

Computer Vision for Movement Analysis: Pose Estimation Technologies for Assessing Exercise Form, Gait, and Rehabilitation Progress Without Laboratory Equipment

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ABSTRACT

Introduction and Objective: Laboratory-based motion capture systems provide highly accurate measurements of human movement but require specialized equipment, controlled environments, and trained personnel. Recent advances in computer vision and markerless human pose estimation (HPE) have created opportunities to assess movement using ordinary cameras. This review examines the application of pose-estimation technologies, particularly OpenPose and MediaPipe, for exercise-form assessment, gait analysis, and rehabilitation progress monitoring, with emphasis on measurement accuracy, reliability, and practical limitations.

Materials and Methods: A narrative review of peer-reviewed literature was conducted focusing on markerless human pose estimation, computer-vision-based movement analysis, OpenPose, MediaPipe, gait analysis, exercise monitoring, and rehabilitation. Studies comparing pose-estimation-derived measurements with conventional marker-based motion-capture systems were considered particularly relevant. Evidence was synthesized according to technical characteristics, movement-analysis applications, measurement agreement, and factors affecting real-world implementation.

Results: The reviewed literature indicates that markerless pose estimation can provide useful estimates of joint positions, movement trajectories, and spatiotemporal gait parameters without laboratory-grade instrumentation. Validation studies have reported good-to-excellent agreement between markerless systems and conventional motion capture for many temporal gait variables, while accuracy tends to be lower for fine-grained joint-angle measurements and small-amplitude movements at distal joints such as the ankle. Performance is also influenced by camera position, lighting, clothing, occlusion, movement direction, and the dimensionality of the camera system (Cao et al., 2019; Hii et al., 2023; Stenum et al., 2021).

Conclusion: Computer-vision-based pose estimation represents a promising and accessible approach for movement screening, exercise-form monitoring, gait assessment, and rehabilitation progress tracking. However, current systems should generally be regarded as complementary tools rather than complete replacements for laboratory-grade motion-capture systems when high-precision biomechanical measurement is required.

Keywords: pose estimation; computer vision; OpenPose; MediaPipe; markerless motion capture

INTRODUCTION

Human movement analysis has traditionally depended on marker-based optical motion capture, force plates, and electromyography—instrumentation that offers high measurement precision but requires dedicated laboratory space, specialized equipment, and trained personnel to operate. These requirements have limited how frequently movement can be assessed, particularly outside elite sport and well-funded clinical settings. Advances in deep learning-based computer vision have introduced an alternative: markerless human pose estimation (HPE), which localizes anatomical keypoints such as joints and limb segments directly from ordinary two-dimensional video without reflective markers, specialized suits, or multi-camera arrays (Stenum et al., 2021).

Open-source frameworks such as OpenPose, which introduced a real-time, multi-person bottom-up detection approach using part affinity fields to associate body parts across individuals in an image, and MediaPipe Pose, a lightweight framework designed for efficient pose tracking on consumer devices, have made quantitative movement assessment increasingly accessible outside traditional laboratories (Cao et al., 2019; Hii et al., 2023). These developments are particularly relevant to exercise science because smartphones, webcams, and other consumer cameras can potentially be used to collect movement data during exercise, gait assessment, and rehabilitation.

The transition toward camera-based movement analysis has therefore shifted part of the focus from highly controlled laboratory measurement toward continuous or repeated assessment in naturalistic environments. A single video recording may provide information about joint trajectories, movement symmetry, cadence, or exercise technique without requiring reflective markers or complex instrumentation. Reviews of pose-estimation applications in sport and physical exercise have documented increasing interest in applications including exercise monitoring, performance analysis, movement assessment, and technique feedback (Badiola-Bengoa & Mendez-Zorrilla, 2021).

However, accessibility does not necessarily imply equivalence with laboratory instrumentation. Pose-estimation systems remain sensitive to camera position, lighting, clothing, occlusion, movement direction, and the anatomical region being analyzed. Consequently, the appropriate role of markerless pose estimation depends on the measurement question, the required level of accuracy, and the environment in which the system is deployed (Stenum et al., 2021). This paper examines these issues across three related applications: exercise-form assessment, gait analysis, and rehabilitation progress monitoring.

MATERIAL AND METHOD

Review Approach

A narrative literature review approach was used to examine the current application of computer-vision-based human pose estimation in exercise science, movement analysis, gait assessment, and rehabilitation. The review focused on peer-reviewed studies and systematic reviews addressing markerless human pose estimation and its comparison with conventional movement-analysis technologies.

Particular attention was given to studies involving OpenPose, MediaPipe, markerless motion capture, gait analysis, exercise-form assessment, and rehabilitation monitoring. Studies that compared pose-estimation-derived measurements with laboratory-based marker motion capture were considered especially relevant because such comparisons provide information about measurement agreement and practical validity.

Literature Focus

The literature was considered across four major areas:

1. Technical development of pose estimation, including OpenPose and lightweight real-time systems;
2. Exercise-form assessment, including the use of estimated joint positions and angles to characterize exercise technique;
3. Gait analysis, including comparisons between markerless systems and conventional motion-capture systems; and
4. Rehabilitation monitoring, including the use of pose estimation for quantitative assessment of movement recovery.

The review also considered methodological factors that influence measurement quality, including camera configuration, occlusion, lighting, clothing, body region, movement amplitude, and two-dimensional versus three-dimensional analysis.

Outcome Measures

The principal outcomes considered were joint-position accuracy, joint-angle estimation, movement trajectories, spatiotemporal gait parameters, movement symmetry, and the feasibility of repeated assessment in non-laboratory environments.

Where available, agreement between pose-estimation systems and marker-based motion capture was considered using reported correlation coefficients, intraclass correlation coefficients (ICC), or other validation statistics. Particular attention was given to whether performance differed between larger proximal joints and smaller distal joints.

RESULTS

Technical Characteristics of Pose-Estimation Systems

The reviewed literature indicates that modern pose-estimation systems can extract multiple anatomical keypoints from ordinary video and convert these keypoints into quantitative movement variables. OpenPose uses a bottom-up architecture that identifies body parts and subsequently associates them into individual human poses through part affinity fields (Cao et al., 2019). This approach supports multi-person pose estimation and has been widely applied in human movement research.

MediaPipe-based approaches emphasize computational efficiency and real-time tracking. Their relatively low hardware requirements make them suitable for smartphones, webcams, and other consumer devices. This characteristic provides an important practical advantage for movement assessment outside conventional laboratories (Hii et al., 2023).

Once keypoints are obtained, researchers can calculate joint angles, segment orientations, movement trajectories, repetition counts, and temporal characteristics. Therefore, pose estimation effectively converts ordinary video into structured movement information.

Exercise-Form Assessment

The literature indicates growing interest in using pose estimation to evaluate exercise technique. Camera-based systems can identify anatomical landmarks and calculate joint angles or movement trajectories during exercises such as squats, lunges, and other resistance-training movements.

These measurements can potentially be compared with predefined movement criteria. For example, changes in knee or hip angles may be used to characterize squat depth, while trunk orientation can provide information about exercise technique. Such systems could also support automated repetition counting and real-time feedback.

A systematic review of camera-based human pose estimation in sport and physical exercise identified exercise monitoring, performance assessment, and movement analysis as important application areas (Badiola-Bengoa & Mendez-Zorrilla, 2021). However, the review also identified important technical challenges associated with occlusion, camera positioning, environmental conditions, and the accuracy of estimated joint positions.

Thus, the evidence supports the feasibility of camera-based exercise monitoring, but current systems should be interpreted according to the precision required for the specific application.

Gait Analysis

Gait analysis is one of the most extensively evaluated applications of markerless pose estimation. Conventional gait laboratories provide highly detailed measurements but require expensive equipment and controlled environments. Pose estimation potentially allows similar basic gait variables to be obtained from ordinary video.

Hii et al. (2023) compared a marker-free pose-estimation system with a Vicon marker-based motion-capture system for automated gait analysis. The study reported good-to-excellent agreement for many temporal gait parameters, with ICC values generally above 0.75 and reaching 0.90 or higher for several variables.

However, some parameters, including double-support time and swing time on one side, demonstrated only moderate agreement.

These findings suggest that markerless systems can reproduce many clinically and scientifically useful gait measurements, particularly temporal variables. Nevertheless, performance is not uniform across all parameters.

Joint-level analysis also demonstrates variation in accuracy. Larger joints such as the hip and knee generally provide more stable estimates than smaller distal joints. The ankle and foot are particularly challenging because their movements may be smaller and more sensitive to camera viewpoint and keypoint localization errors (Hii et al., 2023; Stenum et al., 2021).

Rehabilitation Monitoring

Pose estimation also demonstrates potential for rehabilitation monitoring. Stenum et al. (2021) identified motor assessment in individuals with neurological conditions and other movement-related impairments as an important application of pose-estimation technology.

A major advantage of this approach is the possibility of repeated movement assessment outside the clinic. A patient could potentially perform standardized movements in the home environment while a camera records the session. The resulting data could provide information about range of motion, movement speed, asymmetry, coordination, and repetition quality.

This could complement conventional clinical assessments by providing additional longitudinal information. Instead of relying exclusively on measurements collected during periodic appointments, clinicians may eventually be able to evaluate movement trends across multiple sessions.

However, pose estimation describes movement patterns rather than directly identifying their physiological or pathological causes. Clinical interpretation therefore remains necessary.

Accuracy and Reliability

Across the reviewed literature, measurement accuracy varied according to the outcome being measured. Spatiotemporal gait parameters generally demonstrated stronger agreement with conventional motion capture than detailed joint-angle measurements.

The performance of pose estimation also varied across anatomical regions. Hip and knee measurements tended to be more reliable than ankle and foot measurements, particularly when movements were small or occurred in challenging viewing conditions (Hii et al., 2023).

The evidence therefore indicates that pose estimation can provide useful quantitative movement information, but the degree of agreement with laboratory systems is outcome-specific rather than universal.

DISCUSSION

The findings of this review indicate that computer-vision-based pose estimation has progressed from an experimental computer-vision technology toward a potentially useful tool for exercise science, gait analysis, and rehabilitation. Its principal advantage is not necessarily superior measurement precision, but rather accessibility and scalability.

Traditional motion-capture systems provide high-quality measurements but require specialized environments. By comparison, pose-estimation systems can potentially operate with ordinary cameras, allowing movement to be assessed in gyms, homes, community settings, and outpatient environments (Badiola-Bengoia & Mendez-Zorrilla, 2021; Stenum et al., 2021).

The evidence from gait analysis is particularly encouraging. The relatively strong agreement reported for many temporal gait parameters suggests that markerless systems can provide meaningful quantitative information without requiring a conventional motion-capture laboratory (Hii et al., 2023). This may be especially useful for repeated monitoring rather than one-time high-precision measurement.

However, several limitations remain.

First, measurement accuracy is dependent on the anatomical region and movement characteristic. Large movements of the hip and knee are generally easier to estimate than subtle ankle and foot movements. This is important because some clinical and biomechanical applications depend on precisely measuring small changes.

Second, camera configuration strongly affects measurement quality. A single 2D camera cannot fully represent movements occurring outside the imaging plane. Consequently, frontal- and transverse-plane movements may be difficult to quantify accurately from a single viewpoint. Multi-camera or 3D approaches may address some of these limitations but introduce greater technical complexity.

Third, occlusion remains an important challenge. When one limb crosses in front of another body segment, the relevant anatomical keypoint may become partially or completely invisible. Similar problems can occur because of exercise equipment, other people, loose clothing, or environmental objects.

Fourth, laboratory validation does not automatically guarantee real-world performance. A pose-estimation algorithm may perform well under controlled lighting and camera conditions but experience reduced accuracy in a home, gym, or outdoor environment. Future validation should therefore include realistic environments and diverse populations rather than relying exclusively on laboratory datasets.

An additional consideration is the distinction between measurement validity and practical usefulness. A camera-based system may not reproduce laboratory measurements with sufficient precision for diagnostic biomechanics, yet it may still be useful for monitoring broad changes over time. For example, a rehabilitation system may not need to measure a joint angle with laboratory-level precision if its purpose is to determine whether range of motion has consistently improved over several weeks.

This suggests that the most appropriate role of pose estimation may be complementary rather than substitutive. Laboratory motion capture can remain the reference method for high-precision biomechanical analysis, while markerless systems can provide frequent, low-cost monitoring between laboratory or clinical assessments.

Future systems may also combine pose estimation with other sensing technologies. For example, video-based kinematics could be combined with wearable inertial sensors, electromyography, heart-rate measurements, or force-related information. Such multimodal systems could potentially provide a more comprehensive representation of human movement than camera-based analysis alone.

From a clinical perspective, longitudinal monitoring may ultimately be one of the most valuable applications. Repeated measurements using a standardized camera setup could allow clinicians and researchers to track within-person changes over time. However, this application requires further research into test-retest reliability, sensitivity to clinically meaningful change, and performance across diverse populations.

CONCLUSIONS

Computer-vision-based human pose estimation has created new opportunities for quantitative movement analysis without conventional laboratory equipment. Technologies such as OpenPose and MediaPipe can extract anatomical keypoints from ordinary video and use them to estimate joint positions, movement trajectories, exercise-related kinematics, and gait parameters (Cao et al., 2019; Hii et al., 2023).

Current evidence indicates that markerless pose estimation can achieve useful agreement with conventional motion-capture systems for many movement variables, particularly temporal and spatial gait parameters and movements involving larger proximal joints. However, accuracy is generally less consistent for detailed joint-angle measurements, small-amplitude movements, and distal joints such as the ankle and foot.

The technology therefore appears most appropriate at present for movement screening, exercise-form monitoring, gait assessment, and longitudinal rehabilitation tracking, particularly in settings where

laboratory equipment is unavailable or impractical. It should not yet be regarded as a universal replacement for laboratory-grade motion capture when highly precise biomechanical measurements are required. Future research should emphasize external validation, real-world testing, diverse populations, longitudinal reliability, and multimodal integration. With continued improvements in computer vision and 3D pose estimation, markerless movement analysis may become an increasingly important component of accessible exercise science, sports performance assessment, and rehabilitation monitoring.

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