ASSESSMENT OF ERROR LEVELS ACROSS THE DOMAIN OF A THREE DIMENSIONAL UNDERWATER MOTION CAPTURE METHODOLOGY

Isobel M Thompson[1], Joseph Banks[1], Dominic Hudson[1] and Martin Warner[2]

[1] Performance Sports Engineering Laboratory, Faculty of Engineering and Physical Sciences, University of Southampton, Southampton, United Kingdom
[2] Performance Sports Engineering Laboratory, Faculty of Environmental and Life Sciences, University of Southampton, Southampton, United Kingdom

Assessing human movement underwater presents many challenges, and it is therefore important to understand error across the whole capture domain to ensure accuracy in resulting kinematics. This study assessed the accuracy across the capture domain of a submerged motion capture methodology. Six Qualisys cameras created an underwater capture volume of 8x2x2m. Average error levels across the domain were acceptable in two uncertainty trials (1.23mm ± 8.23mm and 1.34mm ± 9.65mm), but error increased at the ends and top of the domain. By selecting an area of interest for assessment that excluded areas with lower accuracy, error was reduced to 0.53mm (± 1.45mm). This study highlights the need to investigate error levels across a motion capture domain, particularly when this is a large volume, to ensure results obtained from investigations are reliable.

KEYWORDS: data acquisition, accuracy, domain error, submerged

INTRODUCTION: When assessing human movement, it is essential that error levels of motion capture systems are low in order to accurately reconstruct movement and assess resulting kinematics, which may inform future practices in sport. Error levels of motion capture methodologies are not always reported in the scientific literature, possibly due to time constraints placed upon researchers. Where they are reported, this is usually an average error rather than assessment of error throughout the entire capture domain.
When assessing human movement in aquatic sports such as swimming, motion capture systems are often fully submerged or placed behind windows. Capturing motion underwater creates potential for increased error due to issues such as light refraction and visibility of markers due to variations in pixel contrast and the presence of bubbles underwater (Mooney et al., 2015). Where error levels have been investigated previously in underwater motion capture methodologies, often only an average error with maximum and minimum error levels encountered is reported (Bernardina et al., 2016; Monnet et al., 2014). This may be due to time constraints on researchers in both data collection and data processing.
Previous assessments of accuracy in submerged motion capture domains have not discussed error changes in detail. Silvatti et al (2012) presented the error levels observed across the capture volume from three calibration methodologies, but a thorough investigation of the changes in error observed was not provided. Accuracy assessment studies in underwater motion capture often cover a relatively small calibrated volume of 4-4.5m in length (Bernardina et al., 2016; Silvatti et al., 2012), however when assessing human motion underwater it is useful to capture multiple movement cycles for analysis, which may require a much larger calibrated volume. Typically, the accuracy of a measurement system is inversely proportional to the size of the measurement volume (Kruk & Reijne, 2018), and so it could become pertinent to consider how the levels of error change within a capture volume, and how this may affect the resulting kinematics.
The present study assesses the error levels across the domain of a fully underwater three-dimensional motion capture methodology previously developed to assess underwater fly kick kinematics. The purpose of this study is to understand how the error levels change throughout an underwater capture domain, and how this can be improved by selecting an area of interest within the capture volume.

METHODS: An optoelectronic Qualisys system was used for this methodology. Six wide angle cameras (Qualisys 7+ Underwater) were spaced along one side of the pool edge between 5-

20m, submerged beneath the free surface (Figure 1) . Cameras were adjusted individually to ensure the Qualisys calibration L frame, located on the floor of the pool in the centre of the working volume, was in view whilst maintaining maximum measurement volume length. All cameras were synchronised, recording marker locations at 100Hz. The calibration method consisted of a 120s acquisition of a static (L frame with 4 markers), and a moving rigid wand (Qualisys calibration wand with 2 markers). This created an 8x2x2m calibrated volume underwater. Calibration error, provided by Qualisys QTM software, was -1.82mm.

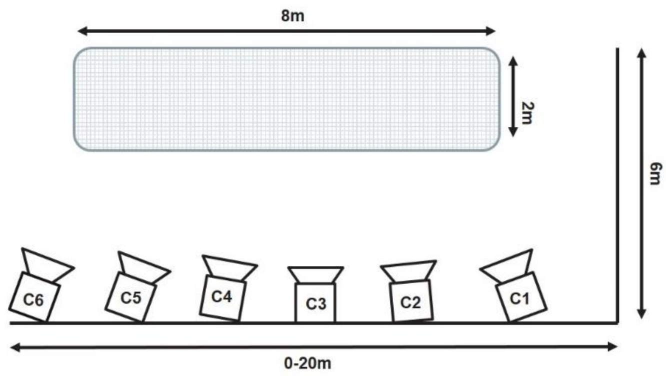

Figure 1. Camera location for three-dimensional underwater motion capture. Grey area represents the calibrated volume underwater.

To assess error levels across the capture volume, two uncertainty trials were completed. For uncertainty trial one, the calibration wand (601.7mm in length) was moved in all directions throughout the capture volume. The operator was instructed to use sweeping motions with the wand throughout the domain, and was informed when to turn around once the wand markers had left the view of the cameras. After the completion of a kinematic data collection session a second calibration was carried out (QTM software error -1.2mm), followed by uncertainty trial two following the wand waving method completed for uncertainty trial one.

Both uncertainty trials were reconstructed in Qualisys QTM software and exported into Vicon Nexus for processing, where wand markers were labelled. Any gaps where either marker dropped out of view were not labelled or gap filled to ensure measurement error was only calculated on tracked marker trajectories. Trajectories were filtered using a low pass 2^{nd} order Butterworth filter with a cut-off frequency of 39.2Hz, calculated using residual analysis. The distance between reconstructed markers was obtained as a function of time. Mean absolute error, standard deviation (SD), minimum and maximum errors were calculated and expressed as measurement difference to the real length of the calibration wand. No statistical analyses were run on the data.

RESULTS: Average absolute error for the initial uncertainty trial was 1.23mm (SD $\pm$ 8.23mm). Maximum error was 40.69mm and minimum error was -450.57mm. Measurement errors indicate that the wand length was, on average, underestimated. Examination of error across the calibration domain (Figure 2A) revealed an increased measurement error at the right-hand side, left hand side, and top of the domain.

The secondary uncertainty trial presented an average absolute error of 1.34mm (SD $\pm$ 9.65mm), with a maximum measurement error of 41.33mm and a minimum of -390.38mm. Again, error levels were observed to be higher at both ends of the domain (Figure 2B). As the secondary uncertainty trial produced higher error levels, the original trials was selected for further analysis.

Selecting an area of interest zone from the initial uncertainty trial (Figure 3, A and B) which excluded the areas identified to have high levels of error resulted in a new 5x1x1m (approx.) volume of interest. Calculating the average error levels within this revealed a reduced absolute measurement error of 0.53mm (SD $\pm$ 1.45mm), with a maximum error of 36.60mm and minimum of -20.64mm.

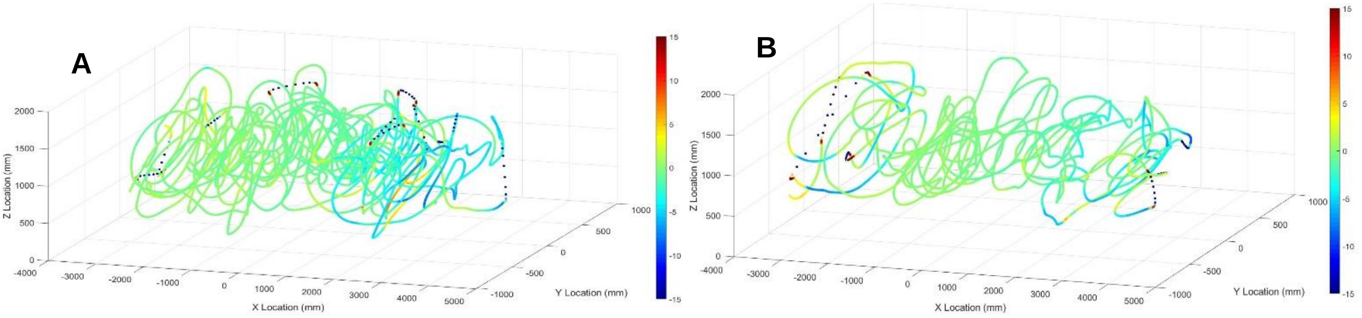

Figure 2. Measurement error levels recorded across the three dimensional domain in uncertainty trial one (A) and uncertainty trial two (B).

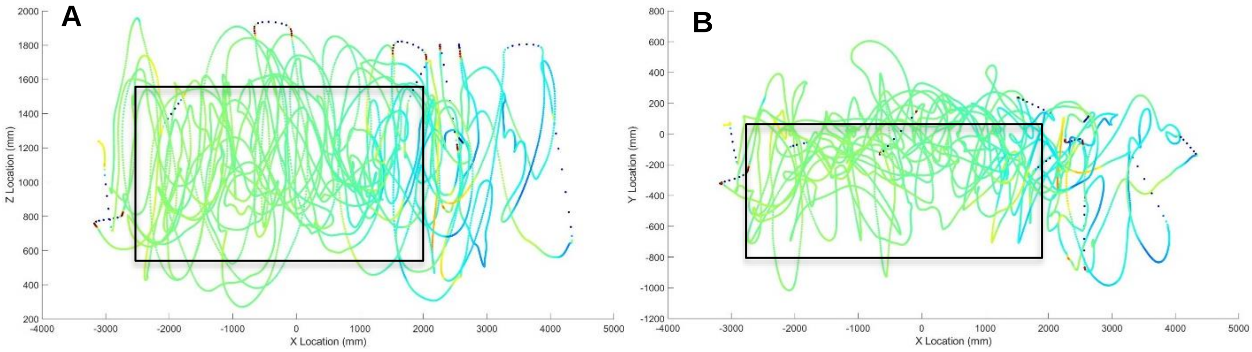

Figure 3. Measurement error levels in uncertainty trial one with selected area of interest in the X and Z (A) and X and Y (B) domains. The area of interest after analysis of error levels is contained within the black box.

DISCUSSION: Average levels of measurement error indicated that the accuracy of the methodology was appropriate (Mooney et al., 2015), and was consistent with previously reported error for underwater motion capture systems (Bernardina et al., 2016; Monnet et al., 2014; Silvatti et al., 2013; Silvatti et al., 2012). Most calculated errors across the domain fell well within the range of ±5mm, however there were some notably higher errors observed. High error levels were observed in the large minimum errors of -450.57mm and -390.38mm, larger than any maximum or minimum error level previously reported. A region identified at the right-hand end of the domain presented increased error. As this was observed in both uncertainty trials one and two under separate calibrations, it is unlikely that this was due to errors in calibration or camera movement. Only two cameras covered each of the two end of the domain (Figure 1, C1 and C2 covered the right-hand side, and C5 and C6 covered the left-hand side). This could have caused increased error in these areas, since all six cameras covered the centre of the domain where accuracy was highest.

Further, regions of high error level observed at the top of the domain were directly associated with markers dropping out of view. This, to the author's knowledge, has not been reported previously. However, the capture duration of the present trials (120s) are much longer than in previous underwater error assessments of Monnet et al (2014) and Silvatti et al (2013), where error was calculated over 20s and 10s trials respectively. It is likely that error assessment over a longer duration will introduce increased marker dropout. This duration however enables a more thorough assessment of error levels in a larger capture volume.

These findings indicate that data analysed within areas of high error, at the two ends and top of the domain, may not produce accurate and reliable results. By cropping the analysis domain to exclude regions of high error, the accuracy of measurement was improved by over 50%, a lower level than in previous studies (Bernardina et al., 2016; Monnet et al., 2014; A. Silvatti et al., 2013; A. P. Silvatti et al., 2012).

Silvatti et al (2012) compared the error levels of different calibration methods across the domain. Plate calibration produced the lowest levels of error (0.73mm), but areas near the

surface and end of the domain produced higher levels of error. Conversely, non-linear DLT calibration produced high levels of error (6.19mm) across the whole volume, particularly near the bottom and end of the domain. These changes in error across the domain were not discussed in depth.
Researchers often use calibration wands with more than two points of known length. Using four points for calibration produced lower error levels than observed using a two marker technique (Silvatti et al., 2013). Furthermore, Monnet et al (2014) used a five marker wand for calibration, but this produced a large level of measurement error underwater (5.75mm) possibly due to the cameras being placed behind windows. These findings highlight the need to consider appropriate calibration methods and their impact upon error levels. However, when using optoelectronic systems, manufacturers often specify a calibration method to be followed. Bernardina et al (2016) compared three wand-waving techniques to assess the impact on error levels. An up-down motion produced significantly higher error (2.63mm) compared to zig-zag (1.17mm) and circular (1.28mm) motions. A combination of these movements were included within the uncertainty trials of the present study, likely influencing the error observed. Moving the wand systematically through the capture volume will lead to the best accuracy results (Bernardina et al., 2016). This would be useful when calibrating over a large volume underwater to increase measurement accuracy and maintain confidence in results observed.
Adding to the recommendation of Kruk and Reijne (2018), the presented study suggests that alongside reporting average accuracy measurements, researchers should investigate accuracy across the entire capture domain to ensure adequate levels are maintained. If there are areas where higher error levels are observed, data collected within this area should be excluded from analysis. This will ensure any resulting reconstructed kinematics are as accurate and representative of the true movement as possible.

CONCLUSION: This study assessed the error across the entire capture domain of an underwater three dimensional motion capture methodology. Although average errors for both uncertainty trials were low and comparable with previous findings, higher error levels occurred at the two ends of the domain, and where the markers dropped in and out of view. If data is being analysed from an area where marker dropout is occurring, or where error levels are unexpectedly high, it is inaccurate to rely solely upon an average error measurement. This highlights the need to assess the error over the whole domain, and exclude areas from analysis where measurement error is high.

REFERENCES

Bernardina, G. R. D., Cerveri, P., Barros, R. M. L., Marins, J. C. B., & Silvatti, A. P. (2016). Action sport cameras as an instrument to perform a 3D underwater motion analysis. *PLoS ONE*, *11*(8), 1–14. https://doi.org/10.1371/journal.pone.0160490

Kruk, E. Van Der, & Reijne, M. M. (2018). Accuracy of human motion capture systems for sport applications; state-of-the-art review. *European Journal of Sport Science*, *18*(6), 806–819. https://doi.org/10.1080/17461391.2018.1463397

Monnet, T., Samson, M., Bernard, A., David, L., & Lacouture, P. (2014). Measurement of three-dimensional hand kinematics during swimming with a motion capture system: a feasibility study. *Sports Engineering*, *17*, 171–181. https://doi.org/10.1007/s12283-014-0152-4

Mooney, R., Corley, G., Godfrey, A., Osborough, C., Quinlan, L., & OLaighin, G. (2015). Application of video-based methods for competitive swimming analysis: A systematic review. *Sports and Exercise Medicine*, *1*(5), 133–150.

Silvatti, A., Cerveri, P., Telles, T., Dias, F. A. S., Baroni, G., & Barros, R. M. L. (2013). Quantitative underwater 3D motion analysis using submerged video cameras: Accuracy analysis and trajectory reconstruction. *Computer Methods in Biomechanics and Biomedical Engineering*, *16*(11), 1240–1248. https://doi.org/10.1080/10255842.2012.664637

Silvatti, A. P., Salve Dias, F. A., Cerveri, P., & Barros, R. M. L. (2012). Comparison of different camera calibration approaches for underwater applications. *Journal of Biomechanics*, *45*(6), 1112–1116. https://doi.org/10.1016/j.jbiomech.2012.01.004