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Kinematic Analysis of the Reconstruction Error of A Calibration Volume for 3d Analysis in Swimming

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Abstract: The purpose of this study was to assess the accuracy and reliability of the three-dimensional reconstruction - above and below water - of a calibration volume for three-dimensional analysis in swimming. The calibration volume (3x3x3m) was placed in a 25m x 12.5m x 2m swimming pool and was recorded simultaneously by 4 under and 2 above water synchronized cameras. To assess the number of control points required to maximise the accuracy of three-dimensional coordinate reconstruction, 12 markers in the calibrated space were digitised over 10 fields for each underwater and above water camera views. Seven series of 12 markers, using 8, 12, 16, 20, 24, 28 and 30 control points were digitised. Direct linear transformation methods were used to estimate the marker locations on the volume. Comparison among different numbers of control points showed that the set of 20 (underwater) and 16 (above water) points produced the most accurate results. The average root mean square errors were (x, y and z, respectively): (i) 4.85mm, 2.52mm and 7.43mm (set of 20 digitised underwater points) and (ii) 4.11mm, 5.69mm and 3.90mm (set of 16 digitised above water points). The standard deviation in underwater cameras was 1.22mm, 0.33mm and 3.47mm, and 1.57mm, 2.63mm and 2.35mm for above water cameras (for x, y and z, respectively). The calibration volume was found to have high accuracy and reliability.

Keywords: Above water, accuracy, biomechanics, reliability, three-dimensional, underwater.

INTRODUCTION

In multiplanar activities such as swimming, kinematical analysis should be three-dimensional (3D). However, most studies in swimming were limited to two-dimensional (2D) analysis techniques, which imply higher number of errors, once disregards especial characteristics of movements, particularly of the limbs. In 3D analysis the most popular technique used for the transformation of the 2D image coordinates into 3D space coordinates is the direct linear transformation procedure (DLT) [1]. With the DLT technique an appropriate number of points with known 3D coordinates (control points) on a calibration volume are used for the calibration of the recording space. In this procedure, the number and distribution [1] of the control points, as well as the size of calibration volume [2] affect reconstruction accuracy. Psycharakis *et al.* [3] showed improvement in the calibration accuracy when the number of control points were increased from 10 to 20, using a calibration volume of $6.75m^3$, while Gourgoulis *et al*. [4] using measurements carried out in two different recording conditions: (i) out of the water and (ii) in the water, found larger reconstruction errors in water compared to above water conditions, whatever the size of the calibration volume. Moreover, Chen *et al.* [1] and Kwon [5] pointed out that reconstruction accuracy should be assessed using a number of validation points that did not serve as control points since the DLT parameters are optimised for the reconstruction of the control points.

The purpose of this study was to assess the accuracy of the 3D reconstruction, above and below water of a calibration volume for 3D analysis in swimming.

METHODS

The calibration volume (3x3x3m) was placed into a 25m x 12.5m x 2m swimming pool and recorded simultaneously by 4 under and 2 above water cameras (Sony® DCR-HC42E). The cameras were at depths varying from 1.0 to 1.5m below the water surface to avoid errors due to the camera axes being in the same planes as the reference planes of the volume. The cameras above water were varying from 3.0 to 3.5m above water surface. The angle between the axes of the two above water camera axes was approximately 120°, while the angles between axes of adjacent below water camera axes varied from approximately 75° to 110° The following procedure was applied to assess the number of control points required to maximise the accuracy of 3D coordinate reconstruction for the below water calibration: 12 markers in the calibrated space were digitised over 10 fields for each underwater and above water camera viewers. Seven series of digitising were performed for this set of 12 markers, using 8, 12, 16, 20, 24, 28 and 30 control points respectively. To avoid overestimating accuracy the 12 markers selected for these comparisons were not included in any set of calibration points [6]. The 3D coordinates were obtained using the DLT procedure [7], and the associated error with RMS. The differences between the obtained and the known values were calculated for the x, y, and z coordinates of each point for each of the 10 video fields. To obtain an estimate of reliability, the same operator (in order to avoid any inter-operator

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errors) repeated the procedure 10 times. The reliability measure was considered to be the standard deviation across all digitisations of the marker.

RESULTS

In Table **1** it is presented the mean difference and the mean RMS errors for the x, y and z coordinates, for different numbers of control points for the underwater cameras. The accuracy increased as the number of control points increased from 8 to 16, and from 20 to 28. A further increase to 30 points did not improve the accuracy of the measurements.

In Table **2** it is possible to observe the mean difference and the mean RMS errors for the x, y and z coordinates, for different numbers of control points in above water cameras, where the accuracy increased as the number of control points increased from 24 to 30.

For the calculations performed following the selection of a set of 12 control points, the average RMS errors for the set of 20 digitised points underwater, was 4.85mm, 2.52mm and 7.43mm for the x, y and z directions, respectively, representing 0.16%, 0.08% and 0.25% of the calibrated space. For the set of 16 digitised points above water, the average RMS errors was 4.11mm, 5.69mm and 3.90mm for the x, y and z directions respectively, representing 0.14%, 0.19% and 0.13% of the calibrated space. These values were lower than the values found for all the sets of different numbers of control points described above, both under and above water. The standard deviation in underwater cameras was 1.22mm, 0.33mm and 3.47mm for the x, y and z directions respectively. In the above water cameras the values are 1.57mm, 2.63mm and 2.35mm.

DISCUSSION

Considering the calibration volume used, the errors were similar or even lower than those reported in other studies. Psycharakis *et al*. [3] reported the mean difference for the set of 30 digitised points was 3.3 mm, 2.6 mm and 4.0 mm, for the x, y and z axes respectively. The average RMS error for these points was 3.9 mm, 3.8 mm and 4.8 mm for the x, y and z directions respectively. Gourgoulis *et al.* [4] using two calibration volumes, one smaller and other larger, were the RMS values were respectively 1.61mm and 2.35mm in the transverse axis, 2.99mm and 4.64mm in the longitudinal axis and 2.83mm and 2.59mm in the vertical axis. Payton and Bartlett [8] reported corresponding values of 2.3mm, 3.3mm and 2.9mm while Payton *et al.* [9] reported mean errors of

Table 1. Mean Difference and Mean RMS Errors for Underwater Cameras in the x, y and z Axis

Underwater Cameras						
Number of Control Points	RMS (mm)			Mean Difference (mm)		
	x	y	z	x	y	z
8	6.38	2.93	3.52	0.09	0.41	0.12
12	5.93	3.31	4.43	0.35	0.11	0.19
16	4.88	2.93	8.09	0.24	0.09	0.65
20	4.85	2.52	7.43	0.24	0.06	0.55
24	4.35	2.38	9.71	0.19	0.06	0.94
28	3.39	2.52	13.9	0.11	0.06	1.93
30	3.05	2.52	9.13	0.09	0.06	0.83

Table 2. Mean Difference and Mean RMS Errors for the Above Water Cameras in the x, y and z Axis

Above Water Cameras						
Number of Control Points	RMS (mm)			Mean Difference (mm)		
	x	y	z	x	y	z
8	1.26	1.26	6.7	0.02	0.02	0.08
12	2.18	8.32	2.85	4.76	0.69	0.12
16	4.11	5.69	3.9	0.17	0.00	0.78
20	4.11	5.69	4.34	0.17	0.00	0.78
24	4.11	3.82	9.87	0.17	0.15	0.06
28	1.65	2.75	4.81	0.00	0.08	0.00
30	0.33	1.17	4.25	0.29	0.00	0.53

1.5 to 3.1 mm for a 1.1 m^3 volume (representing 0.2%, of the calibrated space for each direction). Using a similar volume in a study of the golf swing, Coleman and Rankin [10] reported RMS errors of 5.1 to 9.8 mm (representing 0.4%, 0.5% and 0.3% of the calibrated space, for the x, y and z directions respectively). The reliabilities were lower when compared with Psycharakis' study [3], where the reliabilities indicated by repeated digitisations of one marker were ±0.4 mm, ±0.5 mm and ±0.4 mm, for the X, Y and Z axes respectively.

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