Review Article

Gait analysis methodology for the measurement of biomechanical parameters in total knee arthroplasties. A literature review

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ABSTRACT

Gait analysis using external skin markers provides scope for the study of kinematic and kinetic parameters shown on different total knee arthroplasties (TKA). Thus an appropriate methodology is of great importance for the collection and correlation of valid data. Calibration of equipment is of great importance before measurements, to assure accuracy. Force plates should be calibrated to 1080 Hz and optoelectronic cameras should use 120 Hz frequency, because of the nature of gait activity. Davis model which accurately defines the position of the markers is widely accepted and cited, for the gait analysis of TKA's. To ensure the reproducibility of the measurement, a static trial at the anatomical position must be captured. Following, all acquisitions of dynamic data must be checked for consistency in walking speed, and abnormal gait style because of fatigue or distraction. To establish the repeatability of the measurement, this procedure must be repeated at a pre-defined number of 3–5 gait cycles. Anthropometric measurements should be combined with three-dimensional marker data from the static trial to provide positions of the joint's center and define anatomical axes of total knee arthroplasty. Kinetic data should be normalized to bodyweight (BW) and percentage of BW and height depending on the study. External moments should also be calculated by using inverse dynamics and amplitude-normalized to body mass (Nm/kg). Gait analysis using external skin markers provides scope for the study of biomechanical parameters shown on different TKAs. Thus a standard gait analysis methodology when measuring TKA biomechanical parameters is necessary for the collection and correlation of accurate, adequate, valid and reproducible data. Further research should be done to clarify if the development of a specific kinematic model is appropriate for a more accurate definition of total knee implant joint center in measurements concerning 3D gait analysis.

1. Background

Both joint kinematics and joint kinetics are important input parameters for total knee arthroplasty wear testing according to International Organization for Standardization (ISO), (ISO 14243-3, ISO 14343-1).^{1,2} Gait analysis measurements can sufficiently provide these data to scientists. Such parameters can also be correlated to in vitro data (input waveforms) in order to address wear and longevity as well as to provide an integrated aspect for the development of total knee implant designs. Especially in case of knee prosthesis, the behavior of the joint in transversal plane may represent a crucial factor, because the modern knee prosthesis are focused in stabilizing the knee and allow the most natural movements, such as rotation.^{3,4} Thus the measurement of biomechanical parameters in all three planes is equally important to

identify the actual behavior of the arthroplasty and contribute to a more precise design of the implant.

Knee implants development over the past decade has been greatly advanced in designs and the presence of polyethylene bearings has resulted in superior resistance to wear. The polyethylene bearing is one of the major factors involved in wear performance of the knee. More specifically the method of forming the bearing, the choice of polyethylene resin, the sterilization method of choice, any post-sterilization heat treatments and the shelf aging of the polyethylene bearing before implantation, can majorly affect wear performance. Obvious improvements have been made in the polyethylene bearings as a result of sterilization with the use of radiation in an inert environment or with non-irradiation sterilization methods. However, controversy remains over whether it is preferable to highly-crosslink polyethylene bearings

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in an effort to obtain maximum wear resistance or to use of non-crosslinked polyethylenes to maintain better mechanical properties such as tensile strength and fatigue resistance. Wear can be clinically assessed either from radiographic studies of ongoing patients or from laboratory simulations or through biomechanical assessment such as gait analysis. All of the above represent very demanding tasks and the more exacting the method the fewer number of patients or follow-up duration.

From a biomechanical point of view it would be interesting to study whether wear rate for walking combined with stair climbing would be more severe than for normal walking tests. In such a study, Cottrell et al.⁵ compared NexGen CR Augmentable (CR) to 5 NexGen Legacy PS (LPS: Zimmer, Warsaw). All specimens were 25 kGy gamma/N2 tibial inserts. Three wear tests were conducted: one using standard gait (ISO 14243-1) and two using a combination of gait plus stairs. The authors concluded that higher wear rates were present in standard gait compared to gait with added bouts of stair climbing. Therefore normal walking appeared to be the best estimate for a 'worst case' scenario. Thus our literature review examined studies that approached the biomechanics parameters of TKA's using gait analysis, that being the most important daily activity for humans.

Gait analysis using external skin markers provides scope for the study of kinematic and kinetic parameters shown on different total knee prostheses. Patients after TKA show altered gait mechanics that developed prior to, or soon after surgery.⁶ Patients with TKA walk slower, have less knee flexion excursion during stance, demonstrate lower peak knee flexion during swing phase and altered sagittal plane knee moments compared to controls (Fig. 1).^{7,8}

Previous studies examined level walking patterns in TKA patients.^{9–12} Two recent reviews concluded in agreement that TKA patients walk with a characteristic pattern that differs than that of asymptomatic healthy controls.^{13,14} When walking at a self-selected speed, TKA patients walk with decreased speed, have shorter stride length, and decreased single support. Kinematic abnormalities are characterized by decreased flexion in both stance and swing. A dynamic and proper knee flexion in weight acceptance (early stance) and before lift-off (late stance) is important to propel smoothly the entire body in the changes of balance between stance and swing phases.¹¹

Gait analysis after total knee arthroplasty has been assessed in two systematic reviews over the past few years.^{15,16} These have shown consistently reduced total range of motion in the knee, and reduced range of flexion during stance. There are also indications of knee kinetics alteration, with only one out of three TKA patients in the studies exhibiting a biphasic pattern of sagittal plane moments. More recently, similar results have been reported for reduced knee angle during stance phase, but detailed musculoskeletal modelling has shown that the forces and extension moments developed by the quadriceps are reduced in early stance in TKA.¹⁷ All systematic reviews assessed the findings of the studies without focusing on the gait analysis methodology followed for the data capture.

When an accurate and adequate methodology is followed to minimize as much as possible all sources of errors referred in bibliography, gait analysis procedure can sufficiently calculate the kinematic and kinetic parameters of TKA's. Thus the purpose of this literature review is to provide an in depth evaluation of the gait analysis methodology followed by researchers for the study of the biomechanical behavior of TKAs.

2. Literature review-Body

In our literature review we tried to identify the basic principles of gait analysis methodology followed by researchers for the assessment of TKAs.

A literature review search database of Pubmed, Medline, EMBASE, AMED and CINAL was conducted using the following relevant keywords and phrases that describe relevant studies: Gait analysis, Total knee arthroplasty, Total knee replacement, Kinetic analysis, Kinematic analysis, Force plates, Optoelectronic cameras, Motion analysis, Gait analysis methodology, TKA biomechanics.

All research teams used clinical evaluation tools prior to data collection. Radiological examination is one of the most common methods used. Wilson and colleagues¹⁸ used radiostereometric analysis (RSA) and double clinical examination of the subjects to ensure accuracy according to Valstar directions.¹⁹ The importance of radiological examination^{20,21,22} lies on the fact that it can accurately evaluate the alignment of the knee and the femoral and tibial component positions.

Fig. 1. Kistler force plates calibration.

Table 1
The knee society clinical score.

Objective scoring	Score
Pain	
None	50
Mild or occasional	
Stairs only	45
Walking and stairs	30
Moderate	
Occasional	20
Continuous	10
Severe	0
Range of motion (5° = 1 point)	25
Stability	
Anteroposterior	
< 5 mm	10
5–10 mm	5
> 10 mm	0
Mediolateral	
< 5°	15
6–9°	10
10–14°	5
15°	0
Flexion contracture	
5–10°	–2
10–15°	–5
16–20°	–10
> 20°	–15
Extension lag	
< 10°	–5
10–20°	–10
20°	–15
Alignment	
0–4°	0
5–10°	3 points each degree
11–15°	3 points each degree

The position of the joint line was determined in anteroposterior films by calculating the distance between the tip of the fibular head and the distal margin of the lateral femoral condyle at 2–3 years post-operatively.²³

The examination of knee range of motion through a standard goniometer took place in almost all studies to ensure that all subjects are suitable for 3D gait analysis examination.

The knee society score (Table 1.) was commonly used as clinical evaluation test^{22,24} too. The test is based on clinical parameters that evaluate pain, range of motion, and stability in the coronal and sagittal plane. It also offers deductions for flexion contractures, extension lag, and misalignment.

Wegrzyn et al.²⁴ assessed knee function postoperatively by evaluating pain, patient's function and knee motion. Apart from the Knee Society Score (KSS),²⁵ they used a number of clinical evaluation scores prior to gait analysis (SF-12,²⁶ Knee Injury and Osteoarthritis Outcome Score (KOOS) and UCLA activity^{26,27}).

Yoshida et al. in 2013²⁸ examined the relationship between the performance of the musculature crossing the knee during loading response in early walking and the persistent quadriceps weakness observed in patients subjected to TKA. The parameters were measured by using gait analysis and the clinical evaluation included besides the examination of active knee ROM, the self-report questionnaires – SF-36 which is used to assess the patients' health-related quality of life.^{17–20} The same researcher³³ in another gait analysis study of patients undergone total knee arthroplasty, followed the same clinical evaluation methodology and additionally used performance-based functional testing that included the timed up-and-go test (TUG), the stair-climbing test (SCT), and the 6 min walk test (6MW).

Finally Hatfield et al.,²¹ studied the gait pattern of TKA patients by using 3D gait analysis system. They evaluated their subjects through

standard, weight-bearing anteroposterior and lateral radiographs.³⁴ Their patients were also assessed through a self-reported pain and function at baseline (and at follow-up in the no-TKA group) by using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC).³⁵

Calibration of the equipment used in gait analysis seemed to be important in every study. A few researchers, performed calibration of the laboratory coordinate system (global coordinate system) with respect to the kinematic (optoelectronic cameras') and kinetic (force plates') coordinate system following the calibrating process of the corresponding manufacturer. Two more studies^{22,36} refer such a procedure to assure the accuracy of the measurements as well as to use these data for the computation of each marker's 3D coordinates.

In three dimensional gait analysis the frequency of the optoelectronic cameras and force plates that are used has to be set to a range that corresponds to the measured activity. Hans Gerber³⁷ at his study used Kistler force plates and Vicon motion analysis system. The force data were sampled at 1000 Hz. It is mentioned that when the above range of frequency is combined with the center of pressure of the force and corrected by the method introduced by Dettwyler,³⁸ the accuracy increased to less than ± 1 mm on the surface of the plate. The sampling frequency of the cameras corresponds to a maximum of 500 Hz. And thus the accuracy of the system in the measuring volume was ± 1 mm.

Although in most studies the kinetic equipment was set to a frequency close to 1 kHz (range 1000–1080 Hz)^{22,28,33,39} as in Gerber's study, the cameras system's frequency was set in a magnitude different than 500 Hz. Most researches used 100–120 Hz for the kinematic data capture. According to our opinion this range seems to be more reliable for the data capture of gait study, when the acquisitions are performed at the comfortable velocity of the subject.

The most important anthropometric data that are usually collected refer to body mass and body height, knee and ankle joint diameters as well as ASIS distance and pelvic depth, the later measured with a caliper.^{22,28,33} When combined with the kinematic protocol (marker placement) and the static calibration trial, these data can accurately identify joint centers.

The basic concept of a kinematic data model is standardization. Davis model provides an input for the markers' position and is widely accepted and cited, for the gait analysis of TKA's.^{40,41,42} The necessary markers that should be placed when Davis protocol is used for the kinematic and kinetic data collection that concerns the TKA joint are:

- 1 marker at each anterior superior iliac spine (ASIS), placed directly over the anterior superior iliac spine,
- 1 marker at the sacrum on the skin mid-way between the posterior superior iliac spines (PSIS),
- 1 marker at each greater trochanter.
- 1 marker at each external femoral condyle attached on the lateral epicondyle of each knee femoral component,
- 1 marker at each peroneus head.
- 1 marker at each lateral malleolus placed on an imaginary line that passes through the transmalleolar axis,
- 1 marker at each head of the fifth metatarsal placed over the fifth metatarsal head and
- 1 marker at each heel. This is placed only for the static trial calibration acquisition on the calcaneus at the same height above the plantar surface of the foot as the toe marker.
- Finally 1 thigh wand is used for each femur that is placed on each leg over the lower lateral 1/3 surface of the thigh, just below the swing of the hand. (The antero-posterior placement of the marker is critical for correct alignment of the knee flexion axis. The position of the marker should be in alignment with the plane that contains the hip and knee joint centers and the knee flexion/extension axis.) and
- 1 tibial wand for each tibia. Similar to the thigh markers, these are placed over the lower 1/3 of the shank to determine the alignment of the ankle flexion axis (The tibial marker should lay in the plane

that contains the knee and ankle joint centers and the ankle flexion/extension axis.)

Most researchers used Davis protocol marker placement to identify joint centers usually adding a set of three to four markers attached on an extra rigid thermoplastic shell. Such shells were placed in particular key anatomic positions to ensure an accurate joint center definition by minimizing the markers' movement artifacts.

Following the appropriate standardized kinematic protocol all researchers proceeded to the static trial calibration procedure.^{21,28,33,39} The collected data ensure the reproducibility of the measurement procedure and minimize errors reported in the literature,⁴³ regarding video capture of external skin markers. A static trial at the anatomical position was captured to ensure that all segments could be correctly reconstructed, before collection of the dynamic trials' data that were used at the statistical analysis. The data from this trial were used as reference for the calculation of the joint centers and anatomic angles. The participants were instructed to stand in the anatomic position on one of the two force plates, with their feet parallel and 15 cm apart. The static trial procedure allowed for correction of markers' misalignment. Furthermore, the data from this trial were used as a reference for the definition of zero degrees for the segmental movements in all planes.

Hatfield²¹ proceeded to estimate frontal plane alignment. It was calculated by using motion-captured data from a standing calibration trial as the angle formed between 1) the line connecting the anterior superior iliac spine (ASIS) and the center of knee joint and 2) the line connecting the knee and ankle joint centers. In a subset of 35 participants, this angle measure was found to correlate well with alignment obtained from standing full-leg radiographs.

A predefined number of dynamic trials were used in all studies for the kinematic and kinetic data collection. A successful trial is defined as a trial in which the subjects contacted opposing force platforms with each foot, without evidence of targeting. A minimum of three trials is necessary for the repeatability of the measurements. The number of acquisitions that researchers used in our literature review varied from three to ten complete gait cycles, always following these guidelines.

It is necessary for data expression of gait analysis to consider and accept the subjects as rigid bodies. Yoshida calculated the joint angles using rigid body analysis employing Euler angles and so did all researchers. The net joint moments of the hip, knee and ankle calculated with an inverse dynamics procedure,⁴⁴ and always normalized to body mass and the anatomical joint coordinate system as described by Grood and Suntay.⁴⁵ Kinematic and kinetic data are also time-normalized with regard to the gait cycle. Thus all measurements express internal data (that applied to the subject's body).

3. Conclusions

The collection of reliable kinetic and kinematic data with the use of optoelectronic cameras and force plates during gait in patients subjected to TKAs is of great importance for total knee implant designs development. The purpose of this literature review was to highlight the most important aspects of gait analysis methodology referred in bibliography. In this study we concluded that gait analysis researches for the measurement of biomechanical parameters of TKAs followed the same methodology as in normal subjects. An important issue is that no specific mention was found about the TKA joint center definition. It seems that all researchers assumed that the anthropometric measurements when combined with the static trial calibration data and the kinematic model used, can accurately calculate the artificial joint's center and consequently therefore the kinematic and kinetic data are considered to be reliable. It is widely accepted that total knee implants show substantial differences from the normal knee joint biomechanics as well as differences exist among different types of implants (fixed bearing, mobile bearing, etc). Thus further research should be done to clarify if a specific kinematic model should be developed with respect to

total knee implant designs specifications when biomechanics parameters are studied through gait analysis.

The importance of gait analysis as a tool for the biomechanical study of total knee implants is clearly identified in many researches. The nature of gait activity requires specific frequency range and calibration of the equipment used. The concept of a standard kinematic data model is an integral part of gait analysis and the development of a specific model for the TKAs joint center definition might be the key factor that would lead to more accurate data collection. To ensure the reproducibility of the measurement a static trial at the anatomical position should be captured, before dynamic acquisition, and combined to anthropometric measurements. This procedure is crucial since it allows for the accurate definition of the joint center and the correction of errors regarding the markers placement. Furthermore the data from the static calibration should correlate to the clinical evaluation test, such as the radiographs, so as to provide a more accurate definition of the joint centers. A predefined number of three to ten dynamic acquisitions should be followed according to all research studies to ensure more reliable data. Finally the kinetic data should be calculated by using inverse dynamics so as to concern forces acting to the subject. Amplitude-normalization to body mass and height should be followed to ensure that the results can be interpreted to population.

The necessity of total knee implant research for the determination of its biomechanical behavior is unquestionable. Several methods have been used to predict the longevity and identify the wear mechanisms that affect TKAs. As new implant designs evolve and other improvements take place, researchers and scientists involved should focus in achieving increased longevity and improved patients' function, especially among younger patients. Obviously there is a relationship between the longevity of the implant and the functional use of the joint in a patient's everyday life, since that use reflects the loads and the range of motion that the joint is subjected to. In addition, ultimate breakdown of the prosthesis depends upon these same loads.⁴⁶ An accurate way to estimate longevity is via the number of TKAs that require revision each year. Most current data suggests that knee replacements have an annual failure rate between 0.5–1.0%. This adds up to a 90–95% chance of 10 years, and 80–85% of 20 years longevity. Improvements in technology, may improve these rates.

External knee moments (a representative value for load) have been correlated to the medial and lateral wear scar areas of TKA's since 1986.⁴⁷ Nowadays two separate standards for knee joint prosthesis wear testing are recommended from the International Organization for Standardization (ISO). Input based on joint kinematics is described by ISO 14243-3. ISO 14343-1 determines forces as input for TKA wear testing too.^{1,2} These kinematic and kinetic parameters constitute a significant piece of the biomechanics mosaic since they can be combined with several input waveforms and functional data analysis to provide an integrated insight into wear study and therefore implant longevity. Gait analysis using external skin markers provides scope for the study of these biomechanical parameters shown on different total knee prostheses. Thus a standard gait analysis methodology when measuring TKA biomechanical parameters is necessary for the collection and correlation of accurate, adequate, valid and reproducible data. Further research should be done to clarify if the development of a specific kinematic model is appropriate for a more accurate definition of total knee implant joint center in measurements concerning 3D gait analysis.

Conflict of interest

No author associated with this paper declare that they have any conflict of interest.

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Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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