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A Comparison of Marker-Based and AI-Driven Markerless Motion Capture Technologies for Orthopedic Gait Analysis: Accuracy, Limitations, and Clinical Applications

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Abstract. Accurate assessment of human movement is crucial for identifying abnormal gait patterns and evaluating the effectiveness of orthopedic treatments. Meanwhile, advances in artificial intelligence and computer vision have promoted the development of markerless motion capture as an alternative to traditional marker-based systems. This paper primarily compares marker-based and AI-based markerless motion capture in orthopedic gait analysis, including their principles, errors, accuracy, and clinical applications. Marker-based systems have relatively high accuracy and are already well developed, but they can still be affected by soft tissue artifacts. Moreover, this system requires the pre-installation of markers before testing, and the equipment cost is also relatively high. While the markerless system does not need to attach markers to the body, it is therefore more convenient to use. Yet, limitations remain in complex 3D movements, pathological gait, and some dynamic measurements. Based on relevant research, this paper compares the features and application scenarios of the two technologies, and discusses their future development directions and their different roles in high-precision assessment and daily gait screening.

Keywords: Motion capture, Gait analysis, Orthopedic rehabilitation, Biomechanics

1. Introduction

Gait analysis is an important method for evaluating motor function in orthopedic and rehabilitation clinics. Traditional motion capture based on 3D markers usually involves placing reflective markers on the body surface and using multiple cameras to record body movements. This method has been developed for many years and is relatively mature in clinical and pathological gait analysis [1]. Yet, marker-based systems need markers, professional equipment, and trained staff before testing, so the whole process can be complicated. In recent years, markerless motion capture has begun to utilize computer vision and artificial intelligence technologies to identify key points of the human body in videos and reconstruct body movements [2]. This method reduces the reliance on markers and is expected to enable gait analysis not only to be conducted in traditional laboratories, but also in more convenient places such as clinics and communities. Previous studies have shown that the markerless system has certain accuracy and reliability in measuring gait parameters like walking speed and step length, and can also provide relatively similar results for certain joint movements. Nevertheless, the

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results under different joints and movement directions are not exactly the same [3, 4]. Thus, when comparing these two techniques, not only their overall accuracy needs to be considered, but also the joints being measured, the type of gait of the patient, and the purpose of the detection should be taken into account. However, their performance in different joints and pathological gait conditions is still not completely clear. This paper compares the accuracy, error, and clinical application of the two techniques, and explores their future development directions.

2. 3D localization and soft tissue artifacts in marker-based optical motion capture

2.1. Principles of 3D marker localization

The marker-based optical motion capture begins by placing reflective markers on the surface of the human body. Subsequently, multiple cameras simultaneously record the positions of these markers from different angles. Following camera calibration and 3D reconstruction, the 3D coordinates of the markers can be obtained. These coordinates are then used to calculate the movement trajectories and angles of various body parts and joints [1].

In gait analysis, nearby marker points can be adopted to construct the body's various parts and calculate the changes in the angles of the hip joint, knee joint, ankle joint and other joints during walking [1]. If a force plate is also used, information like joint moments and power can be obtained. Because joint angles and other movement information are calculated from the 3D positions of the markers, errors in marker position can also affect the accuracy of joint motion measurements. This provides the basis for understanding the measurement errors discussed in the following section.

2.2. Application of marker-based motion capture in joint movement measurement

For decades, marker-based motion capture has been widely applied to joint movement measurement and clinical gait analysis. By continuously recording the joint angles of the hip, knee, and ankle, this method enables researchers to assess kinematic changes throughout the gait cycle and identify gait abnormalities [1]. This detailed movement information can be useful in different clinical situations, such as pre-surgical assessment and rehabilitation evaluation. For children with cerebral palsy, gait analysis can provide information about the movement of the hip, knee, ankle, and pelvis before treatment, which can help doctors understand the patient's gait problems and plan treatment [1].

By comparing the gait results of the marked and markerless systems, Moro et al. found that while there were still some differences between the results, certain gait parameters and joint angles of the two methods could be directly compared [4]. Furthermore, one advantage of the marked system is that it can describe abnormal movements in greater detail, like showing the time when the abnormal movement occurs and the degree of change. Therefore, it can help clinicians compare the movement conditions of patients before and after rehabilitation and evaluate the changes in gait function [5]. This is of great significance for understanding the specific gait problems of patients.

2.3. Soft tissue artifacts and other measurement errors

The main problem with the marking method is the issue of soft tissue artifacts. When the human body moves, the soft tissues always shift along with it. Thus, when calculating the joint movement, the marking points on the skin surface may have deviations from the actual positions of the bones [6]. In other words, even though the system captures the marker accurately, the marker itself does not necessarily reflect the actual motion of the bone.

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As marker location is influenced by soft tissue artifact, the location of markers may be another significant source of errors in the procedure. The location of markers may lead to errors. Different patients have various anatomical features. In addition, even for one particular patient, the location of markers may be slightly different at different testing sessions. Thus, the estimation of the joint center and axis will be incorrect [1]. In this way, the displacement of soft tissues and the position of markers may both affect the position used for calculating joint movement.

Furthermore, the obstruction of the camera might result in the failure of recording the motion data of certain markers during the test. The trajectory of such markers will be incomplete because of the fact that sometimes the view of the camera is blocked by one portion of the body itself. This problem is not related to the problem that arises because of the body or the marker placement [7]. It illustrates how human factors and equipment-related factors can affect test results.

3. Human keypoint detection and model errors in markerless motion capture

3.1. Human keypoint detection and skeletal reconstruction process

Unlike marker-based motion capture, markerless motion capture does not rely on reflective markers placed on the body. Instead, cameras capture the movements of the human body, and the algorithm processes the recorded videos to detect key points [2].

The system identifies key points from the video data, including the head, shoulders, elbows, hips, knees as well as ankles, and reconstructs the human skeletal model. Subsequently, the detected key points are combined with the human model to estimate the three-dimensional position and calculate kinematic parameters, such as joint angles [2]. Compared with traditional marker-based methods, markerless motion capture eliminates the need for manual marker placement; but the accuracy of the results largely depends on the key point detection and motion estimation algorithms and models used. Moreover, the training of AI-based algorithms is another important component of markerless motion capture. The training process requires large datasets containing human movements to enable the model to accurately detect pose keypoints. The quality of the training data and the accuracy of keypoint labeling can affect algorithm performance in gait analysis [3]. Thus, the performance of the markerless motion capture system relies on the camera input and the key point detection method, and also depends on the training dataset and the underlying algorithm [3].

3.2. Applications of markerless systems in gait parameter measurement

The first obvious advantage is that the markerless system is easier to set up. As the human body does not require the use of markers, the preparation time before the test can be shortened [5]. This is particularly beneficial for children, patients, and those who need to undergo repeated tests. As for the measurement of gait parameters, the markerless system can obtain spatiotemporal parameters such as walking speed, step length, and step frequency, as well as joint motion estimates from video images [3]. According to the study by Moro et al., some of the spatiotemporal parameters recorded by the two systems are quite similar, although there are still differences in certain joint angles [4]. For patients who need frequent tests, eliminating the installation step of markers will help simplify the entire process.

The high portability, ease of use, and potentially lower cost of single-camera systems compared with other technologies make them suitable for a wider range of applications, not only in hospitals and laboratories, but in home and community environments [7]. However, not all the measurements are accurate. For certain parameters, the measurement accuracy of the markerless technique is

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higher; while for others, there are differences compared to the measurements based on the marked system. Walking speed and some basic gait parameters are highly consistent with the measurement results obtained using markers [3, 4]. Nevertheless, there are differences in some measurements of joint angles, especially when detailed joint kinematics analysis is required [3, 4].

3.3. Keypoint recognition errors and problems with pathological gait

One of the key issues with the markerless method is the errors in key point identification and human model reconstruction. The walking of healthy individuals has a typical pattern, making it easier to identify. In contrast, abnormal gait may be accompanied by compensatory movements, body twists, and limb asymmetry. These variations pose challenges for AI models, as compensatory movements introduce irregular motion patterns and limb asymmetry complicates motion estimation. Abnormal positions or rotations of body parts may prevent certain key points from being detected in the video, making it difficult for the algorithm to accurately identify all movements [2].

In a study on children with cerebral palsy, Wishaupt et al. suggested that the markerless system performed well in measuring the movements of the knee and ankle joints, but had lower accuracy in some important abnormal movements, like pelvic anteversion and hip rotation [8]. This indicates that the good performance of healthy adults cannot directly prove that the markerless system is equally effective for children with more complex movement patterns. In addition, Poomulna et al. have used Gait Deviation Index (GDI) and Gait Variability Index (GVI) to compare the two systems. It is observed that there is no statistical difference between GVI but a clinically relevant difference in GDI [9]. This means that despite having similarities in basic data about walking pattern in both systems, their final results can differ.

4. Evaluation and selection of motion capture technologies for orthopedic gait analysis

4.1. Comparison of measurement accuracy and the effects of errors

The errors in both motion capture techniques can be attributed to specific factors. For marker-based motion capture, the main sources of error include soft tissue artifacts, marker placement errors, and camera occlusion. In comparison, errors in markerless motion capture are mainly linked to keypoint detection, camera occlusion, testing environments, and human body modeling, as shown in Table 1.

Table 1. Measurement accuracy and error sources of marker-based and markerless motion capture

Measurement aspect	Marker-based motion capture	Markerless motion capture
Basic gait parameters	Generally reliable with good consistency for temporal and spatial gait parameters [3, 4]	Generally reliable, but performance varies across different parameters and conditions [3, 4]
Joint kinematics	Provides detailed 3D joint motion measurements, although some differences remain between measurements [3, 4]	Enables joint motion estimation from video data, but accuracy is influenced by keypoint detection and body modeling [3, 4]
Main sources of error	Soft tissue artifacts, marker placement errors, and camera occlusion [6]	Keypoint detection errors, camera occlusion, environmental factors, and body model estimation [3]
CP gait analysis	Provides detailed kinematic assessment, but some pelvic and hip measurements may remain challenging [1, 8]	Shows acceptable performance for some knee and ankle movements but limitations in pelvic tilt and hip rotation estimation [8]

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For measurement accuracy, Scataglini et al. observed good agreement of markerless systems in temporal and spatial gait parameters, whereas some ankle measurements remained limited [3]. In another study, Moro et al. reported comparable gait parameters between the two systems, although markerless methods tended to underestimate maximum knee and ankle flexion angles [4].

In pathological gait analysis, the performance of the markerless system may vary with the type of movement abnormality. For children with cerebral palsy (CP), Wishaupt et al. reported that the markerless method performed well in some knee and ankle movements but showed limitations in evaluating pelvic anteversion and hip rotation [8]. Poomulna et al. found no significant difference in GVI but clinically meaningful differences in GDI between the two methods [9]. For kinetic analysis, both techniques showed similar overall trends; however, differences remained in joint torque and power estimation [10].

4.2. Comparison of equipment conditions and clinical application limitations

The selection of motion capture technology may depend on the availability of equipment and the testing conditions. Generally, marker-based motion capture requires a dedicated laboratory, multiple infrared cameras, reflective markers, and trained professionals. Besides, markers need to be placed on the participant before testing, resulting in higher costs and longer preparation times [1].

Similarly, Moro et al. reported that traditional marker-based gait analysis is limited by factors such as high equipment costs and time-consuming testing procedures [4]. In contrast, markerless technology requires no marker placement, reducing preparation time before testing [5]. Moreover, single-camera systems provide advantages in portability, ease of operation, and potentially lower cost, thereby making them more suitable for home and non-laboratory environments [7]. However, markerless systems are affected by factors like camera viewpoints and body occlusion, which may reduce measurement performance. Furthermore, their accuracy remains limited for detailed 3D joint motion estimation [7]. Lam et al. reported that markerless motion capture is still in the early stages of clinical and rehabilitation applications [5]. The main differences in equipment requirements and clinical applications between the two approaches are summarized in Table 2.

Table 2. Comparison of equipment requirements and clinical applications between marker-based and markerless motion capture

Aspect	Marker-based motion capture	Markerless motion capture
Equipment	Requires specialized motion capture equipment	Mainly relies on cameras and software
Preparation	Requires marker placement before testing	No physical marker placement required [6]
Testing environment	Mainly used in laboratory settings	Can be applied outside laboratory environments [7]
Main limitations	Higher requirements for equipment, preparation, and personnel	More affected by environmental factors and algorithm performance [6, 7]

4.3. Technology selection in different orthopedic situations

Different clinical needs require different gait assessment approaches, and no single technology is universally superior. For example, preoperative CP evaluation requires comprehensive assessment of lower-limb and pelvic movements. In addition, kinetic information may be needed, which places higher demands on the accuracy of three-dimensional motion analysis [1, 8]. In these situations, marker-based systems provide more reliable measurements for complex biomechanical assessments.

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Although markerless systems perform relatively well in the sagittal plane, limitations remain in estimating pelvic tilt, hip rotation, and some transverse plane movements [1, 8]. Poomulna et al. also reported clinically meaningful differences in GDI calculations between the two approaches [9]. In addition, clinical applications such as community-based gait screening have different requirements. In these settings, accessibility, testing efficiency, and cost may be prioritized over highly detailed biomechanical measurements. The reduced preparation requirements of markerless systems allow faster assessments and facilitate data collection in non-laboratory environments [5, 7]. The potential roles of the two technologies in different clinical settings are summarized in Table 3.

Table 3. Clinical applications of motion capture systems

Clinical setting	Marker-based motion capture	Markerless motion capture
Preoperative assessment	Detailed biomechanical evaluation	Supplementary assessment with current limitations
Gait analysis	High-precision three-dimensional analysis	Efficient measurement of basic gait characteristics
Rehabilitation monitoring	Detailed comparison of movement changes	Convenient for repeated assessments
Community screening	Limited by equipment requirements	Suitable for accessible large-scale screening

5. Conclusion

This study finds that there are certain pros and cons for both marker-based and markerless motion capturing approaches. The marker-based technology is more developed and is capable of delivering more detailed information about 3D movement and kinetics, but it requires more complicated setup. Markerless approach can be easier to implement and is suitable for rapid screening and repetitive measurements. Nevertheless, there are certain drawbacks associated with the inability of markerless technology to provide detailed information about complex 3D movement and pathological gait. For practical clinical purposes, both technologies can be used separately and do not replace each other. When precise motion information is needed, the marked method has more advantages; while when ease of use and simple setup are more important, the markerless system may be more practical. With the further development of AI models and testing methods, the markerless technology is expected to be applied to more clinical cases. Further research is needed to validate this technology across different ages, pathological conditions, and environments.

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