Review article

Computer Vision Solutions for Range of Motion Assessment

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Abstract

Joint range of motion (ROM) is an important indicator of physical functionality and musculoskeletal health. In sports, athletes require adequate levels of joint mobility to minimize the risk of injuries and maximize performance, while in rehabilitation, restoring joint ROM is essential for faster recovery and improved physical function. Traditional methods for measuring ROM include goniometry, inclinometry and visual estimation; all of which are limited in accuracy due to the subjective nature of the assessment. With the rapid development of technology, new systems based on computer vision are continuously introduced as a possible solution for more objective and accurate measurements of the range of motion. Therefore, this article aimed to evaluate novel computer vision-based systems based on their accuracy and practical applicability for a range of motion assessment. The review covers a variety of systems, including motion-capture systems (2D and 3D cameras), RGB-Depth cameras, commercial software systems and smartphone apps. Furthermore, this article also highlights the potential limitations of these systems and explores their potential future applications in sports and rehabilitation.

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Introduction

Joint range of motion (ROM) is an important indicator of physical functionality and musculoskeletal health (44). It plays a vital role in the sports field, as athletes require adequate levels of joint mobility to reduce the risk of injuries and maximize their performance (57, 12). Similarly, restoring the joint range of motion in rehabilitation is essential for faster recovery and better physical functionality (16, 32, 68). Therefore, assessment of the joint range of motion is necessary for determining the limitations in joint mobility and creating treatment or training plans that can effectively enhance joint functionality, reduce the risk of injury and maintain optimal levels of performance (40, 51).

Common traditional methods of measuring the range of motion in physical therapy include using goniometers and inclinometers, as well as visual estimation through various mobility tests (38, 52). The goniometer is widely considered the standard tool (i.e. the golden standard) for evaluating a range of motion in clinical settings (52). This tool measures the angle of joints by positioning the arms of the goniometer along the joint's axis. To obtain a more comprehensive and accurate assessment of the joint range of motion, goniometers are often used in conjunction with inclinometers; instruments that measure the position of body segments (38, 52). Finally, a method that is used when specialized tools such as goniometers and inclinometers are not available is a visual estimation of joint mobility during various flexibility tests. This method can provide a quick estimation of the joint range of motion; however, it greatly depends on the rater's ability to visually determine the degree of motion (23).

While all of these methods can provide some degree of accuracy, their estimation is subjective as it may vary depending on the observer's perception and experience or placement of the tool (1). Developments in technology have now opened the possibility of using computer vision for a more objective range of motion assessment in sports and rehabilitation. Computer vision (CV) is a new technology that employs several techniques such as pattern recognition, machine learning and image processing, to extract meaningful information from visual data. This technology can automate many tasks that require subjective assessment, potentially making them more efficient and accurate (35). Current computer vision-based systems have mainly been developed for entertainment purposes (i.e. the gaming industry), although there have been many successful attempts to apply these systems in sports and rehabilitation (48). A common issue with these systems is achieving accurate pose-estimation results, which has limited their use in a range of motion assessment (7).

The rapid advancements of this technology continually introduce new possible solutions, highlighting the importance of constantly assessing the reliability and validity of these novel systems. Therefore, this study aims to present an up-to-date review of currently available computer vision-based systems, focusing on their reliability and validity in range of motion assessment, as well as their practical applicability.

Computer Vision-Based Range of Motion Solutions

The use of computer vision-based systems offers several advantages over the aforementioned traditional range of motion assessment methods: 1) computer vision-based systems eliminate the need for physical contact with the patient, making the assessment more comfortable and efficient (35); 2) these systems can capture a large amount of data in a short period, therefore providing detailed and objective quantitative measurements (56); 3) moreover, computer vision systems can track a range of motion both in real-time and over a longer period, which enables trainers and clinicians to monitor progress and adjust training or treatment plans accordingly (60).

This paragraph will discuss some of the most commonly used computer vision systems for a range of motion assessment, including motion capture cameras (i.e. 2D, 3D and RGB-Depth cameras), commercial software systems and smartphone apps (Table 1).

Table 1. Computer vision systems used for range of motion assessment

Technology	Device / App	Studies (authors)	ROM assessed	Reliability/ validity	Price
Marker-based 3D systems	Vicon; Qualisys	Faber et al. (2009); Inokuchi et al., 2015; Me et al., 1998	shoulder, neck, lower extremities	ICC= 0.78-0.98 r = 0.779–0.863 (compared to CROM device)	>$10,000
Markerless 3D systems	DARI Motion; The Captury	Cabarkapa et al., 2022; Fleisig et al., 2022; Harsted et al., 2019	hip, knee and ankle; shoulder and elbow	ICC= 0.64-0.92 r=0.74-0.99 (compared to Vicon)	>$10,000
RGB-Depth cameras	Kinect	Beshara et al., 2020, 2021; Cai et al., 2019; Hawi et al., 2014; Mortazavi et al., 2018; Özsoy et al., 2022; Zulkarnain et al., 2017	shoulder and lower extremities	ICC=0.62-0.98 r= 0.73-0.97 (compared to Vicon)	~$399
Commercial software systems	Kinetisense	Macaulay, 2017	shoulder and hip; elbow/wrist knee/ankle	ICC= 0.85-0.96 ICC= 0.61-0.69	>$1,000
Smartphone apps	Goniometer Pro	Pourahmadi et al., 2016; Wellmon et al., 2016	wrist and shoulder	ICC= 0.79-0.82 r≥ 0.80 (compared to goniometer and inclinometer)	~$9.99
Combination of systems	MIRA software + Kinect	Wilson et al., 2017	shoulder	r= 0.96-0.99 (compared to Vicon)	>$1,000

Motion-capture (MoCap) camera systems

Motion capture (MoCap) cameras are advanced systems that capture and record movement in two-dimensional or three-dimensional spaces. Some of these systems require the placement of passive markers on the body which reflect infrared light emitted by the cameras (31). In contrast, other systems can automatically detect anatomical markers through depth-of-field sensors or deep-learning-based algorithms (7). Regardless of the need for active or passive marker placement, motion-capture systems have the potential to be used for a range of motion assessment as they can track the movement of anatomical segments of the body. However, the accuracy of measurements can vary depending on the motion-capture technology integrated with the system (7). Based on previous research, some of the most common motion-capture systems that are used for a range of motion assessment include:

2D and 3D systems. These systems use high-speed cameras and specialized software to track the position and movement of the body in a two-dimensional or three-dimensional space (31). The main difference between these two systems is that 2D cameras can track objects and record movement along a two-dimensional axis (i.e. height and width), while 3D cameras also include a third dimension (i.e. depth of field) (63). To estimate the position of body segments and human motion, 2D systems use the techniques of direct regression to identify key points on the body or heat maps to represent the probability of a joint being located at a particular position (9, 70). However, it is important to acknowledge that 2D systems lack the precision and accuracy of 3D motion capture systems, as they do not include the dimension of depth, which is important for a more comprehensive range of motion assessment (i.e. measuring rotation) (15, 63). Therefore, marker-based 3D motion capture systems are highly regarded as the preferred method for a range of motion assessment (6). These systems use marker-based or markerless pose estimation techniques to capture and analyze movement (4, 34).

Marker-based systems (i.e. Vicon and Qualisys) capture the position of markers that reflect the infrared light emitted from the cameras (30). When these markers are placed on specific anatomical landmarks on the body, this reveals the position and orientation of each marker in a three-dimensional space and allows the system to precisely determine the joint orientation (34). Normally, time-of-flight (TOF), triangulation techniques and machine-learning algorithms are used to calculate the position of each marker and estimate human motion with more precision and detail in real-time (31). A crucial step in this process is targeted marker placement around the joint segments of the body (34), which can greatly affect the accuracy of data obtained from the cameras. However, this is usually a time-consuming process that is not very practical for collecting data outside laboratory settings (4, 5).

This poses a significant advantage of markerless systems (i.e. DARI Motion and Captury) as they greatly reduce the time required to prepare the subject for testing and facilitate data collection on the field (4, 5). Previous studies have demonstrated good to excellent reliability (ICC>0.80) of DARI Motion (DARI Motion, Overland Park, KS, USA) (10) in measuring the range of motion related to squat exercise (4, 5). However, only one study directly compared the accuracy of this system to a marker-based system, specifically in relation to baseball pitching-related range of motion (14). The results of this study showed that while the internal consistency of joint angle measurements was good (ICC=0.64–0.92), the magnitudes of angle measurements differed between systems for up to 16 degrees (14). Another study compared the validity of the Captury (The Captury GmbH, Saarbrüken, Germany) (65) markerless system to Vicon (i.e. the golden standard) and found strong correlations for all range of motion measurements related to squat (r=0.74–0.99) and jump exercise (r=0.63–0.98) (19).

While markerless systems certainly show promising results and better practicality of use, marker-based systems are still widely considered the golden standard in human motion analysis (19). Moreover, the cost of both marker-based and markerless systems (~$10,000–$300,000 price per unit) remains a significant obstacle to their broad implementation in sports and rehabilitation (63).

RGB-Depth camera systems are innovative, low-cost solutions that combine the technology of 3D motion analysis with the practicality of use. These systems integrate depth-of-field sensors, which can calculate the distance of each point from the camera and create a three-dimensional representation of the model (22). The techniques for determining the dimension of depth may vary between camera models. Some systems use a narrow-baseline binocular stereo vision technique to estimate the depth dimension by gathering multiple 2D captures (i.e. PointGrey Bumblebee and Stereolabs Zed camera) (22). While other, more advanced systems use time-of-flight (TOF) and infrared (IR) technology to determine the depth of field by calculating the time needed for light to travel between two points (i.e. Microsoft Azure Kinect) (7, 62). These systems also implement machine learning algorithms to estimate the position of joints and track human motion without the need for the placement of reflective markers (47).

Although systems such as Kinect (Microsoft Corp., Redmond, WA, USA) were originally designed for gaming and virtual reality purposes, researchers have identified their potential for implementation in sports and rehabilitation due to their markerless pose estimation technology (2). Previous studies found moderate-to-good intra- and inter-rater reliability (ICC=0.62–0.99) for shoulder range of motion measurements (2, 3, 8, 20, 21, 36, 49, 55, 73). At the same time, validity varied from poor to excellent for active shoulder range of motion compared to a video motion capture system (r=0.53) (59), lateral photographs (r= 0.33–0.79) (42) and Vicon 3D motion capture system (r=0.73–0.97) (6). Similarly, good to excellent agreement was found between Kinect and Vicon for lower extremities flexion and extension measurements (24, 33), while poor agreement was found for rotational movements (33).

These results certainly highlight the vast potential of RGB-Depth cameras being used for a range of motion assessment in the future; moreover, considering their portable, lightweight design and affordable price (~$399 per unit), these systems pose a much more accessible option for widespread use. However, considering the lack of studies and varied results, further research is needed to better assess their accuracy before fully adopting these systems in sports and rehabilitation.

Commercial software systems

Commercial software systems based on computer vision are becoming increasingly popular in sports and rehabilitation. These systems use advanced statistical algorithms and deep-learning frameworks, which are able to interpret and predict visual data, recognize anatomical segments and analyze human motion (50). One of the main advantages of these systems is that they can be paired with various types of video-capturing devices (i.e. standard video cameras or motion-capture cameras) to provide enhanced precision and more detailed measurements of human movement (41). Some of these systems may also include their proprietary sensors or cameras (i.e. Vicon Nexus) developed to work seamlessly with the software (37).

Given the increasing number of commercial software systems available on the market, this review will specifically focus on software systems developed or researched for a range of motion assessment. These systems include:

Vicon Nexus (VICON, Oxford Metrics Ltd., Oxford, UK) is the gold standard in advanced kinematic data analysis (37). This software processes signals from reflective markers captured with Vicon 3D motion-capture cameras, allowing Vicon Nexus to create a 3D representation of the model, which can be viewed and analyzed from any angle (64). The software also provides various tools for measuring joint angles and calculating complex kinematic and kinetic data (i.e. force, velocity, acceleration and inverse kinematics).

Kinetisense (Kinetisense Inc.) is a software designed to upgrade the default algorithm included in the Microsoft software developer kit by offering an advanced range of motion algorithm. This software can be paired with Microsoft Kinect systems for kinematic analysis (39). Although there is a lack of studies assessing the accuracy of this software, one study showed good reliability of Kinetisense in measuring shoulder and hip range of motion (ICC=0.85–0.96) and moderate reliability in measuring elbow/wrist and knee/ankle range of motion (ICC=0.61–0.69) (39).

Theia3D (Theia Markerless Inc.) is a commercial software package that offers a markerless motion-capture solution for a range of motion assessments, among many other types of activities. This software can be integrated with 2D cameras to capture movement and then biomechanically analyze human motion based on computer vision and machine-learning algorithms. This software calculates the 3D coordinates of each anatomical segment by estimating their 2D locations on each frame and then recreates a 3D model of the body (29).

iPi Mocap Studio software (iPi Soft LLC) is a computer vision-based software that can be paired with 2D or RGB-Depth cameras to extract spatiotemporal information, track movement and automatically pinpoint up to 16 anatomical markers at a time (33). Previous studies found that iPi Mocap Studio software can be used as a valid tool for measuring the hip and knee range of motion in the sagittal and frontal planes (33).

Medical Interactive Recovery Assistant (MIRA; MIRA Rehab Ltd., London, UK) is a software platform originally designed for exergaming and telerehabilitation purposes to help patients recover faster from injuries. This software integrates a range of motion measurement tools and requires depth-sensing cameras (i.e. Kinect) to capture and analyze movement data in order to help therapists assess patients virtually (72). A study by Wilson et al. (2017) evaluated the validity of MIRA software paired with a Kinect camera for shoulder range of motion assessment. It showed very strong correlation results between measurements obtained from MIRA+Kinect (r=0.96–0.99) and Vicon 3D motion capture system (72).

Despite the numerous advantages of these systems, their cost (>$1,000–10,000) remains a significant obstacle against their potential widespread use for a range of motion assessment in sports and rehabilitation. While low-cost or free alternatives are available in the form of open-source software (i.e. OpenPose, OpenCam and Free MoCap) or smartphone apps, their accuracy may be inferior to those of a commercial system. Still, it is worth noting that such alternatives are also available on the market for a range of motion assessment.

Smartphone apps

With the advancements in smartphone technology, smartphone apps have emerged as a potentially more affordable option for assessing joint range of motion and identifying joint asymmetry (27, 28). Newer models of smartphones are usually equipped with high-performance motion sensors such as gyroscopes, accelerometers and magnetometers which could potentially be used to assess joint mobility (54). Compared to most previously mentioned methods, smartphone apps are usually cost-effective and easily available to most people who own a smartphone, making them a convenient option for practitioners. There are numerous free or low-cost apps for a range of motion assessment that smartphone users can easily download; however, the accuracy of measurements taken by these apps can differ significantly from one app to another (17, 45, 58, 61). Some apps that have already been studied for their reliability and validity in measuring range of motion include:

ROMcam is a relatively new app that utilizes 2D web cameras and OpenPose (GitHub, San Francisco, California, USA) free library based on machine learning models in order to track and detect the 2D key points of human anatomical segments (60). Although initial studies have found good reliability and validity of this app for pose-estimation assessment, more research is needed to fully evaluate the scope of its potential for a range of motion assessment in sports and rehabilitation (60).

iPhone® Compass app (Apple Inc., California, USA). A study by Furness et al. (2018) examined the potential of using the Compass app, which is pre-integrated into the iPhone's basic software package, to measure the thoracic rotation range of motion (17). The assessment was performed by positioning an iPhone firmly against the T1-T2 levels of the participant's back during active thoracic rotation. Results showed good to excellent inter-rater reliability (ICC=0.72–0.89) and concurrent validity ($r=0.835$, $p<0.001$) compared to the goniometer (17).

Goniometer Pro (Digiflex Labs, Skien, Norway) is an app designed to act as a dual-axis goniometer and bubble inclinometer. Based on previous research, this app showed good-excellent reliability (ICC=0.79–0.82) in measuring active wrist range of motion (58) and shoulder range of motion (11), as well as good concurrent validity ($r\geq0.80$) compared to a universal goniometer (58) and inclinometer (71). Another study also showed excellent reliability of this app (ICC=0.995–1.000) in measuring angular changes that normally happen during the range of motion assessment (71).

Most apps for a range of motion assessment rely on the smartphone camera or built-in motion sensors (i.e. accelerometer, inclinometer, etc.) for data collection (54). Therefore, the limitations of using apps to assess ROM greatly depend on the smartphone model; for instance, older smartphones may not have the technology to accurately measure the range of motion. Moreover, the battery capacity of older models may be degraded, which could result in the phone shutting down during or prior to data collection, and lead to the loss of important information (58).

Additionally, smartphone sensors are company-manufactured and cannot be calibrated by the user, which can also be problematic for older smartphone models that do not have well-developed sensor technology (17). Practitioners should also be aware that the accuracy of measurements can originate from the app itself or the experience of the rater; therefore, while smartphone apps offer a convenient and accessible option for joint ROM assessment, these limitations should be taken into consideration when interpreting the results.

Discussion

With the rapid development of technology, new solutions for a range of motion assessment are introduced regularly. This study aimed to offer insight into novel computer vision-based systems that can potentially be used for a range of motion assessments in sports and rehabilitation fields. As traditional tools for a range of motion assessment (i.e. goniometer and inclinometer) are often limited in their accuracy due to the subjective nature of the assessment (1), novel computer vision-based systems can provide more objective and precise measurements, as well as more detailed information about joint kinematics (2, 4, 11). These systems include motion-capture cameras (i.e. 2D and 3D cameras), RGB-Depth cameras (i.e. Kinect), commercial software systems and smartphone apps.

While 3D systems (i.e. Vicon and Qualisys) are unmatched in their precision and are widely considered the golden standard for kinematic analysis, their high cost and robust design limit their practicality and widespread use in sports and rehabilitation (4, 63). Therefore, RGB-Depth camera systems, commercial software systems and smartphone apps pose a much more feasible solution for assessing a range of motion in a practical setting (2). Based on studies evaluating the validity of these novel systems compared to what is considered the golden standard (i.e. 3D motion capture system or goniometer), RGB-Depth cameras (i.e. Kinect, Microsoft Corp., Redmond, WA, USA) stand out as the most promising option for a range of motion assessment in practical settings, especially when paired with commercial software systems or smartphone apps (39, 72).

More specifically, Kinect paired with MIRA software (MIRA Rehab Ltd., London, UK) shows excellent validity of shoulder range of motion measurements (r=0.96–0.99) compared to Vicon (72). In addition to that, smartphone apps such as Goniometer Pro (Digiflex Labs) and Compass app (Apple Inc., California, United States) also show good validity results (r≥0.70) for a certain range of motion measurements (i.e. shoulder and wrist ROM) (11, 17). However, further research is needed to better assess the accuracy of these systems in automatic pose estimation, which is crucial for measuring the range of motion (5).

The major benefit of RGB-Depth camera systems is that they can easily be mounted in any environment without requiring highly specialized knowledge to operate them (64). Moreover, they can be paired with smartphone apps (i.e. Goniometer Pro) or commercially-available and open-source software systems in order to obtain more precise and field-specific information (39, 72). A possible practical application of these systems in sports and rehabilitation includes remote and real-time monitoring of a range of motion changes during exercise. In sports, this can help trainers track various performance parameters that are important for movement efficiency and injury prevention. While in rehabilitation, this can enable a more objective assessment of the range of motion, as well as facilitate remote sessions for clients who cannot attend in-person appointments. However, further research is required to better assess the possibilities of using these systems in such a way.

Conclusions

Overall, motion capture systems based on computer vision have the potential to significantly improve the range of motion assessment compared to traditional methods such as goniometry, inclinometry and visual estimation. These systems provide more objective and accurate measurements of the range of motion and offer the possibility of real-time or remote feedback, as well as tracking changes in joint kinematics over time. However, as each system mentioned in this review has its advantages and limitations, it is difficult to determine which system could best replace traditional methods used for a range of motion assessment. As these systems continue to develop and become more accessible to the general public, they may become the standard for assessing a range of motion in the future. However, more research is needed to fully assess their accuracy and potential before implementing them in the field of sports and rehabilitation.

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