explore its use in the treatment of osteochondral lesions. Currently, the main disadvantages to CAS surgery are increased operative time, invasive placement required for reference arrays, high cost of equipment, and the learning curve associated with its use. Complications related to reference array placement, such as fracture or wound complications, have also been reported. As technology improves, advances such as noninvasive reference arrays and more user-friendly software are likely to ameliorate many of these problems. CAS techniques remain in their infancy. Further laboratory and clinical studies are needed to determine the role that CAS may play in the future of sports medicine knee surgery.

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