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Current applications of gait analysis after total knee arthroplasty: A scoping review☆

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A B S T R A C T

Introduction: The biomechanics of the knee do not return to normal after knee replacement. The purpose of this scoping review is to summarize the current use of gait analysis in total knee arthroplasty and to identify the preoperative motion analysis parameters for which a systematic review aimed at determining the reliability and validity may be warranted.
Materials and methods: This IRB-exempt scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist. The 279 articles from the five search engines underwent a title/abstract and full-text screening. Included articles were categorized as either: the role of gait analysis as a research tool for operative decisions, other research applications for motion analysis in total knee arthroplasty, gait analysis as a tool in predicting radiologic outcomes, or gait analysis as a tool in predicting clinical outcomes.
Results: Eleven articles studied gait analysis as a research tool in studying operative decisions. Five articles studied other research applications for motion analysis in total knee arthroplasty. Other research applications for motion analysis currently include studying the role of the unicompartmental knee arthroplasty and novel physical therapy protocols aimed at optimizing post-operative care. Two articles studied motion analysis as a tool for predicting radiographic outcomes. 15 articles studied motion analysis in conjunction with clinical scores.
Conclusions: There is a broad range of research applications for motion analysis in knee reconstruction. Current limitations include vague definitions of 'gait analysis' or 'motion analysis' and a limited number of articles with preoperative and postoperative outcomes. Knee adduction moment, knee adduction impulse, total knee range of motion, varus angle, cadence, stride length, and velocity have the potential for integration into composite clinical scores. A systematic review to determine the psychometric properties of these variables is warranted.

1. Introduction

Total Knee Arthroplasty (TKA) are commonly performed with 429 TKA's per 100,000 annually in the United States[1] and an expected 69% increase by 2050.[1] The most common indication is primary osteoarthritis (OA), though other indications include inflammatory arthritis, post-traumatic arthritis, avascular necrosis, and congenital abnormalities.

Much is known about the biomechanics of the end-stage knee osteoarthritis patient. The altered mechanics lead to progressive cartilage degeneration and subsequently joint space narrowing, subchondral sclerosis, and a progressive varus deformity. Knee OA patients experience higher medial loading conditions, instability, and reduced performance on functional tests.[2] There is evidence to suggest that these effects are translated to cause abnormal hip and ankle kinematics.[2]

Modern gait analysis first arose in the context of neurodevelopmental orthopedics in children in the early 1900's.[3] This was performed through the serial analysis of many static images

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referred to as chrono-photography. This was shortly followed by 2-dimensional gait analysis in which a video of a patient walking was taken orthogonal to the plane of interest.[4]

Motion capture was revolutionized by the advent of 3-dimensional motion capture technology. A variety of camera-based systems have been trialed that utilize patient markers to reconstruct the segments of locomotion. When the advent of different motion analyzers in the 1970's, the large volume of data collected through these motion capture systems could be analyzed. In today's world of motion analysis, many of these systems utilize infrared camera-based systems with fixed-point patient markers coupled that are then superimposed over dynamic EMG's that the patient wears throughout the gait cycle.[5]

Gait mechanics partially resolve after total knee arthroplasty.[6–8] Patients after TKA do exhibit a decreased arc of motion with stair climbing[9] and compensatory changes at the hip and ankle.[10] Thus, the biomechanics of the lower extremity may be altered in patients after TKA.

A recent systematic review demonstrated that these alterations after TKA may not affect patient outcomes.[6] However, there is some research to suggest that certain postoperative gait analysis parameters may be related to patient satisfaction.[11] There is an overall lack of knowledge regarding the utility of motion analysis in the realm to knee replacement surgery both in terms of how it is used currently and what can be done with motion capture technology to improve paient outcomes. Specifically knowledge regarding the psychometric properties of motion analysis in knee reconstruction are poorly understood. We define psychometric properties as the test-retest reliability, validity, sensitivity, specificity, positive predictive value, and negative predictive value.[12]

The primary purpose of this scoping review is to identify the preoperative motion analysis parameters for which a systematic review aimed at determining the psychometric parameters may be warranted. The secondary purpose is to describe the current use of gait analysis in total knee arthroplasty.

2. Materials and methods

2.1. General

This was an IRB-exempt scoping review. The Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews Checklist (RPSIMA-ScR) was followed strictly. The international prospective register of systematic reviews (PROSPERO) was contacted regarding our intention for this article and advised that scoping views do not require registration with PROSPERO. The study protocol was drafted using the PRISMA-SCR checklist which was revised by the authors of this article and the librarian at the University of Arizona College of Medicine – Phoenix and is detailed below.

2.2. Search strategy

The following search engines were used: PubMed Advanced Search, Embase, Cochrane library, Scopus, Google Scholar. The search terms included: (total knee arthroplasty[Title/Abstract] or knee replacement[Title/Abstract]); Intervention: (gait analysis[Title/Abstract] or motion analysis[Title/Abstract] or pedobarograph [Title/Abstract] or kinematic[Title/Abstract] or kinetic[Title/Abstract]); Control: none; Outcome: (Functional outcomes[Title/Abstract] or radiographic outcomes[Title/Abstract] or clinical outcomes [Title/Abstract] or clinical scores [Title/Abstract] or success[Title/Abstract] or failure [Title/Abstract]).

Articles published between January 1975 to March 2022 were included. Search fields were varied until no new articles were collected at which point the search was considered exhaustive. This resulted in a total of 279 articles. After the removal of duplicate articles, a total of 256 articles remained (Fig. 1).

2.3. Study screening and selection

All articles were screened by title and abstract independently by three of the authors, under the supervision of a board-certified hip and knee surgeon. A preliminary decision to include or exclude an article was made based title/abstract. This resulted in a preliminary list of 45 articles. This preliminary list of articles was organized into the following subheadings: the role of gait analysis as a research tool to study operative decisions (section 3.1), other research applications for motion analysis in total knee arthroplasty (section 3.2), gait analysis as a tool in predicting radiologic outcomes (section 3.3), gait analysis as a tool in predicting clinical outcomes (section 3.4). Certain articles served more than one of the aforementioned purposes and were included in more than 1 relevant section. These were denoted by an asterisk (*).

2.4. Full-text screening

These articles then underwent a full-text screening process. The primary purpose of the full-text screening was application of the inclusion/exclusion criteria (Table 1), and placement of the article in a given section. The secondary purpose was to define articles as 'Tier 1' or 'Tier 2' based on the quality of motion analysis data presented. 'Tier 1' was defined as 3D kinematic data, 3D kinetic data, or pedobarographic data. 'Tier 2′ was defined as 2D descriptive gait data or temporospatial parameters only. This resulted in a total of 35 included articles.

The bibliographies of the final included articles were also hand-searched to identify any missing articles. Any question regarding the inclusion of an article was discussed by all authors until an agreement was reached.

2.5. Data charting

After the inclusion of an article, the article was first organized into one of the following categories: the role of gait analysis as a research tool for operative decisions, other research applications for motion analysis in total knee arthroplasty, gait analysis as a tool in predicting radiologic outcomes, or gait analysis as a tool in predicting clinical outcomes. The following data elements were extracted for a given article: Lead Author, Year, Journal, Institution, Study Purpose, Study Type, Level of Evidence, Number of Patients, Use of Gait Analysis, Length of Follow-Up, Results, and Conclusions. This was performed in conjunction with the three authors. Articles were organized into respective tables and ranked according to level evidence. Tables were created using Microsoft Word V16.42. The articles were then summarized descriptively (**Section 3**. **RESULTS**).

3. Results

3.1. The role of gait analysis as a research tool to study operative decisions

3.1.1. General

A total of 11 articles studied gait analysis with regards to surgical decision-making. Six articles were level of evidence I, four articles were level of evidence II, and one article was level of evidence III (see Table 2.) Articles included in this category use gait analysis to study tertiary research questions; however, they may or may not include clinical, radiologic, or functional outcomes. They are further broken up into sub-sections (3.1.2 study surgical approaches, 3.1.3

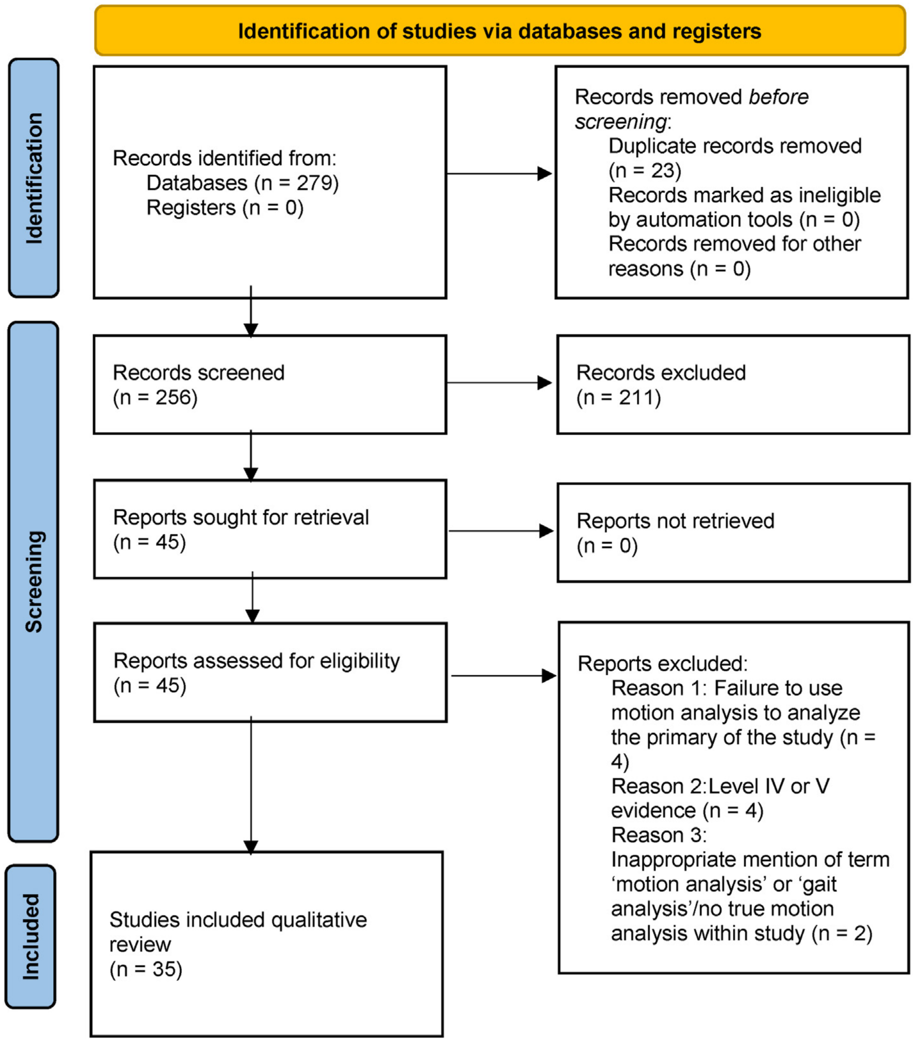

Fig. 1. The PRISMA flow diagram adapted to depict our study screening process including reasons for exclusion.

Table 1
Our inclusion and exclusion criteria as applied independently by three of the authors during full-text screening.

Inclusion Criteria	Exclusion Criteria
• Publication between January 1975–October 2021 • Study of gait analysis in the context of total knee arthroplasty • Level III evidence or higher	• Pediatric population (ages 0–18) • Study of bilateral knee arthroplasty; joined hip and knee arthroplasty study • Case series, case reports, or expert opinion

study surgical techniques, 3.1.4 study implant choice.)

3.1.2. Studying surgical approaches

Two of the screened articles used gait analysis as an outcome measure in studies comparing surgical approaches. These were both prospective, level I studies performed after 2010 (Table 2, *rows 1 and 2*.) Both of these articles included a pre-operative and post-operative gait analysis. Layher et al. 2015[13] compared the mid vastus and medial parapatellar approach in total knee arthroplasty. This single-blinded prospective randomized study of 21 patients studied clinical, Knee Society Scores (KSS), Western Ontario C (WOMAC), and the results of a 3D gait analysis system, all three of which demonstrated superiority of the midvastus approach. The agreement of the KSS and WOMAC scores with the results of the 3D gait analysis system may imply that gait analysis alone is a viable research tool in studying surgical approaches in total knee arthroplasty. Nestor et al.[14] further add to the conversation by showing that isokinetic and isometric testing may also be an additional available tool when comparing surgical approaches (Table 2, *row 2*).

3.1.3. Studying surgical techniques

Five of the screened articles used gait analysis as an outcome measure in studies comparing surgical techniques. Two of these articles included a pre-operative and post-operative gait analysis,[15,16] and three of them included only a post-operative gait analysis.[17,18]

Miozzari et al., 2021 demonstrated no significant difference between the gap balancing and measured resection groups in terms of gait analysis parameters, WOMAC scores, or SF-12 scores.[15] The agreement of no difference between these independent validation tools further points toward the potential use of gait analysis in

Table 2
A summary of the published literature regarding the use of studying surgical decisions in total knee arthroplasty. Rows 1 and 2 concern the surgical approach (**Section 3.1.2**), Rows 3–7 concern the surgical technique (**Section 3.1.3**), and Rows 8–11 concern implant choice (**Section 3.1.4**).

Lead Author	Year	Journal	Institution	Study Purpose	Study Type	Level of Evidence	Number of Patients	Length of Follow-Up (weeks)
Layher + T1 * Also appears in Table 4	2015	Journal of Orthopedics and Trauma Surgery	Jena University Hospital	To compare the midvastus and the medial parapatellar approaches respectively.	Single blinded, prospective, randomized study	I	Medial Parapatellar = 10, Midvastus = 11 Control = 53 Total = 74	26
Bryan Nestor + T1	2010	The Journal of Arthroplasty	Adult Reconstruction and Joint Replacement Division, Department of Orthopaedic Surgery, Hospital for Special Surgery	To determine if the mini-midvastus approach to TKA results in differences in quadriceps strength.	Prospective, randomized, double-blind study	I	27 patients (54 TKAs)	12
Miozzari + T1	2021	The Journal of Knee Surgery	Division of Orthopedic Surgery and Traumatology, Geneva University Hospitals, Geneva, Switzerland	To compare the mechanical alignment achieved using dependent and independent bone cut technique.	Cohort single-center observational longitudinal study	II	Independent bone cut (PFC) = 39 Dependent bone cut (PFC-TRAM) = 19 Total = 58	52
Miozzari + T1 *also appears in Table 5	2013	The European Journal of Medical Sciences	University Hospital of Geneve, University of Geneve	To determine if the use of a bone dependent technique influences gait, function, pain, quality of life, and satisfaction	Prospective Cohort Study	II	Independent bone cuts = 30 Dependent bone cuts = 10 Total = 40	52
Vauclair – T1	2013	Swiss medical weekly	University Hospital of Geneve, University of Geneve	To evaluate mechanical axis with a functional outcome of gait analysis, after a TKA implantation with custom instrumentation and 3d preoperative planning.	Prospective consecutive cohort	II	Custom cutting blocks = 103 Registry = 420 Total = 523	52
Zhang – T1	2020	Acta Orthopaedica et Traumatologica Turcica	Department of Orthopedic Surgery, Affiliated Hospital of Xuzhou Medical University	To compare the effect of measured resection gap balancing on clinical and radiological results of TKA.	Prospective randomized controlled trial	I	Total = 99	52
Young – T1	2017	Arthroscopy	North Shore Hospital, Auckland, Auckland, New Zealand	To compare kinematic alignment and traditional mechanical alignment in restoring limb symmetry during gait analysis after a TKA.	Randomized trial	I	Mechanical alignment = 14 Kinematic alignment = 13 Total = 27	104
Tawy + T1	2020	The Knee	The Division of Cell Matrix Biology & Regenerative Medicine, University of Manchester	To assess the functional outcomes of patients with the Medacta GMK-sphere implant.	Prospective Cohort Study	II	Total = 27	52
Rajgopal + T1 * Also appears in Table 5	2016	Arthroplasty	Medanta Bone and Joint Institute, Medanta	To quantify the functional outcomes of persona cruciate-retaining and persona ultra-congruent polyethylene designs.	Prospective single-blind, single-surgeon randomized controlled trial	I	Total = 105	104
GomezBarrena – T1	2010	The Association of Bone and Joint Surgeons	Department of Orthopaedic Surgery, Fundacio'n Jime'nez Dı'az Hospital,	To compare postoperative knee performance of patients receiving a posterior, stabilized, cemented TKA.	Retrospective case-controlled study	III	Single-radius = 30 Multi-radius = 30 Total = 60	36
Tibesku + T1 * Also appears in Table 4	2011	Knee Surg Sports Traumatol Arthrosc	Sporthopaedicum Straubing, Bahnhofplatz	To analyze patients that had received either a fixed or a mobile TKA.	Prospective randomized clinical study	I	Fixed-bearing inlay = 17 Mobile-bearing inlay = 16 Total = 33	104

A '+' in the column 'Lead Author' denotes presence of preoperative and postoperative gait analysis.
A '-' in the column 'Lead Author' denotes presence of postoperative gait analysis only.
A 'T1' in the column 'Lead Author' denotes classification as a Tier 1 article (see **Section 2.4**.).
A 'T2' in the column 'Lead Author' denotes classification as a Tier 2 article (see **Section 2.4**.).
An asterisk (*) in the column 'Lead Author' denotes inclusion in a table elsewhere. The other table is written underneath the asterisk if present.

studying surgical techniques.

A recent article that demonstrated strong evidence for patient-specific instrumentation did not corroborate the validity of gait analysis.[17] Though functional ($p < 0.05$) and radiographic differences ($p < 0.05$) were noted in this study between the patients with custom femoral and tibial bone blocks, no clinical or gait analysis parameters were statistically significant. As a level I study of 103 patients, this study certainly adds strong evidence for the utility of patient-specific instrumentation in total knee arthroplasty. However, this study limits the interpretation regarding the utility of gait analysis.

A prospective controlled clinical trial examined the clinical and functional outcomes through the 3D kinematic analysis of gap balancing and measured resection techniques.[18] They demonstrated no significant differences in WOMAC (p-values ≥ 0.084) or gait analysis data at one year postoperatively (p-values ≥ 0.05). The agreement seen here and in Young et al. between clinical scores and gait analysis supports the use of gait analysis in studying operative techniques.[19] Certain operative techniques may alter the functional dynamics of the osteoarthritic diseased knee more so than others. For example, resection technique alone, may not play as large of a role in the force distribution and resulting functional gait analysis as compared to implant choice. Thus, gait analysis may shed light on certain operative decisions, but not others.[17–19]

3.1.4. Studying implant choice

Four of the screened articles used gait analysis as an outcome measure for the study of implant choice in total knee arthroplasty.[20–23] Two of these were level I evidence.[20,21] These four studies included both preoperative and postoperative gait analysis data and all four of these studies met our criteria as high-quality 3D kinematic and kinetic data.

The reported uses vary greatly within this section and include functional analysis of the Medacta GMK-Sphere TKA,[23] ultra-congruent knee inserts,[21] the single-radius TKA design,[22] and fixed-versus mobile-bearing devices.[20] The breadth of this section certainly limits our ability to make inferences about the utility of gait analysis for these applications.

Tawy et al. studied the role of the medacta sphere implant. This implant is a form of a medial rotation knee arthroplasty that may improve postoperative mobility.[23] This study demonstrated that knee kinematics correlate with improved outcomes. They also found that active and passive range of motion shows statistically significant differences preoperatively ($p < 0.0001$) that showed no difference to the contralateral side post-operatively ($p > 0.312$.) However, in the absence of validated clinical outcomes, the interpretation of the results of this study is limited. Gait analysis may be an appropriate tool in this setting as it provides information regarding the kinematics, force distributions, and kinetics that are shared by the implant.

The effect of the single-radius implant has been well studied with 2D analysis.[24] This implant type is defined as a single spherical radius with a locus between 10 and 120°.[24] There is evidence to suggest that this implant design may be associated with a statistically significant improvement in motion analysis parameters. Specifically, decreased flexion peak torque, increased extension peak torque, and lower flexor/extensor ratio were seen in combination with increased KSS scores from 80.3 ± 1.90 to 86.6 ± 1.89 with this implant type. Motion analysis may be an appropriate research tool regarding implant choice and the resulting strain environment. In this study, this amounted to different torques in the sagittal plane, which ultimately correlated with clinical outcomes.

The large breadth of uses points towards the potential of gait analysis in studying implant choice in TKA. Given the high level of evidence, large patient numbers, and general agreement with clinical scores, it appears that gait analysis can play some role in research applications concerning studying the reversal of diseased knee biomechanics in patients having undergone total knee arthroplasty.

3.2. Other research applications for motion analysis in total knee arthroplasty

3.2.1. General

A total of five articles studied gait analysis as a research tool in studying 'other' surgical decisions. Three articles were level of evidence I, and two articles were level of evidence II (see Table 3.) These articles studied tertiary research questions apart from surgical approach, surgical technique, or implant choice; however, they did not necessarily include clinical, radiologic, or functional outcomes. They are further broken up into two sub-sections (3.2.2 Studying the role of the UKA and 3.2.3 Study postoperative physical therapy protocols).

3.2.2. Studying the role of the UKA

Two of the identified studies utilized motion analysis to study unicompartmental knee arthroplasty (Table 3, *rows 1 and 2*.) Van Hemert et al., 2009 demonstrated that functional data after UKA and clinical data are both improved. Their study allows for the correlation of the improvement from preoperative status to postoperative status in functional data with that of the KSS scores, the WOMAC, and SF-36. The functional data included is that of the Dynaport Knee Test (performance-based accelerometers).

3.2.3. Studying post-operative physical therapy protocols

There is evidence to suggest that exercise protocols improve gait function after surgery.[2] A recent randomized control trial provides good evidence for home exercise therapy programs through gait analysis. Other post-operative therapy considerations studied using motion capture systems include gait modification devices[25] and accelerated therapy protocols[26] (Table 3, *row 3–5*.)

3.3. Gait analysis as a tool in predicting radiologic outcomes

In general, there was a paucity of studies regarding motion analysis and systems radiologic outcomes. Our literature search revealed two level II articles on this topic (Table 4).

Radiostereometric analysis is used to explore the stability of an implant. Preoperative knee joint loading patterns may be correlated with the total postoperative tibial component migration.[27] Motion analysis may be used in a predictive model regarding TKA outcome. It has been shown that the sagittal plane muscular patterns around the knee (namely the quadriceps and gastrocnemius) have been correlated with radiographic success.[28] Sagittal plane muscular firing patterns may strain the bony-cement/bony-implant interface and be associated with postoperative loosening.

3.4. Gait analysis as a tool in predicting clinical outcomes

3.4.1. General

Our literature search revealed fifteen articles that utilized gait analysis as a clinical tool. Of these, five articles were level of evidence I, nine articles were level of evidence II, and one article was level III (see Table 5.)

Articles were included in this section if they had a gait analysis both preoperatively and postoperatively and a patient-reported outcome both preoperatively and postoperatively.

3.4.2. Clinical results

Debbi et al. demonstrated that peak knee adduction angle and knee adduction impulse were associated with a decrease in Visual Analog Scale (VAS) pain scores. Other kinematic and kinetic parameters concerning the knee have been identified in other studies with clinical results. Orishimo et al. demonstrated that peak varus angle and adduction moment improved postoperatively.[29] The

Table 3
A summary of the published literature studying 'other' (outside of approach, technique, or implant choice) in total knee arthroplasty. Rows 1 and 2 concern the unicompartmental knee arthroplasty (**Section 3.2.1**) and Rows 3−5 concern postoperative physical therapy protocols (**Section 3.2.3**).

Lead Author	Year	Journal	Institution	Study Purpose	Study Type	Level of Evidence	Number of Patients	Length of Follow-Up
Van Hemert + T1	2009	Eur J Orthop Surg Traumatol	Department of Orthopedic Surgery and Traumatology, Atrium Medical Centre	To establish the functional differences and patient perceptions between unicompartmental and total knee replacement.	Prospective cohort study	II	TKR = 52 Meniscal = 24 Total = 76	52
Blyth − T2	2017	Bone Joint Research	Glasgow Royal Infirmary, Glasgow, United Kingdom	To explore reports of the early clinical outcomes of robotic arm-assisted unicompartmental knee arthroplasty (UKA).	Randomized controlled trial	I	Total = 139	52
Heikkila + T1	2017	Gait and Posture	Department of Orthopaedic Surgery, Central Finland Central Hospital	To evaluate the effects of surgery and a postoperative progressive home exercise program on gait parameters among individuals recieving TKA.	Single blinded randomized controlled trial	I	Exercise group (EG) = 53 Control group (CG) = 55 Total = 108	52
Debbi + T1 * Also appears in Table 5	2013	Osteoarthritis and Cartilage	Biorobotics and Biomechanics Lab, Technion Israel Inst. of Technology, Haifa, Israel;	To assess a biomechanical foot-worn therapy after TKA.	Randomized controlled trial	I	Total = 50	52
Taniguchi - T2	2020	Modern Rheumatology	Human Health Sciences, Graduate School of Medicine, Kyoto University	To compare self-efficacy and the recovery of mobility following TKA.	Prospective cohort study	II	Total = 104	26

A '+' in the column 'Lead Author' denotes presence of preoperative and postoperative gait analysis.
A '-' in the column 'Lead Author' denotes presence of postoperative gait analysis only.
A 'T1' in the column 'Lead Author' denotes classification as a Tier 1 article (see **Section 2.4**.).
A 'T2' in the column 'Lead Author' denotes classification as a Tier 2 article (see **Section 2.4**.).
An asterisk (*) in the column 'Lead Author' denotes inclusion in a table elsewhere. The other table is written underneath the asterisk if present.

Table 4
A summary of the published literature using gait analysis as a tool in predicting radiologic outcomes after TKA.

Lead Author	Year	Journal	Institution	Study Purpose	Study Type	Level of Evidence	Number of Patients	Length of Follow-Up
Wilson T2	2010	Acta Orthopaedica	School of Biomedical Engineering and Department of Surgery, Division of Orthopaedics, Dalhousie University, Halifax, Nova Scotia	To examine the association between the post-TKA stability of the tibial component with preoperative mechanical environment of the knee joint during gait,	Prospective Cohort Study[a]	II	Total = 37	52
Wilson T2	2012	Clinical Biomechanics	Department of Surgery, Division of Orthopedics, Dalhousie University, Halifax, Canada	To measure the pre-operative electromyography (EMG) patterns of the knee muscles during gait with the post-operative tibial implant migration.	Prospective cohort study	II	TKR = 52 UKR = 24 Total = 76	52

The '+' and '-' denotations used in the other subsections were not used in Table 3 (Section 3.3) given that these studies have a preoperative gait analysis that is correlated with some post-operative radiologic measure.
A 'T1' in the column 'Lead Author' denotes classification as a Tier 1 article (see **Section 2.4**.).
A 'T2' in the column 'Lead Author' denotes classification as a Tier 2 article (see **Section 2.4**.).
An asterisk (*) in the column 'Lead Author' denotes inclusion in a table elsewhere. The other table is written underneath the asterisk if present.
[a] This study represents a subset of patients from a clinical trial; however, does read most closely as a prospective cohort study.

improvement of KSS in this study lends credibility to the identified parameters. Liebensteiner et al. determined that maximum knee flexion in swing was positively correlated with Hospital for Special Surgery Knee-Rating Scores and KSS preoperatively.[30] While the concomitant change in these variables may lend some credibility to the established parameters, further efforts would be required to determine their clinical validity, if any.

Pedobarography may also play a potential role in predicting clinical outcomes after total knee arthroplasty. A recent prospective randomized controlled trial demonstrated that the weight distribution of the feet during walking is significantly different pre and post-operatively.[21] A concurrent increase in WOMAC and KSS scores was seen. Importantly, other temporospatial parameters were also noted to change post-operatively as confirmed by prior literature.[31–33] These all may play a role in predicting of clinical outcomes.

4. Discussion

In this scoping review of the literature, we identified a wide breadth of applications of motion analysis in studying total knee arthroplasty. Our literature review revealed a total of eleven, seven, two, and 15 articles that explored the role of gait analysis as a research tool to study operative decisions (section 3.1), other

Table 5
A summary of the existing literature studying gait analysis as a clinical tool in patients undergoing TKA. Usage as a ‘Clinical tool’ is defined as having obtained a gait analysis and a patient-reported outcome both preoperatively and postoperatively.

Lead Author	Year	Journal	Institution	Study Purpose	Study Type	Level of Evidence	Number of Patients	Length of Follow-Up
Debbi + T1 * Also appears in Table 3	2013	Osteoarthritis and Cartilage	Biorobotics and Biomechanics Lab, Technion Israel Inst. of Technology, Haifa, Israel;	To assess a biomechanical foot-worn therapy after TKA.	Randomized controlled trial	I	Total = 50	52
Apostolopoulos + T1	2011	Journal of Long-Term Effects of Medical Implants	1‘4th Orthopaedic Department, Askleipion Hospital, Athens, Vasileos Paylou 1, 16673 Voula, Greece	To capture and analyze the functional performance of a knee after TKA via kinetic and kinematic parameters.	Prospective Observational Study	II	Total = 20	36
Rajgopal + T1 * Also appears in Table 1	2016	Arthroplasty	Medanta Bone and Joint Institute, Medanta	To assess the differences in functional outcomes of two different polyethylene designs (cruciate-retaining and ultra congruent).	Prospective single-blind, single-surgeon randomized controlled trial	I	Total = 105	104
Orishimo + T1	2012	Clinical Orthopaedics and Related Research	Nicholas Institute of Sports Medicine and Athletic Trauma, Lenox Hill Hospital	To understand three different parameters surrounding gait as well as KSS scores following TKA.	Prospective Observational Study	II	15	52
Layher + T1 *also appears in Table 1	2015	Journal of Orthopedics and Trauma Surgery	Jena University Hospital	To investigate if the midvastus approach of TKA has a better functional outcome than the medial parapatellar surgical approach.	Single blinded, prospective, randomized study	I	Medial Parapatellar = 10, Midvastus = 11 Control = 53 Total = 74	26
Miozzari + T1 * Also appears in Table 1	2013	The European Journal of Medical Sciences	University Hospital of Geneve, University of Geneve	To determine is the use of a bone dependent technique influences patients' outcomes of gait, pain, function, quality of life, and satisfaction	Prospective Cohort Study	II	Independent bone cuts = 30 Dependent bone cuts = 10 Total = 40	52
Bonnefoy + T1	2020	Arthroplasty	Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals, Geneva University, Geneva, Switzerland	To determine whether Patient Acceptable Symptom State (PASS) or Minimal Clinical Important Improvement (MCII) could be prediected via gait parameters in patients who underwent a TKA.	Retrospective Cohort Study	III	Total = 79	52
Tibesku + T1 * Also appears in Table 1	2011	Knee Surg Sports Traumatol Arthrosc	Sporthopaedicum Straubing, Bahnhofplatz	To analyze patients that had received either a fixed or a mobile TKA via differences in gait analysis, electromyography, and clinical scores.	Prospective randomized clinical study	I	Fixed-bearing inlay = 17 Mobile-bearing inlay = 16 Total = 33	104
Berghmans + T1	2018	BMC Musculoskeletal Disorders	Department of Physical therapy, Maastricht University Medical Center	To systematically assess patients' functions, disabilities, and health before TKA and after on all International Classification of Functioning, Disability and Health domains.	Prospective cohort study	II	Total = 150	52
Solak + T1	2005	Arthroplasty	Clinic of Orthopedics and Traumatology, Dr. Mü Emergency Care and Traumatology Hospital, Balgat, Ankara, Turkey	To compare gait analysis before and after TKA to the parameters of normal knees.	Prospective randomized study	I	Double TKA = 24 Control = 12 Total = 36	104
Liebensteiner + T1	2008	The Knee	Department of Orthopaedic Surgery, Innsbruck Medical University, Innsbruck, Austria	To obtain information about the correlation between the outcome after TKA through the use of clinical scores and locomotion.	Prospective Cohort Study	II	Total = 30	12
Bonnefoy-Mazure + T1	2016	Arthroplasty	Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals, Geneva University, Geneva, Switzerland	To describe the evolution of kinematic and clinical outcomes of knee OA pre and postoperatively following TKA.	Prospective cohort	II	Total start = 118 Total Finish = 79	52
Bonnefoy-Masure + T1	2017	Arthroplasty	Willy Taillard Laboratory of Kinesiology, Geneva University Hospitals, Geneva University, Geneva, Switzerland	To investigate the effects of body mass index on gait parameters preopand 1 year following a TKA.	Prospective Cohort study	II	Total = 79	52
	2018	Gait and posture	Machine Learning and Data Analytics Lab, Department of		Prospective Cohort Study	II	Total = 24	52

(continued on next page)

Table 5 (*continued*)

Lead Author	Year	Journal	Institution	Study Purpose	Study Type	Level of Evidence	Number of Patients	Length of Follow-Up
Kluge – T1			Computer Science, Friedrich-Alexander University Erlangen-Nürnberg	To determine if it was possible to perform an accurate gait assessment in knee OA patients following TKA.				
Hiyama + T2	2017	Knee Surgery	Department of Physical Therapy, School of Health Sciences, Tokyo University of Technology, Ota-ku, Tokyo, Japan	To describe the time course of mobility and to identify the factors affecting it after TKA.	Prospective cohort study	II	Total = 62	26

A '+' in the column 'Lead Author' denotes presence of preoperative and postoperative gait analysis.
A '-' in the column 'Lead Author' denotes presence of postoperative gait analysis only.
A 'T1' in the column 'Lead Author' denotes classification as a Tier 1 article (see **Section 2.4**.).
A 'T2' in the column 'Lead Author' denotes classification as a Tier 2 article (see **Section 2.4**.).
An asterisk (*) in the column 'Lead Author' denotes inclusion in a table elsewhere. The other table is written underneath the asterisk if present.

research applications for motion analysis in total knee arthroplasty (section 3.2), gait analysis as a tool in predicting radiologic outcomes (section 3.3), gait analysis as a tool in predicting clinical outcomes (section 3.4), respectively.

Our purposes were to identify the current applications of motion analysis and to identify any predictive abilities of gait analysis with regard to outcomes after total knee arthroplasty that may exist in the current literature. Only a small fraction of the literature contains a gait analysis study both preoperatively and postoperatively, a clinical score both preoperatively and postoperatively. Of the select articles that have a motion analysis study performed both preoperatively and postoperatively, some articles do have a functional outcome, clinical outcome, or radiographic outcome, but seldom all three.

A handful of studies do demonstrate gait analysis parameters that are associated with clinical outcomes after total knee arthroplasty.[8,34,35] Quadriceps weakness,[8,10] gait speed,[8,10,36] cadence,[33] step length,[33] have all been identified as related to outcomes after TKA. However, the correlation of 3D kinematic or kinetic data with clinical outcomes after total knee arthroplasty is sparse in the literature.[25,29,36]

It is important to recognize the work of Pua et al.[37] concerning the purpose of this scoping review. These authors found that a clinical composite score composed of clinical and demographic could predict walking limitations in patients undergoing total knee arthroplasty. These authors did utilize gait speed as a functional measure; however, their scoring system did not utilize any kinematic, kinetic, or pedobarographic data. Given the ever-changing landscape concerning implant choice and patient-specific implantation in total knee arthroplasty, the incorporation of 3D preoperative gait analysis data could potentially increase the predictive ability of such a scoring system. However, the current literature does not readily allow for that.

Older age,[10] female gender,[10,37] sedentary behavior,[35] higher body mass index (BMI),[37,38] and contralateral knee pain,[37] have been identified as related to functional outcomes after total knee arthroplasty. Demographic and clinical variables as such are significantly easier to collect preoperatively and may have more utility for the clinician in determining candidacy for total knee arthroplasty. Another important next step towards building a clinical composite score would be a systematic review focused on identifying the demographic and clinical factors associated with functional outcomes after total knee arthroplasty.

While our search did demonstrate two promising studies in the regard to the radiologic success of the tibial component in TKA, it is important to note that other demographic and surgical parameters were also found to correlate with tibial component migration. These include implant type and BMI.[39] Thus, it may be so that though motion analysis parameters could play some role in the tibial component migration, demographic and surgical variables could also have a potential predictive role. Further research would be needed before a clinical scoring system based on demographic, surgical, and migration with validated variables from level I evidence could be built.

Of note to this is patient-specific implantation in total knee arthroplasty. Patient-specific implantation has emerged in many subdisciplines with orthopedics with the potential to customize implants, improve surgical accuracy, and improve patient outcomes. Within knee arthroplasty, patient-specific implantation has emerged in both the realms of the UKA and TKA. Of note, to this discussion is the potential role that motion analysis may play as we learn more about the future of patient-specific implantation. Motion analysis represents an in-depth, three-dimensional understanding of the function of the extremity after surgery. When studying the success of patient-specific instrumentation in achieving its goal, that is in restoring the alignment of the extremity and restoring function, motion analysis can be an important outcome in doing so.

Our literature search revealed two articles that directly used motion analysis to study patient-specific implantation. The first of these articles demonstrated that a computer-assisted surgery technique when utilized with a minimally invasive technique was associated with a quicker time to restoration of both kinematic and kinetic gait parameters.[40] This highlights the role that motion analysis may have in studying patient-specific instrumentation. The second of these two articles demonstrated that the knee adduction moment preoperatively was associated with the knee abduction angle as measured intraoperatively during computer-assisted surgery.[41] This can be correlated with prior literature that demonstrated the significance of the adduction moment in terms of postoperative tibial component migration.[28] This study also further highlights the potential role of motion analysis as a research tool as we continue to learn more about patient-specific instrumentation.

It is also important to discuss the effect that gait training may have on patients undergoing TKA. As the goal of knee reconstruction is to restore form and function to the lower extremity, motion analysis can be a valuable tool in determining the success of postoperative rehabilitation. There is evidence to suggest that integration of gait training into rehabilitation can be beneficial. Though not central to the purpose of our scoping review, this does represent another potential application of gait analysis in the realm of total knee arthroplasty.

4.1. Limitations

Our literature search revealed a total of 279 articles, of which the vast majority did have the term ‘gait analysis' or ‘motion analysis' in the title or abstract. However, upon further screening, it was noted that the majority of these articles use visual gait descriptors instead of data collected from motion capture systems. It is possible that due to different descriptors of motion capture technology that our keywords may have been substantially different than some of the published literature. Further, a vast majority of the existing literature does not have both a preoperative and post-operative motion analysis. This reflects the fact that a majority of these are primarily research studies that utilize gait analysis to study a tertiary research question. Lastly, there is variability in terms of the methodology and quality of studies.

5. Conclusions

There is a wide breadth of application of gait analysis in total knee arthroplasty within the clinical domain and the research domain. Gait analysis has demonstrated great potential as a research tool that can help guide many surgical decisions including approach, technique, and component choice. Gait analysis may also be valuable in studying other care-related decisions including optimal modes of physical therapy. However, due to an absence of both preoperative and postoperative clinical data in the majority of literature, many studies are unable to draw inferences regarding the causality of specific motion analysis parameters with overall success or failure. Articles that contain all of the following: preoperative gait analysis, postoperative gait analysis, radiologic, clinical, and functional outcomes may be able to do so. The following motion analysis parameters may be correlated with clinical outcome after TKA: knee adduction moment, knee adduction impulse, total knee range of motion throughout the gait cycle, varus angle, cadence, stride length, and gait velocity. A systematic review aimed at determining the psychometric properties of these variables is warranted.

6. Future scope

The results of the present study highlight the potential for the identified parameters regarding integration into a composite clinical scoring system. Future directions include improvement in the definition of “gait analysis” and “motion analysis” as used in knee reconstruction studies to specify the use of modern 3-dimensional motion analysis technology, the inclusion of both preoperative and postoperative clinical outcomes in studies utilizing motion analysis, and a systematic review aimed at determining the sensitivity, specific, positive predictive value, and negative predictive value of the identified parameters.

CRediT roles

Conceptualization N.V.; C.L.; K.S.; Data curation N.V.; C.L.; Formal analysis N.V.; C.L.; K.S.; Funding acquisition N/A; Investigation N.V.; C.L.; K.S.; Methodology N.V.; C.L.; K.S.; Project administration N.V.; K.S.; Resources N.V.; C.L.; K.S.; Software N.V.; C.L.; K.S.; Supervision K.S.; Validation N.V.; C.L.; K.S.; Visualization N.V.; C.L.; K.S.; Roles/Writing - original draft N.V.; C.L.; K.S.; Writing - review & editing N.V.; C.L.; K.S.;

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In this scoping review that followed the PRISMA-ScR checklist, the major contributions to the work are the determination of the motion analysis parameters for which a diagnostic test accuracy systematic review (DTA-SR) is warranted.

Declaration of competing 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.

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