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RECONSTRUCTION ERROR OF CALIBRATION VOLUME'S COORDINATES FOR 3D SWIMMING KINEMATICS

Pedro Figueiredo[1], João Paulo Vilas-Boas[1,2] and Ricardo J Fernandes[1,2]

CIFI^{2}D, Faculty of Sport, University of Porto, Porto, Portugal[1]
Porto Biomechanics Laboratory (LABIOMEP), University of Porto, Porto, Portugal[2]

The aim of this study was to investigate the accuracy and reliability of above and underwater 3D reconstruction of a calibration volume used for swimming analysis. The calibration volume (3x2x3m^3) was positioned half above and half below the water surface. Recordings with four underwater and two above water synchronised cameras were done and DLT algorithm used to estimate marker locations. Reconstruction accuracy was determined by the RMS error of 12 validation points and reliability by the standard deviation of all digitisations of the same marker. Comparison among different number of control points showed the set of 24 points to be the most accurate for both environments. Although, the RMS values above water were lower than the RMS values presented underwater. The calibration volume was found to have high accuracy and reliability.

KEY WORDS: kinematics, accuracy, reliability**,** digitisation, underwater, above water.

INTRODUCTION: The kinematic analysis of the human movement often requires the measurement of the position of significant body landmarks. Swimming is a complex and highly integrated form of movement developed in a multi-planar environment, where swimmers constantly interact with air and water. However, most studies in swimming were limited to two-dimensional analysis techniques, which imply a higher number of errors, once disregards the multi-planar characteristics, particularly in the upper limb analysis. Three-dimensional reconstruction often uses the DLT algorithm, where an appropriate number of points, with known 3D coordinates on a calibration volume, are used as control points for the calibration of the recording space. In this procedure, the number and distribution of the control points, as well as the size of the calibration volume, affect the reconstruction accuracy (Chen et al., 1994; Lam et al., 1992). Additionally, swimming kinematic analysis imposes obstacles to data acquisition, as the errors associated to image distortion, refraction, digitisation and 3D reconstruction (Kwon & Casebolt, 2006), may influence the final obtained results. Therefore, the purpose of this study was to assess the influence of the number of control points in the accuracy and reliability of the under and above water 3D reconstruction.

METHODS: The calibration volume was recorded simultaneously by four under and two above water stationary video cameras (Sony® DCR-HC42E) (Figure 1). The volume was positioned half above and half below water surface. Cameras' optical axes formed an angle of ~100° between the two above water cameras, varying the angle between underwater cameras between ~75° to 110°. A LED system visible in the field of view of each camera was used for its temporal synchronisation. Underwater cameras were placed at 1.0 to 1.5 m below the water surface and the above water cameras were placed at a 3.0 to 3.5 m high. The calibration volume was made from 1 cm diameter aluminium tubing (composing the rods), with 3 x 2 x 3 m^3 in the horizontal (x), vertical (y) and lateral (z) directions, respectively, and the aluminium tubes were linked through steel wires (Figure 2). Plus, the calibration volume had a total of 184 (92 above and 92 below water) spheres with 3 cm in diameter. The size of the calibration frame was established to allow a complete stroke cycle of front crawl swimming to be performed in it. To assess the number of control points required to maximise the accuracy of 3D coordinate reconstruction, 12 markers in the calibrated space were digitised over 50 frames for each underwater and above water camera views. Seven series of digitising were performed for this set of 12 markers, using 8, 12, 16, 20, 24, 28 and 30 control points, above and below water, respectively.

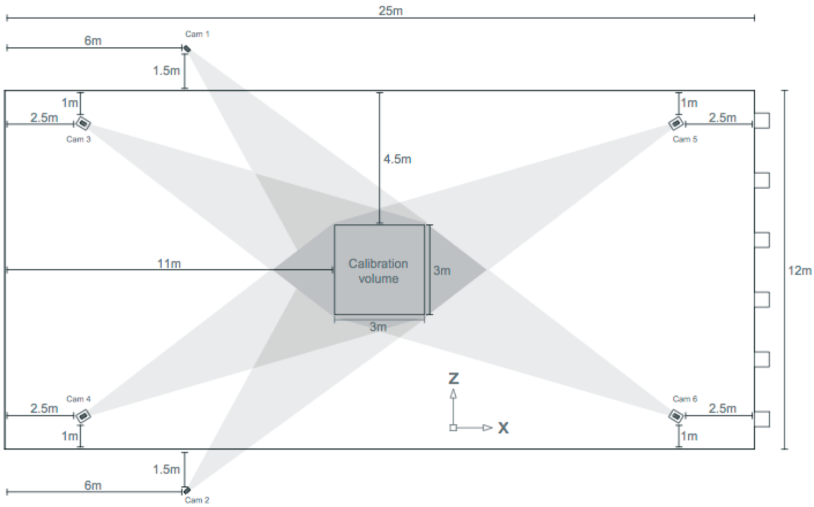

Figure 1: Upper image of the cameras' field of view in the set up.

To avoid overestimating accuracy, the 12 markers selected for these comparisons were not included in any set of calibration points since the DLT algorithm is optimised for its reconstruction (Challis & Kerwin, 1992; Chen et al., 1994).

Figure 2: Calibration volume, with aluminum tubes (black) and steel wires (grey).

All reconstruction errors were calculated from the raw coordinate data without any smoothing procedure (Scheirman et al., 1998), and determined by the Root Mean Square (RMS) error of the 12 validation points for the three axes and for the resultant, using the following equation:

$$E_r = \sqrt{\frac{\sum_{i=1}^{N}(X_{iR} - X_{ir})^2}{N}} \quad (1)$$

where E_r was the reconstruction error, x_{iR} was the reference value, x_{ir} was the reconstructed and N was the number of points used. To obtain reliability estimation, one operator repeated the procedure 10 times, and reliability was considered as the standard deviation value across all digitisation of the same marker.

RESULTS: RMS errors for the x, y, z axes and resultant showed to be lower above the water comparing to the underwater reconstruction values. The sets with lower values for both conditions and axes were 20 and 24 control points (Table 1). Resultant RMS error for under and above water environment, represents 0.2% of the calibrated space, for each underwater axes, and 0.1%, 0.2% and 0.1% of the calibrated space, for the x, y and z above water axes.

Table 1
Underwater and above water RMS errors (mm) for the horizontal (x), vertical (y), lateral (z) axes, and resultant, for the different sets of control points

Number of control points	Underwater				Above water			
	x	y	z	Resultant	x	y	z	Resultant
8	6.67	4.70	7.19	6.19	4.46	4.90	6.61	5.32
12	5.70	4.48	7.21	5.80	4.60	5.20	6.93	5.60
16	5.42	5.42	7.07	5.97	4.56	5.65	6.12	5.44
20	3.46	5.35	7.17	5.33	3.68	5.27	3.50	4.16
24	5.86	3.45	4.38	4.56	3.59	3.11	4.00	3.57
28	5.63	5.80	8.10	6.51	3.80	3.30	3.83	3.64
30	5.37	6.51	7.03	6.30	3.90	3.33	3.68	3.64

Standard deviation in underwater cameras were ± 0.28 mm, ± 0.27 mm and ± 0.29 mm for the x, y and z directions, respectively and for the above water cameras the values were ± 0.30 mm, ± 0.19 mm and ± 0.29 mm for the x, y and z directions, respectively.

DISCUSSION: The obtained results revealed for the underwater recordings an increasing accuracy as the number of control points augmented (until 20-24), as reported previously (Lauder et al., 1998; Psycharakis et al., 2005). Regarding the above water recordings, accuracy also increased with the number of the control points (8 to 20-24) as reported by Shapiro (1978) and Chen et al. (1994). In both environments, a further increase until 30 points did not improve the accuracy of both measurements. Considering the volume of the calibrated space, the errors were similar or lower than those reported previously. For underwater environment Payton & Bartlett (1995) reported values of 2.3 mm, 3.3 mm and 2.9 mm, while Lauder et al. (1996) observed RMS values ranging from 1.86 to 2.82 mm (lateral axis), from 4.53 to 7.32 mm (horizontal axis) and from 3.51 to 7.76 mm (vertical axis). Psycharakis et al. (2005) presented RMS error values of 3.9 mm, 3.8 mm and 4.8 mm for the x, y and z axes respectively, representing 0.1%, 0.2% and 0.5% of the calibrated space. Kwon et al. (1995), for a calibration volume of 3 x 1 x 1 m, referred RMS values of 6.4, 6.6, 4.2 mm for x, y and z axes, respectively. Gourgoulis et al. (2008) presented, for a small (1 x 1x 1 m) and for a large (1 x 3 x 1 m) calibration volumes, RMS values of 1.61 and 2.35 mm (lateral axis), 2.99 and 4.64 mm (horizontal axis) and 2.83 and 2.59 mm (vertical axis). For above water reconstruction, Coleman & Rankin (2005) studied the golf swing and 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 axes, respectively). Challis (1995) presented values ranging from 6.1 to 23.0 mm depending of the position of the calibration volume (1 x 1 x 0.6 m). While Chen et al. (1994), for a calibration volume of 2.10 x 1.35 x 1.00 m found, depending of the number of control points, a mean error ranging from 1.8 to 3.6 mm for x, 1.9 to 2.7 mm for y, 5.4 to 12.8 mm for z, and a resultant from 6.6 to 1.6 mm. In addition, Yanai et al. (1996) reported mean resultant errors ranging from 8.34 to 16.44 mm for the above and from 9.93 to 16.22 mm for the below water control volumes (1.5 x 8.4 x 2 m). The present results revealed that during underwater recordings the RMS reconstruction errors were greater comparing to those obtained above the water, which is in accordance with the literature (Yanai et al., 1996; Lauder et al., 1998). These increased reconstruction errors, when underwater recordings were analysed, were probably due to light refraction (Lauder et al., 1998; Kwon & Casebolt, 2006). In addition, the observed results seem to be reliable sense its study reveal small errors. In fact, the reliability of coordinate reconstruction was similar than the values reported by Psycharakis et al. (2005; ± 0.4mm, ± 0.5mm and ± 0.4 mm, for the x, y and z axes, respectively).

CONCLUSION: The use of 20-24 control points was shown to provide the most accurate results among sets of various numbers of control points. Although, the RMS values above water were lower than the RMS values presented in the underwater reconstruction. In general, the calibration volume analyzed showed to have good accuracy and reliability for 3D swimming analysis.

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