TWO AND THREE-DIMENSIONAL ASSESSMENTS OF LOWER-LIMB KINEMATICS IN UNDERWATER FLY KICK

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The purpose of this study was to compare sagittal plane lower limb kinematics of underwater fly kick measured using two and three-dimensional methods. Eight male participants (average FINA points score 801±138) completed underwater fly kick trials, recorded using a six camera Qualisys underwater system. Each trial was analysed using both two and three-dimensional methods. Lower-limb angles were significantly underestimated using two-dimensional methods, particularly at the hip where flexion and range of motion reduced by 13.73 degrees and 15.91 degrees respectively. The ankle and hip produce a large amount motion in the transverse and frontal planes. The results of two-dimensional analyses of underwater fly kick should be interpreted with caution due reductions in measured angles, and exclusion of out-of-plane kinematic information.

KEYWORDS: motion analysis, biomechanics, angular kinematics, measurement error

INTRODUCTION: Continuous underwater fly kick is a key skill in swimming, performed after the start and turns in butterfly, freestyle and backstroke races. Due to reduced wave drag when fully submerged (Fischer & Kibele, 2015), this is an area where competitive advantage can be gained. The lower limbs produce propulsion during underwater fly kick, with vortex generation and release from the feet at the end of the down-beat (Shimojo et al., 2019). Much focus within the preceding literature is placed upon metrics relating to lower limb motion, producing contradictory findings due to differences in experimental protocols (Veiga et al., 2022).

Most investigations into underwater fly kick kinematics have been completed using two-dimensional methodologies (Veiga et al., 2022). Two-dimensional methods are a cost-effective option, but can introduce inaccuracies due to perspective and digitisation errors, and do not consider motions in the frontal or transverse planes. With these out-of-plane motions identified as important within underwater fly kick performance (Shimojo et al., 2019), three-dimensional analysis may be necessary in order to fully understand the kinematics.

There is currently no quantification of differences observed in underwater fly kick kinematics measured in two and three-dimensional methods. The purpose of this study was to compare the sagittal plane lower limb kinematics of underwater fly kick measured using two and three-dimensional methods.

METHODS: Eight male participants were recruited to participate in this study and provided informed consent. Thirty-six reflective markers were attached to the body at key landmarks (Figure 1). A landside calibration trial consisting of the Star Arc movement task (Camomilla et al., 2006), and knee and ankle flexion/extension allowed for the identification of joint centre locations for three-dimensional analysis using a functional approach (Taylor et al., 2010). Following this, markers were removed from the medial epicondyle of the knee, medial malleolus and the 1st metatarsal of the foot. After a self-directed warm up, participants completed four maximum paced trials with at least three minutes rest between each. Each trial was recorded at 100 Hz using a six camera Qualisys system with the cameras spaced underwater along one side of the pool between 5 m - 20 m.

Joint centre locations for the ankle, knee and hip were determined and local coordinate systems for each segment were created with X, Y and Z axes defining the frontal, sagittal and transverse planes respectively. Euler angles were then calculated in an X, Y', Z" order. For two-dimensional angular assessment, segments were defined using horizontal and vertical coordinates of proximal and distal segment defining markers. The four quadrant inverse tangent was then calculated between each segment pair. Two-dimensional angles were adjusted to ensure definitions in the sagittal plane were directly comparable between methods. All angles were calculated as an average over a kick cycle, beginning at peak toe location and ending at the next peak toe location (beginning of down-beat to end of up-beat). Results presented are an average across all trials (± SD). Range of motion was defined as the average peak angle minus the minimum angle observed across the kick cycle. Wilcoxon signed rank tests identified significant differences between sagittal plane angles measured using two and three-dimensional methodologies, with the alpha level set at 0.05.

Figure 1. Marker placement for the assessment of underwater fly kick kinematics in two and three-dimensional methodologies

RESULTS: Measured sagittal plane motion was significantly altered in all three lower limb joints of interest (Table 1, Figure 2 A-C). Additionally, substantial out-of-plane motion was measured at both the ankle and hip (Table 1).

Table 1. Summary of lower limb sagittal plane angular kinematics measured using two and three-dimensional methods

	Three-Dimensional	Two-Dimensional	P-value
Peak Ankle Flexion (deg)	54.96 ± 15.65	50.56 ± 8.69	0.033
Peak Ankle Extension (deg)	17.94 ± 8.73	12.85 ± 6.67	≤ 0.000*
Ankle Range of Motion (deg)	37.02 ± 15.73	37.71 ± 9.43	0.955
Peak Ankle Inversion (deg)	17.08 ± 9.32	-	-
Peak Ankle Eversion (deg)	2.14 ± 8.21	-	-
Peak Ankle Internal Rotation (deg)	24.15 ± 9.97	-	-
Peak Ankle External Rotation (deg)	-4.18 ± 6.97	-	-
Peak Knee Flexion (deg)	71.86 ± 8.06	68.48 ± 7.79	≤ 0.000*
Peak Knee Extension (deg)	-8.90 ± 5.75	-8.31 ± 4.43	0.483
Knee Range of Motion (deg)	80.77 ± 7.16	76.80 ± 6.30	≤ 0.000*
Peak Hip Flexion (deg)	-38.58 ± 5.19	-24.85 ± 7.88	≤ 0.000*
Peak Hip Extension (deg)	-5.15 ± 4.70	-7.33 ± 8.87	0.224
Hip Range of Motion (deg)	33.43 ± 8.61	17.52 ± 5.16	≤ 0.000*
Peak Hip Adduction (deg)	15.90 ± 4.02	-	-
Peak Hip Abduction (deg)	-5.68 ± 7.09	-	-
Peak Hip Internal Rotation (deg)	34.07 ± 8.47	-	-
Peak Hip External Rotation (deg)	2.79 ± 6.57	-	-

All participants demonstrated anterior pelvic tilt when in a natural standing position (average 8.99 ± 5.05 degrees). Once the three-dimensional hip angle was corrected for this, the profile shift between two and three-dimensional methodologies reduced (Figure 2C). However, peak hip flexion and hip range of motion remained significantly different ($p \leq 0.000$ in both cases).
Peak ankle internal rotation visually occurs at the same time as peak ankle extension (Figure 3A), where the two and three-dimensional methodologies display discrepancies in measured sagittal plane angle. Peak hip internal rotation visually occurs during hip flexion, where the largest difference between two-dimensional and corrected three-dimensional methods occur (Figure 3B).

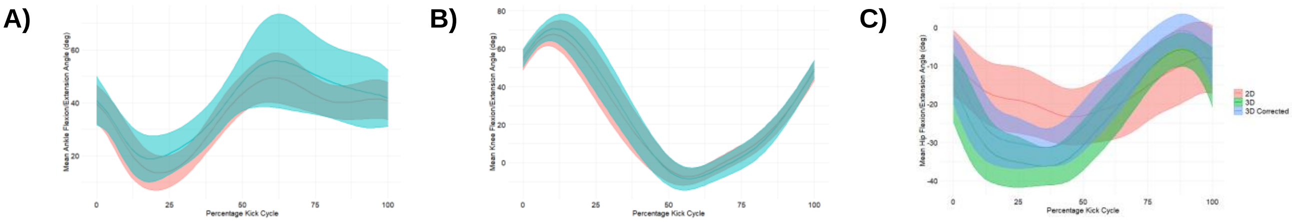

Figure 2. Lower limb sagittal plane angular kinematics for an average kick cycle for the ankle (A), knee (B) and hip (C) joints, measured using two and three-dimensional methods

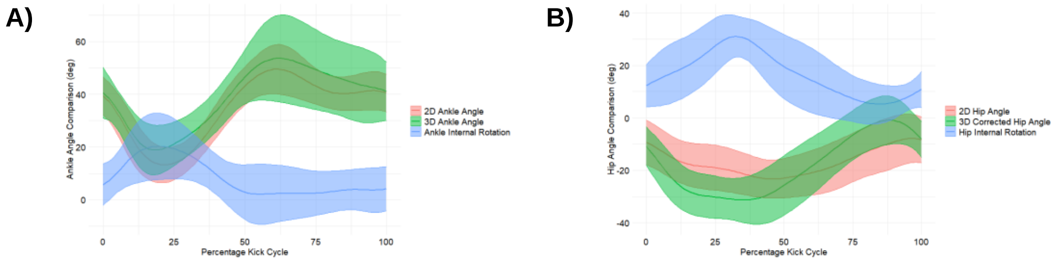

Figure 3. Lower limb sagittal and transverse plane angular kinematics for an average kick cycle for the ankle (A) and hip (C) joints, measured using two and three-dimensional methods

DISCUSSION: This study aimed to compare sagittal plane lower limb kinematics of underwater fly kick measured using two and three-dimensional methods. The main findings suggest that underwater fly kick motion occurs in sagittal, frontal and transverse planes, and that two-dimensional methods are not capable of accurately capturing representative kinematics.
Although boundaries are not defined clearly, it is generally accepted that an error of less than two degrees is clinically acceptable, error between two and five degrees is acceptable with interpretation, and error larger than five degrees signifies that important kinematic data may be missing from the results (McGinley et al., 2009; Pfister et al., 2014). Applying these guidelines, only two presented angles fall within acceptable levels of error; ankle range of motion and knee extension. Four angles present acceptable differences with careful interpretations; ankle flexion, knee flexion, knee range of motion and hip extension. Finally, three of the presented angles produce unacceptable differences between two and three-dimensional analyses; ankle extension, hip flexion and hip range of motion. In all cases where significant differences occur between two and three-dimensional sagittal plane angles, the two-dimensional kinematics are underestimated. In particular, the hip angles are substantially underestimated where a 15.91 degree reduction in range of motion is observed.
The sagittal plane motion at the knee visually produced the most similar results between methods, likely due to the reduction in possible out-of-plane motion (Heesterbeek et al., 2008). In underwater fly kick, the ankle and hip joints are those with the most potential for out-of-plane motion, previously shown to produce increased error in two-dimensional assessments of kinematics (Peebles et al., 2021). Further, transverse plane motion visually occurs at the time of these key differences in sagittal plane motion, although causation cannot be assumed. Two-dimensional methods are not able to accurately replicate the natural pelvic orientation. Once three-dimensional angles are corrected for this, there are remaining observable differences

between the two methodologies. At both the ankle and hip the magnitude of out-of-plane motion is much higher than in previous comparisons of two and three-dimensional methodologies in gait assessment (Hanley et al., 2018; Peebles et al., 2021). It is highly likely that due to the demands of the task, the lower limbs will produce increased levels of out-of-plane motion; the force of the water may elicit greater motion beyond a voluntary range in all three planes.
These higher levels of transverse and frontal plane motion, identified as important in underwater fly kick performance (Matsuda et al., 2021; Shimojo et al., 2019), may influence sagittal plane kinematics measured in two-dimensional methodologies. In two-dimensional analysis, not only may results not be reflective of true movement patterns, key kinematic information in the frontal and transverse plane may be missed. Researchers therefore need to consider these effects when two-dimensional analysis is unavoidable.

CONCLUSION: Lower-limb sagittal plane kinematics are underestimated when using two-dimensional methods to assess underwater fly kick techniques. Where it is not possible to conduct three-dimensional analyses researchers should consider the potential influence of out-of-plane motion on two-dimensional results, and the possibility of missing key kinematics related to performance in these planes.

REFERENCES

Camomilla, V., Cereatti, A., Vannozzi, G., & Cappozzo, A. (2006). An optimized protocol for hip joint centre determination using the functional method. *Journal of Biomechanics*, *39*(6), 1096–1106. https://doi.org/10.1016/j.jbiomech.2005.02.008

Fischer, S., & Kibele, A. (2015). *Contemporary Swim Start Research: Conference Book: Young Experts' Workshop on Swim Start Research 2015*.

Hanley, B., Tucker, C. B., & Bissas, A. (2018). Differences between motion capture and video analysis systems in calculating knee angles in elite-standard race walking. *Journal of Sports Sciences*, *36*(11), 1250–1255. https://doi.org/10.1080/02640414.2017.1372928

Heesterbeek, P. J. C., Verdonschot, N., & Wymenga, A. B. (2008). In vivo knee laxity in flexion and extension: A radiographic study in 30 older healthy subjects. *The Knee*, *15*(1), 45–49. https://doi.org/10.1016/j.knee.2007.09.007

Matsuda, Y., Kaneko, M., Sakurai, Y., Akashi, K., & Yasuo, S. (2021). Three-dimensional lower-limb kinematics during undulatory underwater swimming. *Sports Biomechanics*, 1–15. https://doi.org/10.1080/14763141.2021.1995475

McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait and Posture*, *29*(3), 360–369. https://doi.org/10.1016/j.gaitpost.2008.09.003

Peebles, A. T., Carroll, M. M., Socha, J. J., Schmitt, D., & Queen, R. M. (2021). Validity of using automated two-dimensional video analysis to measure continuous sagittal plane running kinematics. *Annals of Biomedical Engineering*, *49*(1), 455–468. https://doi.org/10.1007/s10439-020-02569-y

Pfister, A., West, A. M., Bronner, S., & Noah, J. A. (2014). Comparative abilities of Microsoft Kinect and Vicon 3D motion capture for gait analysis. *Journal of Medical Engineering and Technology*, *38*(5), 274–280. https://doi.org/10.3109/03091902.2014.909540

Shimojo, H., Gonjo, T., Sakakibara, J., Sengoku, Y., Sanders, R., & Takagi, H. (2019). A quasi three-dimensional visualization of unsteady wake flow in human undulatory swimming. *Journal of Biomechanics*, *93*, 60–69. https://doi.org/10.1016/j.jbiomech.2019.06.013

Taylor, W. R., Kornaropoulos, E. I., Duda, G. N., Kratzenstein, S., Ehrig, R. M., Arampatzis, A., & Heller, M. O. (2010). Repeatability and reproducibility of OSSCA, a functional approach for assessing the kinematics of the lower limb. *Gait and Posture*, *32*(2), 231–236. https://doi.org/10.1016/j.gaitpost.2010.05.005

Veiga, S., Lorenzo, J., Trinidad, A., Pla, R., Fallas-Campos, A., & de la Rubia, A. (2022). Kinematic anlysis of the underwater undulatory swimming cycle: A systematic and synthetic review. *International Journal of Environmental Research and Public Health*, *19*(19), 1–26. https://doi.org/10.3390/ijerph191912196