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Mobile assessment of the lower limb kinematics in healthy persons and in persons with degenerative knee disorders: a systematic review

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Highlights

- In healthy persons trunk, hip, knee and ankle joint kinematics were assessed
- In persons with KOA and TKR, only ankle and knee joint kinematics were measured
- Functional and clinically relevant tasks were assessed in healthy persons and TKR
- Studies that included persons with KOA only assessed level walking
- Inertial sensor measurements were (most) valid and reliable in the sagittal plane

Abstract

Inertial sensor systems are increasingly used in the assessment of persons with knee osteoarthritis (KOA) and total knee replacement (TKR). This systematic review aims to (1) investigate the application of inertial sensor systems and kinematics derived from these systems, and (2) assess if current assessment protocols consist of tasks which are, according to the International Classification of Functioning, Disability and Health (ICF) for KOA, relevant for persons with KOA and TKR. A search was conducted in six electronic databases (ACM, CINAHL, EMBASE, IEEE, PubMed, Web of Science) to include papers assessing the knee and one or more adjacent joints by means of inertial sensors in healthy persons or persons with KOA or TKR. Two reviewers checked the methodological quality. Twenty-three papers were included: 18 in healthy persons and five in persons with KOA or TKR. In healthy persons, 11 tasks were related to metrics of the ICF-function and ICF-activity level. In persons with KOA, only walking was assessed. Apart from walking, four additional tasks were related to the ICF-function and ICF-activity level in persons with TKR. In healthy persons, joints located proximally and distally to the knee were assessed, while in persons with KOA and TKR, only the knee and ankle were assessed. This is a shortcoming since hip and trunk motion potentially contain clinically relevant information, in terms of identifying (mal)adaptive compensatory movement strategies. Additionally, physically more demanding tasks should be evaluated as these might be superior in detecting compensatory movement strategies. Former considerations warrant attention in future research.

Keywords:

Ambulatory, Motion-analysis, Knee osteoarthritis, Knee arthroplasty, Activities

Introduction

Knee osteoarthritis (KOA) is a degenerative, chronic disease of the entire knee joint that is characterized by progressive articular cartilage loss and bone degeneration [1]. The prevalence of KOA increases with age, at the age of 60 and older, 10% of male and 18% of female persons show symptoms of KOA [2]. Knee pain or stiffness are the first symptoms of KOA, resulting in limitations in joint movement and the ability to perform activities of daily living. With regard to the development and progression of KOA, multiple modifiable risk factors should be considered, such as knee malalignment, increased biomechanical joint loading and muscle weakness [3]. A deeper understanding of how these factors are related to the development and progression of KOA, in terms of the occurrence of (mal)adaptive compensatory movement strategies, might improve clinical decision-making and stimulate the development of appropriate intervention programs [4].

The goal of intervention programs and physical therapy in persons with KOA is to optimize lower extremity range of motion (ROM) and muscle balance, and to increase overall muscle strength [5]. Nevertheless, as KOA is a degenerative progressive disease, patients with end-stage KOA are ultimately treated with total knee replacement (TKR) [6]. As assessed by clinical questionnaires, TKR has been proven to be effective for pain reduction and functional improvement [7]. Questionnaires are easy to use and provide the opportunity to measure all levels proposed by the International Classification of Functioning, Disability and Health (ICF). However, clinical questionnaires suffer from ceiling effects, subjectivity and provide little information on movement characteristics (e.g. joint ROM or timing of joint movement) or on compensatory movements during task execution. Objective measures that quantify movement quality and analyse movement patterns during task-execution might additionally be of interest. Such movement analysis is mostly performed in a laboratory, where movements are captured in three dimensions by means of an optical or magnetic motion capture system. These laboratory systems measure with high precision and are therefore accepted as the gold standard for motion analysis [8]. However, they are expensive, and require specific expertise and extensive lab space. Moreover, motion can only be recorded within a calibrated lab area [9]. Therefore, these systems are not regularly available for an orthopaedic surgeon or physical therapist, making them only accessible to a limited number of persons. Lately, new opportunities have emerged through the development of mobile motion capture systems [10].

Accelerometers, gyroscopes or a combination of both (i.e. inertial sensors) are increasingly used for objective lower limb movement analysis [11-15]. Using inertial sensors, the position and orientation of a body segment is estimated based on the integration of signals of the accelerometer and gyroscope [16, 17]. Based on the position and orientation data, joint kinematics (joint angles and spatiotemporal parameters) can be determined directly from the inertial sensors. Magnetometers are added to provide stability in the frontal plane and to correct for the drift induced by integration of the accelerometer's and gyroscope's signals [18, 19]. A disadvantage of a magnetometer is however that it's signal can be disturbed by the proximity of ferromagnetic materials [18]. The accuracy of kinematic data recorded by means of an inertial sensor system is moreover related to the positioning and strapping of the inertial sensors on the body, the complexity and duration of the analysed movement and the applied biomechanical model for data-analysis [20, 21]. Nonetheless the fact that currently reported accuracy results of inertial sensor systems for motion analysis are low (generally higher than 5°) [22], biomechanical models and (functional) calibration techniques are continuously evolving to reduce measurement errors and improve the system's usability [23, 24].

The fact that inertial sensor systems are portable and relatively inexpensive, makes them easy accessible to orthopaedic specialists and/or physical therapists. This opens the opportunity to assess movement patterns of larger cohorts of patients, in a functional and less standardized environment (e.g. in clinical settings), which might reveal new insights in movement patterns related to the development and progression of KOA [25].

Although inertial sensor systems are promising and increasingly used, an overview of currently applied sensor systems and their potential to measure (mal)adaptive movement patterns of the lower limb associated with KOA or TKR, is lacking. It would furthermore be of interest to give an overview of the different assessment protocols that are used in the assessment of persons with KOA and TKR, and to evaluate whether or not these protocols are in line with the guidelines proposed by the ICF. More specifically, the ICF describes a core-set of movement tasks that are typically relevant to assess in persons with KOA [26] and which should therefore be integrated in assessment protocols developed for persons with KOA or TKR. This systematic review therefore aims to firstly investigate the application of inertial sensor systems, and the kinematics of the lower limb they evaluate. Secondly, this review aims to assess to what extent current assessment protocols consist of tasks which are, based on the ICF core-set for OA, relevant to measure in persons with KOA and TKR.

Methods

This review was registered in the International prospective register of systematic reviews (Prospero), under registration number CRD42016039110. Furthermore, the "Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA)" guidelines were applied.

Search strategy and study selection

A systematic search was conducted in six electronic databases (ACM, CINAHL, EMBASE, IEEE, PubMed, Web of Science) until April 2017. Keywords used within the PubMed library are described in Appendix 1. For the other databases, combinations of keywords were used.

To be eligible, studies had to describe at least 1) an inertial sensor system consisting of a 3D accelerometer and 3D gyroscope; 2) two inertial sensors, positioned on the thigh and shank, to ensure the measurement of the knee joint angle; 3) kinematic parameters; 4) the assessment of healthy persons or persons with KOA or TKR. Papers needed to be written in English and a full-text had to be available. Journal papers as well as conference papers were included. Papers were excluded if they described 1) an inertial sensor system for rehabilitation/training purposes; 2) assessments in other populations or in less than five participants; 3) experiments on cadavers or animals. Furthermore, dissertations and theses were excluded. Reference lists of included papers were screened to ensure that no relevant papers were missed.

Eligibility assessment was done by screening on title and abstract by two reviewers independently (RvdS, LDB). The results of this screening were discussed in a consensus meeting, where disagreements were resolved. If no consensus was reached, the paper was added to the full-text screening. If the full-text was not available, the corresponding author was contacted. The full-text screening was independently performed by the same reviewers (RvdS, LDB). After the full-text screening, a second consensus meeting was organised to complete the final list of articles.

Quality assessment

Methodological quality of the included studies was evaluated using the Downs and Black quality index [27], which is recommended by the Cochrane collaboration to evaluate the methodological quality of both randomized and non-randomized controlled trials. For this systematic review, a customized version of the Downs and Black index was used since mainly observational studies were included. This resulted in a 12-item checklist for the observational studies and a 15-item checklist for the cross-sectional case-control studies. Eventually, the total score was converted into a percentage and classified as follow: 0-40% indicated low quality, 41-60% moderate quality, 61-80% substantial quality and ≥ 81% high quality [28]. The quality assessment was performed by two reviewers (RvdS, LDB) individually. In case of disagreement, items were additionally checked according to the description provided per item in the original article [27] and a consensus score was formulated after discussion.

Data extraction

Due to methodological study-heterogeneity (e.g. differences in the applied walking distance or walking speed, or differences in the assessed phase of the gait cycle), there was a lack of comparative data. As such, no meta-analysis could be performed. Data was therefore described descriptively. Data extraction was performed by one assessor (RvdS) and checked by a second assessor (LDB). In accordance to the different study aims, following parameters were extracted from the included studies: 1) study design and population characteristics; 2) applied inertial sensor system, number and location of sensors and reference system (only applicable for validity studies); 3) reported outcome parameters; 4) study results and 5) the tasks and the ICF level to which the tasks pertain.

ICF guidelines

Studies were related to the ICF-function level when the assessment protocol consisted of tasks relying to one of the categories of the ICF-function level [29], i.e. "*Mobility of joint function*", the function of the range and ease of movement of a joint; "*Gait pattern functions*", the function of movement patterns associated with walking, running or other whole body movements.

Studies were related to the ICF-activity level when the assessment protocol consisted of tasks relying to the different categories of the ICF-activity level [29], i.e. *"Changing basis body position",* the ability to change body position from one location to another as in a squat or lunge; *"Lifting and carrying objects"*, the ability to raise an object or transfer this from one place to another, as in manual moving tasks; *"Walking",* the ability to walk short or long distances, on different surfaces or around obstacles and

“Moving around”, the ability to move from one place to another, other than walking as in ascending or descending stairs or jumping.

Results

The result of our systematic search, which identified 2560 articles, is visualized in a flow-diagram (Figure 1). Twenty-three papers were included in this review. Nineteen were journal papers and four were conference papers. Eighteen papers were on kinematics in healthy persons and five on kinematics in persons with KOA or TKA.

Methodological quality

According to the Downs and Black checklist [27], 12 studies were of substantial quality [30-38], 10 of moderate quality [39-48] and one of low quality [49]. Within the studies on kinematics in healthy persons, the methodological quality was 60% on average (range between 42-75%). Nine studies were of substantial quality and nine were of moderate quality (Table 1). Within the studies on kinematics in persons with KOA or TKR, the methodological quality was 60% as well (range between 25-80%). Three studies were of substantial quality, one of moderate quality and one of low quality (Table 1).

The methodological quality of the included studies varied from low to substantial. No included study was of high quality. Since conference papers were also included, it was expected that a portion of the included studies would show quality concerns. However, according to the Downs and Black checklist, not only conference papers (two out of four), but also peer-reviewed journal papers (11 out of 19) showed methodological quality concerns, i.e. methodological quality < 61% (Table 1).

Study design and population characteristics

All papers on kinematics in healthy persons (n=18) were observational studies, on average 19 participants with an average age of 29 (range 18 - 97 years old) were included, with a male to female ratio of 68:32%. From these 18 papers, 16 focussed on reliability or validity assessment of the applied inertial sensor system [30, 31, 33, 35-38, 40-48] and two studies on the description of kinematics [32, 34]. In 12 studies the outcome of the inertial sensor system was compared against the outcomes registered by an optoelectronic or electromagnetic system [30, 33, 35-38, 41-46]. One study compared the sensors' outcomes to the judgement of trained physicians [47], another to outcomes from video-analysis [48]. Finally, one study compared the sensors' outcomes against outcomes reported in literature [31] (Table 2).

The five papers on kinematics in persons with KOA or TKR included on average 12 participants, with an average age of 60 (range 50 - 77 years old), with a male to female ratio of 50:50%. Two studies described the kinematics of persons with TKR [39, 49]. The remaining studies compared kinematics of healthy persons with kinematics of persons with KOA or TKR [50-52]. In two of these comparative studies, the healthy persons and persons with KOA were age-matched, i.e. 70 years and 66 years, respectively [50, 51]. However, in the third study, the age difference (average ± S.D) between the healthy persons (22.9 ± 0.8 years) and the persons with KOA (68.7 ± 4.1 years) was almost 46 years [52].

Sensor systems

Fourteen different inertial sensor systems were reported. The different sensor systems of Xsens Technologies, i.e. Moven, MTw, MTx and Mvn Biomech, were most often reported, i.e. in 6 of the 23 papers (Table 2). The other systems were reported once or twice and included ADMP Opal [32, 49], CoRehab Riablo [46], GaitSmart [34, 51], gaitWALK [50], RehaGait [38], Sunnyvale InvenSense [44], Shimmer [39], CUELA [36, 47] and H-Gait system [52]. In three papers, the inertial sensors were created from individual components (i.e. accelerometers and gyroscopes) and were study-specific [43, 45, 48] (Table 2).

The number of applied sensors varied between two and 17 (Table 2). Four studies applied 17 sensors to assess kinematics from both the upper and lower extremity joints (full body configuration) [31, 33, 40, 47]. From the remaining papers, two measured kinematics of the trunk and lower limb joints (i.e. hip, knee and ankle) [32, 46], seven of the lower limb joints (hip, knee and ankle) [35-39, 48, 52], one of the knee and ankle joints [30] and nine only of the knee joint [34, 41-45, 49-51]. All sensors were positioned directly on the skin with adhesive tape or by the use of straps, except for the study of Cloete and Scheffer (2008) where sensors were positioned in a suit [40]. In all papers, a functional or anatomical sensor calibration was performed, with the exception of Chiang et al (2017) who used a robotic system for sensor calibration prior to the measurement [49].

Reported outcome parameters

The reported kinematics included joint range of motion, minimum and maximum joint angle, walking and running speed, cadence, step/stride length and duration, stance time, and joint center trajectory. These parameters were included in all studies, except for cadence, which was only mentioned in a study that included persons with TKR [39]. In the studies including healthy persons, sagittal (n=15), frontal (n=7) and transverse (n=6) plane joint angles were evaluated (Table 2). In contrast, in the studies including persons with KOA or TKR, only sagittal (n=5) and frontal plane (n=1) joint angles were evaluated (Table 2).

In studies including healthy persons, joints proximal and distal to the knee joint (i.e. trunk, hip and ankle) were assessed, whereas in studies including persons with KOA or TKR only the ankle joint was assessed in addition to the knee joint (Table 2).

Synthesis of the study results

Psychometric study results

Repeatability of joint angles, assessed using inertial sensors, was reported (Table 3) by means of the Coefficient of Multiple Correlation (CMC) [31, 38, 42]. With regard to walking, hip, knee and ankle joint angles were most repeatable in the frontal and sagittal plane (CMC > 0.84), followed by the transversal plane (CMC > 0.79).

The validity of joint angles acquired via inertial sensors, with a lab-based system as reference, was assessed using, CMCs, correlation coefficients (R) and root mean squared errors (RMSE) [35, 37, 38, 40-44, 48]. During walking, sagittal plane joint angles of the hip and knee joint showed the highest correlations (R & CMC > 0.89) and lowest errors (RMSE ≤ 5°). Correlations and errors of sagittal plane joint angles of the ankle varied between studies (R & CMC 0.08 - 0.99; RMSE 2.2° – 11.4°). For hip, knee and ankle joint angles in the frontal and transversal plane during walking, inconsistent validity results were reported (Table 3), i.e. R and CMC values varied across the different studies between 0.55 – 0.94, 0.19 – 0.95 and 0.09 – 0.95, respectively, and RMSE varied between 3.0° – 7.9°, 5.0° - 10.8° and 1.5° – 10.2° respectively (Table 3). With regard to ascending-descending stairs and running [30, 37, 44], across movement planes, the reported CMC and R varied between 0.53 – 0.98 with corresponding RMSE between 0.1° and 7.8°.

Reported kinematics

Knee ROM assessed during the swing phase of walking was reported in five studies [32, 34, 50-52]. The ROM values, as assessed by different sensor systems, varied between 61.2 and 65.6 degrees in healthy controls (Table 4). In persons with KOA, a reduced knee ROM during the swing phase was reported (range between 42.5 – 54.8°). In persons with TKA, knee ROM during the swing phase slightly increased from 44.9° at eight weeks after TKR, to 50.6° at 52 weeks after TKR. With regard to knee flexion ROM during the stance phase of walking, in healthy persons the knee ROM ranged between 18.0° – 19.8°, while the knee ROM in persons with KOA ranged between 6.0° – 10.3° and in persons with TKR it was 8.4° (Table 4)

Tadano et al. (2016) reported the intersecting angle between the left and right joint center trajectory from the knee and ankle joints. In both persons with severe and mild KOA, these parameters were significantly increased in comparison to healthy controls (Table 4). In addition, this author [52] reported a lower ankle abduction angle in stance in persons with mild KOA (5.5° ± 7.7) as compared to persons with severe KOA (0.2° ± 2.8).

Stride duration was reported in four studies. In healthy persons, stride duration varied among different studies and sensor systems between 1.10 and 1.06 seconds (Table 4). Significant higher stride durations were reported in persons with KOA (between 1.12 – 1.31 seconds). In persons after TKR, the stride duration was slightly decreased from 1.33 seconds 8 weeks post-surgery to 1.24 seconds one year post-surgery. Despite the fact that stride duration was reduced after TKR, it was still significantly different from healthy controls. Next to the stride duration, the support ratio and gait cycle duration were reported to be significantly increased in persons with KOA in comparison to healthy controls (Table 4).

Reported tasks and ICF level

Various tasks were included in the different assessment protocols (Table 2). Regarding the studies including healthy persons, two assessment protocols focussed on metrics of the ICF-function level [45, 47]. In these studies, static joint postures and passive joint ROM were assessed. In the other 16 papers, the assessment protocols focussed on metrics of the ICF-activity level [30-38, 40-44, 46, 48]. Included tasks were level walking (n=12), stair ascending and descending (n=3), running (n=2), squatting (n=2), forward stepping/lunge (n=2), sideward stepping/lunge (n=1), jumping (n=1), climbing a ladder (n=1), the timed up and go test (n=1) and manual moving tasks (i.e. lifting, pushing, carrying) (n=1). One study [49], including persons with TKR, focussed on metrics related to the ICF-function level (assessment of joint ROM). In the other four studies, the assessment protocols were related to the ICF-activity, three studies included only persons with KOA [50-52] and the fourth study persons with TKR [39]. Remarkably, all three studies including persons with KOA only assessed kinematics during level walking [50-52]. In persons with TKR, Callies et al. (2014) assessed level walking, stair ascending and descending, running and the timed up and go test [39].

Discussion

The purpose of this review was to investigate the currently applied inertial sensor systems for lower limb movement analysis and the various reported kinematic outcome parameters. Furthermore, this review aimed to assess to what extent assessment protocols consist of tasks which are, based on the ICF core-set for OA, relevant to measure in persons with KOA and TKR.

Fourteen different sensor systems were reported, varying from individual technological components (i.e. accelerometers and gyroscopes) to commercially available full body sensor systems. In persons with KOA and TKR, the reported kinematics were only related to the knee and ankle joints, while in healthy persons, trunk and hip kinematics were additionally assessed. Moreover, in studies including healthy persons and persons after TKR, kinematics were assessed during a variety of tasks, both related to the ICF-function and activity level. In contrast, in the studies including persons with KOA, only kinematics assessed during level walking were reported. Despite the potential of an inertial sensor system to measure outside the laboratory, an out-lab measurement (i.e. walking) was only reported in one study [50].

In the following part of the discussion, the methodological quality of the included studies will be discussed first, followed by the reported outcome parameters and activities according to the ICF guidelines. Finally, recommendations for future research will be given.

Methodological considerations

With regard to the studies including healthy persons, little information was provided on the in/exclusion criteria and the applied sampling method or source . As a result, it was impossible to score the items on external validity (items 9-10, Table 1), which are however important for study results generalisation. Although the methodological quality of the studies including persons with KOA was substantial, the age difference between healthy persons and persons with KOA was remarkably high, i.e. 46 years, in one of the studies [52]. This age-difference will surely have an influence on the results and makes results-interpretation not straightforward. More specifically, it is not clear whether the reported differences are age-related or related to the disease.

With regard to the described statistics, the applied tests to assess validity and/or reliability were not appropriate in multiple studies [31, 45, 47]. The repeatability was assessed by means of the coefficient of multiple correlation [31, 38, 42]. Despite the fact that the CMC is recommended by several authors to assess waveform similarity [53, 54], CMC is affected by the ROM and sample rate which is a shortcoming [55]. Furthermore, Jaysrichai et al. (2015) calculated intraclass correlation coefficients (ICC) to determine the validity of their inertial sensor system. However, the ICC is a reliability measure (i.e. relative consistency). Since reliability furthermore consists of both relative and absolute consistency, the ICC should always be combined with a measure that determines the absolute consistency e.g. Bland-Altman plots (gold standard), standard error of the measurement or the minimum detectable change [23, 56]. Only one study within this review reported ICCs, accompanied with Bland-Altman plots to assess reliability [38]. In addition, Schiefer et al. (2015) did calculate ICCs in order to assess reliability, but did not add measurement errors (i.e. absolute consistency) and therefore only partially explained the reliability in their study.

Outcome parameters

Movement planes

The lower limb joint angles were measured most often in the sagittal plane, followed by the frontal and transverse plane. For the knee and ankle joints, the sagittal plane joint angles showed the highest ROM, which made them less difficult to measure accurately [57]. Smaller ROM, i.e. in the transversal and frontal plane, were more difficult to measure. From a clinical perspective, the accuracy of the sagittal plane kinematics was reasonable, with high R values and CMCs (> 0.89) and acceptable errors (≤ 5 degrees), except for the high measurement errors reported for the ankle joint in the study of Cloete and Scheffer [40]. However, the low accuracy results reported in this study can be explained by the use of a different biomechanical model and the fact that sensors were positioned in lycra suit instead of directly on the skin. The accuracy of the frontal and transverse plane was substantially lower, i.e. R values and CMCs were lower and RMSE was higher (Table 3). Therefore, when using joint angles measured in the frontal and transverse plane for clinical reasoning purposes, care should be taken.

Assessed lower limb joints

From a clinical perspective, it is essential to include multiple joints of the lower limb in the assessment of persons with KOA or TKR, as adjacent joints might show (mal)adaptive strategies to unload a painful knee joint. In this context, a reduced hip adduction angle, a decreased hip internal rotation moment and an increased lateral trunk lean towards the contralateral leg were already reported in persons with KOA [58-60]. However, former results were reported in studies using an optoelectronic system to assess kinematics. Unfortunately, this literature review indicates that today, only the knee and ankle joints were evaluated in persons with KOA or TKR by means of an inertial sensor systems. As such, it is currently not known whether reported adaptations in proximal knee joints (i.e. hip and trunk) can be measured by inertial sensor systems.

Functional tasks

In studies including healthy persons, two studies focussed on metrics of the ICF-function level [45, 47], while the other 16 were related to the ICF-activity level [30-38, 40-44, 46, 48]. In the studies including persons with KOA or TKR, one was related to metrics of the ICF-function level [49], while the remaining four focussed on metrics of the ICF-activity level [39, 50-52]. In the studies including healthy persons and persons with TKR, a variety of functional tasks were included in the assessment protocols. Although level walking was most often assessed, other activities such as stair ascending and descending, squatting, forward and sideward lunges, jumping running and a timed up and go test were performed [30-35, 37-44, 46-48]. In persons with KOA, only level walking was assessed [50-52]. This is a limitation, as it can be expected that in persons with KOA potential compensatory movement strategies of the lower limb will only been detected in physically more demanding tasks than level walking [57]. Therefore, it is recommended to include functional tasks that are in accordance to the ICF guidelines (e.g. stair walking, forward and sideward lunges or cycling) in the assessment protocols of persons with KOA and TKR.

Apart from the ICF-function and activity level, the ICF also consists of a participation level, which measures restrictions that individuals experience during daily life situations. Despite the potential of an inertial sensor system to monitor persons in daily life situations, none of the included studies measured on participation level. Most likely this is due to the fact that most of the assessment protocols were still conducted in a laboratory environment as they focused on psychometric properties of inertial sensor systems for kinematic analysis. In addition, for an objective kinematic assessment of the lower limb joints (e.g. hip, knee and ankle) multiple inertial sensors are required, which is not practical to use in daily life settings. However, reducing costs, minimization of the technology and improvement of sensing systems will boost the use of mobile technology during daily life (e.g. assessments related to the ICF-participation level).

Future research

The potential of an inertial sensor system to assess outside the laboratory is so far not yet completely utilized. However, before out-lab measures can be performed, high quality psychometric research, using appropriate statistics (i.e. describing the relative and absolute consistency by means of ICC and Bland-Altman plots and SEM), needs to be performed in order to determine the validity and reliability of inertial sensor systems for lower limb kinematic analysis. Furthermore, it is recommended to develop an assessment protocol consisting of a larger variety of functional tasks which are related to the ICF guidelines. These may reveal more discriminative parameters, as well as provide a better tool to detect changes in the functioning of the lower limb. In addition, it might be interesting to add more physically demanding tasks, executed in a repetitive manner, in order to detect any (mal)adaptive compensatory movement strategy which will not show up in less demanding tasks [57]. Multiple lower limb joints should furthermore be included in the assessment since adjacent joints' kinematics affect the knee joint loading as well.

In future research, attention should be paid towards the most appropriate way to analyse kinematic data. Assessing waveforms (e.g. by means of statistical parametric mapping) instead of isolated events in the waveform (e.g. start point or peak values) might additionally explain differences between healthy persons and persons with KOA or TKR, as these analysing methods describe the whole waveform and do not ignore temporal information [61]. In the future it should moreover be explored whether it is possible to calculate joint moments and joint forces by using only a force plate and inertial sensor system to enable joint loading assessments. Similar to motion analysis in a laboratory environment, measures such as EMG and muscle strength or musculoskeletal modelling should be added to the assessment based on inertial sensors, to further support the clinical reasoning process.

Conclusion

This review illustrates that in healthy persons both the knee joint and the joints proximal and distal to the knee joint (i.e. hip/trunk and ankle respectively) were assessed. In persons with KOA and TKR, only the ankle and knee joint were investigated. As movement alterations in the hip joint and trunk were reported as (mal)adaptive strategies to reduce knee joint loading, the inclusion of these proximal joints should be considered in the kinematic assessment of persons with KOA or TKR. Reported differences in kinematics between KOA and healthy persons pertained to: knee flexion ROM, ankle abduction angle during stance, the intersecting angle of the frontal plane ankle and knee joint center trajectory, the support ratio and the stride and gait cycle duration. Since in studies including persons with KOA only level walking was assessed, assessment protocols should include a larger number of physical demanding functional tasks and multiple joints in order to provide a comprehensive assessment that supports clinical reasoning and allows for integrative rehabilitation approaches.

Author contributions

On behalf of the co-authors, I declare that all of the listed authors had a substantial contribution to the creation of this systematic review. The contribution of each author is specified below:

1. Conception and design of the study

   R. van der Straaten, L. De Baets, I. Jonkers, A. Timmermans

2. Acquisition of the data

   R. van der Straaten, L. De Baets

3. Analysis and interpretation of the data

   R. van der Straaten, L. De Baets, A. Timmermans

4. Drafting the manuscript

   R. van der Straaten, L. De Baets, I. Jonkers, A. Timmermans

5. Critical revisions and final approval of the version submitted

   R. van der Straaten, L. De Baets, I. Jonkers, A. Timmermans

Yours sincerely,

Rob van der Straaten

Conflict of interest statement

On behalf of the co-authors I declare that none of them have any financial and/or personal relationship with other people or organizations that could inappropriately influence their work in the subject or materials discussed in this manuscript.

Yours sincerely,

Rob van der Straaten

Conflict of interest

None to declare.

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References

1. D.T. Felson, R.C. Lawrence, P.A. Dieppe, R. Hirsch, C.G. Helmick, J.M. Jordan, et al., Osteoarthritis: New Insights. Part 1: The Disease and Its Risk Factors, Annals of Internal Medicine. 133 (8) (2000) 635-46.
2. A.D. Woolf, B. Pfleger, Burden of major musculoskeletal conditions, Bulletin of the World Health Organization. 81 (9) (2003) 646-56.
3. B. Heidari, Knee osteoarthritis prevalence, risk factors, pathogenesis and features: Part I, Caspian Journal of Internal Medicine. 2 (2) (2011) 205-12.
4. J.L. Astephen, K.J. Deluzio, G.E. Caldwell, M.J. Dunbar, Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity, Journal of orthopaedic research : official publication of the Orthopaedic Research Society. 26 (3) (2008) 332-41.
5. D. Bhatia, T. Bejarano, M. Novo, Current interventions in the management of knee osteoarthritis, Journal of Pharmacy & Bioallied Sciences. 5 (1) (2013) 30-8.
6. J.A. Zeni, M.J. Axe, L. Snyder-Mackler, Clinical predictors of elective total joint replacement in persons with end-stage knee osteoarthritis, BMC musculoskeletal disorders. 11 (2010) 86.
7. P.N. Baker, J.H. van der Meulen, J. Lewsey, P.J. Gregg, The role of pain and function in determining patient satisfaction after total knee replacement. Data from the National Joint Registry for England and Wales, The Journal of bone and joint surgery British volume. 89 (7) (2007) 893-900.
8. K. Desloovere, P. Wong, L. Swings, B. Callewaert, H. Vandenneucker, A. Leardini, Range of motion and repeatability of knee kinematics for 11 clinically relevant motor tasks, Gait & posture. 32 (4) (2010) 597-602.
9. H. Zhou, H. Hu, Human motion tracking for rehabilitation - A survey, Biomedical Signal Processing and Control. 3 (1) (2008) 1-18.
10. S.A. Bolink, B. Grimm, I.C. Heyligers, Patient-reported outcome measures versus inertial performance-based outcome measures: A prospective study in patients undergoing primary total knee arthroplasty, The Knee. 22 (6) (2015) 618-23.

11. K. Aminian, B. Najafi, C. Bula, P.F. Leyvraz, P. Robert, Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes, Journal of biomechanics. 35 (5) (2002) 689-99.

12. K. Aminian, K. Rezakhanlou, E. De Andres, C. Fritsch, P.F. Leyvraz, P. Robert, Temporal feature estimation during walking using miniature accelerometers: an analysis of gait improvement after hip arthroplasty, Medical & biological engineering & computing. 37 (6) (1999) 686-91.

13. M. Brandes, M. Ringling, C. Winter, A. Hillmann, D. Rosenbaum, Changes in physical activity and health-related quality of life during the first year after total knee arthroplasty, Arthritis care & research. 63 (3) (2011) 328-34.

14. J.J. Kavanagh, S. Morrison, D.A. James, R. Barrett, Reliability of segmental accelerations measured using a new wireless gait analysis system, Journal of biomechanics. 39 (15) (2006) 2863-72.

15. W. Zijlstra, Assessment of spatio-temporal parameters during unconstrained walking, European journal of applied physiology. 92 (1-2) (2004) 39-44.

16. H.J. Luinge, P.H. Veltink, C.T. Baten, Estimating orientation with gyroscopes and accelerometers, Technology and health care: official journal of the European Society for Engineering and Medicine. 7 (6) (1999) 455-9.

17. R.E. Mayagoitia, A.V. Nene, P.H. Veltink, Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems, Journal of biomechanics. 35 (4) (2002) 537-42.

18. D. Roetenberg, H. Luinge, P. Slycke, Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors, Xsens Motion Technologies BV, Tech Rep. (2009).

19. D. Roetenberg, P.J. Slycke, P.H. Veltink, Ambulatory position and orientation tracking fusing magnetic and inertial sensing, IEEE transactions on bio-medical engineering. 54 (5) (2007) 883-90.

20. A. Forner-Cordero, M. Mateu-Arce, I. Forner-Cordero, E. Alcantara, J.C. Moreno, J.L. Pons, Study of the motion artefacts of skin-mounted inertial sensors under different attachment conditions, Physiological measurement. 29 (4) (2008) N21-31.

21. X. Robert-Lachaine, H. Mecheri, C. Larue, A. Plamondon, Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis, Medical & biological engineering & computing. 55 (4) (2017) 609-19.

22. A.I. Cuesta-Vargas, A. Galán-Mercant, J.M. Williams, The use of inertial sensors system for human motion analysis, Physical Therapy Reviews. 15 (6) (2010) 462-73.

23. J.L. McGinley, R. Baker, R. Wolfe, M.E. Morris, The reliability of three-dimensional kinematic gait measurements: a systematic review, Gait & posture. 29 (3) (2009) 360-9.

24. X. Robert-Lachaine, H. Mecheri, C. Larue, A. Plamondon, Accuracy and repeatability of single-pose calibration of inertial measurement units for whole-body motion analysis, Gait & posture. 54 (2017) 80-6.

25. J.L. Astephen, K.J. Deluzio, G.E. Caldwell, M.J. Dunbar, C.L. Hubley-Kozey, Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels, Journal of biomechanics. 41 (4) (2008) 868-76.

26. K. Dreinhofer, G. Stucki, T. Ewert, E. Huber, G. Ebenbichler, C. Gutenbrunner, et al., ICF Core Sets for osteoarthritis, Journal of rehabilitation medicine. 36 (44 Suppl) (2004) 75-80.

27. S.H. Downs, N. Black, The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions, Journal of epidemiology and community health. 52 (6) (1998) 377-84.

28. L. Weierink, R.J. Vermeulen, R.N. Boyd, Brain structure and executive functions in children with cerebral palsy: a systematic review, Research in developmental disabilities. 34 (5) (2013) 1678-88.

29. C. Pisoni, A. Giardini, G. Majani, M. Maini, International Classification of Functioning, Disability and Health (ICF) core sets for osteoarthritis. A useful tool in the follow-up of patients after joint arthroplasty, Eur J Phys Rehabil Med. 44 (4) (2008) 377-85.

30. J.H. Bergmann, R.E. Mayagoitia, I.C. Smith, A portable system for collecting anatomical joint angles during stair ascent: a comparison with an optical tracking device, Dynamic medicine : DM. 8 (2009) 3.

31. T. Cloete, C. Scheffer, Repeatability of an off-the-shelf, full body inertial motion capture system during clinical gait analysis, Conference proceedings: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. (2010) 5125-8.

32. S. Fantozzi, A. Giovanardi, D. Borra, G. Gatta, Gait Kinematic Analysis in Water Using Wearable Inertial Magnetic Sensors, PloS one. 10 (9) (2015) e0138105.
33. S. Kim, M.A. Nussbaum, Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks, Ergonomics. 56 (2) (2013) 314-26.
34. M. Monda, R. Richards, A.-L. Smith, M. Thornton, I. McCarthy, Kinematics of lower limb segment movement during gait in a healthy population aged 18 to 97 using inertial measurement units, Journal of Aging and Physical Activity. 20 (2012) S256-S7.
35. E. Palermo, S. Rossi, F. Marini, F. Patane, P. Cappa, Experimental evaluation of accuracy and repeatability of a novel body-to-sensor calibration procedure for inertial sensor-based gait analysis, Measurement. 52 (2014) 145-55.
36. C. Schiefer, T. Kraus, E. Ochsmann, I. Hermanns, R. Ellegast. 3D human motion capturing based only on acceleration and angular rate measurement for low extremities. Proceedings of the Third international conference on Digital human modeling; Orlando, FL (2011) p. 195-203.
37. J.T. Zhang, A.C. Novak, B. Brouwer, Q. Li, Concurrent validation of Xsens MVN measurement of lower limb joint angular kinematics, Physiological measurement. 34 (8) (2013) N63-9.
38. C. Nuesch, E. Roos, G. Pagenstert, A. Mundermann, Measuring joint kinematics of treadmill walking and running: Comparison between an inertial sensor based system and a camera-based system, Journal of biomechanics. 57 (2017) 32-8.
39. T. Calliess, R. Bocklage, R. Karkosch, M. Marschollek, H. Windhagen, M. Schulze, Clinical evaluation of a mobile sensor-based gait analysis method for outcome measurement after knee arthroplasty, Sensors (Basel, Switzerland). 14 (9) (2014) 15953-64.
40. T. Cloete, C. Scheffer. Benchmarking of a full-body inertial motion capture system for clinical gait analysis. Engineering in Medicine and Biology Society, EMBS 2008 30th Annual International Conference of the IEEE.
41. G. Cooper, I. Sheret, L. McMillan, K. Siliverdis, N. Sha, D. Hodgins, et al., Inertial sensor-based knee flexion/extension angle estimation, Journal of biomechanics. 42 (16) (2009) 2678-85.
42. J. Favre, R. Aissaoui, B.M. Jolles, J.A. de Guise, K. Aminian, Functional calibration procedure for 3D knee joint angle description using inertial sensors, Journal of biomechanics. 42 (14) (2009) 2330-5.

43. J. Favre, B.M. Jolles, R. Aissaoui, K. Aminian, Ambulatory measurement of 3D knee joint angle, Journal of biomechanics. 41 (5) (2008) 1029-35.

44. C. Jakob, P. Kugler, F. Hebenstreit, S. Reinfelder, U. Jensen, D. Schuldhaus, et al. Estimation of the knee flexion-extension angle during dynamic sport motions using body-worn inertial sensors. Proceedings of the 8th International Conference on Body Area Networks; Boston, Massachusetts (2013) p. 289-95.

45. T. Jaysrichai, A. Suputtitada, W. Khovidhungij, Mobile Sensor Application for Kinematic Detection of the Knees, Annals of rehabilitation medicine. 39 (4) (2015) 599-608.

46. A. Leardini, G. Lullini, S. Giannini, L. Berti, M. Ortolani, P. Caravaggi, Validation of the angular measurements of a new inertial-measurement-unit based rehabilitation system: comparison with state-of-the-art gait analysis, Journal of neuroengineering and rehabilitation. 11 (2014) 136.

47. C. Schiefer, T. Kraus, R.P. Ellegast, E. Ochsmann, A technical support tool for joint range of motion determination in functional diagnostics - an inter-rater study, Journal of occupational medicine and toxicology (London, England). 10 (2015) 16.

48. S. Tadano, R. Takeda, H. Miyagawa, Three Dimensional Gait Analysis Using Wearable Acceleration and Gyro Sensors Based on Quaternion Calculations, Sensors (Basel, Switzerland). 13 (7) (2013) 9321-43.

49. C.-Y. Chiang, K.-H. Chen, K.-C. Liu, S.J.-P. Hsu, C.-T. Chan, Data Collection and Analysis Using Wearable Sensors for Monitoring Knee Range of Motion after Total Knee Arthroplasty, Sensors (Basel, Switzerland). 17 (2) (2017) 418.

50. I. McCarthy, D. Hodgins, A. Mor, A. Elbaz, G. Segal, Analysis of knee flexion characteristics and how they alter with the onset of knee osteoarthritis: a case control study, BMC musculoskeletal disorders. 14 (1) (2013) 1-7.

51. J. Rahman, Q. Tang, M. Monda, J. Miles, I. McCarthy, Gait assessment as a functional outcome measure in total knee arthroplasty: A cross-sectional study, BMC musculoskeletal disorders. 16 (1) (2015).

52. S. Tadano, R. Takeda, K. Sasaki, T. Fujisawa, H. Tohyama, Gait characterization for osteoarthritis patients using wearable gait sensors (H-Gait systems), Journal of biomechanics. 49 (5) (2016) 684-90.

53. A. Ferrari, A.G. Cutti, A. Cappello, A new formulation of the coefficient of multiple correlation to assess the similarity of waveforms measured synchronously by different motion analysis protocols, Gait & posture. 31 (4) (2010) 540-2.

54. M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten, J. Gainey, G. Gorton, G.V. Cochran, Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait, Journal of orthopaedic research : official publication of the Orthopaedic Research Society. 7 (6) (1989) 849-60.

55. J. Roislien, O. Skare, A. Opheim, L. Rennie, Evaluating the properties of the coefficient of multiple correlation (CMC) for kinematic gait data, Journal of biomechanics. 45 (11) (2012) 2014-8.

56. J.P. Weir, Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM, Journal of strength and conditioning research / National Strength & Conditioning Association. 19 (1) (2005) 231-40.

57. I. Komnik, S. Weiss, C.H. Fantini Pagani, W. Potthast, Motion analysis of patients after knee arthroplasty during activities of daily living – A systematic review, Gait & posture. 41 (2) (2015) 370-7.

58. M.A. Hunt, T.V. Wrigley, R.S. Hinman, K.L. Bennell, Individuals with severe knee osteoarthritis (OA) exhibit altered proximal walking mechanics compared with individuals with less severe OA and those without knee pain, Arthritis care & research. 62 (10) (2010) 1426-32.

59. K. Mills, M.A. Hunt, R. Ferber, Biomechanical deviations during level walking associated with knee osteoarthritis: a systematic review and meta-analysis, Arthritis care & research. 65 (10) (2013) 1643-65.

60. M. Simic, R.S. Hinman, T.V. Wrigley, K.L. Bennell, M.A. Hunt, Gait modification strategies for altering medial knee joint load: a systematic review, Arthritis care & research. 63 (3) (2011) 405-26.

61. B. Dingenen, B. Malfait, J. Vanrenterghem, M.A. Robinson, S.M. Verschueren, F.F. Staes, Can two-dimensional measured peak sagittal plane excursions during drop vertical jumps help identify three-dimensional measured joint moments?, The Knee. 22 (2) (2015) 73-9.

FIGURE CAPTIONS

Figure 1: Flowchart of the selection procedure

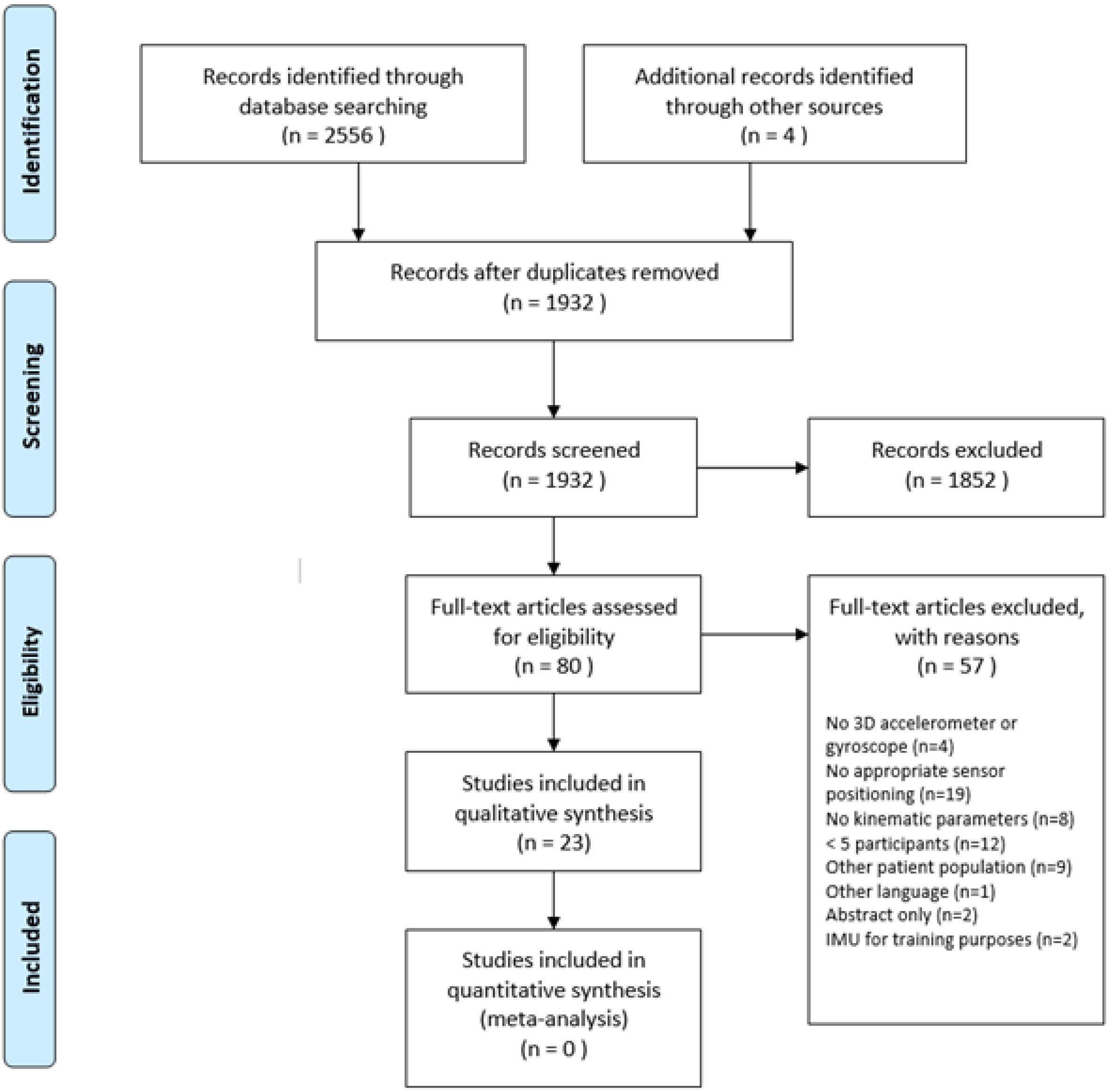

TABLE CAPTIONS

Table 1: Methodological quality assessment with customized Downs and Black quality index

Table 1: Methodological quality assessment with customized Downs and Black quality index

Authors / Items	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total
ICF Function level - Healthy																
Jaysrichai et al. 2015	1	1	1	-	1	0	-	U	U	U	1	0	1	-	0	50
Schiefer et al. 2015	1	1	1	-	0	1	-	U	U	U	0	0	1	-	1	50
ICF Activity level - Healthy																
Bergmann et al. 2009	1	1	1	-	1	1	-	0	U	U	1	1	1	-	1	75
Cloete and Scheffer 2008	0	1	0	-	1	1	-	U	U	U	1	1	0	-	1	50
Cloete and Scheffer 2010	1	1	1	-	1	1	-	U	U	U	1	1	1	-	0	67
Cooper et al. 2009	1	0	1	-	1	0	-	U	U	U	1	1	1	-	0	50
Fantozzi et al. 2015	1	1	1	-	1	1	-	0	U	U	1	1	0	-	1	67
Favre et al. 2008	1	1	0	-	1	1	-	U	U	U	1	1	1	-	0	58
Favre et al. 2009	1	1	0	-	0	0	-	U	U	U	1	1	1	-	0	42
Jakob et al. 2013	1	1	0	-	1	1	-	U	U	U	1	1	1	-	0	58
Kim and Nussbaum 2013	1	1	1	-	0	1	-	1	U	U	1	1	1	-	0	67
Leardini et al. 2014	1	1	1	-	1	1	-	U	U	U	1	0	1	-	0	58
Monde et al. 2015	1	1	1	-	1	1	-	0	1	U	1	1	U	-	U	67
Neüsch et al. 2017	1	1	1	-	1	1	-	0	U	U	1	1	1	-	0	67
Palermo et al. 2014	1	1	0	-	1	1	-	0	U	U	1	1	1	-	1	67
Schiefer et al. 2011	0	1	1	-	1	1	-	U	U	U	1	1	1	-	1	67
Tadano et al. 2013	0	0	1	-	1	0	-	U	U	U	1	1	1	-	1	50
Zhang et al. 2013	1	1	1	-	1	1	-	U	U	U	1	1	1	-	0	67
ICF Function - Patients																
Chiang et al. 2017	1	1	0	-	0	0	-	0	U	U	1	U	U	-	U	25
ICF Activity level - Patients																
Calliess et al. 2014	1	1	1	-	1	0	-	0	U	U	1	U	0	-	0	42
McCarthy et al. 2013	1	1	1	1	1	1	0	1	1	U	1	1	0	1	1	80
Rahman et al. 2015	1	1	1	1	1	1	0	1	1	1	1	1	0	1	0	80
Tadano et al. 2016	1	1	1	1	1	1	0	1	U	U	1	1	1	0	1	73

Items: 1. Is the hypothesis / aim / objective clearly described? 2. Are the main outcomes to be measured clearly described in introduction or methods section? 3. Are the characteristics of the patients included clearly described? 4. Are the distribution of principal confounders in each group of subjects to be compared clearly described? 5. Are the main findings of the study clearly described? 6. Does the study provide estimates of the random variability in the data for the main outcomes? 7. Have the characteristics of the patients lost to follow-up been described? 8. Have actual probability values been reported for the main outcomes except where it is less than 0.001? 9. Were the subjects asked to participate in the study representative of the entire population from which they were recruited? 10. Were those subjects who were prepared to participate representative of the entire population from which they were recruited? 11. If any of the results of the study were based on "data dredging", was this made clear? 12. Were the statistical test used to assess the main outcomes appropriate? 13. Were the main outcomes used accurate (valid and/or reliable?) 14. Were the patients in different intervention groups or were the cases and controls recruited from the same population? 15. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn? Scores should be interpreted as: 0 = No, 1 = Yes, U = unable to determine and (-) = not applicable to this type of study, except for item 4 were: 0 = No, 1 = Partially, 2 = Yes, U = unable to determine and (-) = not applicable to this type of study.

Table 2: Characteristics of included studies

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Authors	Population	Inertial system	N sensors	Sensors location	Reference system	Tasks	Main outcome parameters
ICF Function level – Healthy							
Jaysrichai et al. (2015)	N = 10 M/F = 7/3 Age = 26,8 (± 3,7)	Razor IMU-AHRS (SparkFun electronics)	4	Thighs and shanks	Qualysis	Knee flexion test Hip and knee flexion test Forward step test Leg abduction test	Frontal + Sagittal plane joint angles Knee
Schiefer et al. (2015)	N = 20 M/F = 14/6 Age = 37,4 (± 9,9)	CUELA (IFA)	13	Head, L5/S1, Th4, upper/fore arms Hands and upper/lower legs	Physicians	Static joint movements	Active ROM Cervical, Thoracic and Lumbar spine Passive ROM Shoulder Elbow Wrist Hip Knee
ICF Activity level – Healthy							
Bergmann et al. (2009)	N = 14 M/F = 9/5 Age = 27,0 (20-37)	MTx (Xsens)	6	Thighs, shanks and feet	Coda motion	Stair ascent	Sagittal plane joint angles Thigh Knee Ankle
Cloete and Scheffer (2008)	N = 8 M/F = 8/0 Age = ns.	Moven (Xsens)	16	Head, shoulders, upper/fore arms, hands, pelvis, upper/lower legs and feet	Vicon	Walking on a 7m walkway (5 velocities)	3D joint angles Hip Knee Ankle
Cloete and Scheffer (2010)	N = 8 M/F = ns. Age = (19-25)	MVN Biomech (Xsens)	16	Head, pelvis and bilateral on shoulders, upper/lower arms, upper/lower legs, hands and feet	Other studies [49, 58]	Walking on a 12m walkway (self-selected speed)	3D joint angles Hip Knee Ankle

Cooper et al. (2009)	N = 7 M/F = 5/2 Age = 30 (± 6)	-	4	Thighs and shanks	Qualysis	Walking on a treadmill (5 velocities) Running	Sagittal plane joint angle Knee
Fantozzi et al. (2015)	N = 11 M/F = 6/5 Age = 27,0 (± 3,4)	Opal (ADMP)	8	Trunk, pelvis, thighs, shanks and feet	-	Walking 10 meter barefoot (self-selected speed)	Sagittal plane joint angles Trunk Hip Knee Ankle Stride, stance and swing time (s) stance and swing percentage (%) stride length (cm) number of steps walking speed (cm/s)
Favre et al. (2008)	N = 10 M/F = ns. Age = 29 (23-40)	ADXL 3D - accelerometer ADXRS 3D - gyroscope	2	Thigh and shank	Liberty	Walking 30m	3D joint angle Knee
Favre et al. (2009)	N = 8 M/F = 8/0 Age = 26 (19-28)	-	2	Right thigh and shank	Liberty	Walking 7m	3D joint angle Knee
Jakob et al. (2013)	N = 10 M/F = 7/3 Age = 26,8 (± 3,7)	Invensense (Sunnyvale)	2	Right thigh and shank	Qualysis	Walking on a treadmill Jogging Running Squats Jumps	Sagittal plane joint angle Knee
Kim & Nussbaum (2013)	N = 14 M/F = 11/3 Age = 22,9 (± 4,9)	MVN Biomech (Xsens)	17	Head, sternum, pelvis, scapulae, upper/lower arms, hands, thighs, shanks and feet	Vicon	Manual moving tasks (symmetric & asymmetric lifting, carrying, pushing and pulling)	3D joint angle L5/S1 Shoulder Hip Sagittal plane joint angle Knee

Leardini et al. (2014)	N = 17 M/F = 10/7 Age = 26,3 (± 3,8)	Riablo (CoRehab)	5	Trunk, thighs and shanks	Vicon	Lunge Squatting Knee flexion against gravity (upright) Knee flexion against gravity (sitting)	Sagittal plane joint angle Trunk Knee
Monda et al. (2015)	N = 136 M/F = ns. Age = 53,8 (18-97)	GaitSmart (ETB)	4	Thighs and shanks	-	Walking	Sagittal plane joint angle Thigh Knee Shank Stride Duration (s)
Nüesch et al. (2017)	N = 12 M/F = 8/12 Age = 27,4 (± 3,8)	RehaGait	7	Pelvis, Thighs, Shanks and feet	Vicon	Walking Running	Sagittal plane joint angles Hip Knee Ankle
Palermo et al. (2014)	N = 10 M/F = ns. Age = 25 (± 2)	MTw (Xsens)	7	Pelvis, thighs, shanks and feet	Vicon	Walking 20 strides	3D joint angles Hip Ankle Sagittal plane joint angle Knee
Schiefer et al. (2011)	N = 11 M/F = 6/5 Age = 34,4 (± 8,4)	CUELA (IFA)	5	Pelvis, thighs and shanks	Vicon	Forward stepping sideward stepping squatting stair ascent & 180° turn ascending a ladder	Knee angle Hip azimuth angle
Tadano et al. (2013)	N = 5 M/F = 5/0 Age = 23,8 (± 1,9)	WAA-006 (Wireless Technologies Inc.)	7	Pelvis, thighs, shanks and feet	CCD cameras	Walking 5 m	Sagittal plane joint angle Hip Knee Ankle Sagittal + Frontal plane Joint trajectories Hip Knee Ankle
Zhang et al. (2013)	N = 10 M/F = 5/5	MVN Biomech (Xsens)	7	Pelvis, thighs, shanks and feet	Optotrak	Walking Stair ascent	3D joint angles Hip Knee

	Age = 24 (± 4)					Stair descent	Ankle
ICF Function level – KOA and TKA							
Chiang et al. (2017)	TKR: N = 18	Opal (ADMP)	2	Thigh and Shank	-	Knee ROM	Sagittal plane joint angle Knee
ICF Activity level – KOA and TKA							
Calliess et al. (2014)	TKR: N = 4 M/F = 2/2 Age = 61,3 (± 5,3) UKR: N = 2 M/F = 1/1 Age = 58,0 (± 8,4)	Shimmer	3	Pelvis, thigh and shank (of the affected limb)	-	TUG Walking 100m (self-selected speed) 50m running as fast as possible max acceleration sprint with abrupt stop Stair ascent & descent	Sagittal plane joint angle Knee Walking speed (m/s) running speed (m/s) cadence (steps/min) step length (m) time per step (s)
McCarthy et al. (2013)	Healthy: N = 21 M/F = 4/17 Age = 71,3 (± 6,1) KOA: N = 23 M/F = 9/14 Age = 65,1 (± 7,7)	GaitWALK	4	Thighs and shanks	-	Walking 20 m	Sagittal plane joint angle Knee Stride duration (s)
Rahman et al. (2015)	Healthy N = 29 M/F = 12/17 Age = 68,1 (± 7,1) KOA/TKR N = 74 M/F = 32/42 Age = 66,9 (± 10,7)	GaitSmart (ETB)	4	Thighs and shanks	-	Walking 20m	Sagittal plane joint angle Knee Stride duration (s)

Tadano et al. (2016)	Healthy: N = 8 M/F = ns. Age = 22,9 (± 0,8) KOA: N = 10 M/F = ns. Age = 68,7 (± 4,1)	H-gait systems	7	Pelvis, thighs, shanks and feet	-	Walking 7m (self-selected speed)	Sagittal plane joint angle & joint trajectory Knee Frontal plane joint angle & joint trajectory Ankle Step length (cm) Support ratio (%) Gait cycle (s) Joint acceleration

N = number of participants / sensors
M/F = number of males / females included
Age = age in years (± standard deviation, SD) or age range (minimum – maximum age)

Table 3: Study results – psychometric properties

Table 3: Study results – psychometric properties

Author	Task	Outcome parameter	Sagittal	Frontal	Transverse
Bergmann et al., 2009	Stair ascent	R Thigh Knee Ankle	 0.96 0.98 0.93		
		RMSE Thigh Knee Ankle	 5 (± 3) 4 (± 3) 4 (± 2)		
Cloete and Scheffer, 2008	Walking	R Hip Knee Ankle	 0.94 0.89 0.08	 0.55 0.19 0.09	 0.54 0.25 0.27
		RMSE Hip Knee Ankle	 5.8 (± 3.8) 8.5 (± 3.0) 11.4 (± 4.6)	 7.3 (± 5.2) 10.8 (± 5.8) 10.2 (± 3.6)	 7.9 (± 4.9) 7.3 (± 3.6) 18.3 (± 7.1)
Cloete and Scheffer, 2010	Walking (within day repeatability)	CMC Hip Knee Ankle	 0.98 0.96 0.94	 0.99 0.99 0.97	 0.89 0.93 0.93
		CMD Hip Knee Ankle	 0.96 0.93 0.89	 0.98 0.98 0.95	 0.79 0.86 0.87
	Walking (between day repeatability)	CMC Hip Knee Ankle	 0.96 0.90 0.92	 0.99 1.00 0.97	 0.96 0.91 0.96
		CMD Hip Knee Ankle	 0.92 0.84 0.85	 0.99 0.99 0.94	 0.93 0.83 0.92
Cooper et al., 2009	Walking	RMSE Knee	 1.6 (± 0.5)		
Favre et al., 2008	Walking	R Knee	 1.00	 0.86	 0.95
		RMSE Knee	 1.5	 1.7	 1.6
Favre et al., 2009	Walking (repeatability) (precision)	CMC Knee R	 1.00	 0.89	 0.91
		Knee	1.00	0.76	0.85
Jakob et al., 2013	Walking Jogging Running Squads Jumps	R Knee	0.97 0.96 0.96 0.98 0.99		
Neüsch et al., 2017	Walking (repeatability)	CMC Hip Knee Ankle	 0.898 0.964 0.893		

	(precision)	RMSE Hip Knee Ankle	 3.3 (± 0.8) 5.0 (± 1.7) 2.5 (± 0.9)		
	Running (repeatability)	CMC Hip Knee Ankle	 0.538 0.881 0.677		
	(precision)	RMSE Hip Knee Ankle	 5.3 (± 2.2) 7.8 (± 3.5) 5.4 (± 3.6)		
Palermo et al., 2014	Walking	R Hip Knee Ankle	 0.97 0.97 0.89	 0.93 - 0.81	 0.94 - 0.94
Tadano et al., 2013	Walking	R Hip Knee Ankle	 0.98 0.97 0.78		
		RMSE Hip Knee Ankle	 10.1 7.9 9.8		
Zhang et al., 2013	Walking	CMC Hip Knee Ankle	 0.99 0.99 0.99	 0.39 0.71 0.95	 0.96 0.88 0.77
		RMSE Hip Knee Ankle	 2.5 (± 1.6) 1.9 (± 1.3) 2.2 (± 1.2)	 4.8 (± 3.2) 5.1 (± 4.2) 1.8 (± 1.3)	 3.0 (± 1.6) 2.7 (± 2.2) 1.8 (± 1.1)
	Stair ascent	RMSE Hip Knee Ankle	 2.4 (± 1.7) 1.7 (± 1.5) 2.9 (± 1.6)	 3.6 (± 2.5) 4.7 (± 3.8) 2.6 (± 1.8)	 2.3 (± 1.4) 5.2 (± 3.1) 1.6 (± 1.1)
	Stair descent	RMSE Hip Knee Ankle	 1.9 (± 1.2) 2.0 (± 1.1) 4.0 (± 2.1)	 2.1 (± 2.2) 5.5 (± 3.8) 6.7 (± 3.2)	 1.4 (± 1.1) 3.7 (± 3.6) 2.6 (± 1.6)

Table 4: Study results – joint kinematics

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Author	**Tasks, repetitions**	**Outcome parameter**	**Sagittal**	**Frontal**	**Transverse**	**Spatiotemporal**
Bergmann et al., 2009	Stair ascent	Max ROM Thigh Knee Ankle	 56 (± 5) 91 (± 8) 63 (± 8)			
Fantozzi et al., 2015	Walking	At heel strike Knee Ankle	-3.5 (± 5.7) -6.6 (± 5.3)			
		At toe off Hip Ankle	-2.1 (± 5.7)	11.0 (± 6.2)		
		Maximum angle Hip Knee	25.0 (± 3.0) 56.8 (± 4.4)			
		Minimum angle Hip	-11.1 (± 3.9)			
		ROM Knee Ankle	64.9 (± 3.8) 29.8 (± 4.3)			
		Stride duration (s) Stance percentage (%) Stride distance (cm)				1.1 (± 0.1) 57.9 (± 2.6) 161.2 (± 13.8)
Monda et al., 2015	Walking	ROM Knee Thigh Shank	62.9 (± 3.1) 40.9 (± 6.4) 75.1 (± 6.3)			
		Stance Knee	18.5 (± 4.9)			
		Stride duration (s)				1.07 (± 0.13)
Callies et al., 2014	Stair ascent	Knee angle Max pre-op Max post-op	77 79			
	Stair descent	Knee Max pre-op	72 74			

		Max post-op				
		At heel strike Pre-op Post-op	23 22			
	Walking	Walking speed (m/s) Pre-op Post-op				1.22 1.44
		Cadence (steps/min) Pre-op Post-op				110 121
		Step length (m) Pre-op Post-op				0.65 0.72
McCarthy et al., 2013	Walking	ROM (swing) * OA knee Non OA knee Healthy controls	54.8 (± 5.5) 57.6 (± 4.6) 61.2 (± 6.1)			
		ROM (stance) * OA knee Non OA knee Healthy controls	10.3 (± 4.0) 14.0 (± 4.3) 18.0 (± 4.0)			
		Stride duration OA knee Healthy controls				1.12 (± 0.09) 1.06 (± 0.11)
Rahman et al., 2015	Walking (pre-operative)	Knee angle stance * OA knee Non OA knee Control	6.0 (± 3.4) 9.6 (± 6.0) 19.8 (± 4.9)			
		Knee angle swing * OA knee Non OA knee Control	42.5 (± 10.1) 47.5 (± 9.4) 62.6 (± 5.7)			
		Stride duration * OA knee Non OA knee Control				1.31 (± 0.16) 1.31 (± 0.16) 1.07 (± 0.09)

	Walking (post-operative)	Knee angle stance # OA knee - 8wk OA knee - 52wk Non OA knee - 8wk Non OA knee - 52wk	6.2 (± 4.0) 8.4 (± 3.7) 10.2 (± 4.8) 10.6 (± 4.4)			
		Knee angle swing # OA knee - 8wk OA knee - 52wk Non OA knee - 8wk Non OA knee - 52wk &	44.9 (± 12.8) 50.6 (± 7.8) 49.2 (± 7.7) 50.7 (± 9.1)			
		Stride duration # OA knee - 8wk OA knee - 52wk Non OA knee - 8wk Non OA knee - 52wk				1.33 (± 0.23) 1.24 (± 0.18) 1.33 (± 0.23) 1.24 (± 0.18)
Tadano et al., 2016	Walking	Knee max angle swing KOA mild KOA severe Healthy	72.5 (± 5.1) 72.2 (± 5.5) 68.6 (± 7.3)			
		Knee max angle stance KOA mild KOA severe Healthy	54.5 (± 6.3) 54.3 (± 4.9) 52.8 (± 7.3)			
		Knee min angle stance KOA mild KOA severe Healthy	4.2 (± 1.9) 5.8 (± 1.8) 6.0 (± 2.2)			
		Knee ROM KOA mild KOA severe	68.7 (± 4.4)			

		Healthy	67.0 (± 5.0) 65.6 (± 6.9)				
		Ankle angle stance $ KOA mild KOA severe Healthy		5.5 (± 7.7) 0.2 (± 2.8) 14.8 (± 11.7)			
		Step length (cm) * KOA mild KOA severe Healthy				52.7 (± 17.6) 54.0 (± 9.2) 46.8 (± 7.3)	
		Gait cycle (s) * KOA mild KOA severe Healthy				1.1 (± 0.1) 1.1 (± 0.1) 1.2 (± 0.1)	
		Support ratio (%) * KOA mild KOA severe Healthy				49.6 (± 4.8) 49.4 (± 7.3) 38.5 (± 6.4)	
		Angle between left and right knee trajectory (°) * KOA mild KOA severe Healthy				21.3 (± 7.4) 21.3 (± 7.4) 11.6 (± 5.5)	
		Angle between left and right ankle trajectory (°) * KOA mild KOA severe Healthy				14.9 (± 7.1) 14.9 (± 7.1) 7.8 (± 5.5)	

* Statistically different between healthy and persons with KOA
# Statistically different between healthy and persons with TKR
$ Statistically different between KOA severity
& Statistical difference between KOA and TKR