

Review Article

Single-Camera Markerless Assessment Of Knee Function In Musculoskeletal Physiotherapy: A Narrative Review Of Smartphone And Portable RGB Video Systems.

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Running title: Single-Camera Markerless Knee Assessment.

Abstract

Background: Objective assessment of knee range of motion and kinematics is central to rehabilitation monitoring. Laboratory three-dimensional motion capture provides detailed biomechanical data but is rarely available in routine physiotherapy. Computer vision has made markerless assessment from smartphones and other portable RGB cameras increasingly feasible.

Methods: A targeted narrative review examined smartphone and portable single-camera RGB methods for quantitative knee assessment. Direct validation studies, musculoskeletal applications, reference-method comparisons, and clinically relevant technical limitations were prioritised. Searching was updated through 28 September 2026, and different agreement metrics were interpreted separately rather than pooled.

Results: Performance varied substantially across systems, tasks, populations, acquisition geometry, and reference methods. Several controlled studies reported knee mean absolute error (MAE) or root mean square error (RMSE) of approximately 2–6°, whereas other monocular implementations reported RMSE or mean bias around 7–11° and/or wide limits of agreement. High intraclass correlation coefficients or correlations sometimes coexisted with important absolute offsets. Camera geometry, occlusion, algorithm choice, task complexity, and reference method materially influenced performance.

Conclusion: Single-camera markerless analysis from smartphones and portable RGB video should be regarded as a measurement-specific adjunct rather than a general substitute for laboratory motion analysis. The best-supported applications involve selected sagittal-plane outcomes acquired under standardised conditions, but validity remains specific to the system, task, population, outcome definition, and recording protocol. Independent validation in clinical populations and reproducible acquisition protocols are required before broader implementation.

Keywords: knee joint; smartphone; markerless motion capture; physiotherapy; range of motion; kinematics; computer vision; gait analysis.

INTRODUCTION

Objective assessment of knee function is a routine component of musculoskeletal physiotherapy. Range-of-motion (ROM) measurement, observation of functional tasks, and repeated assessment during rehabilitation help clinicians plan treatment and monitor change. Goniometry remains widely used because it is inexpensive and accessible, but measurements may vary with landmark identification, instrument placement, examiner technique, and procedural standardisation [1,2]. Smartphone-based goniometers were introduced as a convenient alternative or adjunct, and several

studies and systematic reviews have reported good reliability for selected knee ROM measurements [3–5]. Performance varies among applications and protocols, however, so evidence obtained for one tool cannot automatically be transferred to another [3,4].

A more recent development is the use of video and computer-vision algorithms for human pose estimation. These systems identify image-based representations of body landmarks, such as the hip, knee, and ankle, and use their relative positions to estimate kinematic variables. This approach underpins contemporary markerless motion capture (MMC) [6,7]. Unlike conventional laboratory systems, which require

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calibrated cameras, physical markers, specialised space, and technical expertise, video-based systems may reduce equipment and setup requirements. Solutions based on smartphones or other ordinary portable RGB cameras are therefore particularly relevant to routine physiotherapy [6–8]. Mobile and portable systems now range from simple two-dimensional angle estimation to platforms that combine video with musculoskeletal modelling. OpenCap, for example, uses smartphone video to reconstruct movement and estimate kinematics and kinetics, although it requires at least two camera views and is therefore more complex than the monocular approaches considered as core evidence here [9]. Recent work has evaluated lower-limb kinematics in people with knee osteoarthritis (OA) [10], single-camera knee ROM assessment in OA [11], single-camera smartphone gait analysis [12], and smartphone pose estimation during functional tasks relevant to anterior cruciate ligament (ACL) rehabilitation [13].

The growing evidence base is encouraging but heterogeneous. Broad MMC reviews combine different algorithms, camera configurations, populations, anatomical regions, tasks, and reference standards [6–8]. Importantly, newer monocular validation studies show that sagittal-plane performance is not uniformly accurate: some systems produce MAE or RMSE values of only a few degrees, whereas others show systematic bias or RMSE near or above 10° for knee measurements. For a practising physiotherapist, the clinically relevant question is therefore not whether single-camera analysis is generally accurate, but whether a specific system can measure a specific knee variable with an error profile acceptable for the intended decision.

The aim of this narrative review was to summarise current evidence on single-camera markerless assessment of knee function using smartphones and other clinically portable RGB video systems in musculoskeletal physiotherapy, with particular emphasis on measurement validity and reliability, clinical applications, sources of error, and limitations that influence interpretation and implementation.

MATERIALS AND METHODS

Review design

This article was prepared as a targeted narrative review focused on the clinical utility of smartphone and portable single-camera RGB markerless assessment of knee function. The synthesis prioritised direct validation studies, measurement accuracy and repeatability, clinically relevant musculoskeletal applications, and factors that may limit use in routine physiotherapy. The review was not designed or reported as a systematic review and was not intended to identify every eligible publication. During pre-submission revision, the six domains of SANRA (Scale for the Assessment

of Narrative Review Articles) were used as an internal quality framework rather than as a formal risk-of-bias tool; the self-check is provided in Supplementary File S1.

Literature search

Literature searching was conducted and updated through 28 September 2026. PubMed, including MEDLINE-indexed records, was the principal bibliographic source. Searches were supplemented by reference-list screening of relevant reviews and targeted searches of publisher platforms and DOI/PubMed records to identify primary studies not retrieved by the initial search. A final update was performed during pre-submission revision, and newly identified candidate studies were checked against the eligibility criteria before inclusion. The core search logic combined device/acquisition terms (smartphone, mobile, single camera, single-camera, monocular, RGB camera, webcam), markerless-analysis terms (markerless motion capture, markerless, pose estimation, computer vision), knee/lower-limb terms (knee, knee joint, lower limb), and task/clinical terms (range of motion, ROM, goniometry, gait, running, squat, sit-to-stand, jump, functional movement, rehabilitation, physiotherapy, osteoarthritis, ACL). Boolean combinations were adapted to the source being searched. Additional targeted searches used the names of relevant algorithms and systems identified during citation screening, including MediaPipe, OpenPose, OpenPifPaf, BlazePose, MeTRAbs, OpenCap, and proprietary clinical applications. A reproducible PubMed search string corresponding to the final search logic is provided in Supplementary File S1.

Potentially relevant records were screened by title and abstract and then by full text or detailed publisher-indexed record where required for source verification; duplicate bibliographic records were removed manually. No formal language restriction was built into the search logic, but evidence was included only when the relevant methods and results could be verified reliably. Because the search was targeted and narrative rather than systematic, no PRISMA-style record flow, exhaustive record count, or formal pooled risk-of-bias assessment was performed. This limitation is considered explicitly in the Discussion.

Eligibility and evidence hierarchy

Peer-reviewed studies were considered when they examined smartphones, tablets, ordinary RGB video, webcams, or other clinically portable monocular systems for quantitative assessment of knee motion. Core evidence required the knee outcome of interest to be derived from a single ordinary RGB view or single mobile-camera view and to be compared with an established reference such as marker-based three-dimensional motion capture, validated multi-camera markerless systems, inertial measurement systems,

or conventional goniometry. If a validation session used an additional camera for separate outcomes but the reported knee measure itself was derived from one view, the study could be retained with that limitation stated explicitly. Both healthy participants and clinically relevant populations were considered, including people with knee OA and individuals undergoing ACL-related rehabilitation.

Studies of walking, running, squatting, sit-to-stand, reaching, jumping, and return-to-sport tasks were included when they provided knee-related measurements. Earlier smartphone goniometry studies and broader MMC reviews were retained to describe technological development. Multicamera smartphone systems, depth-camera systems, and non-video smartphone goniometry were treated as contextual rather than core evidence because their measurement characteristics are not directly equivalent to ordinary monocular RGB video. Studies using ordinary RGB cameras or webcams were retained when their monocular acquisition geometry and pose-estimation workflow were directly transferable to smartphone or portable-camera recording.

Data synthesis

For relevant studies, the review considered the population, recording technology, camera configuration, movement

task, knee variables, reference method, and reported indices of agreement or repeatability. Reference standards were interpreted hierarchically: simultaneous optical marker-based motion capture provided the strongest direct comparator for angle agreement, whereas inertial sensors, manual goniometry, multi-camera markerless systems, or non-concurrent measurements answered related but different validation questions. Particular attention was paid to error expressed in degrees, intraclass correlation coefficients (ICC), mean absolute error (MAE), root mean square error (RMSE), correlation or coefficient-of-multiple-correlation measures, Bland–Altman bias and limits of agreement (LoA), and differences among movement planes.

Agreement metrics were not treated as interchangeable. High correlation or ICC may coexist with systematic bias or a large absolute error; MAE and RMSE quantify different forms of absolute discrepancy, while mean bias and LoA describe systematic offset and individual-level agreement. Accordingly, cross-study values were not pooled into a single accuracy estimate. Absolute-error metrics, bias, LoA, and repeatability were interpreted in the context of the specific task and reference method, with emphasis on whether the observed error was small relative to the clinical change or decision threshold of interest.

Table 1. Direct single-camera validation studies relevant to knee assessment.

Study	Sample / system	Task / reference standard	Agreement metric(s) / key knee findings	Main limitation / interpretation
Langley et al., 2026 [11]	15 knee OA; single smartphone, msk.ai Deep Vision	Knee flexion, extension, ROM; 3D marker-based capture + Kinovea	Mean differences and 95% LoA remained within study-defined $\pm 5^\circ$ / $\pm 10^\circ$ thresholds.	Small clinical sample; thresholds were study-defined assumptions rather than universally established clinical thresholds.
Russo et al., 2026 [12]	27 healthy adults; smartphone + MediaPipe	Gait; OPAL IMU reference	MAE flexion 3.15–4.10°; extension 2.30–3.12°; ROM 4.15–4.55°.	Healthy sample; reference was IMU rather than optical motion capture.
Lambricht et al., 2025 [13]	12 healthy adults; smartphone + OpenPifPaf	Reach and jump tasks; simultaneous marker-based 3D motion capture	Knee RMSE 2.8°; ICC >0.97 for several knee/task outcomes.	Healthy participants despite ACL-rehabilitation task selection.
Akturk et al., 2026 [26]	15 healthy volunteers; Redmi Note 9 Pro + MediaPipe	Sit-to-stand; marker-based Kinovea comparison from standardised sagittal video	Knee and hip angle trajectories were visually similar to Kinovea; knee joint-moment correlation $r=0.95$.	No complete numeric knee-angle agreement analysis (e.g., MAE, RMSE, or Bland-Altman LoA); supports feasibility more strongly than interchangeability.
Koul et al., 2025 [15]	26 healthy adults; DETROM video goniometer	Knee flexion/extension; universal goniometer	ICC 0.98 flexion, 0.87 extension; mean difference -3.50° / 0.78° .	Developer-led study; planned commercial development; needs independent clinical validation.

Das et al., 2026 [16]	14 healthy rehabilitation staff; MediaPipe + single consumer camera	Seated knee extension; simultaneous 14-camera optical marker-based motion capture	Individual ICC 0.43 left, 0.27 right; ROM bias -6.7° and -10.8° with wide LoA.	Small proof-of-concept sample; demonstrates substantial error despite sagittal task.
Iizuka et al., 2026 [17]	30 healthy men; monocular webcam MMC	Bodyweight squat; marker-based optical motion capture	Raw knee bias -10.6° , RMSE $10.9 \pm 3.3^\circ$; geometry correction reduced RMSE to $3.9 \pm 1.5^\circ$.	Highly standardised setup; corrected model may not generalise to uncontrolled recording.
Ino et al., 2023 [18]	21 healthy young adults; single video camera + OpenPose	Bilateral gait; 3D motion-analysis reference	MAE $2.3-3.1^\circ$ camera side and $3.1-4.1^\circ$ opposite side; high waveform similarity.	Healthy gait; side-facing camera produced asymmetry in accuracy.
Young et al., 2023 [19]	31 healthy experienced runners; BlazePose smartphone application; side-view knee analysis	Treadmill running; 14-camera Vicon marker-based 3D motion capture	Knee-flexion ICC(2,1) 0.961 left and 0.979 right; waveform tracked Vicon but overestimated flexion near maximum extension/IC-FC.	Validation also captured a rear phone view for other gait outcomes; knee measure was side-view monocular. Excellent ICC coexisted with angle-specific offset.
Du et al., 2026 [20]	20 healthy participants; MobileGait on iPad; ordinary RGB mobile video	5-m gait; simultaneous Vicon marker-based motion capture	Knee flexion-extension MAE approximately 5.5° ; CMC approximately 0.96.	Mobile tablet rather than smartphone; healthy sample; sagittal-plane gait only.
Wang et al., 2024 [21]	14 healthy adults; single RGB camera + HuMoR	Gait; marker-based motion tracking	Strong relationships for several lower-limb variables; accuracy changed with view angle and distance.	Authors considered accuracy insufficient for some clinical applications; no pathological gait.
Usami et al., 2025 [22]	3 healthy men; 24 straight walks recorded, 22 analysed; iPhone X + Sportip Motion 3D	Straight gait; infrared motion capture	Maximum knee flexion $r=0.84-0.93$; minimum knee flexion only $r=0.30-0.47$.	Extremely small participant sample ($n=3$); repeated walking trials are not independent participants; several outcomes reported mainly as correlations; one author had a Sportip R&D affiliation.
Pratapneni et al., 2026 [23]	51 participants, 669 trials; smartphone + MeTRAbs	Gait, sit-to-stand, trunk tasks; THEIA3D multi-camera markerless reference	Knee-flexion RMSE 8.45° left and 10.98° right; ROM ICC >0.93 across angles.	Shows high reliability can coexist with large absolute error; mixed task/population sample.
Chao et al., 2026 [24]	69 older adults; single RGB camera; CNN-Transformer	Gait across varied views, speeds, and gait patterns; end-to-end angle estimation	Overall angle MAE approximately 4.20° with ICC 0.9285; reported knee-angle ICC 0.9652.	Not primarily musculoskeletal; high ICC does not by itself establish interchangeability or small absolute error.
Barzyk et al., 2024 [27]	11 participants; iPhone X AI system	Countermovement jump; Vicon marker-based motion capture	Knee waveform $r=0.99$; MAE across lower-limb joints $<4.5^\circ$; max-amplitude error $<3.2^\circ$.	Small sample; two coauthors belonged to company developing the software.
Ota et al., 2020 [28]	20 healthy young adults; single digital camera + OpenPose	Bilateral squat; Vicon marker-based 3D motion capture	Within-device reliability was very high; knee agreement with Vicon was substantial-to-near-perfect, but a fixed knee bias was present.	Healthy sample; fixed bias limits interchangeability; financial conflicts and patent-related involvement were disclosed.

Haberkamp et al., 2022 [30]	22 adolescent athletes; OpenPose 2D video analysis	Single-leg squat; 3D motion capture plus conventional 2D analysis	Sagittal relationships $r=0.68-0.94$; frontal-plane knee $r=0.20$.	Correlation does not establish absolute agreement; athlete sample.
Wegner et al., 2026 [32]	30 patients with knee OA; CE-registered monocular 2D app	Treadmill gait; multi-camera markerless 3D reference	Selected normalised knee metrics reached ICC approximately $0.67-0.74$; useful waveform agreement but systematic absolute flexion offset.	Reference was multi-camera markerless rather than marker-based; best for relative monitoring, not precise absolute angles.

Note: MAE, RMSE, mean bias, LoA, ICC, correlation, and CMC quantify different measurement properties and should not be compared as if they were interchangeable. Reference systems, tasks, camera configurations, dimensionality, and populations also differed substantially across studies.

Table 2. Contextual mobile and technically non-equivalent evidence.

Study	Reason for contextual classification	Main contribution
Uhlich et al., 2023 [9]	OpenCap requires at least two smartphone views.	Demonstrates mobile 3D biomechanics and establishes a useful performance benchmark for richer multicamera analysis.
Wang et al., 2025 [10]	OpenCap multicamera smartphone system.	Clinical OA gait study; mean RMSE 6.1° and ICC 0.67 in OA when walking toward cameras; performance depended on population and walking direction.
Barzyk et al., 2024 SMARTGAIT [25]	Neurological stroke population rather than musculoskeletal knee rehabilitation; single smartphone but different clinical scope.	Eight stroke patients; handheld Google Pixel 6a vs 12-camera Vicon. Sagittal correlations ≥ 0.79 ; maximum RMSE 4.6° . Several authors were affiliated with the company providing the AI reconstruction tool.
Pottorf et al., 2026 [29]	Single camera but depth-sensing KinoteK/ Kinect rather than ordinary RGB smartphone video.	Limited interchangeability with Vicon for peak knee flexion; illustrates that portable single-camera systems still require task-specific validation.
Turner et al., 2024 [31]	OpenCap used two smartphones.	Return-to-sport tasks after ACLR; strong sagittal agreement but weaker frontal/transverse agreement.
Chew et al., 2024 [34]	Accelerometer-based smartphone goniometry, not markerless video.	Shows feasibility of patient-led knee ROM measurement after TKA; ICC >0.97 and mean absolute difference 4.5° for flexion and 2.2° for extension.
Zhao et al., 2024 [35] and Gordon et al., 2025 [36]	Mobile rehabilitation context rather than markerless validation.	Supports feasibility of smartphone-supported postoperative rehabilitation and home monitoring workflows.

Abbreviations: ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; CMC, coefficient of multiple correlation; ICC, intraclass correlation coefficient; IMU, inertial measurement unit; LoA, limits of agreement; MAE, mean absolute error; OA, osteoarthritis; OMC, optical motion capture; RMSE, root mean square error; ROM, range of motion; TKA, total knee arthroplasty.

From Goniometry to Markerless Motion Analysis

Conventional goniometry and smartphone applications

Knee ROM is commonly measured with a universal goniometer because the procedure is inexpensive, familiar, and feasible in almost any clinical environment. Its limitations are particularly relevant when small differences are interpreted as evidence of rehabilitation progress. The widespread availability of smartphones created an opportunity to supplement conventional goniometry using built-in accelerometers, gyroscopes, or digital photographs.

Validation studies and systematic reviews found that some smartphone applications provide good or very good reliability for lower-limb ROM, including the knee [3–5]. Hahn et al. [4] nevertheless showed substantial variation among applications, highlighting that measurement properties belong to a specific tool and protocol rather than to smartphones as a general

category. Mehta et al. [5] also emphasised standard error and minimal detectable change: a highly correlated measurement may still be insufficient for identifying a small true change in an individual patient.

From static measurement to video analysis

Traditional goniometry, whether mechanical or smartphone-based, usually provides an angle at a selected position. Rehabilitation assessment also requires information about how the knee behaves during gait, squatting, sit-to-stand, and landing. Video recording extends measurement from a single position to successive phases of movement, although early video approaches still required manual frame selection and landmark identification.

Parati et al. [14] demonstrated the clinical feasibility of video-based goniometer applications for measuring knee angles during walking in people after stroke, people with Parkinson disease, and healthy participants. Although the population was not primarily musculoskeletal, the study illustrates the transition from static knee measurement to dynamic video-based assessment.

Automated pose estimation

Human pose-estimation algorithms automate the detection of body landmarks across video frames. Coordinates representing the hip, knee, and ankle can be used to calculate segment orientation and knee angles over time [6,7]. Markerless systems also remove the need to attach physical markers to the patient, potentially shortening preparation time and enabling assessment outside a specialised biomechanics laboratory [6].

Detecting landmarks on a two-dimensional image is not equivalent to full three-dimensional biomechanical reconstruction. Single-camera accuracy depends on camera orientation and distance, movement direction, landmark visibility, body-segment projection, and algorithm performance. Out-of-plane movement and occlusion can cause systematic rather than random error [6–8].

From joint angles to biomechanical modelling

Some contemporary markerless systems extend beyond simple angle calculation. OpenCap combines smartphone video with biomechanical modelling to estimate kinematics and dynamics [9]. This illustrates the direction of mobile motion analysis but also an important trade-off: richer three-dimensional information generally requires multiple synchronised views and more complex processing.

For routine physiotherapy, the attraction of a single-camera system is therefore not that it reproduces every function of a motion-analysis laboratory. Its potential advantage is the ability to obtain objective, repeatable measurements of selected variables with minimal additional equipment. The

relevant question is whether error for a particular variable is sufficiently small for the intended clinical use.

VALIDITY AND RELIABILITY OF KNEE ASSESSMENT

Clinical interpretation of measurement error

Evaluation of markerless technology requires a distinction between association, repeatability, and agreement. A high correlation between a new system and a reference method does not demonstrate that the two methods provide interchangeable values. Similarly, a high ICC for repeated or relative measurements can coexist with systematic bias. Clinically relevant evaluation therefore includes the type and magnitude of absolute error in degrees, mean bias, LoA, standard error or minimal detectable change where available, and repeatability across trials. No single degree threshold can be assumed to represent clinical importance across all knee populations, tasks, and decisions.

This distinction is especially important for serial rehabilitation monitoring. If the change between two measurements is smaller than the typical measurement error, or smaller than a validated minimal detectable change for that system and population, it cannot confidently be interpreted as true improvement or deterioration. Conversely, a stable but biased measure may still have value for longitudinal monitoring if its repeatability and bias are well characterised.

Flexion, extension, and range of motion

Langley et al. [11] evaluated the msk.ai Deep Vision single-camera system in 15 patients with knee OA and compared it with three-dimensional motion capture and Kinovea analysis. The authors assessed agreement against study-defined thresholds of $\pm 5^\circ$ for mean difference and $\pm 10^\circ$ for LoA, based on the assumption that changes greater than 5° would be clinically meaningful. Deep Vision measurements of maximum flexion, extension, and total ROM remained within these thresholds, with good within-session repeatability. The study is particularly relevant because it tested a clinical OA population rather than healthy volunteers, but its thresholds should not be interpreted as universal clinical cut-offs.

Koul et al. [15] evaluated the AI-based DETROM video goniometer in 26 healthy participants. Reliability was high for knee flexion (ICC 0.98) and extension (ICC 0.87), with mean differences from conventional goniometry of -3.50° and 0.78° , respectively. These results support feasibility, but interpretation should account for the developer-led nature of the validation: all authors were affiliated with DetMedX, and the publication disclosed plans to develop the software toward a commercial product. Independent validation in clinical populations is therefore important.

Not all sagittal-plane knee measurements perform this well. Das et al. [16] compared a single consumer camera

using MediaPipe-based analysis with a 14-camera optical reference in 14 healthy rehabilitation staff members. For knee extension, individual-measure ICC was 0.43 on the left and 0.27 on the right. Knee ROM was underestimated by 6.7° on the left and 10.8° on the right, with wide 95% limits of agreement. This study demonstrates that a movement being predominantly sagittal does not itself guarantee clinically acceptable monocular accuracy.

Iizuka et al. [17] provide a complementary explanation for part of this variability. During monocular squat assessment in 30 healthy men, uncorrected knee angles showed a mean bias of -10.6° and RMSE of $10.9 \pm 3.3^\circ$. A geometry-informed correction reduced knee RMSE to $3.9 \pm 1.5^\circ$ and effectively removed the mean bias. The finding supports camera geometry and projection bias as major determinants of error and shows that algorithmic or geometric correction can materially change the measurement properties of the same acquisition setup.

Knee assessment during gait

Dynamic gait analysis is more demanding because knee angle changes continuously and landmark visibility varies across the gait cycle. Russo et al. [12] compared a single smartphone camera using MediaPipe with an OPAL inertial-sensor system in 27 healthy adults. MAE for knee flexion was 4.10° on the right and 3.15° on the left; extension MAE was 2.30° and 3.12° , and ROM MAE was 4.55° and 4.15° . These data are encouraging but should be interpreted in light of the inertial-sensor reference rather than an optical laboratory standard. Ino et al. [18] compared OpenPose-based bilateral gait analysis from one camera with three-dimensional motion analysis. MAE ranged from 2.3° to 3.1° for the camera-side lower limb and from 3.1° to 4.1° for the opposite limb, with very good to excellent waveform similarity. The side facing the camera was slightly more accurate, supporting the importance of visibility and occlusion.

Young et al. [19] evaluated a BlazePose-based smartphone application against a 14-camera Vicon system during treadmill running in 31 healthy experienced runners. Knee-flexion ICC(2,1) was 0.961 for the left leg and 0.979 for the right leg, but the markerless waveform overestimated flexion around maximum extension and initial/final contact. The validation session used side and rear iPhone recordings for the broader gait protocol, whereas the knee-flexion analysis was derived from the side view. The study therefore illustrates both the potential of a single-view knee measure and the need to inspect absolute waveform offset even when ICC is excellent. Du et al. [20] validated the MobileGait mobile application against Vicon during 5-m walking in 20 healthy participants. The system used ordinary mobile-device video and reported knee flexion-extension MAE of approximately 5.5° with a coefficient of multiple correlation of approximately 0.96.

This extends the evidence toward an automated deployable workflow, although the validation used an iPad rather than a smartphone and remained limited to sagittal-plane gait in a healthy sample.

Wang et al. [21] compared single-camera computer-vision gait analysis with marker-based motion tracking in 14 healthy adults and found strong relationships for several lower-limb variables, including knee flexion/extension. However, camera viewing angle and distance significantly affected accuracy, and the authors concluded that accuracy remained insufficient for some clinical applications. Usami et al. [22] performed a very small pilot study in three healthy men: 24 straight walks were recorded and 22 were analysed using a single iPhone X with Sportip Motion 3D and an infrared motion-capture reference. Maximum knee-flexion correlations were strong, whereas minimum knee-flexion correlations were much lower. The participant sample, rather than the number of repeated walking trials, is therefore the major limitation.

Pratapneni et al. [23] evaluated MeTRABs from a single smartphone camera against THEIA3D during 669 gait, sit-to-stand, and trunk-movement trials in 51 participants. Across joint angles, RMSE ranged from 2.10° to 10.98° ; specifically, left and right knee-flexion RMSEs were 8.45° and 10.98° . At the same time, ROM ICCs exceeded 0.93. This is a particularly useful example of why high reliability does not imply small absolute error.

A newer end-to-end single-RGB approach provides a positive counterpoint. Chao et al. [24] evaluated lower-limb joint-angle estimation in 69 older adults, including participants with sarcopenia and Parkinson disease and controls. A CNN-Transformer model estimated angles directly from single-view RGB frames and achieved an overall angle MAE of approximately 4.20° with ICC 0.9285; the reported knee-angle ICC was 0.9652. Although the population was not primarily musculoskeletal, and high ICC does not by itself establish interchangeability or small absolute error, the study suggests that algorithm architecture can materially influence monocular performance.

Clinical pathological-gait evidence is also available outside musculoskeletal rehabilitation. Barzyk et al. [25] validated the single-smartphone SMARTGAIT system against a 12-camera Vicon reference in eight people after stroke. Sagittal-plane correlations across analysed joint kinematics were at least 0.79 and the maximum reported RMSE was 4.6° . The smartphone camera was manually operated while following the participant, which increases the real-world relevance of the validation. Because the population was neurological rather than musculoskeletal, and several authors were affiliated with the company providing the AI reconstruction tool, this study is best treated as contextual clinical evidence. A multicamera smartphone study in knee OA provides additional clinical context. Wang et al. [10] studied 53 people

with knee OA and 30 healthy participants using OpenCap during gait. In the OA group, when participants walked toward the cameras, mean RMSE across analysed lower-limb angles was 6.1° and ICC was 0.67. Error was greater in OA than in healthy participants and varied with walking direction, reinforcing the importance of target-population validation and recording geometry.

Functional tasks relevant to rehabilitation

Lambricht et al. [13] used a single smartphone and OpenPifPaf pose detection to analyse anterior reach, forward jump, and vertical jump tasks relevant to ACL rehabilitation. Twelve healthy participants were recorded simultaneously with smartphone video and marker-based motion capture. Mean knee RMSE was 2.8°, and ICC values exceeded 0.97 for several clinically relevant outcomes. The participants were healthy, so equivalent validity after ACL reconstruction cannot be assumed. Akturk et al. [26] used a Redmi Note 9 Pro smartphone and MediaPipe to analyse sit-to-stand movement in 15 healthy volunteers, comparing markerless joint angles with marker-based Kinovea measurements from a standardised sagittal view. The authors reported visually similar knee and hip angle trajectories, while the quantitative comparison of knee joint-moment estimates showed a strong correlation ($r=0.95$). A complete numeric agreement analysis for knee angle itself, such as MAE, RMSE, or Bland–Altman limits, was not reported; the study therefore supports feasibility more strongly than interchangeability.

Barzyk et al. [27] evaluated smartphone AI markerless capture during countermovement jumps in 11 participants. Knee angular waveforms showed a correlation of $r=0.99$ with Vicon, while overall MAE across hip, knee, and ankle remained below 4.5° and maximum-amplitude error below 3.2°. Two coauthors were members of the start-up that developed the software, which should be considered when interpreting a small developer-associated validation study.

Earlier single-camera squat validation by Ota et al. [28] showed similarly high within-device reliability and substantial-to-near-perfect agreement for several lower-limb joint angles compared with Vicon, but Bland–Altman analysis identified a fixed bias for the knee. The authors also disclosed financial conflicts of interest and patent-related involvement. This study reinforces that strong reliability or association does not establish interchangeability with the reference method.

Pottorf et al. [29] compared a portable single-camera Kinotek depth-camera system with Vicon during squat and other movements in 21 healthy adults. Significant between-system differences were found for knee flexion, with only moderate or fair knee correlations and generally lower repeatability for Kinotek. Although a depth-sensing camera is not equivalent to ordinary smartphone RGB video, the study is useful contextual evidence that portability and single-camera acquisition do not

ensure interchangeability with marker-based motion capture.

Importance of movement plane and measurement definition

A recurring finding across markerless research is that measurement performance differs by plane, task, and joint definition [6–8]. Haberkamp et al. [30] compared two-dimensional pose-estimation measures with three-dimensional motion capture during a single-leg squat. Sagittal-plane relationships ranged from moderate to very strong ($r=0.68$ – 0.94), whereas the relationship for frontal-plane knee angle was weak ($r=0.20$). Turner et al. [31] reported a similar pattern with a two-smartphone OpenCap system during return-to-sport tasks after ACL reconstruction: knee and hip agreement was highest in the sagittal plane (CMC >0.94), but lower in the frontal (0.47 – 0.78) and transverse planes (0.51 – 0.60).

However, the newer monocular evidence shows that the simple rule ‘sagittal good, frontal/transverse poor’ is incomplete. Das et al. [16], Pratapneni et al. [23], and Iizuka et al. [17] all reported sizeable knee error despite analysing predominantly sagittal variables. Young et al. [19] likewise reported excellent knee-flexion ICC during running despite visible overestimation near maximum extension. The more defensible interpretation is that accuracy is a property of a specific combination of algorithm, camera geometry, task, population, outcome definition, and reference method.

Overall interpretation

There is no single error value that characterises single-camera knee assessment, and MAE, RMSE, mean bias, and LoA should not be collapsed into one numerical range. Under controlled conditions, several studies report knee MAE or RMSE values of approximately 2–6° for selected sagittal-plane measures [12,13,18,20,27]. Other monocular implementations report knee RMSE or mean bias around 7–11° and/or wide individual LoA [16,17,23]. Reliability or waveform similarity may remain high despite clinically important absolute offset [19,23].

Accordingly, single-camera systems should not be described as generally accurate or inaccurate. Their validity is measurement-specific. A system may be useful for monitoring relative change or waveform shape while remaining unsuitable for precise absolute-angle measurement. Direct single-camera or single-view validation studies are summarised in Table 1; contextual evidence from multicamera, depth-camera, and non-video mobile approaches is summarised in Table 2.

CLINICAL APPLICATIONS IN KNEE PHYSIOTHERAPY

Knee osteoarthritis

Knee OA is a logical setting for accessible motion analysis because clinical assessment commonly includes ROM, gait

observation, and functional tasks. Langley et al. [11] provide direct evidence that one single-camera system can quantify maximum flexion, extension, and ROM in people with knee OA within study-defined agreement thresholds. Such measurements may support serial monitoring when the same validated system and protocol are used and when observed change exceeds the known measurement error.

Clinical gait evidence is more nuanced. The multicamera OpenCap study by Wang et al. [10] found poorer accuracy in people with OA than in healthy participants. More recently, Wegner et al. [32] compared a CE-registered monocular two-dimensional pose-estimation application with a multi-camera markerless reference in 30 people with knee OA. After normalisation at initial contact, selected knee kinematic measures reached moderate-to-good reliability (ICC approximately 0.67–0.74), although agreement remained parameter-specific; the raw data also contained a systematic flexion offset. The authors therefore supported the system for screening and monitoring relative changes rather than precise absolute-angle quantification. This distinction is clinically important: repeated relative measures may be useful even when absolute anatomical angles are biased.

ACL injury and reconstruction

ACL rehabilitation requires recovery of ROM and strength together with progressive assessment of functional tasks such as single-leg squats, balance tasks, jumping, and landing. Smartphone pose estimation may add quantitative information about knee flexion, ROM, and movement strategy during these tasks [13,27].

This potential should not be overstated. Evidence from healthy participants does not establish the same validity after ACL reconstruction, and multiplanar variables remain more difficult to quantify [30,31]. Return-to-sport progression is based on multiple clinical and functional criteria rather than a single kinematic variable [33]. Smartphone or portable-camera markerless analysis should therefore be viewed as one possible adjunct within a broader assessment rather than a stand-alone return-to-sport criterion.

Arthroplasty, home monitoring, and telerehabilitation

Mobile technology may also support rehabilitation after total knee arthroplasty (TKA), when flexion and extension are measured repeatedly. Chew et al. [34] showed that 30 patients within 16 weeks of TKA could self-measure knee ROM with an accelerometer-based smartphone application. Intra- and intersession reliability exceeded ICC 0.97, and mean absolute differences from extendable-arm goniometry were approximately 4.5° for flexion and 2.2° for extension. Although this was not markerless video, it demonstrates that patients can perform structured knee measurements outside the clinic.

Broader telerehabilitation evidence supports the feasibility of mobile rehabilitation pathways. In a randomised trial of 100 patients after TKA, smartphone-supported remote rehabilitation produced a mean 12-week ROM of approximately 124° compared with 119° in the control pathway [35]. A 2025 systematic review identified 31 level 1 or 2 publications meeting its inclusion criteria on smartphone applications, wearable devices, or combined digital approaches after TKA [36]. These studies do not show that markerless analysis itself improves outcomes; they show that patients can engage with mobile measurement and rehabilitation technologies.

A plausible future model would combine a standardised home task with automated video analysis. Before this becomes routine care, studies must establish whether patients can reproduce camera placement, clothing, framing, and task execution sufficiently well for home measurements to retain clinically useful accuracy.

Current place in clinical practice

The most realistic current role for single-camera knee analysis is to complement, rather than replace, clinical examination. It may be useful when a physiotherapist wants repeated measurement of a clearly defined variable using a system that has been validated for that task and population. Its practical value lies in low equipment requirements, the possibility of recording movement, and the potential to standardise serial assessments.

Conversely, a single camera is presently less suitable for precise three-dimensional biomechanical diagnosis or for absolute-angle decisions when the expected clinical change is similar to the system's measurement error. Laboratory systems and appropriately validated multicamera approaches remain preferable when the question depends on small multiplanar differences.

LIMITATIONS AND BARRIERS TO CLINICAL IMPLEMENTATION

Camera geometry and standardisation

The principal strength of single-camera analysis - simplicity - is also its principal technical limitation. A camera records a two-dimensional projection of three-dimensional movement. Camera height, distance, angle, and patient orientation can therefore change the measured value even when true movement has not changed [17,21]. Iizuka et al. [17] demonstrated that a geometry-informed correction reduced knee RMSE from 10.9° to 3.9°, illustrating how strongly systematic projection error can affect results.

Serial clinical use therefore requires a reproducible protocol for camera position, framing, distance, and task instructions. Validation results obtained under one geometry should not automatically be assumed to apply when a phone is held at a

different height or angle.

Occlusion and environmental conditions

Body landmarks can become occluded when one limb passes in front of the other or during complex tasks. Wade et al. [37] showed that during gait, variability and LoA for occluded hip and knee joints were approximately twice those of directly visible joints. Ino et al. [18] similarly found slightly larger errors on the limb opposite the camera, while Young et al. [19] reported side-dependent distortion associated with occlusion during running.

Real clinical and home environments add variability in lighting, background contrast, clothing, image quality, framing, and device characteristics. Das et al. [16] specifically noted sensitivity of MediaPipe-based estimates to factors such as lighting, movement complexity, body proportions, occlusion, and camera placement. These considerations make home deployment a separate validation problem rather than a simple extension of laboratory results.

Algorithm dependence, reference methods, and statistics

Markerless motion capture is not a single technology. Systems differ in pose-estimation model, landmark definitions, calibration, camera geometry, and the transformation of image coordinates into biomechanical variables. MediaPipe, OpenPose, OpenPifPaf, MeTRAbs, and proprietary systems therefore cannot be assumed to have equivalent measurement properties. A positive validation study for one software version should not be generalised to another application or later algorithm update without evidence.

The reference method also matters. Comparisons against optical marker-based motion capture, inertial sensors, manual goniometry, multi-camera markerless systems, or non-concurrent Vicon trials answer different questions. Correlation, ICC, CMC, MAE, RMSE, and limits of agreement are likewise not interchangeable. The practical question is not simply whether a reported coefficient is high, but whether absolute error is smaller than the change that needs to be detected.

Evidence base, commercial involvement, privacy, and data governance

The evidence base remains methodologically heterogeneous, with different cameras, algorithms, tasks, populations, and statistical reporting. Many studies include small samples of healthy participants. Several evaluations also involve developers or companies associated with the tested software, including DETROM [15] and the system evaluated by Barzyk et al. [27]. Such studies remain informative but strengthen the need for independent replication.

Video-based assessment also creates data-governance considerations that do not arise with a mechanical

goniometer. Recordings may identify the patient and reveal information about the home or clinical environment. A systematic review of video recording for direct care found recurring professional guidance around consent, privacy, and secure storage, while also noting practical gaps in implementation [38]. Clinical deployment should therefore define what is recorded, whether raw video is retained, where processing occurs, who has access, how transmission and storage are secured, how long data are retained, and how consent or withdrawal is handled. These considerations do not determine measurement validity, but they materially affect real-world adoption.

DISCUSSION

The updated evidence suggests that single-camera markerless analysis from smartphones and portable RGB devices is moving from technical feasibility toward selective clinical usefulness, but the field is more heterogeneous than a simple single-degree error summary implies. Several direct studies report knee MAE or RMSE values in the approximate 2–6° range for selected controlled tasks [12,13,18,20,27], whereas others report RMSE or mean bias approaching or exceeding 10° [16,17,23]. The central finding is therefore not that single-camera assessment is inherently accurate or inaccurate. Accuracy is a property of a specific algorithm × camera geometry × task × population × outcome × reference-method combination.

This interpretation also changes how reliability statistics should be read. Pratapneni et al. [23] reported ROM ICCs above 0.93 despite knee-flexion RMSEs of 8.45° and 10.98°. Young et al. [19] reported excellent knee-flexion ICCs during running despite a visible extension-phase offset, and Wegner et al. [32] found useful agreement for normalised knee waveform shape in OA while cautioning against precise absolute-angle interpretation. A system may therefore be valuable for longitudinal relative change, screening, or waveform monitoring even when it should not be used as an interchangeable substitute for laboratory angles.

Sagittal-plane variables remain attractive because they can often be captured with favourable geometry, but plane alone is not sufficient. Seated knee extension in Das et al. [16] performed poorly, whereas geometry correction markedly improved squat measurements in Iizuka et al. [17]. Conversely, some gait and jump studies obtained MAE or RMSE of only a few degrees [18,20,27]. Camera standardisation and task-specific validation are therefore as important as the nominal movement plane.

The clinical population is another determinant of performance. Wang et al. [10] found worse agreement in knee OA than in healthy participants, whereas Wegner et al. [32] showed that a monocular clinical app could capture useful relative

knee gait patterns in OA despite systematic absolute offset. Several ACL-related validations were conducted in healthy participants [13,27] or used multicamera systems [31]. Clinical adoption requires evidence in the same population and task for which the tool is intended.

The possibility of patient self-recording remains important. Smartphone self-goniometry and broader telerehabilitation studies show that patients can engage with mobile measurement and rehabilitation workflows [34–36]. Combining these workflows with markerless video could increase objective monitoring between visits, but only if recording geometry, task execution, privacy safeguards, and data handling can be reproduced reliably outside the clinic.

This review has limitations. It is a targeted narrative review rather than a systematic review, used PubMed as the principal bibliographic source rather than an exhaustive multi-database strategy, did not use a PRISMA screening process, and did not perform a formal risk-of-bias assessment. Reference-list and targeted publisher searches, together with a final pre-submission update, reduced but did not eliminate the possibility of selection or retrieval bias. The evidence base is also rapidly evolving, and measurement properties may change with software or model updates. The conclusions should therefore be interpreted as a clinically oriented synthesis of verified evidence rather than an exhaustive ranking of available technologies.

Future Research and Practical Implications

Future studies should prioritise larger clinical samples with knee OA, TKA, and ACL reconstruction, use simultaneous reference measurements where possible, and describe recording geometry in sufficient detail for replication. Test-retest reliability across days and patient-led home recording require direct investigation.

Validation reports should include clinically interpretable and metric-specific error information. MAE and RMSE should be reported and labelled separately, alongside mean bias, LoA, standard error of measurement, and minimal detectable change where appropriate, rather than relying only on correlation or ICC. Studies should also disclose developer involvement and commercial relationships clearly and seek independent replication.

For clinical use, a tiered interpretation may be practical. Variables with small, well-characterised MAE or RMSE and acceptable bias/LoA can be used quantitatively for the validated task; variables with stable but biased measurements may be useful for relative longitudinal monitoring; and poorly validated variables should remain qualitative or research measures. The key requirement is not laboratory-equivalent accuracy for every movement, but evidence that a specific measurement is sufficiently accurate and reproducible for a specific clinical decision.

CONCLUSION

Single-camera markerless motion analysis using smartphones and other portable RGB devices is a developing approach that may support objective assessment of selected aspects of knee function. Reported validity is highly variable and should be described with the original metric: several controlled studies report knee MAE or RMSE of approximately 2–6°, while other monocular implementations report RMSE or mean bias around 7–11° and/or wide individual LoA.

A single mobile or portable RGB camera should therefore not be considered a general substitute for laboratory three-dimensional motion analysis. Its more defensible present role is as a measurement-specific adjunct when the exact system, task, population, outcome definition, and recording protocol have been validated for the intended use. Standardised camera geometry, independent clinical validation, transparent reporting of metric-specific error, and careful distinction between relative monitoring and absolute-angle measurement are required before broader implementation.

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Competing interests

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Ethics approval and consent to participate

Not applicable. This narrative review used published literature and did not involve new human-participant or animal research.

Consent for publication

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Data availability

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