Analysis of measurement performance in optical motion capturing

A protocol for precise and fast laboratory setup evaluation

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Validity and reliability as scientific quality criteria have to be considered when using motion capture systems for research purposes. System characteristics such as accuracy and precision are often not addressed in scientific reports of human motion analysis studies, even though literature and standards recommend individual laboratory setup evaluation. One reason could be due to the lack of a simple and practical method to evaluate system performance. We developed a protocol for practical laboratory setup evaluation in context of usability in human movement analysis. The estimated measurement uncertainties were ± 0.45 mm, ± 0.54 mm and ± 0.91 mm for foot, knee and hip regions. Taking into account current literature reports and our own assessment of good inter-trial reliability, it is concluded that the protocol can be easily reproduced and that it provides valuable estimations of system setup accuracy. Further investigations have to be done on linking the uncertainty estimations to model outputs such as joint angles.

Motion capture, measurement, uncertainty, accuracy, precision, system evaluation

1. INTRODUCTION

The use of optical motion capture systems is widespread. Entertainment [1], biomechanics [2], ergonomics [3] and sports [4] are possible fields of application. Validity and reliability as scientific quality criteria have to be considered when using motion capture systems in research. Miller reported that the functional characteristics, namely accuracy, repeatability and resolution had to be determined to confidently report data from motion capture systems [5]. In fact, measurement performance is often not specified in scientific reports of experiments dealing with human motion analysis. The reason may be because manufactures give only rough performance specifications due to the fact that performance is influenced by many factors, such as camera setup, measurement and calibration volume, camera resolution, lighting conditions, etc. [6]. Windolf reported that performance of motion capture systems strongly depends on their setup and that accuracy and precision should be determined for an individual laboratory installation [6]. Own experience showed that the number of cameras seemed to be one of the most important parameters. Published studies addressing the lack of measurement performance information included examinations on system comparison [7] [8], accuracy and precision in angular [9] and linear [7] measurements and setup parameter influence [6]. Different definitions of accuracy and precision limit the comparability between studies, even though most often accuracy was defined as mean absolute error and precision as mean standard deviation. Examination methods most often included special reference devices or positioning equipment, which is unpractical for everyday use in the laboratory. Only Miller related his experiments on accuracy, repeatability and resolution to anatomical regions of interest [5]. Standards like the ISO/IEC 17025:2005 state that test laboratories need methods to determine measurement uncertainty [10]. As of today no simple and practical methods exist to evaluate system performance with a close relation to anatomical regions of interest in biomechanical analysis. The purpose of this study was therefore to develop a protocol for fast and precise laboratory setup evaluation.

2. MATERIAL AND METHODS

The setup consisted of eight symmetrically arranged cameras (Vicon Bonita 3, 200 Hz, Vicon Motion Systems Ltd., Oxford, UK) resulting in a measurement volume of $(5.5 \cdot 1.2 \cdot 2)\ m^3$. Region of interest for performance analysis (ROI_{PA}) was defined by the usual region of interest for biomechanical assessment of the lower extremity (above two centrally placed force plates) $(1 \cdot 0.6 \cdot 1.2)\ m^3$. For the reference object two spherical markers with a diameter of (16.18 ± 0.04) mm and an inter-center distance of (95.50 ± 0.04) mm were placed at both ends of a rod. Based on biomechanical regions of interest when analyzing lower extremities, the reference rod was placed dorsally on the left foot (crosswise to gait direction), laterally on the left knee (horizontal) and on the sacrum (horizontal) from a test person. For each situation the reference object was captured while the subject was passing the measurement volume in the longitudinal direction. Ten trials per reference object position were captured whereas the volume was crossed five times from the left and five times from the right to avoid measurement asymmetry. According to Willmott [11] mean absolute error (MAE), root-mean-square error (RMSE) and mean bias error (MBA) were calculated for the ROI_{PA} (from left foot strike to right toe off events) in each trial. Average marker distances and standard deviations (SD) were calculated respectively. MAE was defined as accuracy, which describes the difference between Vicon-data and the reference value. SD of Vicon-data was defined as precision, which states the repeatability of measurements taken under identical circumstances. The RMSEs were only calculated for comparability reasons. The system performance quantities for the ten trials per anatomical region (eg. foot, knee, hip) were averaged. Expanded measurement uncertainty (U) was calculated as $U = k \cdot SD = 2 \cdot SD$ (95.5 % CI) for foot, knee and hip regions. Overall performance was calculated as the average value of the three regions.

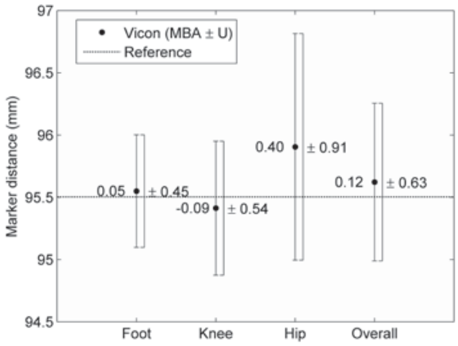

Figure 1. Marker distances with bias and expanded uncertainty for foot, knee, hip and overall regions

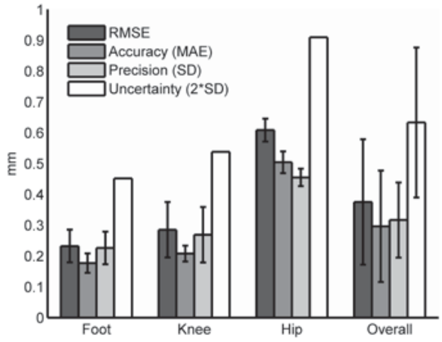

Figure 2. RMSE, accuracy, precision and expanded uncertainty for foot, knee, hip and overall regions.

3. RESULTS

Vicon measurements revealed marker distances (mean ± SD) of (95.55 ± 0.03) mm, (95.41 ± 0.04) mm and (95.90 ± 0.06) mm for foot, knee and hip regions respectively. The average marker distance over all three regions was (95.62 ± 0.25) mm. The smallest bias and uncertainty were found for the foot region, the largest for the hip region (Fig. 1). Accuracy (mean ± SD) was (0.18 ± 0.03) mm, (0.21 ± 0.03) mm and (0.50 ± 0.04) mm for the foot, knee, and hip regions. Precision (mean ± SD) for the respective regions was (0.23 ± 0.05) mm, (0.27 ± 0.09) mm and (0.45 ± 0.03) mm. Resulting measurement uncertainties were ± 0.45 mm, ± 0.54 mm and ± 0.91 mm respectively. Overall accuracy, precision and uncertainty were found to be (0.30 ± 0.18) mm, (0.32 ± 0.12) and (0.63 ± 0.24) mm. Accuracy, precision and uncertainty values were best found for the foot region and worst for the hip region (Fig. 2). The RMSEs (mean ± SD) equaled (0.23 ± 0.05) mm, (0.29 ± 0.09) mm, (0.61 ± 0.04) mm and (0.38 ± 0.20) mm for the foot, knee, hip region and overall.

4. DISCUSSION

The relatively small SDs of accuracy and precision for the foot, knee and hip region (≤ 0.09 mm) indicate a good inter-trial reliability of the measurement method (Fig. 2). All examined performance quantities, namely bias, RMSE, accuracy, precision and uncertainty, tend to increase for the hip region (Fig. 1 & 2). The increased SDs of the overall values represent this inter-region variability and indicate measurement volume inhomogeneity. The examined laboratory installation was developed with a focus on foot measurements. The examination showed the best system performance in the foot region and therefore confirmed the correctness of our efforts for setup development. The most recent publication [6] on accuracy and precision analysis of video motion capturing systems reports an overall RMSE of (63 ± 5) µm and an overall SD of 15 µm for a measurement volume of $(0.18 \cdot 0.18 \cdot 0.15)\ m^3$ and the most favorable parameter setting. The authors also state that their findings may be scaled to other measurement volumes. Scaling to the examined volume obtained in this study (meaning to each axis and then averaging) results in an RMSE of 0.33 mm and a SD of 0.08 mm. Compared with our findings at least the scaled RMSE is in the same range. Older studies [7-9] reported minimal MAEs from 0.47 mm to 0.90 mm and smallest SDs from 0.24 mm to 1.39 mm. The estimated overall uncertainty of ± 0.63 mm is comparable to the estimation of ± 0.41 mm from colleagues who did similar experiments [12]. Even though comparisons have to be drawn carefully, it seems that our examination revealed realistic system performance estimations. In comparison to methods that were used for motion capture system characterization in the past, our protocol is very simple and links the estimations directly to the anatomical regions of interest. We propose a method that may be compliant to the ISO/IEC 17025:2005 for uncertainty estimation and that is practical and precise enough for fast motion laboratory setup evaluation. Further investigations have to be done on linking the estimations to functional outcome variables such as joint angles.

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