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Short communication

Accuracy map of an optical motion capture system with 42 or 21 cameras in a large measurement volume

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ABSTRACT

Optical motion capture is commonly used in biomechanics to measure human kinematics. However, no studies have yet examined the accuracy of optical motion capture in a large capture volume (>100 m^3), or how accuracy varies from the center to the extreme edges of the capture volume. This study measured the dynamic 3D errors of an optical motion capture system composed of 42 OptiTrack Prime 41 cameras (capture volume of 135 m^3) by comparing the motion of a single marker to the motion reported by a ThorLabs linear motion stage. After spline interpolating the data, it was found that 97% of the capture area had error below 200 µm. When the same analysis was performed using only half (21) of the cameras, 91% of the capture area was below 200 µm of error. The only locations that exceeded this threshold were at the extreme edges of the capture area, and no location had a mean error exceeding 1 mm. When measuring human kinematics with skin-mounted markers, uncertainty of marker placement relative to underlying skeletal features and soft tissue artifact produce errors that are orders of magnitude larger than the errors attributed to the camera system itself. Therefore, the accuracy of this OptiTrack optical motion capture system was found to be more than sufficient for measuring full-body human kinematics with skin-mounted markers in a large capture volume (>100 m^3).

1. Introduction

Optical motion capture (OMC) is used in a variety of fields, including biomechanics (Bell-Jenje et al., 2016; Le and Marras, 2016). The accuracy of various optical motion capture systems has been extensively evaluated in the past (Carse et al., 2013; Ehara et al., 1995, 1997; Richards, 1999; Thewlis et al., 2013). However, these evaluations are typically performed in small volumes, from 0.005 to 15 m^3 (Eichelberger et al., 2016; Windolf et al., 2008). Research on occupational ergonomics interventions, sports biomechanics, and rehab biomechanics often involve activities that span a larger volume, and thus require a more expansive motion capture system. Windolf and Eichelberger found that accuracy varies by location within the capture volume. In relatively large capture volumes (>100 m^3), it is expected that accuracy has the potential to vary considerably by location, and a single measurement of accuracy at or near the center of the space is not adequate. No studies could be found that examined how accuracy changed approaching the edges of the capture space. Additionally, most previous studies have compared inter-marker distance to a more precisely known length of the same object. However, by only considering error in the measured distance (1D) between two markers, this technique fails to capture off-axis (3D) errors.

Thus, the aims of the current study were to establish the 3D accuracy of an OMC system for tracking individual markers within a large capture volume that is currently being used for biomechanical research, and to determine what portion of the capture area has acceptable accuracy for full-body biomechanics applications, such as gait analysis and occupational ergonomics.

2. Materials and methods

The OMC system used in this study was composed of 42 OptiTrack Prime 41 cameras and operated using OptiTrack Motive 1.10.1 Final software (NaturalPoint, Corvallis, Oregon, USA). Each calibration of the OMC system was performed by hand using an OptiTrack CWM-250 calibration wand with a length of 250.018 ± 0.002 mm. A panorama of the motion capture area can be seen in Fig. 1.

A ThorLabs LTS300 (Newton, New Jersey, USA) linear motion stage was used to evaluate the accuracy of the OMC data. The stage was calibrated by the manufacturer to an on-axis error of 5 µm. A single brand new 15.9 mm retroreflective (passive) OMC marker purchased from OptiTrack was mounted to this stage by a rigid stem, resulting in the marker being approximately 43 mm above the surface of the stage.

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Fig. 1. Panorama of capture volume. Note linear motion stage near the center of the capture space.

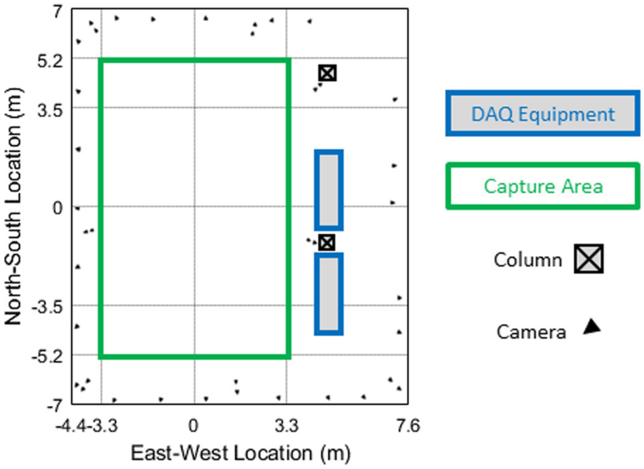

Fig. 2. Overhead view of OMC setup.

The capture space evaluated was based on typical use and had an extent of 10.4 m × 6.5 m × 2 m = 135 m^3, an overhead view of which can be seen in Fig. 2. A fully-balanced repeated measures study design was used in this assessment. The independent variables consisted of (1) the number of cameras used (2 levels) and (2) location within the capture area (15 levels: each intersection of gridlines in Fig. 2). One repetition of each combination of these variables was collected on three separate days. Each day, a new calibration was performed after the cameras had warmed up for at least 30 min, and all data recordings were captured within 66, 71, and 58 min of calibration, respectively. The linear motion stage was homed at the beginning of each day to ensure the stage began from the same position each time. Following calibration and homing, one recording was captured with the stage at each of the 15 locations in the capture area. All tests were performed with the marker 83 mm above the floor. For each recording, 60 s of data were recorded at 180 Hz as the stage moved a total distance of 100 mm while pausing for 3 s at every 10 mm increment. The maximum speed of the marker was 10 mm/s. One copy of each recording was processed using all 42 cameras, while a second copy was processed using 21 cameras (every other camera was disabled, moving around the perimeter of the room).

The only processing performed on the ThorLabs stage was to apply the calibration that came with the device. To compare data to the OMC system, the location of the stage at the beginning of each recording was used as the origin of a local coordinate system for data from the stage.

Processing of the data from OMC system followed a series of steps. The origin of the OMC system for each recording was taken to be the average marker location prior to its first motion. The motion of the marker location was then filtered using a digital zero-phase 4th order Butterworth filter with half-power frequency of 6 Hz (default setting in OptiTrack's Motive software) to remove high-frequency noise. The orientation of the stage was calculated from the optical data by minimizing off-axis motion of the marker location using a specialized optimization algorithm.

The data from the two systems was synchronized by optimizing the time delay between the beginnings of the two signals to minimize root-mean-square of the 3D error. Error was measured by subtracting the ThorLabs stage measurement from the OMC measurement, calculating the magnitude (root-sum-square of the XYZ components), and finally calculating the root-mean-square across all samples in the recording (both static and dynamic portions were included in this measurement).

Finally, two maps of the error within the capture area were generated, one for each number of cameras. The mean of the error across all three days was taken at each of the 15 stage locations. These fifteen data points, along with their spatial locations in meters were spline interpolated to estimate how errors varied throughout the capture area.

3. Results

Maps of mean RMSE for each number of cameras are shown in Fig. 3. The majority of the capture area had an interpolated RMSE <200 μm (~97% for 42 cameras; ~91% for 21 cameras). Every point had a mean RMSE less than 1 mm, and the only locations that that exceeded 200 μm of error were those in the extreme corners of the capture area.

As expected, there is generally less error toward the center of the capture area. Errors then increase nonlinearly approaching the edges of the capture area, as revealed by the increasing frequency of the contours. It can also be seen that errors tend to be lower on the east side of the room than the west. The maps also reveal better accuracy when using the full set of cameras. The distribution of error observed with 42 and 21 cameras is shown in Fig. 4. As expected, using fewer cameras resulted in a higher mean error and greater variation between recordings. The two recordings with a mean error above 600 μm were observed in the extreme corners of the capture area while using only half of the cameras.

4. Discussion

The results of this study confirm that OMC can be used to measure passive marker locations with accuracy better than 200 μm in the vast majority (97%) of even relatively large capture volumes (>100 m^3), given optimal marker visibility conditions. Even when using only half (21) of the cameras, 91% of the capture area was found to achieve the same accuracy.

One objective of this study was to understand the magnitude of error contributed by the OMC system compared to other known sources of error when quantifying human kinematics using skin-mounted markers. The degree of accuracy observed in the current study is generally more than sufficient for measuring full-body human kinematics using skin-mounted markers, due to the presence of other sources of greater measurement error. First, there is uncertainty regarding how markers are located relative to internal geometry (Della Croce et al., 2005). In addition, soft-tissue artifact (STA) can further displace the marker from its preferred location, up to 55 mm (Leardini et al., 2005; Shultz et al., 2011; Zemp et al., 2014). These artifacts exceed the instrumental error of OMC and propagate to error in bone kinematics (Li et al., 2012), thus being "regarded as the most critical source of error in human movement analysis" (Leardini et al., 2005). The magnitude of these artifacts make accuracy exceeding what has been demonstrated by the current study to be unnecessary for capturing full-body human kinematics.

This is the first study that has considered how accuracy deteriorates as markers approach the edges of the capture area. In addition, no studies could be found measuring the accuracy of OMC systems of this size (>100 m^3) (Kedgley et al., 2009; Liu et al., 2007; Maletsky et al., 2007; Windolf et al., 2008). The most comparable study found

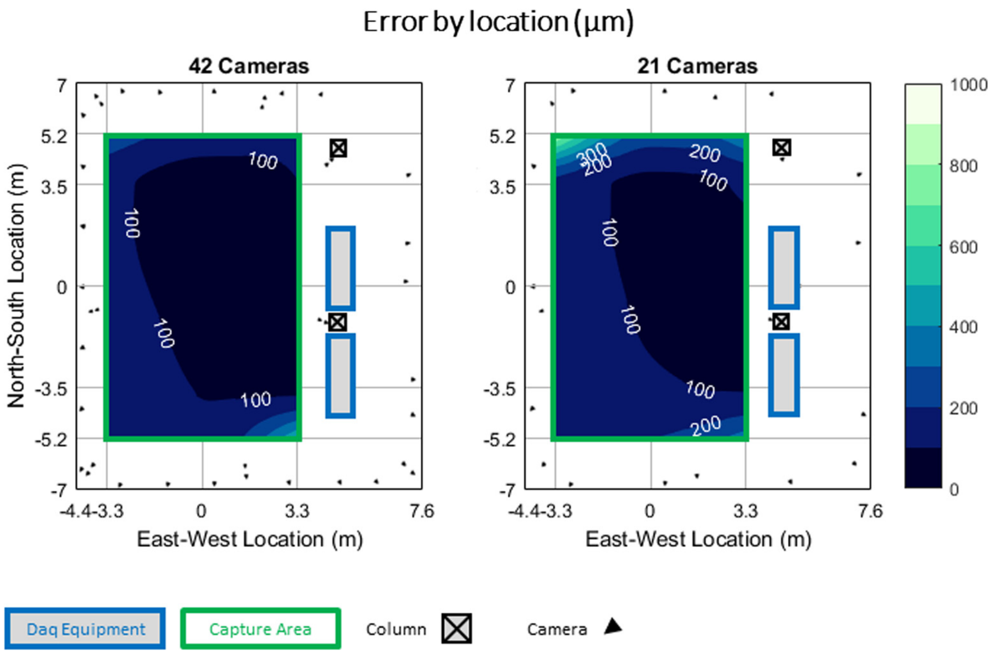

Fig. 3. Map of error as a function of location, separated by number of camerasNote that north and east are considered positive on their respective axes.

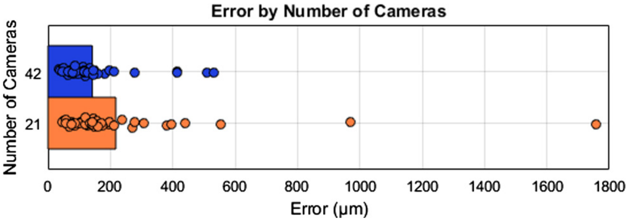

Fig. 4. Error by number of cameras. Each circle represents one recording, and the bar shows the mean.

measured inter-marker distance using 6–10 Vicon cameras within a 13.2 m^3 (5.5 m × 1.2 m × 2 m) capture volume (Eichelberger et al., 2016). Though differences in the methods of the two studies makes them difficult to compare, errors measured by Eichelberger were of the same order of magnitude as the current study.

There are a variety of limitations to this study. First, the motion capture system used in this study was set up for practical biomechanics use, rather than optimized for tracking accuracy. For example, constraints regarding accessibility to the capture area required irregular camera placement, and all cameras were adjusted to have the same f-stop, gain, exposure, threshold, and LED brightness for simplicity rather than optimized for tracking accuracy.

Second, while the marker was moving during the recordings, it was moving at very low speeds (maximum speed = 10 mm/s) as limited by the linear motion device used in this study. As a result, this study did not evaluate the effects of motion blur on accuracy. In addition, the number of objects that could cause occlusion of the marker was relatively low, and the marker was on a stem to reduce possible occlusion from the stage itself. During realistic biomechanical data collection, it is expected that more occlusion, more motion blur, and higher individual marker errors would be observed since this study has demonstrated a relationship between the number of cameras tracking a marker and accuracy.

Third, marker tracking accuracy is not equivalent to skeleton tracking accuracy. The model used to reconstruct body kinematics from the marker locations can affect the accuracy of the resulting body segment locations and orientations (Leardini et al., 2005).

Finally, each location in the capture area was only assessed at one height (83 mm above the floor). Error could differ at other heights. Nonetheless, it is expected that measurements very near the floor are subject to greater error, particularly in the corners of the capture volume. For instance, it was observed that a marker near the floor in the corner of the capture area could only be observed by 3 cameras on the far side of the room. In this circumstance, lines of sight were long and the angle between them was small, tending to decrease spatial resolution. However, when the marker was raised up to waist height, 4 additional cameras on the near side of the room could also see the marker. This shortened the average line of sight, and vastly increased the mean angle between lines of sight. Thus, it is expected that higher errors were observed near the floor than would have been seen at higher locations in the capture volume.

5. Conclusion

The OMC system demonstrated submillimeter mean accuracy at every location in the capture volume, and error was found to be less than 200 μm in 97% of the capture volume (using all 42 cameras). Only very near the edges of the capture volume did error exceed 200 μm. The errors of the OMC system were found to be orders of magnitude smaller than other known sources of error associated with skin-mounted markers (marker placement errors and soft tissue artifact). Therefore, a large OMC system like the one used in this study would be expected to have more than sufficient accuracy for full-body human kinematics applications, such as gait analysis and occupational ergonomics.

Conflict of interest statement

OptiTrack (NaturalPoint, Corvallis, Oregon USA) provided equipment (including the linear motion stage and calibration wand) and technical assistance to optimize the system for this study.

Acknowledgments

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