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Computer-Assisted Navigation Systems in Anterior Cruciate Ligament Reconstruction: a Scoping Review

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**Computer-Assisted Navigation System in Anterior Cruciate Ligament
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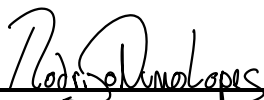
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"Science is not only a disciple of reason but, also, one of romance and passion." - Stephen Hawking

Resumo

Introdução: A integração dos sistemas de navegação assistida por computador (SNAC) na reconstrução do ligamento cruzado anterior (LCA) representa um avanço tecnológico significativo, prometendo maior precisão e resultados clínicos potencialmente melhores. Esta revisão visa sintetizar as evidências atuais sobre a utilização dos SNAC na reconstrução do LCA, identificar lacunas de conhecimento e avaliar o alcance da literatura existente.

Métodos: Foi realizada uma pesquisa nas bases de dados PUBMED e SCOPUS em dezembro de 2023. Os critérios de inclusão foram: reconstruções primárias e de revisão do LCA que utilizem SNAC; estudos que relatem as tecnologias implementadas; estudos que reportem resultados relevantes e publicados em inglês. A triagem de títulos, resumos e artigos na íntegra foi realizada de forma independente por dois autores.

Resultados: De um total de 1024 estudos inicialmente identificados, 54 cumpriram os critérios de inclusão. Destes, 37 eram estudos experimentais, 9 revisões sistemáticas, 4 revisões bibliográficas, 3 notas técnicas e 1 estudo experimental/nota técnica. A tendência de publicação mostrou um aumento significativo entre 2004-2013, com a investigação experimental a ser a mais comum. Entre os estudos experimentais, 22 envolveram sujeitos humanos (1511 pacientes) e 16 utilizaram modelos de joelho ou cadáveres. Um total de 926 pacientes foram submetidos a cirurgia com recurso aos SNAC. O OrthoPilot® (36,2%) e o Praxim Medivision® (35,7%) foram os sistemas mais frequentemente utilizados em estudos com humanos. Foram identificados dezasseis sistemas distintos, categorizados em sistemas passivos (sem imagem e com imagem) e ativos. Os sistemas passivos, especialmente os sem imagem, como o OrthoPilot®, foram predominantes entre 2004-2013. Os sistemas com imagem utilizavam frequentemente tomografia computadorizada (TC) ou fluoroscopia. Os sistemas ativos, embora menos comuns, têm sido utilizados com maior frequência recentemente, com sistemas como o TiRobot® a tornarem-se mais prevalentes. Os resultados quantitativos foram reportados em 28 estudos, enquanto 10 relataram resultados tanto quantitativos como clínicos. A precisão da colocação dos túneis foi o foco principal de 35 estudos, com 83% dos estudos a indicarem uma colocação precisa. Os métodos de avaliação variaram, sendo o raio-X o mais comum (41%), seguido do próprio sistema de navegação (24%), TC (22%), RM (8%) e fluoroscopia (5%). Os resultados clínicos foram avaliados em 10 estudos, com 8 a comparar os SNAC com a cirurgia convencional. Adicionalmente, os estudos exploraram a laxidade, os impactos económicos, as curvas de aprendizagem e a cinemática.

Conclusão: Os sistemas de navegação assistida por computador mostram potencial para melhorar a precisão na reconstrução do LCA. No entanto, são necessários mais ensaios clínicos para validar a sua eficácia e abordar as limitações existentes. A evolução contínua nas tecnologias de navegação

e uma investigação rigorosa são essenciais para otimizar os resultados clínicos na reconstrução do LCA.

Palavras-chave: Ligamento Cruzado Anterior; Reconstrução; Cirurgia Assistida por Computador; Robótica; Simulação por Computador

Abstract

Introduction: The integration of computer-assisted navigation systems (CANS) into anterior cruciate ligament (ACL) reconstruction represents a significant technological advancement, promising enhanced precision and potentially improved clinical outcomes. This scoping review aims to synthesize the current evidence on the use of CANS in ACL reconstruction, identify knowledge gaps and evaluate the scope of existing literature.

Methods: A comprehensive search was conducted in PUBMED and SCOPUS databases in December 2023. Inclusion criteria included primary and revision ACL reconstructions using CANS, reporting technological details, relevant outcomes and published in English. Title, abstract and full-text screenings were performed independently by two authors.

Results: Out of 1024 initially identified studies, 54 met the inclusion criteria. These included 37 experimental studies, 9 systematic reviews, 4 bibliographic reviews, 3 technical notes and 1 experimental/technical note. The publication trend showed a significant increase from 2004-2013, with experimental research being the most common. Among the experimental studies, 22 involved human subjects (1511 patients) and 16 used knee models or cadavers. A total of 926 patients underwent CANS. OrthoPilot® (36.2%) and Praxim Medivision® (35.7%) were the most frequently used systems in human studies. Sixteen distinct systems were identified, categorized into passive (image-free and image-based) and active systems. Passive systems, especially image-free ones like OrthoPilot®, were predominant between 2004-2013. Image-based systems often used computed tomography scan (CT scan) or fluoroscopy. Active systems, although less common, have seen increased usage recently, with systems like TiRobot® becoming more prevalent. Quantitative outcomes were reported in 28 studies, while 10 studies reported both quantitative and clinical outcomes. Tunnel placement accuracy was the primary focus of 35 studies, with 83% of the studies indicating accurate tunnel placement. The methods of evaluation varied, with X-ray being the most common (41%), followed by the navigation system itself (24%), CT (22%), MRI (8%) and fluoroscopy (5%). Clinical outcomes were assessed in 10 studies, with 8 comparing CANS with conventional surgery. Additionally, studies explored laxity, economic impacts, learning curves and kinematics.

Conclusion: Computer-assisted navigation systems show promise in improving precision in ACL reconstruction. However, further clinical trials are necessary to validate their effectiveness and address existing limitations. Continued advancements in navigation technologies and rigorous research are essential for optimizing clinical outcomes in ACL reconstruction.

Key-words: Anterior Cruciate Ligament; Reconstruction; Computer-Assisted Surgery; Robotics; Computer Simulation

Abbreviations List

3D: Three-dimensional
ACL: Anterior Cruciate Ligament
CA: California
CASPAR: Computer Assisted Surgical Planning And Robotics
CANS: Computer-assisted navigation surgery
CO: Colorado
CT: Computed Tomography
IKDC: International Knee Documentation Committee
KT-1000: Knee Tester 1000
MRI: Magnetic Resonance Imaging
NS: Navigation System
USA: United States of America

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Introduction

The Anterior Cruciate Ligament (ACL) plays a pivotal role in knee stability, being responsible for resisting anterior tibial translation and rotational loads, as well as avoiding valgus and varus knee movements and excessive knee extension ⁽¹⁾.

Nowadays, given the rising participation in sports activities within our society, a natural rise in the incidence of ACL injuries has been observed. Injuries connected to the ACL are thought to affect 200,000 people a year in the USA, of which 95,000 suffer ruptures. ⁽²⁾ Most of these are sports-related injuries that result from low-energy rotational movements (non-contact); however, they can also stem from direct trauma. A common body position associated with ACL injuries is characterized by valgus collapse of the knee, which results from the hip being internally rotated, the knee being almost fully extended, the foot being planted and the body descending. Additionally, there are several risk factors to be considered: previous injury, gender, age, anatomic and anthropometric factors and neuromuscular factors⁽³⁾.

Thus, nowadays, ACL reconstruction arthroscopies are common, with an increasing incidence over the last decade^(4, 5). The goal of this surgery is to restore joint stability using grafts, involving the placement of femoral and tibial tunnels to anchor the graft, aiming to replicate the anatomical biomechanical stability of the ACL. Despite the high success rate, there is an increase in the need for surgery revisions, which are not only costly, but can also lead to worse clinical outcomes compared to the initial surgery^(6, 7). Revisions arise for two main reasons: ruptures due to new traumatic injuries and non-anatomical tunnel placement⁽⁸⁾. This way, one of the most critical factors for the success of the reconstruction and long-term stability is the anatomical positioning of the tunnels, as incorrect placement can lead to roof erosion, poor isometry, or even loss of knee movement after surgery^(9, 10). However, positioning the bone tunnel correctly and reproducibly is a technical challenge when using only an arthroscopic view in ACL reconstruction. Previous studies demonstrated significant variability in tunnel placement, even when performed by experienced surgeons, resulting in up to 10-40% of tunnels being incorrectly placed⁽¹¹⁻¹⁴⁾. Therefore, the accuracy of the tunnel placement is an area where further improvement is possible and could potentially translate into better outcomes.

Currently different methods are available to determine the placement of the bone tunnel in the ACL reconstruction. Some of these use anatomic landmarks, such as identifying the lateral intercondylar ridge and the center of the ACL footprint; others may use image-based techniques, taking advantage of preoperative images, such as MRIs or x-rays, to plan the placement of bone tunnels in a more personalized and patient-specific manner⁽¹⁵⁾.

Computer-assisted navigation surgery (CANS) is one of the methods that have been explored to address this issue. It refers to the utilization of CANS to assist orthopedic surgeons in planning and executing procedures with enhanced precision and it is aimed at improving surgical accuracy, increasing reproducibility and improving patient outcomes by offering three-dimensional (3D) real-time guidance during surgery. With image-based or non-image-based equipment, the knee joint, including the femoral and tibial landmarks, may be mapped in three dimensions. Preoperative imaging, such as computed tomography (CT) or magnetic resonance imaging (MRI) is used by image-based systems to direct the surgeon throughout the procedure. Conversely, non-image-based systems frequently rely on intraoperative data collected using devices that include infrared probe⁽¹⁶⁾.

CANS helps identify particular anatomical reference points in the tibia and femur during surgery. Infrared cameras and other signal-emitting devices record the movement and location of these spots. After processing this data, the computer generates a comprehensive, three-dimensional model of the knee joint. This technology has been previously employed in other areas of orthopedic surgery, such as spinal surgery, knee and hip replacement surgery and traumatic surgery⁽¹⁷⁻²⁰⁾.

The aim of this scoping review is to summarize and give a better understanding of the current state of CANS in the ACL reconstruction, synthesizing types of evidence, identifying knowledge gaps, mapping key concepts and accessing the scope of the literature.

Methodology

Search strategy and study eligibility

The electronics database PUBMED and SCOPUS were searched in December 2023 for literature addressing the use of CANS in ACL reconstruction. The following terms were searched: “anterior cruciate ligament”, “reconstruction”, “computer-assisted surgery”, “robotics” and “artificial intelligence”.

The inclusion criteria for this scoping review were (1) primary ACL reconstruction or revision ACL reconstruction, (2) use of CANS, (3) report of the technology used, (4) studies that published outcomes of interest and (5) studies published in the English language. This scoping review's exclusion criteria were: (1) studies that focus on ACL repair, (2) studies with no use of CANS, (3) studies where the use of computer assisted navigation systems does not assist tunnel placement in ACL reconstruction, (4) navigated laxity studies, (5) biomechanical studies, (6) books.

Study screening

The titles of the papers that were extracted after the literature search were independently screened by two authors. At this point, included studies were subjected to abstract screening based on the inclusion and exclusion criteria. Finally, a full text screening was done. Disagreements in any of the stages were resolved by consensus between the two authors. If no agreement was reached, a senior author was consulted to resolve discrepancies.

Data extraction

Using Google Sheets (Google LLC, Mountain View, CA, USA), two reviewers separately extracted pertinent data from the included articles. The abstracted data comprised, but were not restricted to: authors; year of publication; country of origin; type of study; objective of the study; technology used; total number of patients; number of patients that did CANS surgery; clinical outcomes; quantitative outcomes; study limitations.

Results

Literature search

Out of the 1024 studies initially identified through the literature search, 233 duplicate studies were removed. Subsequently, 791 studies underwent title screening, with 592 deemed out of scope. A combined title and abstract screening of the remaining 199 papers led to the removal of 117 of them. After a full-text screening for ultimate eligibility, 28 of the 82 studies that remained were excluded [Fig. 1]. Following full-text screening, 54 studies were included in all. Of these investigations, there were 37 experimental studies, 9 systematic reviews, 4 bibliographic reviews, 3 technical notes and 1 combination of an experimental study and a technical note. The experimental research will be the main focus of our review.

Trend of publication and type of study

Among the studies included, four⁽²¹⁻²⁴⁾ were published between 1994 and 2003, while thirty-one^(13, 25-54) were published between 2004 and 2013, representing a remarkable increase of 775% over a decade. Subsequently, in the following ten-year period from 2013 to 2022, nineteen studies⁽⁵⁵⁻⁷³⁾ were conducted.

During the initial period analyzed, all four studies were experimental⁽²¹⁻²⁴⁾. From 2004 to 2013, the majority of published studies, twenty-two (71%), were experimental^(13, 26-31, 33, 34, 36, 41-43, 45-50, 52-54), followed by five (16%) systematic reviews^(38-40, 44, 51), three (10%) technical notes^(25, 32, 35) and one (3%) bibliographic review⁽³⁷⁾ [Fig. 2].

Moving forward to the most recent period, between 2014 and 2023, eleven (58%) of the studies were experimental^(59-63, 65, 67-70, 73), representing a 50% decrease compared to the previous time frame. Additionally, there were four (21%) systematic reviews^(55, 57, 64, 72), three (16%) bibliographic reviews^(56, 58, 71) and one (5%) technical note/experimental study⁽⁶⁶⁾.

In the realm of experimental inquiry, a total of 22 studies^(13, 21, 26-31, 33, 34, 36, 43, 45-47, 52, 54, 59-61, 70, 73) involving patients and 16 studies^(21-24, 41, 42, 48-50, 53, 62, 63, 65, 67-69) utilizing knee models or cadavers were identified [Fig. 3]. Amongst the studies involving patients, analysis was directed towards 1511 subjects, of which 926 underwent CANS. Furthermore, the other 16^(21-24, 41, 42, 48-50, 53, 62, 63, 65, 67-69) studies involved the utilization of over 250 knee models/cadavers. Remarkably, while only one study⁽²¹⁾ involving human subjects was documented between 1994 and 2003, the subsequent time frame witnessed a substantial surge, with human-based studies constituting 73% of the publications^(13, 26-31, 33, 34, 36, 43, 45-47, 52, 54), denoting a remarkable increase exceeding 1600% in the volume of published works. However, between 2014 and 2023, 55% of the published literature pertained to investigations^(62, 63, 65, 67-69) conducted employing knee models/cadavers.

Finally, only 7 out of the 16 identified navigation systems were tested on human subjects. Among them, OrthoPilot[®](^{27, 28, 30, 33, 34, 36, 45, 52, 70}) and Praxim Medivision[®](^{29, 47, 60, 61}) were the most commonly used systems, with 335 (36.2% of the patients who underwent CANS) and 331 patients (35.7% of the patients who underwent CANS), respectively. Additionally, StealthStation[®](^{26, 43, 54, 59}) was used in 119 patients, Vector Vision ACL[®](^{13, 46}) in 86 patients, the Centre Hospitalier Lyon Sud⁽³¹⁾ NS in 37 patients, the Faculté de Médecine de Grenoble NS⁽²¹⁾ in 12 patients and the TiRobot[®](⁷³) in 6 patients.

Types of navigation systems

In the collated experimental studies and technical notes, a total of 16 distinct navigation systems were identified. These navigation systems fall into two broad categories: passive systems, which assist the surgeon in determining tunnel placement and active systems, where a robot conducts the drilling process [Fig. 4].

Furthermore, passive systems can be subdivided in image-free, where bone morphing technology is used, and image-based, where either x-ray, CT scan, MRI or fluoroscopy images are used preoperatively/intraoperatively. Among these systems, 9 were passive image-based navigation systems, 3 were passive image-free navigation systems and 4 were active robots. Of the 40 studies reviewed, 19 referenced the use of passive image-free systems, 15 involved passive image-based systems and 6 utilized active systems.

In respect to the image-free navigation systems, only 3 systems were described and all of them use bone morphing technology to create the knee anatomy reconstruction. Out of the 19 studies that describe this type of technique, 79% of them were used between 2004 and 2013^(25, 27-30, 32-34, 36, 41, 45, 47, 48, 52, 53) and 16% after this period^(60, 61, 70). Orthopilot[®] (B.Braun-Aesculap, Tuttlingen, Germany) (^{27, 28, 30, 33, 34, 36, 45, 48, 52, 70}) was the most frequently cited, appearing in 53% of the publications (10 studies), followed by the Praxim Medivision[®] (Praxim Medivision, La Tronche, France)^(25, 29, 32, 41, 47, 53, 60, 61) used in 42% (8 studies) and by the Faculté de Medecine de Grenoble NS⁽²¹⁾, mentioned only once.

Passive image-based systems were described in 15 studies^(13, 23, 26, 31, 35, 42, 43, 46, 50, 54, 59, 62, 63, 66-68). Notably, 2/3 of the described NS utilize intraoperative bone registration to enhance accuracy^(13, 23, 42, 46, 50, 62, 63, 67, 68). An equal proportion of systems^(13, 23, 26, 42, 43, 46, 50, 54, 59, 62, 63, 67) may use CT scan as preoperative imaging. In addition, solely one study, from the University of Coimbra⁽⁶⁸⁾, employed MRI exclusively for preoperative imaging and only 2 studies referred the use of only fluoroscopy images through all reconstruction^(31, 66). The majority of the studies, 53% (8 studies)^(13, 26, 31, 42, 43, 46, 50, 54) were published between 2004-2013, with 40%^(59, 62, 63, 66-68) being published on subsequent years, between 2014-2023. The most frequently cited technologies were StealthStation[®] (Medtronic

Surgical Navigation Technologies, Louisville, CO), featured in 4 studies^(26, 43, 54, 59) and Vector Vision ACL® (BrainLAB, Feldkirchen, Germany), featured in 4 studies^(13, 42, 46, 67), both of which can utilize multiple sorts of preoperative imaging, such as CT, fluoroscopy and MRI, collectively representing 53% of passive image-based technology studies (8 studies). In the most recent period analyzed, the scope of studies has diversified, with each of the six studies focusing on distinct NS. For instance, the KneeNav ACL® (CASurgica, Inc., Pittsburgh, PA)⁽²³⁾ system utilizes both CT and fluoroscopy preoperatively. Studies from Hallym University Medical Center⁽⁶²⁾, Soonchunhyang University School of Medicine⁽⁶³⁾ and the University of Pittsburgh⁽⁵⁰⁾ predominantly rely on CT scans for preoperative imaging, supplemented by bone registration during surgery. Additionally, the University of Pittsburgh⁽⁵⁰⁾ incorporates intraoperative fluoroscopic overlay. Furthermore, the systems developed by Beihang University⁽⁶⁶⁾ and Centre Hospitalier Lyon Sud⁽³¹⁾ reported the use of fluoroscopy for preoperative imaging; notably, the latter also employs fluoroscopy intraoperatively. Active systems require preoperative imaging for operation, for instance, the CASPAR® (MAQUET GmbH Co. KG, Rastatt, Germany)^(22, 24) uses preop CT scan, while the TiRobot® (Beijing Tianzhihang Medical Technology Co.LTD, China)^(69, 73) employs preop CT scan along with intraoperative fluoroscopy. The Kyung Hee University NS⁽⁴⁹⁾ uses preoperative CT scan and bone registration, while the University of Ulsan College of Medicine NS⁽⁶⁵⁾ uses MRI and bone registration preoperatively. Moreover, between 1994 and 2003, only 2 studies^(22, 24) were conducted using active systems, more specifically using CASPAR®, however an increase in 50% of publications was noted in the last time frame analyzed, between 2014-2023, with the introduction of TiRobot®^(69, 73) and Ulsan College of Medicine NS⁽⁶⁵⁾. Both CASPAR®^(22, 24) and TiRobot®^(69, 73) were the most cited navigation system, with 2 studies each.

Regarding technical notes, two from 2004 and 2008 presented the Praxim Medivision® NS^(25, 32). This navigation system was mentioned in eight instances, seven of which occurred after 2008. Additionally, a technical note on the Stealth Station® navigation system⁽³⁵⁾ was published in 2008, with 75% (3 studies) of related studies appearing after this publication.

Objective of the studies

A total of 37 experimental studies^(13, 21-24, 26-31, 33, 34, 36, 41-43, 45-50, 52-54, 59-63, 65, 67-70, 73) and one technical note/experimental study⁽⁶⁶⁾ were conducted with various objectives; however, the evaluation of tunnel placement and accuracy was a common focus in 35 of the studies^(13, 21-24, 26-31, 33, 34, 36, 41-43, 45-47, 49, 50, 53, 54, 59, 61-63, 65, 67-70, 73). Among these, 43% (15 studies)^(13, 22, 23, 28, 29, 31, 33, 34, 36, 45-47, 62, 70, 73) compared the positioning with a control group undergoing conventional surgery. Additionally, 20% (7 studies) specifically analyzed either the femoral tunnel (5 studies)^(53, 54, 59, 63, 67) or the tibial tunnel (2 studies)^(26, 30) in comparison to a control group. Furthermore, 37% (13 studies)^{(21, 24, 27, 41-43, 49, 50, 61,}

^{65, 66, 68, 69}) examined the positioning in the computer-assisted surgery group without a control group, most of the cases comparing to the anatomic position of the ACL.

In addition, 10 studies^(29, 31, 33, 36, 47, 54, 60, 61, 70, 73) included clinical evaluation as part of their objectives. Of these, 80% (8 studies)^(29, 31, 33, 36, 47, 60, 70, 73) compared the clinical outcomes of the computer NS with those of a control group. One study solely evaluated the clinical outcomes of CANS⁽⁶¹⁾, while another compared CANS with conventional surgery, focusing only on femoral tunnel placement⁽⁵⁴⁾. Other objectives included: presenting new surgical technologies (13 studies), from which 9 were experimental studies^(21, 43, 49, 59, 62, 63, 65, 68, 73), 3 technical notes^(25, 32, 35) and 1 experimental study/technical note⁽⁶⁶⁾; evaluating the economic impact of CANS (3 studies)^(47, 60, 73); assessing the learning curve for novice surgeons (2 studies)^(47, 60); comparing outcomes of experienced surgeons without CANS to novice surgeons with CANS (2 studies)^(30, 48); studying gender differences in single-bundle and double-bundle surgeries using CANS (1 study)⁽⁵²⁾; and evaluating kinematics with the navigation system (1 study)⁽³⁴⁾.

Outcomes Analyzed

Of the 37 experimental studies^(13, 21-24, 26-31, 33, 34, 36, 41-43, 45-50, 52-54, 59-63, 65, 67-70, 73) and 1 technical note/experimental study examined⁽⁶⁶⁾, 28 studies (74%) reported only quantitative outcomes^(13, 21-24, 26-28, 30, 34, 41-43, 45, 46, 48-50, 52, 53, 59, 62, 63, 65-69), while 10 studies (26%) reported both quantitative and clinical outcomes^(29, 31, 33, 36, 47, 54, 60, 61, 70, 73) [Fig. 5].

Regarding quantitative outcomes, tunnel positioning and accuracy were the most frequently evaluated outcomes, with 97% of the studies reporting it^(13, 21-24, 26-31, 33, 34, 36, 41-43, 45-50, 52-54, 59, 61-63, 65-70, 73). Multiple methods were used for evaluation, with X-ray being the most common (41%)^(13, 23, 26, 28-30, 33, 34, 41, 42, 45, 47, 61, 66, 70), followed by the NS itself (24%)^(21, 22, 24, 27, 34, 49, 52, 53, 68), CT-scan (22%)^(43, 46, 54, 59, 62, 65, 69, 73), MRI (8%)^(26, 36, 48), fluoroscopy overlay (3%)⁽⁵⁰⁾ and digital caliper (3%)⁽⁶⁷⁾ [Fig. 6]

Other reported outcomes included knee laxity (5 studies)^(31, 33, 52, 54, 61) measured by the Knee Tester-1000 (KT-100) arthrometer, economic impact (3 studies)^(47, 60, 73), radiographic laxity (2 studies)^(29, 47), operation time (2 studies)^(47, 73), learning curve considering operation time (2 studies)^(47, 60), complication rate (2 studies)^(47, 60) and knee kinematics (1 study) evaluated by the NS⁽³⁴⁾.

Regarding clinical outcomes, only 26% of the experimental studies reported them^(29, 31, 33, 36, 47, 54, 60, 61, 70, 73). The IKDC score was evaluated in every study (10 studies)^(29, 31, 33, 36, 47, 54, 60, 61, 70, 73), consistently appearing across all studies that included clinical outcomes. Following the IKDC score, the Lysholm Score was assessed in 6 studies^(13, 33, 36, 52, 54, 70), the Lachman test in 4 studies^(34, 54, 73), the Tegner Activity Score in 3 studies^(36, 52, 70) and the Pivot Shift in 1 study⁽⁵²⁾.

In timeline, the precision and accuracy of tunnel positioning were consistently evaluated, despite measurement methods changing over time. During the first decade, 75% of tunnel positions were

determined using the navigation system itself (3 studies)^(21, 22, 24). However, between 2004 and 2013, the majority of measurements were obtained using X-rays in 52% of the studies (12 studies)^(13, 26, 28-30, 33, 34, 41, 42, 45, 47, 61), while the use of CT scans^(43, 46, 54) and MRIs^(26, 36, 48) increased to 13% each (3 studies each) and the use of navigation systems decreased to 17%^(27, 34, 49, 52), down from 75% previously. Furthermore, in the most recent time frame analyzed, between 2014 and 2023, there has been a significant increase in the use of CT scans (50%)^(59, 62, 65, 69, 73), as well as the adoption of a new technology, the digital caliper, mentioned in 1 study⁽⁶⁷⁾, while the use of X-ray, navigation systems and MRI has decreased dramatically.

Other quantitative outcomes included a 50% increase in economic outcome evaluation between the second and last time frames studied^(60, 73), as well as a 75% decrease in knee laxity evaluation by the KT-1000 arthrometer, in the same period⁽⁶¹⁾. Furthermore, radiographic laxity (2 studies)^(29, 47) and knee kinematics (1 study)⁽³⁴⁾ assessed by the NS were only present in the second time frame examined. Additionally, operation time, complication rate and the learning curve were outcomes analyzed in only 2 studies each^(47, 60, 73), with each outcome being evaluated only once within each analyzed period.

No clinical outcomes were analyzed during the first decade. Following that, there was a significant increase, particularly between 2004 and 2013, with 27% (6 studies)^(29, 31, 33, 36, 47, 54) including clinical outcomes, with all of them reported using the IKDC score. Furthermore, over the next decade, there was a percentual increase, with 36% of studies (4 studies)^(60, 61, 70, 73) reporting clinical outcomes, all of which used the IKDC score as an outcome measure. Other clinical outcomes saw a decrease in usage, apart from the Tegner Activity Score, which remained consistent (9%)⁽⁷⁰⁾.

Outcomes reported

Regarding the outcomes documented in the analyzed studies concerning tunnel positioning and accuracy, 83% of the experimental studies reported positive results^(13, 21, 23, 24, 26, 27, 29, 31, 33, 34, 41-43, 45, 49, 50, 53, 54, 59, 61-63, 65-70, 73), meaning precise and accurate tunnel positioning, compared to an anatomical position or control groups. Among the systems investigated, the StealthStation® (with 4 positive outcomes)^(26, 43, 54, 59) and the TiRobot® (with 2 positive outcomes)^(69, 73) were the sole systems to report 100% positive outcomes. Following closely, Praxim Medivision® demonstrated an 80% success rate (with 4 positive outcomes out of 5)^(29, 41, 53, 61), VectorVision ACL® exhibited a 75% success rate (with 3 positive outcomes out of 4)^(13, 42, 67), OrthoPilot® showed a 63% success rate (with 5 positive outcomes out of 8)^(27, 33, 34, 45, 70) and CASPAR® recorded a 50% success rate (with 1 positive outcome out of 2)⁽²⁴⁾. All other navigation systems reported solely positive outcomes concerning tunnel positioning, even those supported by only one study^(21, 23, 31, 49, 50, 62, 63, 65, 66, 68). Moreover, two studies evaluated the comparison between the tunnel positioning among

experienced surgeons without CANS and novice surgeons with CANS^(30, 48), both with OrthoPilot® and 1 reported neutral results⁽³⁰⁾, this means both groups having no significant difference, and 1 study reported better results in the experience surgeon group without the use of CANS⁽⁴⁸⁾.

In regard to other quantitative outcomes, particularly economical outcomes encompassing costs, complication rates and operation times, two-thirds of the studies documented negative outcomes^(47, 60), meaning that CANS is more expensive. Specifically, two studies employing Praxim Medivision® noted that surgeries utilizing CANS were less cost-efficient, required more time and had similar complication rates. However, the most recent study focusing on the economical aspect, utilizing the TiRobot^{®(73)}, reported a positive outcome, indicating shorter surgery durations, reduced necessity for medical imaging and subsequently lower costs.

With respect to knee laxity, 60% of the studies examining laxity outcomes reported positive results, indicating reduced laxity. Praxim Medivision® (in 1 study)⁽⁶¹⁾, StealthStation® (in 1 study)⁽⁵⁴⁾ and the Centre Hospitalier Lyon Sud NS (in 1 study)⁽³¹⁾ all yielded positive results, while OrthoPilot® (in 2 studies)^(33, 52) exhibited neutral results compared to conventional surgery. Furthermore, two studies investigated radiographic laxity^(29, 47), both utilizing the Praxim Medivision®, with only one reporting positive results⁽²⁹⁾.

Concerning learning curve outcomes, two studies^(47, 60), both employing the Praxim Medivision®, reported positive results, suggesting that novice surgeons could comprehend and enhance their tunnel placement proficiency faster with the assistance of navigation systems.

Additionally, one study⁽⁵²⁾ compared gender differences following CANS with single- and double-bundle ACL reconstruction, concluding that female patients undergoing computer-navigated double-bundle ACL reconstruction exhibited significantly poorer outcome scores than males undergoing the same procedure. Furthermore, one study approached the use of the navigation system for the study of kinematics⁽³⁴⁾ with OrthoPilot® and had positive conclusions regarding its use as a measuring tool of knee kinematics.

Regarding clinical outcomes, which were less frequently reported (in 26% of the experimental studies^(29, 31, 33, 36, 47, 54, 60, 61, 70, 73), OrthoPilot® and Praxim Medivision® were the only navigation systems with more than two studies reporting these results. Although Praxim Medivision® demonstrated superior clinical outcomes compared to conventional surgery clinical outcomes at 50% (with 2 positive outcomes out of 4) (29, 61) and OrthoPilot® exhibited comparable results to the conventional surgery (with no superior outcome out of 3); neither system reported negative outcomes compared to conventional surgery. Furthermore, StealthStation^{®(54)} reported one positive clinical outcome, while TiRobot^{®(73)} and Centre Hospitalier Lyon Sud NS⁽³¹⁾ reported a neutral clinical outcome.

Studies limitations

Among the 54 studies analyzed, only 23 (43%)^(22, 28, 29, 31, 36, 37, 39, 41, 43-45, 47, 49, 50, 54, 55, 60, 62, 65, 67, 69, 70, 73) reported study limitations. The most cited limitations were the need for a larger population size^(36, 39, 43, 44, 50, 54, 55, 65, 69, 73) and a longer follow-up period^(29, 31, 39, 44, 47, 54, 55, 60, 70, 73), each mentioned in 10 studies. Additionally, the necessity for clinical trials, as opposed to cadaveric or model studies, was highlighted in 5 articles^(36, 49, 50, 67, 69). A better biomechanical evaluation of the effect of drilling the tunnel on knee kinematics was noted in 4 studies^(22, 37, 41, 44). Other limitations included a lack of randomization (3 studies)^(39, 55, 60), the need for improved imaging evaluation of tunnel placement (2 studies)^(28, 50), the requirement for multiple surgeons (2 studies)^(45, 62), the absence of blind trials (1 study)⁽⁵⁵⁾, the lack of guidelines for robot-assisted surgery (1 study)⁽⁷³⁾, the need for evaluation of clinical outcomes (1 study)⁽⁴³⁾ and the necessity for comparison of clinical outcomes before and after surgery (1 study)⁽³⁶⁾.

Discussion

For a comprehensive understanding of the state of research on computer navigation systems in ACL reconstruction, the variety of studies included provides valuable insights. This broad diversity is essential for capturing all perspectives. The emphasis on experimental studies, which made up the bulk of the studies included, is important, since this type of studies offer comprehensive and tangible proof of the usefulness and effectiveness of computer navigation systems, which forms the basis for comprehending their clinical use and significance.

When looking at publishing trends, it is evident that research activity has increased over time. This is especially the case between 2004 and 2013, when there was a notable 775% rise in published papers^(13, 25-54) compared to the preceding ten years⁽²¹⁻²⁴⁾. This can be ascribed to several things, including the development of fundamental research that encouraged additional study, increased clinical interest in computer-assisted surgery and technological developments.

Despite the overall high volume of publications, a notable 50% decline in experimental research^(59-63, 65, 67-70, 73) was observed in the following decade, from 2014 to 2023. This may happen due to various reasons such as shifts in funding priorities, challenges in clinical adoption and maturation of the research field, with most of the initial questions being addressed in previous studies, leading to a shift towards more systematic-reviews and meta-analysis, which was also documented in our study, rather than primary experimental studies. This change is consistent with studies by Knight (2021), which found that developing surgical research domains had a similar trend of growing the number of meta-analyses and highlights the importance of this type of evidence⁽⁷⁴⁾.

Interestingly, the notorious rise in human studies, particularly from 2004 onwards, marks an important shift towards clinical applicability of CANS and patient-centered studies. This significant increase in human-based studies, which surpasses 1600% publications^(13, 26-31, 33, 34, 36, 43, 45-47, 52, 54) between 1994-2003 and 2004-2013, demonstrates a transition from theoretical and model-based research to practical investigations, reflecting the maturing of CANS technology and their integration into the surgical practice, validating this systems in real-world clinical settings, corroborating findings from Zaffagnini et al. (2016), who also noted increased human subject research as technologies matured⁽⁶⁴⁾.

Our review identified 16 different navigation systems, which reflects the broad diversity and specialization within the field of computer navigation systems for ACL reconstruction, indicating a dynamic and continually evolving field of technological innovations.

Significant developments in the field can be observed in the evident technological evolution from image-free technologies to image-based and active robotic systems. During the second decade under analysis, image-free navigation systems—which depend on bone morphing technology—saw a sharp rise in use (2004-2013)^(25, 27-30, 32-34, 36, 41, 45, 47, 48, 52, 53). However, a notable decline was noted

in the most recent period examined, most likely as a result of limitations by the accuracy of the morphing technologies. On the other hand, preoperative imaging methods including CT, MRI and fluoroscopy that are based on image-based technologies have shown a percentage rise in research between 2014 and 2023^(59, 62, 63, 66-68), which may have happened because these systems might provide enhanced precision through detailed anatomical imaging, despite higher radiation exposure in most cases. There has also been a rise in the use of active systems, which need preoperative imaging in order to operate. One of the first active systems, CASPAR[®]^(22, 24), uses preoperative CT scans; more recent systems, like as TiRobot[®]^(69, 73), combine intraoperative fluoroscopy and CT scans for increased precision. As indicated by the results of Dargel et al. (2007) about the biomechanical benefits of precise tunnel positioning, there is an increasing tendency towards automation in surgical procedures, with the goal of reducing human error and improving consistency in tunnel placement. This trend is reflected in the growing interest in robotic systems⁽⁷⁵⁾.

Ultimately, the prevalence of particular systems, such OrthoPilot[®] and Praxim Medivision[®], can be attributed to commercial influences, the systems accessibility across research institutions, their perceived efficacy and possibly their earlier market introduction. The established role of these systems in the area is emphasized by their frequent citation and usage in studies^(21, 25, 27-30, 32-34, 36, 41, 45, 47, 48, 52, 53, 60, 61, 70).

Among the literature reviewed, the studies consistently focused on evaluating tunnel placement and accuracy, which were assessed using a variety of methodologies, including X-ray, CT scan and others. This focus on tunnel placement is crucial as it is a critical step to the success of ACL reconstruction and highlights the importance of navigation systems in enhancing surgical precision and accuracy. Comparatively, prior reviews, such as those by van Grinsven et al. (2010), also emphasized tunnel placement accuracy as a critical measure of success in ACL reconstructions⁽⁷⁶⁾.

Considering clinical evaluation, even though less commonly reported, is fundamental to assess the real-world effectiveness on patient recovery and long-term function, beyond technical use. The low number of studies including clinical outcomes suggests that further investigation is needed. A study by Nasca et al (2022) also draws attention to this gap in clinical outcome research and advocates for more rigorous clinical trials to gain a better understanding of long-term patient outcomes⁽⁷⁷⁾.

Furthermore, the economic impact assessment appeared as an important objective in recent studies^(60, 73), highlighting its growing importance in the evaluation of novel surgical technologies. In the analyzed studies, three assessed the cost-effectiveness of CANS, including factors such as surgery duration, need for medical imaging and overall treatment expenses. Understanding the economic impact is crucial to determine the possibility of widespread adoption of CANS in clinical

practice, to understand financial implications for healthcare systems and to aid decision-making processes regarding resource allocation and funding in advanced technologies.

The studies also explored other objectives, such as learning curves, gender differences, among others. This wide variety of objectives underscores the need for a holistic approach when evaluating new technologies, since it considers not only their technical performance, but also its economic viability and impact on clinical practice.

As mentioned earlier, tunnel positioning and accuracy were the most evaluated outcomes, with 97% of the studies reporting them^(13, 21-24, 26-31, 33, 34, 36, 41-43, 45-50, 52-54, 59, 61-63, 65-70, 73). The methodology to evaluate this outcome evolved through out the years, which can be seen by the wide variety of technologies used. In the first decade, 75% of the studies^(21, 22, 24) relied on the navigation systems themselves, suggesting an initial phase of validating the primary capabilities of the systems. On the following decade, a shift occurred, with the prevalence of X-ray with 52% of the studies^(13, 26, 28-30, 33, 34, 41, 42, 45, 47, 61) mentioning it. The use of CT and MRI also increased to 13% each^(26, 36, 43, 46, 48, 54), indicating a diversification in imaging techniques to enhance accuracy. On the final decade analyzed, the use of CT increased to almost 50%^(59, 62, 65, 69, 73), reflecting their precision and reliability on evaluating the tunnel position, as well as new measurement tool emerged, such as the digital calipers and X-ray, MRI and navigation systems usage decreased, showcasing the ongoing evolution and adoption of more advanced technologies.

Concerning other quantitative outcomes, economic impact assessment emerged, specifically in the last decade analyzed, representing an increase of 50%^(60, 73), highlighting a growing awareness of the cost-effectiveness of CANS. The knee laxity, which was evaluated in five studies with the use of KT-1000 arthrometer, saw a decrease of 75% from the second to third time frame studies⁽⁶¹⁾, indicating a shift away from this traditional evaluation method, which wasn't probably a good indicator of the surgery performance.

With reference to clinical outcomes, IKDC score was the most consistently used clinical metric, probably due to its standardization, reliability, comprehensive assessment capabilities, global acceptance, relevance to ACL reconstruction and ease of use, making it an ideal tool for evaluating the success of knee surgeries. Even though there were no reports on clinical outcomes during the first decade analyzed, on the second one there was a significant increase (6 studies including clinical analysis)^(29, 31, 33, 36, 47, 54), which marks a growing recognition of the importance of evaluating real-world benefits of CANS usage. On the last decade, the proportion of studies reporting clinical outcomes increased to 36% (4 studies)^(60, 61, 70, 73), with decrease in usage in other outcomes apart from IKDC score and Tegner Activity score, probably due to its specific focus on assessing the patient's return to sports and physical activity, which is a critical aspect of the functional success of ACL reconstruction.

The outcomes related to tunnel positioning were predominantly positive, with 83% of the studies reporting precise and accurate tunnel placement^(13, 21, 23, 24, 26, 27, 29, 31, 33, 34, 41-43, 45, 49, 50, 53, 54, 59, 61-63, 65-70, 73), compared to control groups or the anatomical position. This high rate of success emphasizes the efficacy of CANS in achieving the critical task of accurate tunnel placement, which is the most important factor for success in ACL reconstruction. Notably, the StealthStation® and TiRobot® systems reported 100% positive outcomes^(26, 43, 54, 59, 69, 73), suggesting their robust performance and reliability in clinical settings. Comparatively, other systems like Praxim Medivision®^(29, 41, 53, 61) and Vector Vision ACL®^(13, 42, 67) also showed high success rates, with 80% and 75%, respectively, reinforcing the overall positive trend observed with CANS. However, other systems such as the Orthopilot®^(27, 33, 34, 45, 70) and CASPAR®⁽²⁴⁾ showed lower success rates, which may suggest that systems performance varies. This might be due to differences in technological sophistication and functionality, user interface and surgeon familiarity with the system.

On one hand, the positive results regarding the learning curve, as reported in studies using the Praxim Medivision®^(33, 52), indicate that CANS can facilitate faster proficiency in tunnel placement for novice surgeons. This aligns with the findings of Smith et al. (2010), who noted that navigation systems could significantly reduce the learning curve for complex surgical procedures⁽⁷⁸⁾. On the other hand, the negative results from the comparison between experienced surgeons without CANS versus novice surgeons with CANS, might demonstrate the importance of experience which can impact ACL reconstructions, leading to similar results independently of the use of CANS.

Concerning to economic outcomes, 2/3^(47, 60) reported negative results, indicating increased operation times, imaging, complication rates and overall costs, as documented in studies with Praxim Medivision®. These findings are in line with previous studies⁽⁷⁹⁾, which underscored the higher initial costs and longer operation times associated with adopting new surgical technologies. Nevertheless, the most recent study with TiRobot®⁽⁷³⁾ reported overall reduced costs, including shorter surgeries and reduced imaging requirements, suggesting that advancements in CANS technology could mitigate some of these economic drawbacks over time.

Knee laxity outcomes were positive in 60% of the studies^(31, 54, 61), indicating that CANS can effectively reduce knee laxity post-surgery. Even though systems like Praxim Medivision®⁽⁶¹⁾, StealthStation®⁽⁵⁴⁾ and Centre Hospitalier Lyon Sud navigation system⁽³¹⁾ yielded positive results, the neutral results from OrthoPilot®^(33, 52) suggest that while CANS can improve outcomes, the extent of its benefits may vary depending on the system and its implementation.

The reported gender differences, with female patients showing poorer outcomes than males in double-bundle ACL reconstruction using CANS, warrant further investigation. These findings, however, are consistent with the study by Devana et al (2022), which highlighted potential gender-based differences in ACL reconstruction outcomes⁽⁸⁰⁾.

Among the systems with more than two studies reporting clinical outcomes, Praxim Medivision® had half of the studies with positive outcomes^(29, 61), while OrthoPilot® did not outperformed the conventional technique. This suggests that while Praxim Medivision® can achieve better clinical performance, there is still room for improvement. Nevertheless, the absence of negative outcomes indicates that even when clinical results are not significantly better than conventional methods, they are at least comparable, ensuring that the use of CANS does not detract from patient outcomes. Additionally, the tremendous difference of results among Orthopilot® and Praxim Medivision® raises questions concerning the variability of performance among navigation systems and factors such as the complexity of the cases and others, which may contribute to these results. This variation highlights the need for more study to determine the variables affecting the various CANS systems clinical performance.

Other systems, with less studies approaching the clinical outcomes, reported mixed results, suggesting that while these systems may not always lead to superior clinical outcomes, they do not perform worse than conventional methods.

The identification of limitations is a crucial step in a scientific paper, as it reveals critical areas that need attention to enhance the reliability and applicability of findings. The need for larger population sizes and longer follow-up periods were the most frequently cited limitations^(29, 31, 36, 39, 43, 44, 47, 50, 54, 55, 60, 65, 69, 70, 73). This is a common issue in surgical research, especially in studies involving new technologies, as these factors are essential to ensure results are statistically significant and clinically relevant.

Regarding the frequent call for more clinical trials^(36, 49, 50, 67, 69), although cadaveric and model studies are valuable for initial testing and validation, clinical trials are indispensable for assessing real-world clinical outcomes and complications. Furthermore, the need for a better biomechanical understanding of the effect of tunnel drilling on knee kinematics was noted in four studies^(22, 37, 41, 44). This is particularly important, as there is still no scientific consensus on the best methodology to determine graft placement, which significantly impacts the outcomes of ACL reconstruction.

Other reported limitations included the lack of randomized blind clinical trials^(39, 55, 60), which are the gold standard in clinical research because they minimize bias and provide high-quality evidence. The absence of these trials can introduce bias and affect the validity of the outcomes. Additionally, the involvement of multiple surgeons^(45, 62) is essential to generalize findings across different skill levels and surgical approaches. Moreover, the need for improved imaging evaluation of tunnel placement is critical to ensure accurate assessment^(28, 50). Finally, the lack of guidelines⁽⁷³⁾ for robot-assisted surgery and the need for thorough evaluation of clinical outcomes⁽⁴³⁾ underscore the complexity and multidisciplinary nature of this field and highlight areas for improvement to enhance the robustness and applicability of future research findings.

Study Limitations

The selection criteria may have limited the review's reach by excluding pertinent studies, especially those published in less accessible publications or in languages other than English. Due to the review's dependence on publicly available data, its scope is constrained by the veracity and quality of the information provided, which could lead to bias. The synthesis of findings may also be hampered by inconsistent terminology and concepts employed in different investigations. The variability in the types of navigation systems and surgical techniques reviewed also presents a challenge in drawing definitive conclusions. The rapid advancements in technology mean that some reviewed studies might be outdated, impacting the relevance of the findings. Furthermore, this review may not fully capture the latest developments and emerging trends in the field. Finally, the review's conclusions are inherently constrained by the heterogeneity of the included studies, making it difficult to generalize the findings across all clinical settings.

Conclusion

This scoping review provides a comprehensive analysis of the current research landscape on computer navigation systems in ACL reconstruction. The findings highlight the efficacy of these systems in achieving precise tunnel placements, though challenges remain in terms of economic costs and clinical outcome validation. In addition, the study also reveals an important increase in research activity over the time, with a significant transition to human-based studies reflecting the growing clinical applicability and integration of the technology. While there was a decrease in experimental studies in the last years, a surge in clinical trials highlights a maturing field focusing on real-world effectiveness and patient-centered outcomes. This transition is accompanied by advancements in navigation system technologies, moving from passive to active systems, aiming to automate surgical procedures. Despite that, the variations in the systems performance and the need for further clinical trials, demonstrates the complexity and on-going evolution of this field of science. Finally, addressing the identified study limitations, such as larger populations samples, or long follow-up times, will be critical for advancements on reliability and applicability of future research in CANS for ACL reconstruction.

Appendix

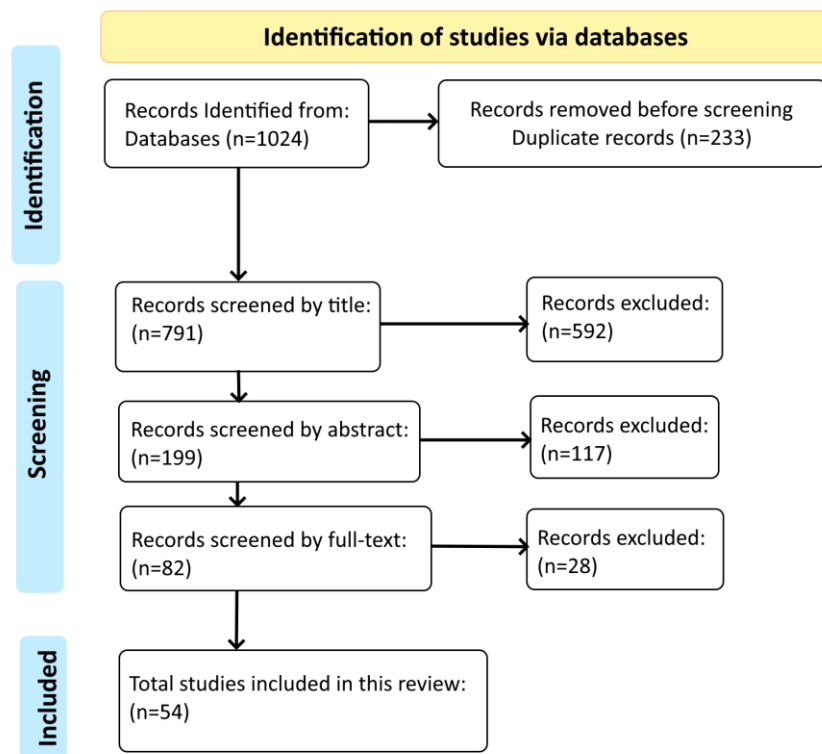


Figure 1 - Flowchart of the search. Flowchart summary of search engaged for articles regarding the use of computer assisted navigation system in anterior cruciate ligament reconstruction. Over 1024 articles were initially identified and, following title, abstract and full-text screening, 54 studies met inclusion criteria and were included in this scoping review

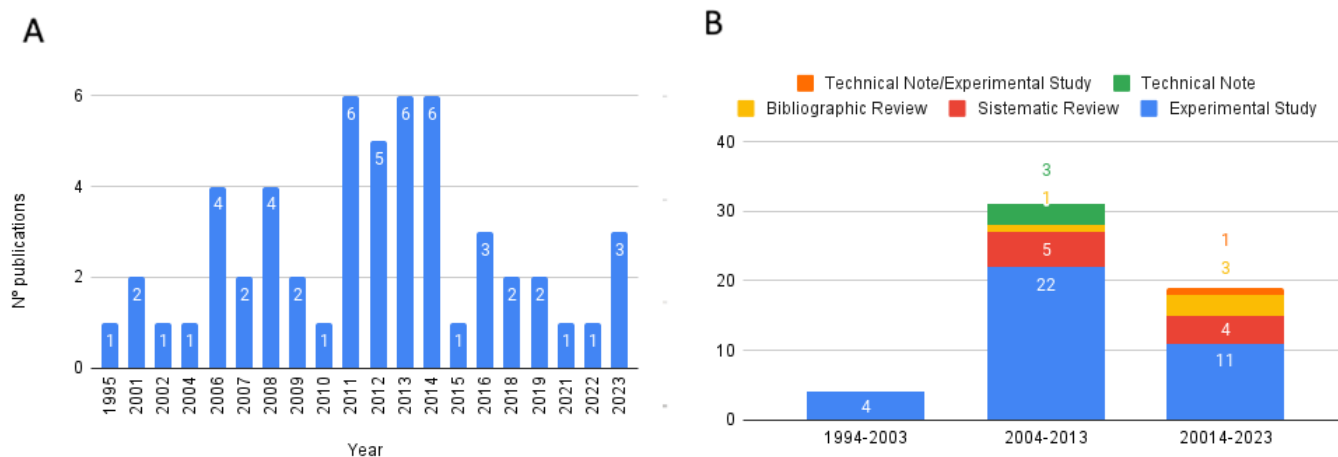
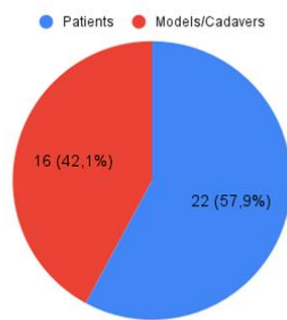


Figure 2 - Trend of Publication. A – Number of studies per year; B – Type of study per decade

A



B

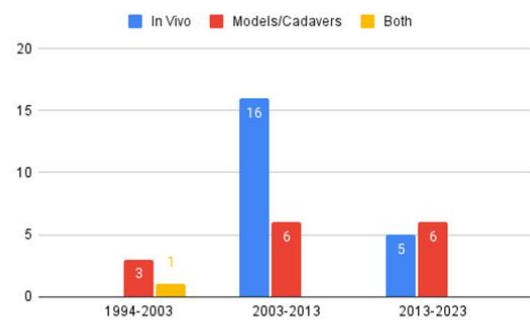


Figure 3 - Experimental Studies. A – Type of experimental studies. B – Trend of experimental studies

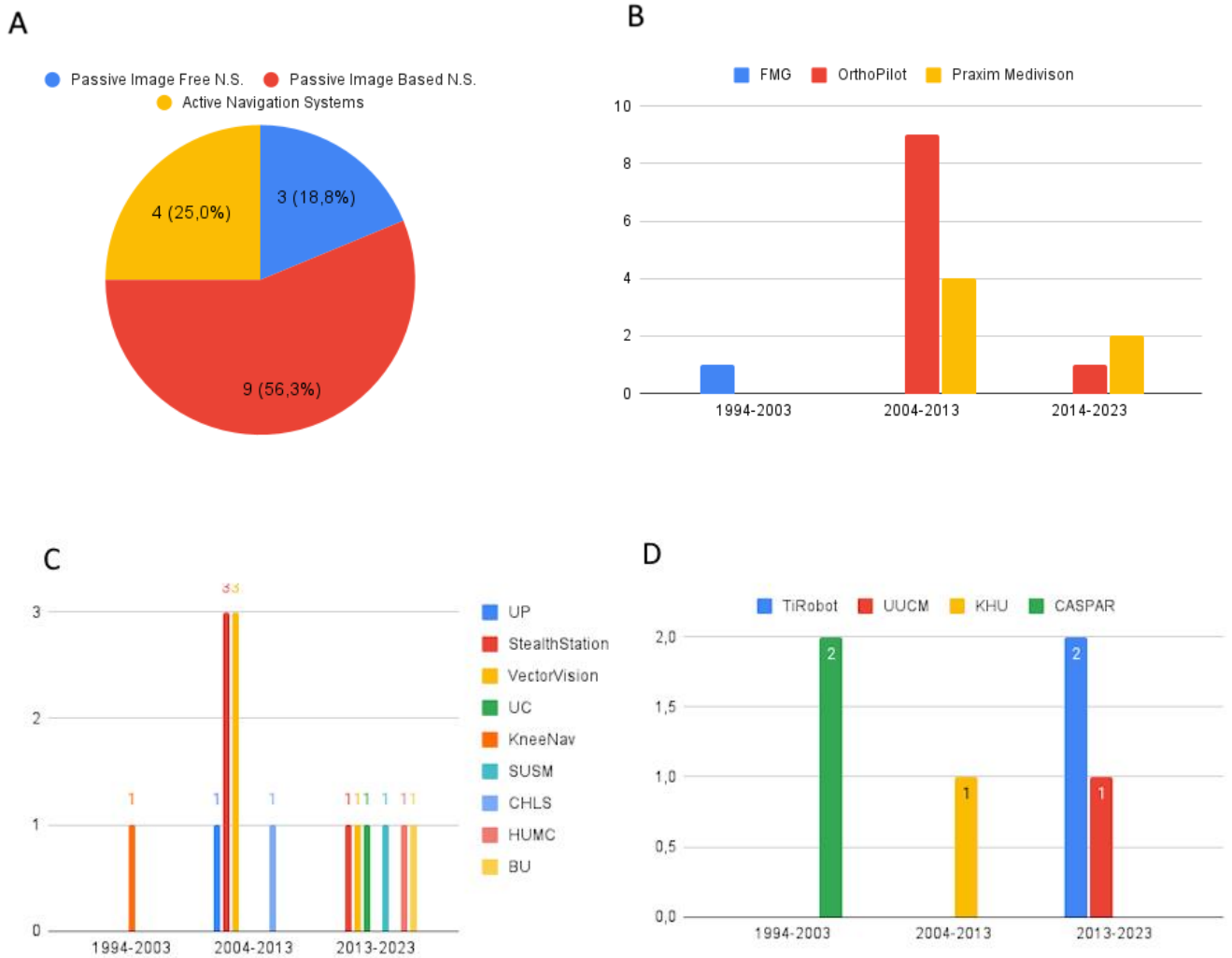


Figure 4 - Navigation Systems. A – Types of navigation systems described in the studies. B – Trend of Passive Image Free Navigation Systems in experimental studies; FMG, Faculté de Medecine de Grenoble; C – Trend of Passive Image Based Navigation Systems in experimental studies; UP, University of Pittsburgh navigation system; UC, University of Coimbra navigation system; SUSM, Soonchunhyang University School of Medicine navigation system; CHLS, Centre Hospitalier Lyon Sud navigation system; HUMC, Hallym University Medical Center navigation system; BU, Beihang University navigation system; D – Active Navigation System in experimental studies; UUCM - University of Ulsan College of Medicine navigation system; Kyung Hee University navigation system;

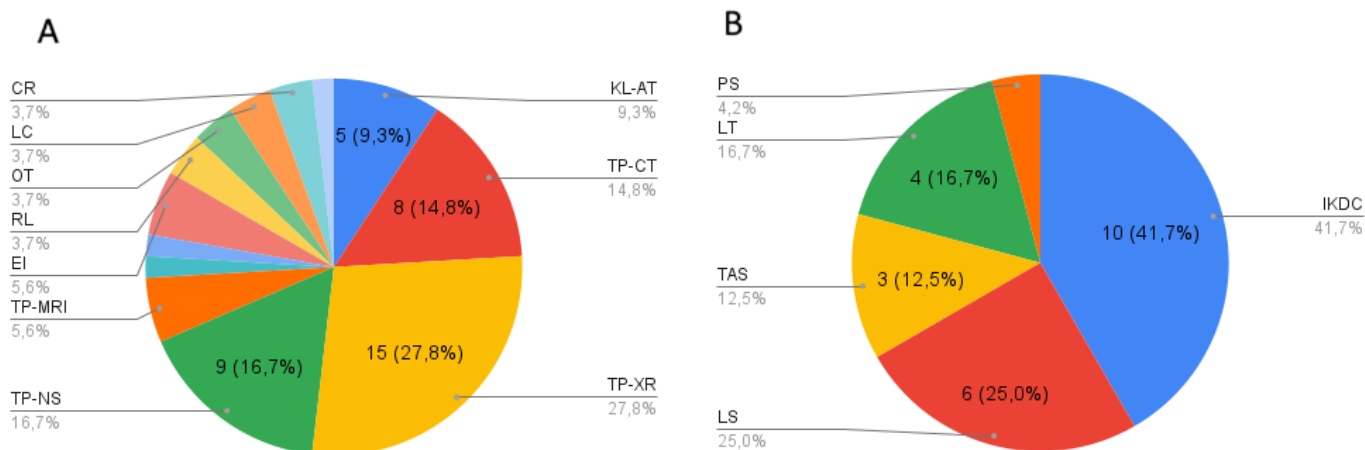


Figure 5 - Type of Outcomes. A – Quantitative outcomes; CR: complication rate; EI: economical impact; KL-AT: knee laxity – knee tester 1000 arthrometer; LC: learning curve; OT: operation time; TP-CT: tunnel placement – computed tomography; TP-MRI: tunnel placement – magnetic resonance imaging; TP-NS: tunnel placement – navigation system; TP-XR: tunnel placement – x-ray; RL: radiographic laxity; B – Clinical outcomes. IKDC: international knee documentation committee score; LS: Lysholm score; LT: Lachman test; PS: pivot-shift; TAS: Tegner activity score

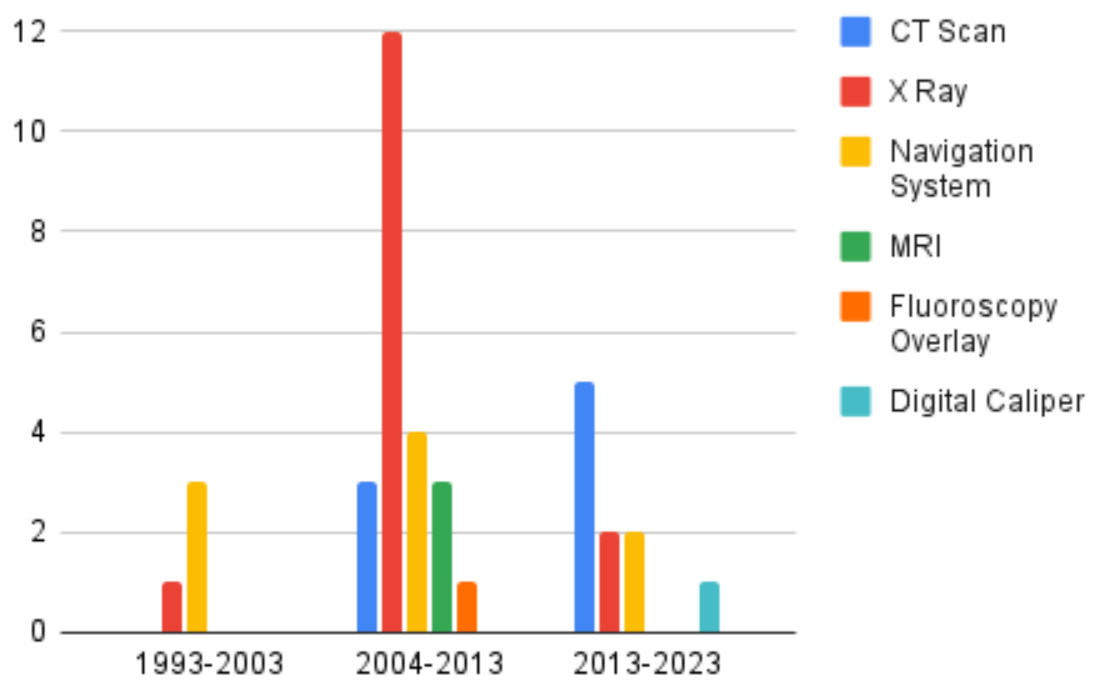


Figure 6- Tunnel Positioning and Accuracy Outcomes: methodology used in the experimental studies for evaluating tunnel positioning and accuracy. CT: computer tomography; MRI: magnetic resonance imaging

Table I- Characteristics of included studies

Experimental Studies					
Year	Author	Country	Subjects		Technology
			Patients	Models	
1995	V. Dessenne et al (21)	France	12	8	Faculté de Medecine de Grenoble NS
2001	F. Picard et al (23)	United States of America	NA	40	KneeNav ACL®
2001	A. Burkart et al (22)	United States of America	NA	50	CASPAR®
2002	V. Musahl et al (24)	United States of America	NA	13	CASPAR®
2006	H. Hiraoka et al (26)	Japan	32	NA	StealthStation®
2006	Y. Ishibashi et al (27)	Japan	38	NA	OrthoPilot®
2006	S. Plaweski et al (29)	France	60	NA	Praxim Medivision®
2006	J. Koh et al (28)	France	65	NA	OrthoPilot®
2007	F. Mauch et al (30)	Germany	53	NA	OrthoPilot®
2007	J. Chouteau et al (31)	France	73	NA	Centre Hospitalier Lyon Sud NS
2008	P. Kodali et al (34)	United States of America	76	NA	OrthoPilot®
2008	R. Hart et al (33)	Czech Republic	80	NA	OrthoPilot®
2009	D. Endele et al (36)	Germany	40	NA	OrthoPilot®
2011	K. Tensho et al (43)	Japan	22	NA	StealthStation
2011	Y. Kawakami et al (81)	Japan	55	NA	Vector Vision ACL®
2011	S. Plaweski et al (41)	France	NA	10	Praxim Medivision®
2011	S. Shafizadeh et al (42)	Germany	NA	10	Vector Vision ACL®
2012	J. Jean-Yves et al (45)	France	56	NA	OrthoPilot®
2012	E. Meuffels et al (46)	Netherlands	100	NA	Vector Vision ACL®
2012	S. Plaweski et al (47)	France	271	NA	Praxim Medivision®
2012	L. M. Huynh et al (49)	South Korea	NA	6	Kyung Hee University NS
2013	S. Taketomi et al (54)	Japan	34	NA	StealthStation®
2013	S. Aldrian et al (52)	Austria	55	NA	OrthoPilot®
2013	J. W. H. Luites (53)	Netherlands	NA	12	Praxim Medivision®
2013	G. Moloney et al (50)	United States of America	NA	20	University of Pittsburgh NS
2013	C. A. Anthony et al (48)	United States of America	NA	20	OrthoPilot®
2014	S. Taketomi et al (59)	Japan	47	NA	StealthStation®
2014	J. Margier et al (60)	France	214	NA	Praxim Medivision®
2015	S. Plaweski et al (61)	France	52	NA	Praxim Medivision®
2016	B. H. Lee et al (62)	South Korea	NA	10	Hallym University Medical Center NS
2016	S. H. Park et al (63)	South Korea	NA	20	Soonchunhyang University School of Medicine NS
2018	W. J. Cho et al (65)	South Korea	NA	4	University of Ulsan College of Medicine NS
2019	C. A. Popkin et al (67)	United States of America	NA	10	Vector Vision ACL

2019	C. Raposo et al (68)	Portugal	NA	NA	University of Coimbra NS
2021	G. Ding et al (69)	China	NA	16	TiRobot®
2022	W. Y. X. Foo et al (70)	Singapore	60	NA	OrthoPilot®
2023	L. Zhang et al (73)	China	16	NA	TiRobot®
Systematic Reviews					
Year	Author	Country	Number of Articles		
2010	S. Zaffagnini et al (38)	United States of America	84		
2011	D. E. Meuffels (40)	Netherlands	4		
2011	T. Cheng et al (39)	China	5		
2012	T. Cheng et al (44)	China	5		
2013	S. W. Young et al (51)	United States of America	6		
2014	V. Eggerding et al (55)	Netherlands	5		
2014	T. Klos et al (57)	Netherlands	84		
2016	S. Zaffagnini et al (64)	Italy	146		
2023	E. Yavari et al (72)	Canada	11		
Bibliographic Review					
Year	Author	Country			
2009	A. D. Pearle et al (37)	United States of America			
2014	V. K. Goradia et al (56)	United States of America			
2014	J. Koh et al (58)	United States of America			
2023	F. Figueroa et al (71)	Chile			
Technical Notes					
Year	Authors	Country	Technology		
2004	U. W. Müller-Alsbach et al (25)	Switzerland	Praxim Medivision		
2008	D. Colombet et al (32)	France	Praxim Medivision		
2008	T. Nakagawa et al (35)	Japan	StealthStation		
Technical Notes/Experimental Study					
Year	Author	Country	Models	Technology	
2018	B. Yang et al (66)	China	8	Beihang University NS	

ACL: anterior cruciate ligament; NA: not available; NS: Navigation System

Table II- Characteristics of the Navigation Systems analyzed and its outcomes

Passive Image Free Navigation Systems					
Technology	Functioning	% Positive Quantitative Outcomes – Tunnel Positioning and Accuracy	% Positive Clinical Outcomes	% Positive Economical Outcomes	Other quantitative outcomes
Faculté de Medecine de Grenoble NS	Bone Morphing Technology	n=1 (100%)	NA	NA	NA
OrthoPilot®	Bone Morphing Technology	n=5 (63%)	n=0 (3 neutral outcomes)	NA	Kinematics: n=1 (100%) Knee laxity: n=0 (2 neutral outcomes) Experienced surgeons without CANS vs novice surgeon with CANS: n=0 (1 neutral and 1 negative) Female patients had worst outcomes with double bundle reconstruction with CANS: n=1
Praxim Medivision®	Bone Morphing Technology	n=3 (80%)	n=2 (50%)	n=0 (2 negative outcomes)	Knee laxity: n=1 (100%) Radiographic laxity: n=1 (50%) Learning curve: n=2 (100%)
Passive Image Based Navigation System					
Technology	Functioning	% Positive Quantitative Outcomes – Tunnel Positioning and Accuracy	% Positive Clinical Outcomes	% Positive Economical Outcomes	Other quantitative outcomes
StealthStation®	CT/MRI/fluoroscopy	n=4 (100%)	n=1 (100%)	NA	Knee laxity: n=1 (100%)

VectorVision ACL®	CT/MRI/fluoroscopy + bone registration	n=3 (75%)	NA	NA	NA
University of Pittsburgh NS	CT + bone registration/fluoroscopy	n=1 (100%)	NA	NA	NA
University of Coimbra NS	MRI + bone registration	n=1 (100%)	NA	NA	NA
Knee Nav®	CT/fluoroscopy + bone registration	n=1 (100%)	NA	NA	NA
Soonchunhyang University School of Medicine	CT + bone registration	n=1 (100%)	NA	NA	NA
Centre hospitalier Lyon Sud	Fluoroscopy	n=1 (100%)	n=1 (100%)	NA	Knee laxity: n=1 (100%)
Hallym University Medical Center	CT + bone registration	n=1 (100%)	NA	NA	NA
Beihang University	Fluoroscopy	n=1 (100%)	NA	NA	NA
Active Navigation Systems					
Technology	Functioning	% Positive Quantitative Outcomes – Tunnel Positioning and Accuracy	% Positive Clinical Outcomes	% Positive Economical Outcomes	Other quantitative outcomes
Tirobot	CT + fluoroscopy	n=2 (100%)	n=0 (1 neutral)	n=1 (100%)	NA
University of Ulsan College of Medicine	MRI + bone registration	n=1 (100%)	NA	NA	NA
CASPAR	CT	n=1 (50%)	NA	NA	NA
Kyung Hee University	CT + bone registration	n=1 (100%)	NA	NA	NA

CANS: computer-assisted navigated surgery; CASPAR: Computer Assisted Surgical Planning And Robotics; CT: computed tomography; KT-1000: knee tester 1000 MRI: magnetic resonance imaging; NA: not available; NS: Navigation System
Positive Quantitative Outcomes – Tunnel positioning and Accuracy: precise and accurate tunnel placement compared to a control group or anatomical position

Table III- Outcomes analyzed

Clinical Outcomes	n = 10 (26%)
IKDC score	n = 10 (26%)
Lysholm score	n = 6 (16%)
Lachman test	n = 4 (11%)
Tegner Activity Score	n = 3 (8%)
Pivot Shift	n = 1 (3%)
Quantitative Outcomes	n = 38 (100%)
Tunnel positioning and accuracy – X-ray	n = 15 (39%)
Tunnel positioning and accuracy – Navigation System	n = 9 (24%)
Tunnel positioning and accuracy – CT scan	n = 8 (21%)
Tunnel positioning and accuracy – MRI	n = 3 (8%)
Tunnel positioning and accuracy – Fluoroscopy overlay	n = 1 (3%)
Tunnel positioning and accuracy – Digital Caliper	n = 1 (3%)
Knee laxity – KT-1000 arthrometer	n = 5 (13%)
Knee laxity – Radiographic laxity	n = 2 (5%)
Economic impact	n = 3 (8%)
Learning curve	n = 2 (5%)
Operation time	n = 2 (5%)
Complication rate	n = 2 (5%)
Knee laxity – Navigation System	n = 1 (3%)

CT: computed tomography; IKDC: international knee documentation committee; KT-1000: knee tester 1000; MRI: magnetic resonance imaging

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