Short communication

Accuracy and repeatability of joint angles measured using a single camera markerless motion capture system

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A B S T R A C T

Markerless motion capture systems have developed in an effort to evaluate human movement in a natural setting. However, the accuracy and reliability of these systems remain understudied. Therefore, the goals of this study were to quantify the accuracy and repeatability of joint angles using a single camera markerless motion capture system and to compare the markerless system performance with that of a marker-based system. A jig was placed in multiple static postures with marker trajectories collected using a ten camera motion analysis system. Depth and color image data were simultaneously collected from a single Microsoft Kinect camera, which was subsequently used to calculate virtual marker trajectories. A digital inclinometer provided a measure of ground-truth for sagittal and frontal plane joint angles. Joint angles were calculated with marker data from both motion capture systems using successive body-fixed rotations. The sagittal and frontal plane joint angles calculated from the marker-based and markerless system agreed with inclinometer measurements by < 0.5°. The systems agreed with each other by < 0.5° for sagittal and frontal plane joint angles and < 2° for transverse plane rotation. Both systems showed a coefficient of reliability < 0.5° for all angles. These results illustrate the feasibility of a single camera markerless motion capture system to accurately measure lower extremity kinematics and provide a first step in using this technology to discern clinically relevant differences in the joint kinematics of patient populations.

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1. Introduction

The use of marker-based motion capture technology has grown exponentially in both its use as a research tool and for clinical assessments, as evidenced by its widespread utilization (e.g. McGinley et al., 2009). However, there are a number of limitations inherent in the way that data are collected that preclude its use in some settings and environments. For instance, because of the need to use an array of cameras, marker-based motion capture is difficult to perform in settings such as a patient’s home, on the sports field, or in public. One potential solution that has been suggested is to use a markerless motion capture system (Mundermann et al., 2006).

Markerless motion capture technology has shown promise to assess both gait and postural control (Clark et al., 2012, 2013; Corazza et al., 2006; Mentiplay et al., 2013; Stone and Skubic, 2011). The accuracy of marker-based systems has been analyzed (Holden et al., 1997; Kiran et al., 2010; Miranda et al., 2013; Richards, 1999) whereas the accuracy of markerless motion capture techniques has not been studied as extensively. The accuracy of markerless systems has been assessed using marker-based measures as ground-truth (Clark et al., 2012, 2013; Mentiplay et al., 2013; Mundermann et al., 2005; Steele et al., 2009; Stone and Skubic, 2011). While providing important insights between the two systems, these studies do not provide information into whether the markerless systems were more or less accurate than the marker-based system. Other ground-truth measures have been used: a virtual walking model for lower-extremity kinematics (Corazza et al., 2006) and a landmark identification method for hand kinematics (Metcalf et al., 2013). However, an assessment of the accuracy of a single camera markerless motion capture system with a ground-truth measure and how this compares to traditional marker-based motion capture to measure lower extremity kinematics still remains understudied.

Repeatability of marker-based systems has also been extensively studied (Ferber et al., 2002; Leardini et al., 2007; McGinley et al., 2009; Miller et al., 2002; Schwartz et al., 2004; Vander Linden et al., 1992). By comparison there are few reports on markerless motion capture repeatability (Clark et al., 2012;
Mentiplay et al., 2013). In these studies, repeatability was assessed using correlation coefficients, which while informative, are not expressed in units consistent with the measurements made. This makes them difficult to relate to the measurements themselves (e.g. joint angles) (Keating and Matyas, 1998).

Establishing the repeatability and accuracy inherent in markerless motion capture is an important first step to gauge the minimum detectable differences that can be found within and between patients. To date, there have been few reported attempts at establishing the reliability using units relatable to the measure itself and accuracy of markerless and marker-based motion capture to the same ground-truth. Therefore, the goals of this study were to quantify the accuracy and repeatability of joint angles using a single Kinect camera (Microsoft) markerless motion capture system and to compare the markerless system performance with that of a marker-based system.

2. Methods

Multiple positions of a testing jig (Fig. 1) were determined during seven testing sessions: one session to gather data to assess accuracy and six sessions to accumulate data for test–retest reliability. For evaluation of accuracy, the jig was placed in six static postures where each rotational degree of freedom was separately manipulated while the others were approximately zero. To measure test–retest reliability, the jig was positioned in a static configuration, data collected, systems recalibrated, and data collected again. This was done for three static configurations: jig flexed, adducted, and internally rotated.

Motion data were captured for each configuration using both a Kinect (Microsoft) and a marker-based motion capture system (Fig. 2). First, one Kinect camera was used in conjunction with the KinectFusion software (Microsoft, Redmond, WA, USA) to build a surface model template of the jig, where the positions of fourteen retroreflective markers were included (Fig. 1). Then, for each pose of interest, depth map and two-dimensional images were collected at 30 Hz using the Kinect. An articulated iterative closest point algorithm (Pellegrini et al., 2008) assuming a ball-and-socket joint at the knee was used to align these captured data with the template. Then, virtual marker trajectories were exported for each trial. Simultaneously collected at 200 Hz were marker positions using a 10 camera motion analysis system (Motion Analysis Corp, Santa Rosa, USA).

To provide a measure of ground-truth, a digital inclinometer (Craftsman, Model 320.4829S, accuracy of 0.1°) was used to measure the primary angle manipulated in each configuration. The inclinometer was not used to measure axial rotation since this tool utilizes gravity.

The marker data from both systems were processed using Visual3D (C-Motion, Germantown, MD, USA) (Fig. 2). First, body-fixed reference frames were constructed using markers positioned on the ends of the segments (Fig. 1). Next, the marker trajectories were lowpass filtered at 8 Hz using a fourth-order, zero-lag Butterworth filter. This cutoff frequency was chosen based on the results of a power spectral analysis of the data. Then, with the knee modeled as a six degree-of-freedom joint, the filtered trajectories of the marker clusters were used to compute the orientation of the distal segment relative to the proximal segment using Cardan angles (Grood and Suntay, 1983).

For each trial recorded for each of the static postures, the mean and standard deviation of the measured angle was calculated using 30 frames. Accuracy was based on the data for the six configurations of one testing session and quantified for each system (markerless and marker-based) as the difference between the mean calculated angle of the system and the angle measured by the inclinometer. A paired t-test was used to statistically compare the accuracy of the two systems with significance defined as p < 0.05. The normality of the data was qualitatively verified prior to the t-test by plotting a histogram of the data. The difference in accuracy between the marker-based and markerless systems was also quantified as the difference between the mean angles calculated by the two systems. Test–retest reliability was assessed using the three configurations collected across six sessions. For each configuration, the coefficient of repeatability, bias, and limits of agreement were calculated for each system (Bland and Altman, 2010). The assumption of homoscedasticity was qualitatively assessed using Bland–Altman plots (Bland and Altman, 2010).

3. Results

Flexion–extension and ab–adduction angles calculated from both the marker-based and markerless system deviated from the inclinometer measurements by < 0.5° (Table 1). The marker-based system was significantly more accurate at estimating abduction while the markerless system was more accurate for adduction (Table 1). The accuracy of both systems agreed with each other ± 0.5° or less for flexion–extension and ab–adduction and by ± 2° or less for axial rotation (Table 1). The marker-based system had a lower coefficient of repeatability and a lower bias, except for internal rotation where the markerless system showed a smaller bias (Table 2).

![Fig. 1. A jig with a ball-and-socket joint was built to simulate a leg. (left) Fourteen retroreflective markers were used to record the motion of the thigh and shank segments. (right) Segment fixed coordinate systems used to calculate joint angles.](image-url)
4. Discussion

The advent of improved camera technology makes the use of a single camera 3D motion capture system a possibility. We sought to establish the accuracy and reliability of a single camera markerless motion capture system in evaluating joint angles compared to a marker-based system. The differences in accuracy and reliability between the marker-based and markerless systems were small, indicating the performance of the Kinect camera and the associated algorithm for reconstructing the segments may be a viable tool for calculating lower extremity joint angles.

Joint angles measured with the markerless motion capture system agreed with our measure of ground-truth, the inclinometer, within 2° or less. This accuracy is less than kinematic alterations we would expect to see in patient populations, e.g. 3–5° in hip and knee kinematics (Butler et al., 2011; Noehren et al., 2012, 2013). While additional studies are needed in human

Table 1
Accuracy of the motion capture systems. Significant p-values are bolded and italicized.

<table>
<thead>
<tr>
<th>Degree of freedom</th>
<th>Accuracy of marker-based system (deg.)</th>
<th>Accuracy of markerless system (deg.)</th>
<th>p-Value</th>
<th>Marker–markerless system (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexed</td>
<td>−0.2 ± 0.1</td>
<td>−0.2 ± 0.0</td>
<td>0.351</td>
<td>−0.0</td>
</tr>
<tr>
<td>Extended</td>
<td>−0.2 ± 0.1</td>
<td>−0.2 ± 0.0</td>
<td>0.415</td>
<td>−0.0</td>
</tr>
<tr>
<td>Adducted</td>
<td>0.0 ± 0.1</td>
<td>0.4 ± 0.0</td>
<td>&lt;0.001</td>
<td>0.3</td>
</tr>
<tr>
<td>Adducted</td>
<td>0.4 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>&lt;0.001</td>
<td>−0.1</td>
</tr>
<tr>
<td>Abducted</td>
<td>−</td>
<td>−</td>
<td>−2.0</td>
<td></td>
</tr>
<tr>
<td>Internally rotated</td>
<td>−</td>
<td>−</td>
<td>1.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
95% limits of agreement (LOA), the bias, and coefficient of repeatability of the motion capture systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Lower LOA (deg.)</th>
<th>Upper LOA (deg.)</th>
<th>Bias (deg.)</th>
<th>Coefficient of repeatability (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marker</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Kinect</td>
<td>0.5</td>
<td>1.1</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Adduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marker</td>
<td>−0.2</td>
<td>−0.2</td>
<td>−0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Kinect</td>
<td>−0.4</td>
<td>−0.2</td>
<td>−0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Internal rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marker</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Kinect</td>
<td>0.1</td>
<td>0.8</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>
populations, our results do suggest that a markerless based system may be sensitive enough to detect clinically relevant differences. The use of several measures (Table 2) to assess repeatability helps to present a complete description of a system's precision. The bias, average test–retest difference, of both systems was less than 1°, as would be expected since the same method of measurement (i.e. marker-based or markerless) was used for both trials when investigating the repeatability of each system (Bland and Altman, 2010). The coefficient of repeatability was less than 0.5° for both systems, which reflects where we would expect 95% of the differences between two trials to be for each system (Bland and Altman, 2010). Considering all planes of motion, the limits of agreement, an interval for test–retest differences, for the markerless system (−0.4° to 1.1°) was comparable to that of the marker-based system (−0.2° to 0.9°). These results are within the range reported by other studies who have found markerless and marker-based systems to be repeatable with each other by −8.2° to 0.2° for trunk angle during a lateral reach (Clark et al., 2012) as well as between 0° and 2.5° for calcaneal inversion–eversion (Mentiplay et al., 2013). The largest 1.1° reliability found in our markerless system also meets the suggestion of McGinley et al. (2009) that a reliability of 2° or less may be acceptable for a tool to be clinically viable.

The relative accuracy of the markerless system using the marker-based system as ground-truth is an important feature to consider in defining if the markerless values given are comparable to those of the marker-based system. In the current study, we found that the single Kinect marker-based systems agreed within 0.0° for flexion–extension (p > 0.3) and 0.3° for ab–adduction (p < 0.001) angles. While the differences in frontal plane kinematics were statistically significant, these differences were small and below the threshold of variations in clinical populations seek to define (Butler et al., 2011; Nothken et al., 2012, 2013). In addition, these results are within a previously published range of values (0.01–9.1° for flexion–extension and ab–adduction) from other studies that assessed relative accuracy (Corazza et al., 2006; Mündermann et al., 2005).

There are some limitations of the study to consider. First, the accuracy of the Kinect depth sensor is a function of distance from the camera. As the distance from the camera increases, the random error in depth measurements increases and resolution decreases, reaching up to 4 cm in depth measurement error at the range of the camera view (Khoshelham and Elberink, 2012). Therefore, we limited our analysis to only one joint so the joint could be placed within 1–3 m of the camera, as recommended for <2.5 cm error (Khoshelham and Elberink, 2012). Capturing the motion of a whole leg might prove more difficult as subjects may move closer and further from the camera during movement, varying the accuracy of the data. Secondly, the sampling rate of the Kinect was 30 Hz while that of the marker-based system was 500 Hz. This work was funded in part by the Division of Information and Intelligent Systems of the National Science Foundation, grant 1231545.

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Conflicts of interest statement

None declared.

References


