Journal of Biomechanics 89 (2019) 139–142

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Static accuracy analysis of Vicon T40s motion capture cameras arranged externally for motion capture in constrained aquatic environments

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ARTICLE INFO

Article history:
Accepted 19 April 2019

Keywords:
Motion capture
Aquatic therapy
Vicon
Static accuracy
Underwater treadmill

ABSTRACT

While the capabilities of land-based motion capture systems in biomechanical applications have been previously reported, the possibility of using motion tracking systems externally to reconstruct markers submerged inside an aquatic environment has been under explored. This study assesses the ability of a motion capture system (Vicon T40s) arranged externally to track a retro-reflective marker inside a glass tank filled with water and without water. The reflective tape used for marker creation in this study was of Safety of Life at Sea (SOLAS) grade as the conventional marker loses its reflective properties when submerged. The overall trueness calculated based on the mean marker distance errors, varied between 0.257 mm and 0.290 mm in different mediums (air, glass and water). The overall precision calculated based on mean standard deviation of mean marker distances at different locations varied between 0.046 mm and 0.360 mm in different mediums. Our results suggest, that there is no significant influence of the presence of water on the overall static accuracy of the marker center distances when markers were made of SOLAS grade reflective tape. Using optical motion tracking systems for evaluating locomotion in aquatic environment can help to better understand the effects of aquatic therapy in clinical rehabilitation, especially in scenarios that involve equipment, such as an underwater treadmill which generally have constrained capture volumes for motion capture.

1. Introduction

Motion capture (Mo-cap) is one of the most common methodologies used in biomechanical analysis (Muller et al., 2015; Thewlis et al., 2013). While this instrumentation plays a vital role in areas such as clinical gait analysis to improve treatment of injuries and conditions, it can also be used to address other clinical problems, such as treatment of neuromuscular disorders and cerebral palsy (Andriacchi and Alexander, 2000). Recent studies in clinical rehabilitation have demonstrated the potential benefits of aquatic-based therapies in comparison to land-based therapies (Becker, 2009; Denning et al., 2010; Hinman et al., 2007), and the benefits of exercise in an underwater treadmill have been shown (Conners et al., 2018, 2014; Denning et al., 2010). Factors like density, specific gravity, buoyancy, and other physical principles of water contribute to the advantages of performing physical exercises in an aquatic environment (Becker, 2009). However, in order to quantify these effects, it is important to completely understand human locomotion in an aquatic environment.

Mo-cap systems use different methodologies to collect and analyze human locomotion (Richards, 1999). The reliability and validity of data from such Mo-cap systems has continued to be an area of interest among the scientific community (Eichelberger et al., 2016; Kaufman et al., 2016; Miller et al., 2016; Windolf et al., 2008). In the past decade, the assessments of Mo-cap systems for validity have been predominantly performed on systems that utilize the tracking of retro-reflective marker positions in three-dimensional (3D) space (Eichelberger et al., 2016; Windolf et al., 2008). However, the aforementioned studies have been limited to land-based applications. Rehabilitation scenarios, such as aquatic therapy, have progressed towards trying to evaluate patterns of locomotion while underwater (Kwon and Casebolt, 2006; Silvatti et al., 2013).

Conducting Mo-cap in an underwater environment can be a challenge because the default retro-reflective markers provided by the manufacturers for a Mo-cap system lose the retro-

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https://doi.org/10.1016/j.jbiomech.2019.04.029
0021-9290/

reflective properties due to change in medium once they are submerged. As the surface of the default retro-reflective marker is wetted, it loses its retro-reflective properties. This necessitates identifying a potential retro-reflective material that could retain its retro-reflectivity when submerged in water for aquatic applications. Also, it could be argued that Mo-cap systems that are specifically made for aquatic applications could be used in place of a land-based Mo-cap systems to capture aquatic locomotion (Abdul Jabbar et al., 2017; Lauer et al., 2016). However, in aquatic applications specifically with systems like an underwater treadmill that are used in clinical rehabilitation scenarios, the view window is restricted, and the capture volume is small. Under such conditions, it would be challenging to use an underwater system to capture the human locomotion from inside the unit. Bearing these thoughts, the notion behind utilizing Mo-cap setup arranged externally in this study to evaluate the accuracy derives its motivation from scenarios to detect the motion in such environments. Consequently, this study aims to evaluate the static accuracy of a land-based Mo-cap system arranged externally to track retro-reflective marker position in 3D in different mediums (air, glass and water). The present study also ascertains the influences of medium in the reconstruction of the distances that can affect the overall accuracy of the Mo-cap system.

2. Materials and methods

2.1. Cameras, markers and, template

The tests were performed using five Vicon T40s Mo-cap cameras (Vicon Motion Systems, LA, USA). The potential retro-reflective material that could retain its retro-reflectivity when submerged in water was found to be 3M™ Scotchlite™ Reflective material, Safety of Life at Sea (SOLAS) Grade 3150 – A. This commercially available retro-reflective tape was cut in the form of equally sized petals to be wound around a spherical marker of 14 mm diameter (d_M; [Fig. 1a]). Also, a small patch of SOLAS tape was adhered to conceal the uncovered portions of the top surface of the marker. A custom-made five marker template was made in a mirrored L-shape with four markers (M_r, M_1, M_2 and M_3) and was used for the evaluation of static distances (Fig. 1b). The static accuracy analysis was based on three static distances (d_1, d_2, and d_3) between the marker centers as perceived by the Vicon T40s cameras (Fig. 1b). The distances measured between these markers were measured with Vernier calipers to provide the reference values in the static accuracy analysis; $(d_1)_{ref}$ = 27.00 mm, $(d_2)_{ref}$ = 52.00 mm and $(d_3)_{ref}$ = 73.00 mm.

2.2. Calibration, Setup, and processing

The system calibration was performed using a Vicon wand with all five cameras arranged in a row (see Fig. 2a and c). The Vicon wand is a T-shaped tool with five precisely spaced retro-reflective markers provided for routine calibration. A routine calibration was performed by waving the wand in the field of view of the cameras. This was since the available capture volume for calibration is small, which restricts the movement of the calibration wand in the capture volume. However, investigations could be made to derive ways in which the systems are calibrated according to the medium the data is being recorded in. The calibration of cameras was performed in air medium, as it is conventionally established by the Vicon Company on its product guide for Vicon Nexus (Version 1.8.5). Vicon Nexus is a software commonly used as an interface for biomechanical, engineering and life sciences Mo-cap applications for preparation, acquisition and review of Mo-cap data.

Following calibration, an origin was set using the same wand on a table for further assessments. This origin acts as a reference frame for position data. Once calibrated, a glass tank ($610 \times 300 \times 410$ mm^3 and thickness of glass = 4.90 mm) was placed on a table facing the cameras. The static reference template was attached to metallic bars in the shape of a T (Fig. 2b). The process of calibration and recording of data was done using the Nexus 1.8.5 to yield marker-position data. Further analysis of position data was done using MATLAB (Version R2016b).

2.3. Procedure

The aim of this test was to evaluate the static distances between the marker centers on the template in three scenarios: in air, in the glass tank without water, and in the glass tank filled with water. Three stations S_1, S_2 and S_3 were marked at different locations across the glass tank (see Fig. 2d). The static reference template was then placed at these stations sequentially, and the data was recorded at a sampling rate of 200 Hz. The data was first recorded by placing the reference template in air (outside the glass tank) at all the stations. The template was next placed inside the tank without water at all stations. Finally, the tank was filled with water, and the template was again placed at all stations. At each station, the position data (x, y and z) was recorded as three trials lasting one second per trial. The recorded data was then processed using pipeline operations in Nexus 1.8.5 to yield the position data with respect to the set origin as a comma separated value (CSV) file.

2.4. Method of analysis

The CSV file containing the coordinates of the marker centers were processed using a MATLAB script to calculate the Euclidean distances. The Euclidean distances d_p in (1) were obtained between marker centers at each station S_q. Here, p and q represent the marker distance index and station index respectively. Also, i represents the marker index with i = 1, 2, and 3; $\bar{x}$, $\bar{y}$ and $\bar{z}$ represent the average value of coordinates of the marker centers obtained through Vicon in one second (200 frames).

Trueness T in (2) and Precision P in (3) and (4) for each is obtained on similar lines to Trueness and Precision in Eichelberger et al. (2016) respectively.

$$d_p = \sqrt{(\bar{x}_{M_r} - \bar{x}_{M_i})^2 + (\bar{y}_{M_r} - \bar{y}_{M_i})^2 + (\bar{z}_{M_r} - \bar{z}_{M_i})^2} \quad (1)$$

$$T = \frac{1}{m}\sum_{p=1}^{m}\left[\frac{1}{N}\sum_{q=1}^{N}\left|(\bar{d}_p)_{S_q} - (d_p)_{ref}\right|\right] \quad (2)$$

$$P = \left(\frac{1}{m}\right)\sum_{p=1}^{m}\left[\sqrt{\frac{1}{N-1}\sum_{q=1}^{N}\left(\mu_p - (\bar{d}_p)_{S_q}\right)^2}\right] \quad (3)$$

$$\mu_p = \frac{1}{N}\sum_{q=1}^{N}(\bar{d}_p)_{S_q} \quad (4)$$

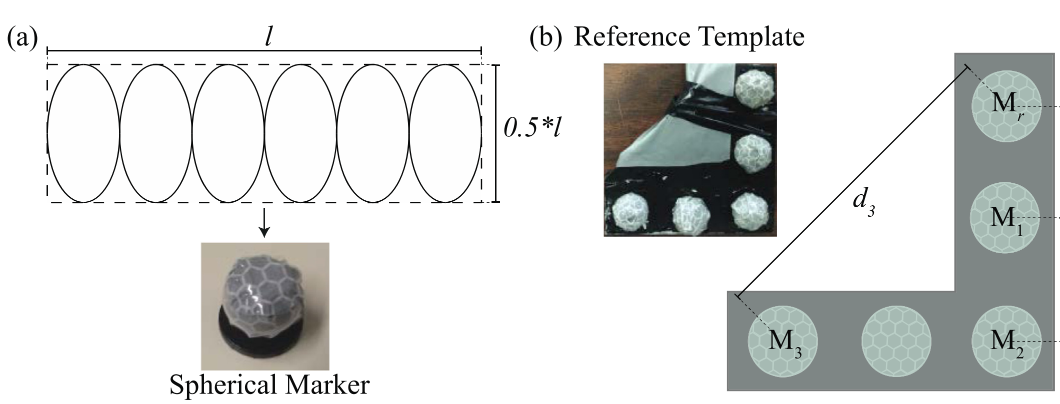

Fig. 1. Marker creation and reference template for static measurements. (a) SOLAS reflective tape cut into petals of equal sizes wound around a spherical marker (length, $l = \pi d_M$ = 43.98 mm). (b) Static reference template used for analysis with measured distances between marker centers; (d_1: Distance between markers M_r and M_1; d_2: Distance between markers M_r and M_2; d_3: Distance between markers M_r and M_3).

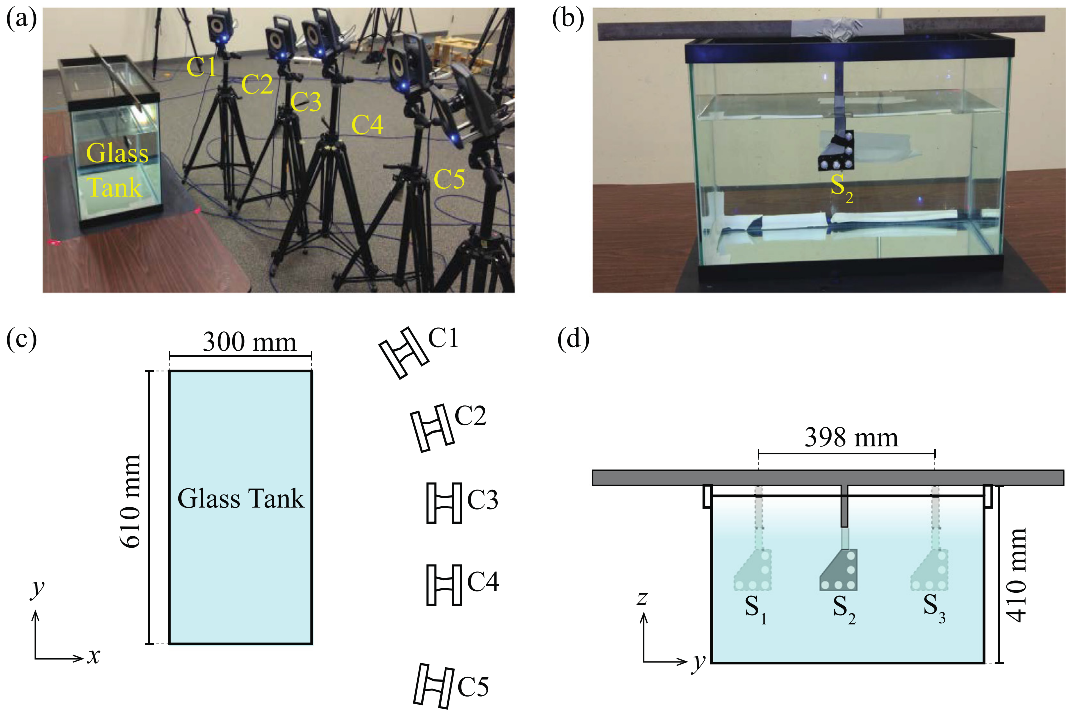

Fig. 2. Experimental setup and test schematic. (a) Cameras C1-C5 setup in front of the glass tank. (b) The template attached to the T shaped bar and placed in the glass tank with water as viewed by cameras. (c) Top-view schematic of the setup with cameras C1–C5 in front of the glass tank with water. (d) Front-view schematic of the glass tank setup with template attached to T-shaped bar moved at different stations S_1, S_2 and S_3 sequentially.

Furthermore, the Trueness T for each scenario is obtained as mean marker distance error of the three distances measured at all stations with respect to the reference values. Here, $m = 3$ and $N = 3$ represent the number of marker center distances and number of stations respectively and $\bar{d}_p$ represents the mean distance obtained between the appropriate marker centers in three trials. Finally, Precision P is obtained as mean standard deviation of mean marker distances measured by Vicon cameras in (3) and (4).

Due to the size of the sample, marker distance and accuracy outcomes across mediums were analyzed using Friedman analysis of variance (ANOVA), a non-parametric repeated measures testing procedure. This was done in order to assess the influence of mediums in measurement of distances and accuracy outcomes. The analyses were performed using the IBM Statistical Package for the Social Sciences (SPSS) Statistics, Version 25. Level of significance was set at $p < 0.05$.

3. Results

3.1. Marker distance outcomes

Friedman ANOVA revealed no significant difference in all three mediums: air, glass, and water (see Table 1) for marker distances d_1 ($p = 0.368$), d_2 ($p = 0.264$) and d_3 ($p = 0.264$).

3.2. Accuracy outcomes

The accuracy outcomes for the three marker distances in the different mediums are listed in Table 2. The overall trueness for air (mean = 0.270 ± 0.074 mm), glass (mean = 0.257 ± 0.087 mm), and water (mean = 0.290 ± 0.106 mm) are based upon equation (2). The overall precision for air (mean = 0.046 ± 0.036 mm), glass (mean = 0.068 ± 0.063 mm), and water (mean = 0.360 ± 0.081 mm) are based upon Eq. (3). Also, the Friedman ANOVA on trueness outcomes revealed no significant differences for d_1 ($p = 0.264$), for d_2 ($p = 0.717$), and for d_3 ($p = 0.264$) in all three mediums. Therefore, the resultant mean precision calculated as mean standard deviation of the mean marker distances at different locations varied between 0.046 mm and 0.360 mm in all three mediums (see Table 2).

4. Discussion

The results of this study revealed the highest magnitude of error for an underwater scenario, which is in line with previous findings

Table 1
Medians of each marker distance in different mediums.

Medium	Distance	Median	Interquartile range (IQR)	
			25th percentile	75th percentile
Air (mm)	d_1	26.790	26.783	26.836
	d_2	51.722	51.689	51.727
	d_3	72.645	72.608	72.775
Glass (mm)	d_1	26.751	26.745	26.752
	d_2	51.685	51.618	51.757
	d_3	72.778	72.670	72.930
Water (mm)	d_1	27.120	26.683	27.179
	d_2	51.758	51.678	52.460
	d_3	72.751	72.595	73.317

Note. Median marker distances and associated interquartile ranges perceived by Vicon T40s cameras in different mediums with respect to reference distances $(d_1)_{ref}$ = 27.00 mm, $(d_2)_{ref}$ = 52.00 mm and $(d_3)_{ref}$ = 73.00 mm (air [outside the glass tank], glass [glass tank without water] and water [glass tank with water]).

Table 2
Accuracy outcomes across different mediums.

Medium	Distance	Trueness outcomes (mm)				Precision (mm)
		Trueness	Median	Interquartile range (IQR)		
				25th percentile	75th percentile	
Air	d_1	0.197	0.210	0.164	0.218	0.029
	d_2	0.288	0.278	0.273	0.311	0.021
	d_3	0.324	0.355	0.225	0.392	0.088
Glass	d_1	0.251	0.249	0.248	0.255	0.004
	d_2	0.313	0.315	0.243	0.382	0.069
	d_3	0.208	0.223	0.070	0.330	0.131
Water	d_1	0.205	0.179	0.120	0.317	0.271
	d_2	0.341	0.322	0.242	0.460	0.430
	d_3	0.324	0.317	0.249	0.405	0.380

Note. Trueness and Precision outcomes in different mediums for individual marker distances (air [outside the glass tank], glass [glass tank without water] and water [glass tank with water]).

(Gourgoulis et al., 2008; Lauder et al., 1998). The cause for the increased errors in an underwater scenario, pointed out in these findings, could be due to light refraction. However, the overall results in the present study reveal that there is in fact no significant influences of medium. Also, in agreement with previous findings, such small instrumental errors (<1 mm) may not seem relevant for biomechanical assessments with large ranges of motion. Hence, there is indeed a strong potential for using a land-based Mo-cap system arranged externally to perform human locomotion analysis in constrained aquatic environments.

Previous findings based on accuracy analysis of land-based Mo-cap systems, however, indicate that the errors should be estimated in a laboratory or application specific manner in order to obtain high quality research data (Eichelberger et al., 2016; Windolf et al., 2008). In consensus with recommendations from these studies, both dynamic and static error assessments could be performed during an underwater treadmill exercise with SOLAS reflective markers placed on human subjects at anatomical regions of interest. There is the need to quantify the correlation between different parameters, such as the height of cameras, size of the capture volume, number of cameras, and depth of the water and the thickness of the glass interface.

The results in the present study offers maiden insights to outweigh the minimal threat of inaccuracy in Mo-cap for the aforementioned dynamic and static error assessments. Furthermore, this will help to quantify the ability and reliability of Mo-cap systems in real time biomechanical assessments of aquatic rehabilitation against conventional pre and post assessments (Denning et al., 2010). This study demonstrates the potential to advance abilities of land-based Mo-cap systems to capture human locomotion in constrained aquatic environments.

Conflict of interest

We do not have any proprietary, financial, professional, or other personal interest of any nature or kind in any product, service, and/or company that could be construed as influencing this manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.04.029.

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