SN Comprehensive Clinical Medicine (2024) 6:6
https://doi.org/10.1007/s42399-023-01635-5

REVIEW

Gait Analysis Technologies for Measurement of Biomechanical Parameters of Knee Osteoarthritis

Priyanka Choursiya[1] · **Zubia Veqar**[2] · **Zainy Khan**[2] · **Tarushi Tanwar**[2] · **Iram Iram**[2] · **Mosab Aldabbas**[3]

Accepted: 19 December 2023

Abstract

Knee osteoarthritis (KOA) is a progressive degenerative joint disease. This degenerative process leads to an alteration in the gait mechanics. There are varieties of methods that can be used to evaluate these gait differences. The purpose of this review is to critically analyze the research findings and to outline strategies for evaluating gait anomalies in KOA, including observational, vision-based, and sensor-based and hybrid gait assessment technologies. The gait analysis, carried out by these methods, enables the implementation of procedures suited to patients' particular need is discussed. In all indices, the advantages and drawbacks of the available tools will be addressed after a concise description of the methods and the implementations in the KOA patients. The quantitative methods, categorized as vision, sensor-based, and hybrid technologies, have features that make them powerful and competitive for various types of requirements. Among these technologies, hybrid technology seems to be the most reliable and accurate because it can assess all aspects of gait assessment. Future studies should be done to develop a KOA gait dataset available publicly, consider all severity levels and all compartment KOA.

Keywords Gait analysis technologies · Wearable sensors · Hybrid system · Optoelectronic system · Knee osteoarthritis

Background

Knee osteoarthritis (KOA) is a degenerative joint disease with a global prevalence of 16.0% in individuals aged 15 and over and 22.9% in individuals aged 40 and over, incidence of 203 per 10,000 person per year in individuals aged 20 and over, and the ratios of prevalence and incidence in females and males of 1.69 and 1.39, respectively [1]. A prevalence of 28.7% was found in Indian population with higher prevalence in villages (31.1%) and big cities (33.1%) as compared to towns (17.1%) and small cities (17.2%) [2]. The degenerative changes associated with KOA lead to biomechanical changes which eventually lead to an alteration in the gait. These patients attempt to unload the affected joint while walking by developing altered gait habits and hence have more swing phase than stance phase. The gait of patients with KOA is often distinguished by a higher knee adduction moment, a medial joint load marker, and a recognized risk factor for arthritis progression [3]. The altered gait pattern leads to changes in the kinematics, kinetics, and spatiotemporal gait parameters [4] and linked with KOA growth and progression. It is thought that abnormal gait can be a cause and effect of KOA and these abnormal gait patterns can be used as a diagnostic index [5]. Therefore, gait analysis becomes an essential tool as it provides better understanding of biomechanical abnormalities related to development and progression of KOA. It also leads to a better planning and designing of the therapeutic program [3] for the patients as gait correction becomes one of the primary goal.

✉ Zubia Veqar
veqar.zubia@gmail.com

Priyanka Choursiya
5priyankachourasiyampto@gmail.com

Zainy Khan
khanzainy131@gmail.com

Tarushi Tanwar
tarushitanwar@gmail.com

Iram Iram
iram.physio@jmi.ac.in

Mosab Aldabbas
mosab.m.aldabbas@gmail.com

[1] Fortis Hospital, Shalimar Bagh, Delhi 110088, India

[2] Centre for Physiotherapy and Rehabilitation Sciences, Jamia Millia Islamia (Central University), New Delhi 110025, India

[3] Al-Azhar University, Gaza, Palestine

Different methods for assessing gait are present in the literature. These methods vary from basic visual observation to video images to more computer-based 3D approaches that are more comprehensive. Technological developments have contributed to the rise of wearable sensors, and hence it is possible to capture and analyze gait beyond traditional gait laboratories with these sensors [6]. Although gait assessment is essential in assessment and management of gait in KOA, there are marked discrepancies in the methods used by researchers to analyze gait. Therefore, this literature review provides an in-depth critical analysis of the current methodologies for gait analysis in KOA.

Method

A literature review search was conducted (till 30 September 2020) on the database of PubMed, Science Direct, Google Scholar, and Web of Science using keywords: gait analysis technologies, knee osteoarthritis, wearable sensors, hybrid system, optoelectronic system. This narrative review includes literature data from randomized controlled trials and from review articles, summarizing the studies which include gait assessment in KOA patients. This article discusses common gait technologies used for KOA and the significance of this specific field of research, focusing on KOA gait. In this article, available gait technologies are briefly introduced by reflecting on the benefits and drawbacks of the technologies.

Observational Gait Assessment (OGA)

It is the most common method used to assess gait in clinical practice. The advantage of this method is that it does not require any equipment which can be an important consideration for clinical practice. But, this method is inadequate in providing quantitative data which affects its accuracy and reproducibility of the measurements. Thus, minor gait alterations could be undetected and the research appropriate data is unattainable. In comparing 3D gait analysis and OGA in KOA, Taş et al. [4] recorded the lowest rate of agreement in both validity ($r=0.06$, $p>0.05$) and inter- (ICC − 0.12–0.06) and intra-observer (ICC 0.30–0.45) OGA reliability. Various factors reduce the validity and reliability of OGA such as unclear gait disorders, joint stiffness which lead to inconsistent gait pattern, and high BMI [4]. All these limitations discourage the use of this method for scientific research purposes. With the advancement in technology, various gait analysis methods which facilitate effective diagnosis and treatment of KOA have been developed and provide accurate quantitative based on different gait parameters.

Common Technologies Used in Gait Analysis of KOA

Current gait technologies used for gait assessment of KOA can be discussed under three distinct types: vision-based, sensor-based, and hybrid/combination [7].

Vision-Based Gait Assessment

This method involves the use of optoelectronic system. It is a type of optical sensor that uses digital cameras to detect human movement and thus estimate motion parameters and orientation more accurately [7]. Vision-based modality is classified into two categories based on application of markers: marker-based and markerless. In marker-based modality, several active or passive retro-reflective markers are attached on the body landmarks that specify joint angles. To detect the position of indicated body landmarks, video-based optoelectronic devices such as VICON [8] and Qualisys [9] are then used. A research was carried out by Ishikawa et al. [5] to determine the angle of elevation during gait in KOA and healthy subjects. A plug-in-gait marker collection (eight markers) and nine VICON cameras were used. Results revealed that planar law was applicable to patients and obtained improved precision 0.69 ± 0.14, (curved area) AUC 0.69 ± 0.767, accuracy = 0.84 ± 0.23, recall 0.57 ± 0.26. This study shows that gait motion evaluation using elevation angle offers a valid diagnosis metric for KOA with a single index [5].

Markerless modality uses only single camera such as Kinect V2 [10] and no markers are attached on patient's body. For effective and precise gait analysis of KOA patients, Cui et al. [11] used markerless modality using a single Kinect sensor consisting RGB-D camera to capture the depth details of patient body joints. They suggested that applying support vector machine—a machine learning method for classification—results in Kinect's high efficiency in KOA diagnosis with a 97% accuracy rate [11].

Optoelectronic system produces tremendous amount of gait data. Analysis and reduction of this data is a barrier to clinical use of gait information. Deluzio et al. [12] conducted a gait study in KOA and healthy subjects to assess difference in gait pattern using optoelectronic system. Principal component analysis was used for gait data reduction and explanation. The main purpose of principal component analysis is to summarize the most important information in the gait data. The principal component waveform analysis technique used in this study identified gait pattern differences in the knee flexion angle, the knee adduction moment, and the knee flexion moment [12]. Similarly, Federolf et al. [13] identified systematic gait differences between healthy and patients with medial KOA using principal component analysis. Machine learning approaches such as principal component analysis and support vector machine can provide insight into complex relationships of biomechanical gait variables, as compared to multiple univariate analysis methods [14]. Optoelectronic system provides robust and precise acquisition of physical movements over virtual modeling [15]. But this system needs special setup for experiment, expensive to conduct, and need to combine with other methods for effective gait assessment.

Sensor-Based Gait Assessment

Sensor-based devices for gait assessments are classified into two categories: non-wearable sensors and wearable sensors [16]. Table 1 provides a description of these sensors.

Non-wearable Sensors

The patients walk on a clearly marked walkway on which sensors are embedded and gait data is captured [16]. These sensors are useful for gait assessment as they calculate forces derived from foot-to-ground contact while the patients walk on them [7] which is especially helpful in identifying faulty contact forces. It includes force plates, electronic and pressure mats, and instrumented treadmill. As the patients walk on them, these methods quantify forces and translate them into electrical signals for the measurement of the center of pressure and ground reaction forces [16]. The floor sensors have no direct attachment on subject body. However, they are suitable only for laboratory and need to combine with limb kinematics for gait analysis [15]. Two Kistler force plates on a 6-m long walkway were used by Kotti et al. [17] to examine ground reaction force by using random forest method and assess the efficacy of rule-based approach in 47 KOA and healthy subjects. Using the random forest

Table 1 Description of non-wearable and wearable sensors

Sensors	Description	Parameters measured	References
Force plates	Force plate mechanism measures the force induced on the plate and its directions when one walks on them	• Ground reaction force • Center of pressure	(15–17)
GAITRite® system	It consists of a portable electronic mat embedded with pressure sensors. A patient needs to walk on the mat from one end to the other	• Spatiotemporal parameters • Foot pressure • Ground reaction force	(15,20)
Instrumented treadmill	They are embedded with force plates on top and allow fast capturing of force data at known speeds	• Ground reaction forces • Center of pressure	(21)
Inertial sensors	The inertial device incorporates accelerometers and gyroscopes and runs on the inertial measurement principle An accelerometer is based on the Newton's law of motion. By knowing the mass of object and all the forces, acceleration can be calculated A gyroscope is an angular velocity sensor centered on the concept of measuring the Coriolis force	• Angular velocity • Segment acceleration • Segment orientation • Spatiotemporal parameters • Joint angles • Trunk sway	(6,15,16,23–26)
Electromyography (EMG)	EMG sensors are used to assess muscles electrical activity during locomotion. The measured signal is amplified, conditioned, and recorded	• Analysis of muscle activity • Intensity and time of muscle activation during gait	(15,16,29)
Electrogoniometry (EGM)	EGM deals with resistors that change based on the flexibility of the sensor. The material shaping it stretches while the sensor is flexed; this ensures that the current flowing through it needs to follow a longer distance, so that its resistance increases proportionally to the flexed angle. The EGM changes the mechanical signals into electrical signals as the leg moves	• Joint angles	(15,16,31)
Pressure sensors	Pressure sensors measure the force applied on the sensor by integrating them into instrumented shoes	• Foot plantar pressure distribution • Ground reaction forces • Center of pressure • Spatiotemporal parameters	(15,16,32,33)
Ultrasonic sensors	By applying the speed of sound through the air, the ultrasonic sensor uses the time taken to transmit and receive reflected wave signals. Knowing the time the signal takes to pass and return, and the speed, it is easy to calculate the difference between the two points, such as measuring the distance between the foot and the floor itself	• Spatiotemporal parameters	(15,16,34)

regression learning process, a fivefold cross-validation precision of 72.61% ± 4.24% was achieved. The study concluded that random forests are ideal for evaluating ground reaction forces to differentiate patients with KOA from healthy ones [17].

GAITRite® system [18] is a type of foot sensor used to assess spatiotemporal gait variables. It is a 5.4-m rubber electronic mat with embedded pressure sensors. It is a portable, no attachments on subject, and easy-to-use device that exhibits excellent test–retest reliability in gait assessment of older individuals (ICC ranging from 0.82 to 0.91, depending on the evaluated parameter) [19]. But it needs to combine with limb kinematics and usable for laboratory only [15]. Peixoto et al. [20] utilized GAITRite® system on which KOA patients walked at self-selected speed. They observed that older women with bilateral KOA walked with reduced speed, cadence, and step length, but have symmetrical step length and single support phase between lower limbs [20].

The instrumented treadmill consists of a treadmill ergometer with an integrated pressure sensor mat with force sensors and analysis software. The system measures the dynamic pressure distribution under the feet while walking on the treadmill. Spatiotemporal gait characteristics are computed automatically from the pressure data within the software. Using instrumented treadmill with tandem piezoelectric force plates, Wiik et al. [21] assessed gait patterns and ground reaction force symmetry in KOA patients at higher walking speed. They showed that KOA patients walk more slowly and asymmetrically, with wider base of support and a shorter step length. They also showed less symmetrical push-off force and impulse in KOA suggesting a weakness during the terminal stance phase as a factor causing slower walking speeds [21].

Wearable Sensors

Wearable sensors are placed on patients body and results are analyzed even outside the laboratory [16]. They are noninvasive, low cost, small-sized, low weight, power-efficient, and wirelessly connected [22]. Wearable sensors are of different kinds based on their function. They include inertial sensors, electromyography (EMG), electrogoniometers, pressure sensors, and ultrasonic sensors.

Inertial Sensors.

They consist of a combination of accelerometers and gyroscopes to measure angular velocity, acceleration, direction, and gravitational forces [16]. They are inexpensive, completely portable devices that can be used in almost any environment and allow 3D measurement to be made possible by measuring triaxial data. In capturing kinematic data, accelerometers and gyroscopes are as effective as the 3D motion capture device; as they are reliable, repeatable, and calculate metrics at similar accuracy to motion capture system [23, 24]. The drawback of using this device is the artifacts of skin movement that can impact the readings [15]. In KOA patients following complete knee arthroplasty, Tereso et al. [25] investigated spatiotemporal, posture, and fall-related consequences by using assistive devices, using two 3-axis accelerometers, one was attached to the operated leg ankle to measure spatiotemporal parameters, and the other at the sacrum (trunk) to measure posture and fall risk-related parameters. This study concluded that assistive devices should be prescribed depending on the state of recovery of the patient and demonstrated that standard walker is good to give stability while rollator with forearm supports provide a gait pattern closer to a natural gait [25]. A single 3D inertial sensor was used by Bolink et al. [26] to assess the spatiotemporal and kinetic gait characteristics of KOA patients. The findings showed the potential of inertial sensors in KOA and reported that KOA patients had lower walking speed, knee flexion, and more trunk lean [26].

Accelerometers and gyroscopes are fitted with the Intelligent Device for Energy Expenditure and Activity (IDEEA) [27], thus making them a valuable, time-based device composed of sensors and recorders for tracking movement and calculating gait parameters with greater data storage. The accuracy and reliability of IDEEA3 measurements for cadence, gait phase, and velocity step length and step counts in KOA patients were assessed by Sun et al. [6] and found that it is an accurate instrument for calculating gait parameters in KOA.

Accelerometer provides the opportunity to take advantage of advanced analytical methods such as autocorrelation analysis, which can be used to extract discrete parameters such as the stride time and step time, in addition to using the entire acceleration waveform to determine the regularity and symmetry of the gait cycle [28]. These findings suggest that waist-mounted accelerometry and autocorrelation analysis could be used to conduct clinical assessments of gait abnormalities in individuals with KOA.

Electromyography EMG is a tool which makes it easy to study muscle functions. The EMG signal can be measured either by surface electrodes or by needle electrodes. The signal is amplified, conditioned, and recorded afterwards [16]. But, it needs to combine with other system response for effective gait analysis [15]. Various studies confirmed that EMG is a useful assessment method in many musculoskeletal problems affecting gait. Hubley-Kozey et al. [29] conducted a gait assessment using EMG to determine activation of major muscles crossing the knee joint during ambulation in KOA. The EMG data were entered into a pattern recognition procedure that captured both the amplitude and shape characteristics of EMG waveforms. KOA patients demonstrated a high degree of agonist/antagonist co-activity around the knee joint during ambulation thus leading to a slower speed than healthy control [29]. Pattern recognition procedure provides a novel approach to quantify synergistic co-activity. With the advancement of wireless technologies and its application to sensors, EMG has become a very accurate and wearable gait analysis tool [30].

Electrogoniometry Electrogoniometers are widely used to measure joint angles of the body, such as the ankle, knee, and hip. Two kinds of electrogoniometers, potentiometer and strain gauges (Fig. 1), are commonly used. They are cheap, provide immediate output signals, and do not need complicated algorithms for processing. However, they are cumbersome to use, provide only single plane movement and limited gait parameters, and are often difficult to match for joints with more than one degree of freedom [15]. Tarniţă et al. [31] compared KOA patients with healthy subjects using a treadmill and electrogoniometers for each leg to determine knee range of motion and amplitude of flexion–extension moments. The placement of electrogoniometer is shown in Fig. 2. Study concluded that KOA patients had less range of motion during the gait cycle than the healthy subjects and a large difference between the amplitude of knee flexion during 25–50% of gait cycle phase and 65–80% of gait cycle phase could be due to the walking speed [31].

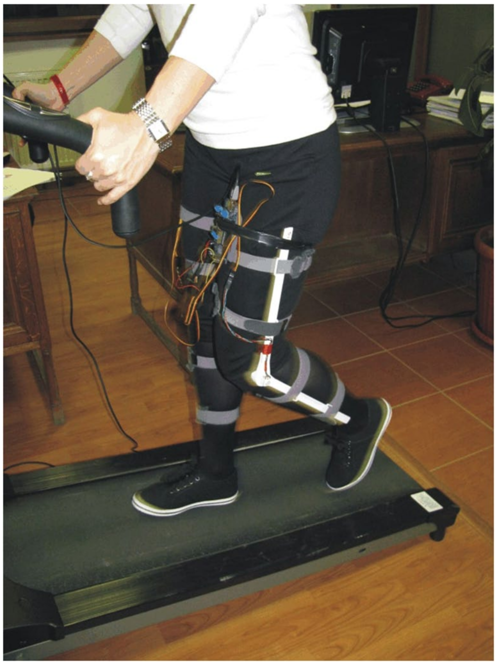


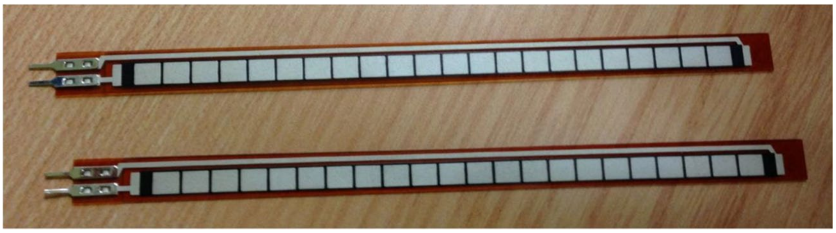
Fig. 2 Placement of electrogoniometers (strain gauge). Adapted from Tarniţă D, Catană M, Tarniţă DN. 2013 [31]

Pressure Sensors Pressure sensors measure the forces applied on the sensor (Fig. 3). Pressure sensor devices can be used everywhere because of active attachment of sensors with shoes but for rough surfaces and moving up-down stairs, they are less efficient, and to measure the ground reaction force and center of pressure, these devices must be combined with limb kinematic data [15]. Muñoz-Organero et al. [32] examined 14 KOA patients with healthy subjects to determine the correlation between mild knee pain and plantar loading using a smart insole equipped with pressure sensors. All subjects wore the insole and walked 10 m. Data was recorded from eight sites on sole of foot using piezoresistive sensors using kinematrix laptop application. Study provides evidence that patients with mild knee pain delay the transition from heel to midfoot loading and move maximum pressure time in midfoot region toward the maximum pressure time in forefoot [32].

Foot switches are pressure sensors commonly used to assess spatiotemporal parameters of gait. Spinoso et al. [33] used foot switches in KOA patients and located foot switches bilaterally at the calcaneus and hallux base to determine gait phases (Fig. 4). The study concluded that in contrast to healthy controls, KOA patients walked with slow pace, longer support time, and a longer step time reduction in swing time.

Ultrasonic Sensors To measure spatiotemporal parameters, ultrasonic sensors are used. These sensors are used to indicate heel contact and can be used on uneven or bumpy walking surface and also for ascending-descending stairs; however, they are not accurately providing information because of noise [15]. A computerized ultrasound-based motion analysis system (Zebris CMS-HS—a triplet of UV sensors) (Fig. 5) was used by Kiss [34] to examine the impact of speed with different grades of KOA on the gait. This study found that variability in gait parameters increased when the walking speed varied from the self-selected speed and this variation is more prominent in severe grades of KOA [34].

Fig. 1 Flexible electrogoniometer. Adapted from Muro-de-la-Herran A, García-Zapirain B, Méndez-Zorrilla A. 2014 [16]



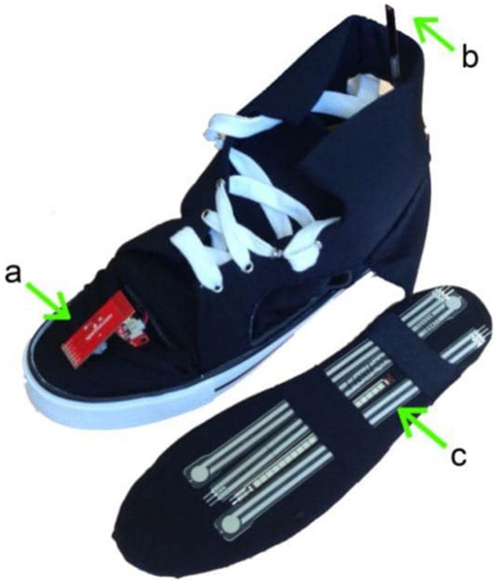


Fig. 3 Instrumented shoe. **a** Inertial measurement unit; **b** flexible goniometer; and **c** pressure sensors inside the insole. Adapted from Muro-de-la-Herran A, García-Zapirain B, Méndez-Zorrilla A. 2014 [16]

Fig. 4 Foot Switch (Noraxon®)—a pressure sensors positioning for gait assessment. Adapted from Spinoso DH, Bellei NC, Marques NR, Navega MT. 2018 [33]

Fig. 5 Gait assessment using ultrasonic sensor. Adapted from Kiss RM. 2011 [34]

Hybrid System

This system incorporates both vision-based and sensor-based technologies (Fig. 6) to measure gait effectively and accurately [7]. It provides quantitative information about kinematics, spatiotemporal, and kinetics data [35]. This system consists of motion sensors mounted to the body and force plates under the foot that provide three-dimensional data on forces and moments. The accelerometer and gyroscope sensor can also be combined with force plates [15]. Therefore, for successful gait analysis, these instruments are used in many clinical studies. The maximum number of KOA gait assessment studies was carried out on this modality, reflecting its usefulness in the evaluation of KOA gait. But there is a lack of appropriate reporting protocol to use hybrid technology to assess gait in KOA. Different studies utilized different device combinations, different kinematic data collection frequencies (50 to 200 HZ), kinetic data collection frequencies (50 to 2000 HZ), number of sensors, force plates, and number of reflective markers, which are included in the analysis of KOA gait study. Table 2 provides the list of gait analysis studies done in KOA using hybrid system along with the key findings. The integration of various modalities offers additional quantitative data of subjects that will enable a more precise measure of KOA gait. Most of the studies use these modalities to enable more productive KOA gait evaluation but are constrained by wide space and heavy setup requirements.

Discussion

The aim of this review was to provide a description, covering both qualitative and quantitative approaches, of the technologies and methods used for gait analysis in KOA. An OGA in KOA is the most common approach used to evaluate gait, as no equipment is required and it is quick and easy. 3D gait analysis was contrasted with OGA and found that it only offers qualitative data and has low validity and reliability that compromises its accuracy. Both these limitations preclude the use of this method for research purposes. Different gait analysis techniques have evolved with the advancement of technology, providing precise quantitative data centered

Fig. 6 BTS Gait Lab configuration. (1) infrared video cameras; (2) inertial sensor; (3) ground reaction force measurement walkway; (4) wireless EMG; (5) workstation; (6) video-recording system; (7) TV screen; (8) control station. Adapted from *BTS GAITLAB | Integrated Gait Analysis Systems | BTS Bioengineering*. [36]

on various gait parameters that promote successful diagnosis and treatment of KOA.

The utilization of automated systems utilizing vision-based, sensor-based, and hybrid gait analysis modalities has received more attention in the field of KOA diagnosis. In a recent study, Derek et al. [50] used retro-reflective markers in conjunction with an instrumented gait treadmill to examine the variations in gait characteristics between KOA and healthy patients. A total of 94–58% accuracy was effectively attained by the application of inverse dynamics. The hybrid modality's great potential for KOA has drawn more researchers to this field. Leading the effort, Kotti et al. [17] achieved great accuracy in analyzing KOA gait just utilizing sensor-based modality. Ishikawa et al.'s amazing work [5] employing a model-based method was directed toward vision-based KOA recognition. The potential of planar law to quantify differences in gait was demonstrated by their research. Like thus, Cui et al.'s [1] use of the Kinect sensor for KOA gait collection created new opportunities for vision-based model-free modalities while achieving 97% accuracy.

Data analysis shows that although vision-based KOA diagnosis is very accurate and economical, it has some limitations, including the need for huge spaces, highly precise cameras, and overlapping. While sensor-based modality works well, it is limited by other aspects including cost, power and time consumption, and wearability [7]. It should not be stated that one is better than the other among the modalities based on wearable and non-wearable sensors, since each has different features that make it more appropriate for certain kinds of study. In laboratories or controlled environments, non-wearable sensors are used that separate the sample from external influences that might influence the measurements, allowing for a more monitored interpretation of the parameters being tested. The key concern with non-wearable sensors is that they require a very pricey laboratory configuration. Another issue is their small size, so the subject must walk on a mat for a long time to get relevant evidence, and the subject must therefore take care to properly position his/her feet to get an impression of the whole step. This will change the way patients normally walk, impacting the measurements' repeatability. Another downside to non-wearable sensors is that, during daily activities, gait cannot be assessed.

In contrast to the limitations of non-wearable sensors, wearable sensors can be used by positioning them on various parts of the body as small sensors and using wireless communication technologies such as Bluetooth to measure gait outside the laboratory. However, these instruments, such as pressure sensors and accelerometers and gyroscopes, can be used with in-lab research to provide cheaper gait analysis solutions. In recent research, the inertial sensor is the most widely used wearable sensor and it is considered to be as effective and precise in gathering kinematic data as 3D gait analysis [23, 24]. Wearable sensors, however, have some limitations, such as complicated analytical methods, the issue of ambient noise, and the need to position them on the body of the participant, which may be unpleasant or intrusive.

The literature thus clearly illustrates the potential for a successful KOA gait assessment with a hybrid gait assessment method. This technology incorporates both vision-based and sensor-based technologies for precise gait measurement. More number of gait variables, such as kinematic, kinetic, and spatiotemporal variables, will thus be measured simultaneously by using hybrid technologies. Although hybrid technologies provide more reliable and accurate gait data, but it is limited by large space and heavy setup requirements. Approximately 70% of research articles on the aforementioned modalities published between 2000 and 2018 that were part of the survey focused on hybrid modes for KOA studies. Force sensors, for example, are the most often used sensor type because

Table 2 Gait dataset used in various researches using hybrid technology

References	Resources	Dataset	Key findings	Limitations
Fukaya et al. [37]	8-camera Vicon (200 Hz), 2 Kistler force plates (1200 Hz), 9 Plug-In-Gait® marker set	11 patients with bilateral severe KOA	Severity of knee pain led to the decline in joint function of the knee	Small sample size
Robbins et al. [38]	Eight camera 3D mocap (Qualisys) (100 Hz), 2 force plates (AMTI) (2000 Hz), reflective markers, EMG (2000 Hz)	22 non-traumatic KOA, 19 post-traumatic KOA patients, 22 healthy adults	Muscle activation and knee dynamics is different between non-traumatic and post-traumatic KOA patients and healthy adults	Observational, cross-sectional study
Nie et al. [39]	28 retro-reflective markers,10 camera mocap (290 Hz), 2 Bertec force plates	95 KOA patients	Relationships between KAM-related variables and KOA symptoms	Trunk movements were not measured in 3D gait analyses
Baker et al. [40]	Retro-reflective marker with eight Qualisys motion analysis cameras (100 Hz), dual-belt instrumented treadmill (GAITRite™) (2000 Hz), EMG (2000 Hz)	20 healthy subjects, 20 KOA patients	No biomechanical changes and characteristics of unexpected medial translations in all classes of elevated and extended muscle activation	The treadmill has been adapted at its full speed and has a span of 5 cm from the midline
Meireles et al. [41]	3D motion analysis system (100 Hz), 27 LEDs, 1 force plate (Bertec) (1000 Hz)	18 early symptomatic KOA patients, 16 established KOA patients, 19 control	In patients with early KOA, knee joint loading and kinematics were found to be changed during gait	Only females patients included in the study
Rutherford et al. [42]	4 retro-reflective markers, 8 Qualisys motion analysis cameras (100 Hz), dual-belt instrumented treadmill (2000 Hz), EMG (2000 Hz)	20 young adults, 20 older, 40 moderate KOA patients	KOA have different patterns of biomechanics and muscle activity relative to matching old and young asymptomatic individuals	Only moderate severity was considered
Resende et al. [43]	12-camera motion capture system (Qualisys) (200 Hz), 6 force platforms (AMTI), markers	15 KOA patients	Mild difference in leg length determines the kinetic chain of individuals with KOA Increased knee sagittal loading during gait enhancing the development of knee arthritis	Only focused on the immediate effects of mild LLD in moderate KOA
Farrokhi et al. [44]	8-camera Vicon mocap system (120 Hz), Plug-in Gait marker set, 2 Bertec force platforms (1080 Hz)	17 patients with KOA and self-reported knee instability, 36 patients with KOA	The knee instability of the self-reported patients is related to major changes in the hip, knee, and ankle joint function in persons with KOA during the stance phase	Only include individuals with medial compartment KOA
Chang et al. [45]	8-camera, Eagle Digital Real-Time motion measurement system (MAC) (120 Hz), 6 AMTI force Platforms (960 Hz), reflective markers	391 KOA patients	The higher baseline KAM peaks and KAM impulses have each been associated with the rise in the medial tibiofemoral lesions of the bone marrow, but not with cartilage damage	Only include mild KOA patients
Rutherford et al. [46]	EMG (1000 Hz), infrared emitting diode skin markers, 2 optoelectronic motion analysis sensors (Optotrak™) (100 Hz), 1 force plate (AMTI™) (100 Hz)	82 moderate KOA patients, 35 control	Changes in the specific patterns of knee joint muscle activation have been associated with an increased structural severity, whereas the involvement of OA has been related to other changes	Only moderate KOA patients were considered

Table 2 (continued)

References	Resources	Dataset	Key findings	Limitations
Bechard et al. [47]	22 passive reflective markers, instrumented treadmill (Kistler Instrument), 6-camera, motion analysis system (60 Hz)	20 KOA patients, 20 healthy control	During prolonged walk, toe out and trunk lean vary among people with or without medial KOA, and patients with greater pain lean the trunk more	Only medial KOA were included
Astephen et al. [48]	Optotrak_3020 motion capture system, AMTI force platform 3infrared light emitting diodes, EMG (1000 Hz)	40 mild-moderate KOA patients	Radiographic KOA severity appears to be associated with only biomechanical factors and pain severity associated with neuromuscular factors and gait speed	Severe KOA patients were included
Liikavainio et al. [49]	Two triaxial Meac-x accelerometers, EMG (2000 Hz) 2 AMTI force plates (2000 Hz)	44 KOA male patients, 53 healthy control	There were only small variations between SMA and GRF variables during level walking when comparing KOA patients with controls subjects	Only men were recruited in the study, though the prevalence of KOA is higher in females

KOA knee osteoarthritis, *EMG* electromyography, *GRF* ground reaction force, *SMA* surface mounted accelerometer, *KAM* knee adduction moment, *RMS* root mean square, *LLD* leg length discrepancy, *3D* three dimensional, *mocap* motion capture system

they can immediately record gait information. Furthermore, using sensor- and vision-based modalities separately results in good accuracy measures, according to recent research findings. Nonetheless, combining sensor-based and vision-based modalities offers a distinct advantage over using them separately. Improved performance accuracy is mostly owing to increase efficiency in obtaining big and meaningful KOA gait data. Thus, it is evident from the literature that combined factors have the potential to improve KOA diagnosis.

Conclusion and Future Scope

The quantitative methods, categorized as vision, sensor-based, and hybrid technologies, have features that make them powerful and competitive for various types of requirements. Among these technologies, hybrid technology seems to be the most reliable and accurate because it can assess all aspects of gait assessment. Previous studies focused only on medial knee compartment and few severity levels. Future studies should be done to develop a KOA gait dataset, consider all severity levels and all compartment KOA. Research should be carried out with each examination to assess the most suitable sensor sites. Future experiments should also focus on developing technologies to promote greater autonomy at the workplaces and large periods of energy resources to perform studies over lengthy periods of time.

Abbreviations KOA: Knee osteoarthritis; OGA: Observational gait analysis; 3D: 3 Dimensional; ICC: Intraclass correlation coefficient; IDEEA: Intelligent Device for Energy Expenditure and Activity; EMG: Electromyography

Author Contribution Conceptualization: PC and ZV; writing—original draft: PC; writing—review and editing: PC, ZV, ZK, TT, Iram, MA. All authors read and approved the final manuscript.

Data Availability All data generated or analyzed during this study are included in this published article.

Code Availability Not applicable.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare no competing interests.

References

1. Cui A, Li H, Wang D, Zhong J, Chen Y, Lu H. Global, regional prevalence, incidence and risk factors of knee osteoarthritis in population-based studies. EClinicalMedicine. 2020;29–30:100587. https://doi.org/10.1016/j.eclinm.2020.100587.

2. Pal CP, Singh P, Chaturvedi S, Pruthi KK, Vij A. Epidemiology of knee osteoarthritis in India and related factors. Indian J Orthopaedic. 2016;50(5):518–22. Available from: /pmc/articles/PMC5017174/?report=abstract
3. Favre J, Jolles BM. Gait analysis of patients with knee osteoarthritis highlights a pathological mechanical pathway and provides a basis for therapeutic interventions. EFORT Open Rev. 2016;1(10):368–74.
4. Taş S, Güneri S, Kaymak B, Erden Z. A comparison of results of 3-dimensional gait analysis and observational gait analysis in patients with knee osteoarthritis. Acta Orthop Traumatol Turc. 2015;49(2):151–9.
5. Ishikawa Y, An Q, Nakagawa J, Oka H, Yasui T, Tojima M, et al. Gait analysis of patients with knee osteoarthritis by using elevation angle: confirmation of the planar law and analysis of angular difference in the approximate plane. Adv Robot. 2017;31(1–2):68–79.
6. Sun J, Liu Y, Yan S, Cao G, Wang S, Lester DK, et al. Clinical gait evaluation of patients with knee osteoarthritis. Gait Posture. 2017;58:319–24. https://doi.org/10.1016/j.gaitpost.2017.08.009.
7. Kour N, Gupta S, Arora S. A survey of knee osteoarthritis assessment based on gait. Arch Comput Methods Eng. 2020;20:1–41. https://doi.org/10.1007/s11831-019-09379-z.
8. Clinical GAIT & Biomechanics | Life Sciences | Motion Capture Systems [Internet]. Available from: https://www.vicon.com/applications/life-sciences/gait-analysis-neuroscience-and-motor-control/. [Accessed 6 Oct 2020].
9. Qualisys | Motion Capture Systems [Internet]. Available from: https://www.qualisys.com/. [Accessed 6 Oct 2020].
10. Kinect - hardware [Internet]. Available from: https://developer.microsoft.com/en-gb/windows/kinect/. [Accessed 6 Oct 2020].
11. Cui X, Zhao Z, Ma C, Chen F, Liao H. A gait character analyzing system for osteoarthritis pre-diagnosis using RGB-D camera and supervised classifier. World Congress Med Phys Biomed Eng, Springer Singapore. 2019;297–301. https://doi.org/10.1007/978-981-10-9035-6_10
12. Deluzio KJ, Astephen JL. Biomechanical features of gait waveform data associated with knee osteoarthritis. An application of principal component analysis. Gait Posture. 2007;25(1):86–93.
13. Federolf PA, Boyer KA, Andriacchi TP. Application of principal component analysis in clinical gait research: identification of systematic differences between healthy and medial knee-osteoarthritic gait. J Biomech. 2013;46(13):2173–8. https://doi.org/10.1016/j.jbiomech.2013.06.032.
14. Phinyomark A, Osis ST, Hettinga BA, Kobsar D, Ferber R. Gender differences in gait kinematics for patients with knee osteoarthritis. BMC Musculoskelet Disord. 2016;17(1):1–12. https://doi.org/10.1186/s12891-016-1013-z.
15. Akhtaruzzaman MD, Shafie AA, Khan MR. Gait analysis: systems, technologies, and importance. J Mech Med Biol. 2016;16(7):1630003. https://doi.org/10.1142/S0219519416300039.
16. Muro-de-la-Herran A, García-Zapirain B, Méndez-Zorrilla A. Gait analysis methods: an overview of wearable and non-wearable systems, highlighting clinical applications. Sensors (Switzerland). 2014;14(2):3362–94.
17. Kotti M, Duffell LD, Faisal AA, McGregor AH. Detecting knee osteoarthritis and its discriminating parameters using random forests. Med Eng Phys. 2017;43:19–29. https://doi.org/10.1016/j.medengphy.2017.02.004.
18. GAITRite | Temporospatial Gait Analysis [Internet]. Available from: https://www.gaitrite.com/. [Accessed 6 Oct 2020].
19. Menz HB, Latt MD, Tiedemann A, Kwan MMS, Lord SR. Reliability of the GAITRite® walkway system for the quantification of temporo-spatial parameters of gait in young and older people. Gait Posture. 2004;20(1):20–5.
20. Peixoto JG, de Souza MB, Diz JBM, Timoteo EF, Kirkwood RN, Teixeira-Salmela LF. Analysis of symmetry between lower limbs during gait of older women with bilateral knee osteoarthritis. Aging Clin Exp Res. 2019;31(1):67–73. https://doi.org/10.1007/s40520-018-0942-9.
21. Wiik AV, Aqil A, Brevadt M, Jones G, Cobb J. Abnormal ground reaction forces lead to a general decline in gait speed in knee osteoarthritis patients. World J Orthop. 2017;8(4):322–8.
22. Tarniţă D. Wearable sensors used for human gait analysis. Rom J Morphol Embryol. 2016;57(2):373–82.
23. Staab W, Hottowitz R, Sohns C, Sohns JM, Gilbert F, Menke J, et al. Accelerometer and gyroscope based gait analysis using spectral analysis of patients with osteoarthritis of the knee. J Phys Ther Sci. 2014;26(7):997–1002.
24. Hafer JF, Provenzano SG, Kern KL, Agresta CE, Grant JA, Zernicke RF. Measuring markers of aging and knee osteoarthritis gait using inertial measurement units. J Biomech. 2020;99:109567. https://doi.org/10.1016/j.jbiomech.2019.109567.
25. Tereso A, Martins MM, Santos CP. Evaluation of gait performance of knee osteoarthritis patients after total knee arthroplasty with different assistive devices. Res Biomed Eng. 2015;31(3):208–17.
26. Bolink SAAN, Van Laarhoven SN, Lipperts M, Heyligers IC, Grimm B. Inertial sensor motion analysis of gait, sit-stand transfers and step-up transfers: differentiating knee patients from healthy controls. Physiol Meas. 2012;33(11):1947–58.
27. MiniSun_IDEEA [Internet]. Available from: http://www.minisun.com/paa.htm. [Accessed 6 Oct 2020].
28. Barden JM, Clermont CA, Kobsar D, Beauchet O. Accelerometer-based step regularity is lower in older adults with bilateral knee osteoarthritis. Front Hum Neurosci. 2016;10(DEC2016):1–9.
29. Hubley-Kozey C, Deluzio K, Dunbar M. Muscle co-activation patterns during walking in those with severe knee osteoarthritis. Clin Biomech. 2008;23(1):71–80.
30. Tao W, Liu T, Zheng R, Feng H. Gait analysis using wearable sensors. Sensors. 2012;12(2):2255–83.
31. Tarniţă D, Catană M, Tarniţă DN. Experimental measurement of flexion-extension movement in normal and osteoarthritic human knee. Rom J Morphol Embryol. 2013;54(2):309–13.
32. Muñoz-Organero M, Littlewood C, Parker J, Powell L, Grindell C, Mawson S. Identification of walking strategies of people with osteoarthritis of the knee using insole pressure sensors. IEEE Sens J. 2017;17(12):3909–20.
33. Spinoso DH, Bellei NC, Marques NR, Navega MT. Quadriceps muscle weakness influences the gait pattern in women with knee osteoarthritis. Adv Rheumatol (London, England). 2018;58(1):26.
34. Kiss RM. Effect of severity of knee osteoarthritis on the variability of gait parameters. J Electromyogr Kinesiol. 2011;21(5):695–703.
35 Cimolin V, Galli M. Summary measures for clinical gait analysis: a literature review. Gait Posture. 2014;39(4):1005–10. https://doi.org/10.1016/j.gaitpost.2014.02.001.
36. BTS GAITLAB | Integrated Gait Analysis Systems | BTS Bioengineering [Internet]. Available from: https://www.btsbioengineering.com/products/bts-gaitlab-gait-analysis/. [Accessed 6 Oct 2020].
37. Fukaya T, Mutsuzaki H, Mori K. Influence of pain on knee joint movement and moment during the stance phase in patients with severe bilateral knee osteoarthritis: a pilot study. Medicina. 2019;55(12):1–7.
38. Robbins SM, Morelli M, Martineau PA, St-Onge N, Boily M, Dimentberg R, et al. A comparison of muscle activation and knee mechanics during gait between patients with non-traumatic and post-traumatic knee osteoarthritis. Osteoarthr Cartil. 2019;27(7):1033–42. https://doi.org/10.1016/j.joca.2019.02.798.
39. Nie Y, Wang H, Xu B, Zhou Z, Shen B, Pei F. The relationship between knee adduction moment and knee osteoarthritis symptoms

according to static alignment and pelvic drop. Biomed Res Int. 2019;2019(8):7603249. https://doi.org/10.1155/2019/7603249.

40. Baker M, Stanish W, Rutherford D. Walking challenges in moderate knee osteoarthritis: a biomechanical and neuromuscular response to medial walkway surface translations. Hum Mov Sci. 2019;68:102542. https://doi.org/10.1016/j.humov.2019.102542.
41. Meireles S, Wesseling M, Smith CR, Thelen DG, Verschueren S, Jonkers I. Medial knee loading is altered in subjects with early osteoarthritis during gait but not during step-up-and-over task. PLoS One. 2017;12(11):1–20.
42. Rutherford D, Baker M, Wong I, Stanish W. The effect of age and knee osteoarthritis on muscle activation patterns and knee joint biomechanics during dual belt treadmill gait. J Electromyogr Kinesiol. 2017;34:58–64. https://doi.org/10.1016/j.jelekin.2017.04.001.
43. Resende RA, Kirkwood RN, Deluzio KJ, Morton AM, Fonseca ST. Mild leg length discrepancy affects lower limbs, pelvis and trunk biomechanics of individuals with knee osteoarthritis during gait. Clin Biomech. 2016;38:1–7.
44. Farrokhi S, O'Connell M, Gil AB, Sparto PJ, Fitzgerald GK. Altered gait characteristics in individuals with knee osteoarthritis and self-reported knee instability. J Orthop Sports Phys Ther. 2015;45(5):351–9.
45. Chang AH, Moisio KC, Chmiel JS, Eckstein F, Guermazi A, Prasad PV, et al. External knee adduction and flexion moments during gait and medial tibiofemoral disease progression in knee osteoarthritis. Osteoarthr Cartil. 2015;23(7):1099–106. https://doi.org/10.1016/j.joca.2015.02.005.
46. Rutherford DJ, Hubley-Kozey CL, Stanish WD. Changes in knee joint muscle activation patterns during walking associated with increased structural severity in knee osteoarthritis. J Electromyogr Kinesiol. 2013;23(3):704–11. https://doi.org/10.1016/j.jelekin.2013.01.003.
47. Bechard DJ, Birmingham TB, Zecevic AA, Jones IC, Giffin JR, Jenkyn TR. Toe-out, lateral trunk lean, and pelvic obliquity during prolonged walking in patients with medial compartment knee osteoarthritis and healthy controls. Arthritis Care Res. 2012;64(4):525–32.
48. Astephen Wilson JL, Deluzio KJ, Dunbar MJ, Caldwell GE, Hubley-Kozey CL. The association between knee joint biomechanics and neuromuscular control and moderate knee osteoarthritis radiographic and pain severity. Osteoarthr Cartil. 2011;19(2):186–93. https://doi.org/10.1016/j.joca.2010.10.020.
49. Liikavainio T, Bragge T, Hakkarainen M, Karjalainen PA, Arokoski JP. Gait and muscle activation changes in men with knee osteoarthritis. Knee. 2010;17(1):69–76. https://doi.org/10.1016/j.knee.2009.05.003.
50. Rutherford DJ, Baker M. Knee moment outcomes using inverse dynamics and the cross product function in moderate knee osteoarthritis gait: a comparison study. J Biomech. 2018;10(78):150–4.