A CALIBRATION FRAME FOR 3D SWIMMING ANALYSIS

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The purpose of this study was to construct a calibration frame for accurate three-dimensional analysis of swimming and to assess its accuracy and reliability. A 6.75 m^3 frame was constructed. The frame was positioned in a 25 m pool so that half was above and half below the water surface and recorded with four underwater and two above water synchronised cameras. Direct linear transformation methods were used to estimate marker locations on the frame. Comparison among different numbers of control points showed the set of 20 points to produce the most accurate results. Selection of the most accurate control points improved the accuracy of the measurements even when only 10 control points were used. The frame was found to have high accuracy (mean errors: 3.3 mm, 2.6 mm and 4.0 mm; root mean square errors: 3.9 mm, 3.8 mm and 4.8 mm) and reliability (standard deviation: 0.4 mm, 0.5 mm and 0.4 mm).

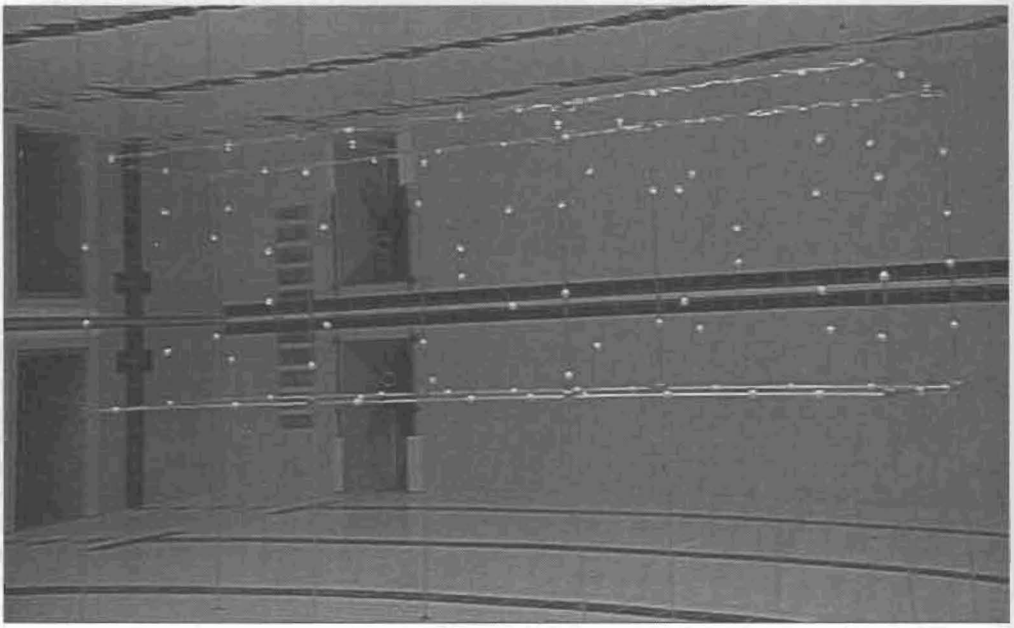
KEY WORDS: Biomechanics, underwater, three-dimensional, accuracy, reliability

INTRODUCTION: Most studies of swimming have been limited to two-dimensional (2D) analysis techniques. Errors associated with 2D analysis can be great because swimming is not a planar activity for any of the major strokes. Therefore, a single-camera 2D analysis does not enable accurate quantification of the motion of the whole body. The assumption of bilateral symmetry is also untenable due to asymmetric patterns in the technique (Arellano et al., 2003) and asymmetries in the anthropometric characteristics (Tomkinson et al., 2003).
Therefore, accurate analysis of swimming technique requires three-dimensional (3D) analysis methods. The application of such methods in swimming is complicated due to several factors including the need to digitise body landmarks that move across two media. In addition, filming underwater is problematic and introduces errors additional to those associated with analyses of motion in air (Kwon, 1999).
One of the pre-requisites for accurate quantification of the variables of interest is accurate calibration of the 3D space as part of the process of 3D coordinate reconstruction by the direct linear transformation (DLT) method. Therefore, the purpose of this study was to construct a calibration frame for 3D swimming analysis and to assess the accuracy and reliability of this frame for calculation of points in the space below water.

METHODS: A 3D calibration frame was constructed comprising three parts with the following dimensions: 1.5 m (length) x 1.5 m (height) x 1 m (width). The parts were designed to join to form a rectangular prism of 4.5 m length, 1.5 m height and 1 m width, enabling the calibration of a space of 6.75 m^3 in total. Each side of each part was a 12 mm diameter aluminium tube. This material was selected on the basis of its high flexural stiffness relative to its weight to minimise distortion of the frame during research or storage in a pool environment. Joints were formed by inserting tubes into holes that had been drilled with fine tolerances into solid cubes of aluminium (sides of 51 mm length). Lengths of 2 mm wire were used to triangulate each part of the frame to minimise distortion and adjusted according to the readings of the surveying tools to ensure that the adjoining sides of the frame were orthogonal. The frame was supported on 8 aluminium tubes with circular bases of 64 mm diameter attached to the bottom eight joints of the frame. The supporting tubes were adjustable to enable the frame to be positioned with half above and half below the surface of the water. Figure 1 shows an underwater view of the frame.
A total of 92 (46 above and 46 below water) polystyrene spheres, 3 cm in diameter, were drilled through the centre and arbitrary placed on the tubes and wires as control points. The spherical shape ensured that their centres were easily identified from any viewing perspective. The exact co-ordinates of each marker (using a fixed point in the frame as a reference) were measured with the use of surveying techniques and specialist equipment

such as square edges, centre finders, spirit levels, and steel rulers. Additional calculations took into account minor alterations in marker locations due to slight bowing of the tubes due to tension. These methods enabled the calculation of the actual values of the coordinates for each marker to an accuracy of ±1 mm.

Figure 1 Underwater view of the calibration frame.



The calibration frame was placed into a 25 m swimming pool and videoed simultaneously by 4 under and 2 above water synchronised JVC KY32 CCD video cameras. The underwater cameras were approximately 8 m and the above water 12 m away from the centre of the frame. The cameras were at depths varying from 0.5 to 1.5 m below the water surface to avoid errors due to the camera axes being in the same planes as the reference planes of the frame. The angle between the axes of the two above water camera axes was approximately 100°, while the angles between axes of adjacent below water camera axes varied from approximately 75° to 110°. The camera settings were adjusted so that each camera was recording a space 6.5 m long, that is, 1 m each side beyond the frame.

The following procedure was applied to assess the number of control points required to maximise the accuracy of 3D co-ordinate reconstruction for the below water calibration: 10 markers in the calibrated space were digitised over 10 fields for each underwater camera view. Five series of digitising were performed for this set of 10 markers, using 10, 15, 20, 25 and 30 control points respectively. To avoid overestimating accuracy the 10 markers selected for these comparisons were not included in any set of calibration points (Challis and Kerwin, 1992). The 3D coordinates were obtained using the DLT equations based on the data of all four underwater cameras. 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. The absolute values of the average differences for each marker were then summed across the 10 markers and divided by 10 to obtain a mean measure of accuracy for each reference axis. In addition, root mean square (RMS) errors were calculated (Bartlett, 1997). This measure represents the error bounds within which 68% of measures would fall and is the combined effect of accuracy and reliability.

To improve accuracy and reduce digitising time for future research, control points that reduced overall accuracy were eliminated. A set of 10 markers was selected and accuracy estimated for 30 markers (independent of the control markers). Mean differences and RMS errors were calculated for the set of 30 markers using the procedures described above.

To obtain an estimate of reliability, one marker (as well as a set of 10 control points) was digitised over 10 fields. The same operator (in order to avoid any inter-operator errors) repeated the procedure 10 times. The reliability measure was the standard deviation across all digitisations of the marker.

Finally, the underwater cameras at the Centre for Aquatics Research and Education are in the water, rather than viewing through external windows. This may reduce errors due to distortion and refraction (Kwon, 1999). However, the cameras are shielded from the swimming public by removable perspex transparent screens. It was of interest to assess whether recording through the perspex screens would increase errors. Therefore, 10 markers in the calibrated space recorded with and without the screens were digitised over 10 fields (with the use of an independent set of 10 control points) and accuracy and reliability assessed in the same manner as described above.

RESULTS AND DISCUSSION: Table 1 shows the mean difference and the mean RMS errors for the X, Y and Z coordinates of the set of 10 markers, for different numbers of control points. Generally, accuracy increased as the number of control points increased from 10 to 20. A further increase to 25 and 30 points did not improve the accuracy of the measurements. For the calculations performed following the selection of a set of 10 control points, 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, representing 0.1%, 0.2% and 0.5% of the calibrated space. These values were lower than the values found for all the sets of different numbers of control points described above. Thus, by careful selection of control points the accuracy of the measurements can be improved even when only 10 control points are used. Considering the volume of the calibrated space (6.75 m^3), the errors in this study were similar or lower than those reported in other studies. Payton et al. (2002) reported mean errors of 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 to this study for a study of the golf swing, Coleman and Rankin (2005) 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 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. No reference has been made to the reliability of calibration frames used in other swimming studies.

The mean differences and the RMS errors with and without screens are shown in Table 2. These calculations revealed that the screens had only a small effect on the accuracy of the measurements.

Table 1 Mean difference and mean RMS errors for the X, Y and Z co-ordinates of a set of 10 markers, for sets of 10, 15, 20, 25 and 30 control points.

Number of control points	Mean difference (mm)			Mean RMS errors (mm)		
	X	Y	Z	X	Y	Z
10	7.3	4.8	5.9	7.8	6.2	6.7
15	5.9	5.8	4.4	6.3	6.9	5.4
20	4.1	4.9	4.2	4.8	6.5	5.2
25	4.0	6.3	5.5	4.7	7.3	6.4
30	5.0	6.1	5.2	5.7	6.9	6.1

Table 2 The mean differences and RMS errors are shown without screens and with screens.

Without Screens						With Screens					
Differences (mm)			RMS errors (mm)			Differences (mm)			RMS errors (mm)		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
3.6	2.9	5.3	4.1	3.8	6.1	4.2	3.3	5.1	4.6	3.7	6.0

CONCLUSION: The use of 20 control points was shown to provide the most accurate results among sets of various numbers of control points. Nevertheless, a selection of the most accurate markers to serve as control points improved the accuracy of the measurements even with the use of 10 control points. In general, the calibration frame constructed in this study appeared to have good accuracy and reliability relative to others reported in the literature. There was no obvious increase in errors caused by light refraction due to the presence of transparent screens in front of the camera lenses. Based on these results it was concluded that the constructed frame could be used for 3D swimming analysis.

REFERENCES:

Arellano R., Lopez-Contreras G. & Sanchez-Molina J. A. (2003). Qualitative evaluation of technique in international Spanish junior and pre-junior swimmers: An analysis of error frequencies. In J. C. Chatard (Ed.), *Biomechanics and Medicine in Swimming IX* (pp. 87-92). St Etienne: University of St Etienne Publications.

Bartlett R. (1997). *British Association of Sport and Exercise Sciences: Biomechanical Analysis of Movement in Sport and Exercise.* Leeds: The British Association of Sport and Exercise Sciences.

Challis J. H. & Kerwin D. G. (1992). Accuracy assessment and control point configuration when using the DLT for photogrammetry. *Journal of Biomechanics*. 25, 1053-1058.

Coleman S. & Rankin A. (2005). A three-dimensional examination of the planar nature of the golf swing. *Journal of Sports Sciences*. 23, 227-234.

Kwon Y H. (1999). Object plane deformation due to refraction in two-dimensional underwater motion analysis. *Journal of Applied Biomechanics*. 15, 396-403.

Payton C., Baltzopoulos V. & Bartlett R. (2002). Contributions of rotations of the trunk and upper extremity to hand velocity during front crawl swimming. *Journal of Applied Biomechanics*. 18, 243-256.

Tomkinson G., Popovic N. & Martin M. (2003). Bilateral symmetry and the competitive standard attained in elite and sub-elite sport. *Journal of Sports Sciences*. 21, 201-211.

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