KINEMATIC DIFFERENCES BETWEEN UPKICK AND DOWNKICK IN UNDULATORY UNDERWATER SWIMMING

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Undulatory underwater swimming (UUS) is performed for up to 15 m of each lap in a swimming race, and is important for overall performance. This undulatory motion has two phases- the upkick (knee flexion and hip extension) and the downkick (the converse). This study assessed kinematic differences between the two phases, and determined whether these differences were related to performance in an elite sample. Each of the ten participants performed three 20 m UUS trials, and seven landmarks were manually digitised from the single camera view perpendicular to swimming direction. Differences between phases were found for vertical toe velocity, body wave velocity, hip and knee angular velocities and phase duration ($p < 0.05$), with differences in mean hip angular velocity and phase duration ($p < 0.05$) being strongly related to UUS performance.

KEYWORDS: Dolphin kick, body wave, asymmetry.

INTRODUCTION: The international governing body of swimming Fédération Internationale De Natation (FINA) allows only the first 15 m of each lap to be completed underwater. Underwater undulatory swimming (UUS) takes advantage of the reduced wave drag encountered when the body is fully immersed (Vennell et al. 2006). For this reason, swimmers perform this skill 0.5 to 1.5 m below the surface of the water, and hold their upper body in a streamlined position with arms outstretched over the head. Further, Mason and Cossor (2001) recommended that elite swimmers should maximise underwater distance in starts and in turns, as underwater distance correlated positively to overall performance in the majority of events.
UUS technique is described as having two phases, which are defined by the turning points of the toe landmark. The upkick is performed by hip extension and knee flexion; and the downkick is the converse action (Atkison et al. 2013). This simultaneous vertical motion of the feet is coordinated by allowing the knee action to lag behind the hip action. It has been suggested that a travelling wave moves caudally from hips to toes (Gavilan et al. 2006).
Most swimmers are able to coordinate the anteriorly directed kicking motion of the downkick, and can generate thrust, but it is more difficult to produce force kicking in the posterior direction. The ability to generate thrust during the upbeat can distinguish elite performers from novices (Atkison et al. 2013), but it is unknown whether the kinematics related to thrust imbalance can be used to distinguish between performers in the elite category. A recent study considered the importance of kick symmetry in a sub-elite sample (FPS 663 $\pm$ 134), and found that the relative values for phase duration, chest flexion/extension and toe vertical velocity were important for performance (Atkison et al. 2013). The purpose of this study was to further the understanding of the importance of UUS imbalance, by determining the kinematic differences between the upkick and the downkick to UUS performance in an elite sample.

METHODS: Seven male and three female swimmers participated in this study (age 21.1 $\pm$ 2.6 years, streamlined body length 2.50 $\pm$ 0.10 m, FINA point score 804 $\pm$ 58). FINA point score was based on the 2013 FINA point chart, and the highest score achieved at the 2013 Australian Swimming Championships was recorded. Swimmers who participated only in breaststroke were excluded. Ethical approval was granted by the Australian Institute of Sport Ethics Committee. The protocol was explained to the participants and they provided written informed consent to participate.
Participants were landmarked on the right side by a Level 1 ISAK accredited anthropometrist with a circle of black oil based make up 0.03 m in diameter in four locations: the acromion, trochanterion, lateral femoral epicondyle and lateral malleolus. The shoulder landmark was

translated along the transverse plane for visibility. This landmark size was required for uninterrupted visibility. Participants then performed their established race warm up before completing three 20 m maximal effort UUS trials. Participants gently pushed off the wall 1 m below the surface in the centre of the lane in a prone streamlined position, holding that depth for the entire trial. Participants travelled at least 4 m before capture began, to ensure push off did not affect UUS velocity. The calibrated Wetplate system was used to capture each trial at 100 Hz (Mason et al. 2012). A single camera view was selected for manual digitisation. The selected Allied Vision Technologies Prosilica GE680/680C camera was fixed behind a glass window, axis positioned perpendicular to the direction of travel of the participant.

Data Analysis: Digitised coordinates of the four landmarked locations, the fingertips, toes and vertex of the head were exported to Microsoft Excel. Bilateral symmetry was assumed (Atkison et al, 2013). A 2-dimensional five segment model consisting of the foot, shank, thigh, trunk and head, and arms was used to calculate centre of mass (COM) position in each frame. Positions of segment COM as a percentage of segment length were based on approximations by de Leva (1996). Proportional segment masses were combined with position coordinates to resolve whole body COM position at 50 Hz by summation of moments. A Fourier Analysis of COM acceleration was performed using LabChart Pro version 8 (AD-Instruments, Bella Vista, Australia), to select the cut off frequency of the 2nd order Butterworth filter. At least 99.8% of the power of the signal was retained when a 5 Hz cut off was used.

Radial distortion caused by the camera lens and the glass viewing window was corrected by a routine in the Wetplate software (Bax, 2002). Thigh length has been shown to be an appropriate scale to calibrate 2D video for underwater motion analysis (Clothier et al. 2004), so the proportion of digitised thigh length and measured thigh length was used to correct the scaling factor.

A randomly selected trial was digitised three times to quantify digitising error. Potential error associated with the temporal precision of sampling video frames was also estimated for peak values by taking the mean difference between the selected peak and the values immediately before and after.

Variables: Smoothed and scaled coordinates were used to calculate two performance variables and nine kinematic phase variables. The primary performance variable was mean horizontal COM velocity (V_{COM}). V_{COM} was also normalised to outstretched body length (nV_{COM}), so any impact of this variable could be isolated.

Phase duration and peak vertical toe velocity were identified as described by Atkison et al. (2013). Peak horizontal COM acceleration gave an indication of peak propulsion for each phase, and whether thrust was great enough to overcome resistance. Overall change in velocity was calculated by subtracting the initial velocity from the final velocity of each phase to indicate which phase was more effective, as fluctuations in COM velocity indicate imbalances between propulsive and resistive impulses. Body wave progression velocity was calculated as described in Zamparo et al. (2012).

Body wave progression is associated with cyclic flexion-extension movements of the hip and knee joints. Angular velocities of these joints were derived from angular position of the associated segments. Knee angle was calculated using the ankle, knee and hip landmarks, while hip angle was calculated using the knee, hip and shoulder landmarks. Peak and mean values for each phase were reported for each participant.

The 50 Hz signals were divided into individual cycles based on the vertical position of the toe landmark. Either one or two full cycles were extracted from each trial, so the full data set for each participant included three to six cycles, which is considered to be reliable (Connaboy et al. 2010). Data were then time normalised to percentiles of total cycle time. The mean value at each percentile gave a representation of intra-cyclic kinematic information, which was used to calculate representative values for each variable.

Statistical analysis: SPSS Statistics 17 (IBM Corporation, New York, USA) was used to assess the kinematic differences between phases using paired T-tests ($p < 0.05$). Ratios of downkick/upkick were correlated to performance (V_{COM}) using bivariate correlations to determine the importance of phase differences ($p<0.05$).

RESULTS AND DISCUSSION: All kinematic variables were significantly different between upkick and downkick ($p < 0.05$), except for change in V_{COM} and mean hip angular velocity. All values were greater in the downkick than the upkick except for phase duration, toe vertical velocity and peak angular velocity at the hip.

Table 1
Kinematic differences between downkick and upkick including differences between means, standard deviation (SD), standard error in the mean (SEM), calculated maximum percentage error (%E), t-value (t), degrees of freedom (df) and 2-tailed significance (Sig. (2-tailed)). Angular velocity is represented by ω. Significance at 0.05 level was indicated by *.

Downkick – Upkick	Mean	SD	SEM	%E	t	df	Sig. (2-tailed)
Change in V_{COM} (ms^{-1})	0.11	0.29	0.09	11.4	1.14	9	0.29
Peak COM acceleration (ms^{-2})	2.09	1.69	0.53	15.4	3.92	9	0.00*
Duration (s)	-0.04	0.03	0.01	10.0	-3.84	9	0.00*
Vertical toe velocity (ms^{-1})	-0.48	0.47	0.15	6.6	-3.26	9	0.01*
Body wave velocity (ms^{-1})	0.49	0.26	0.08	8.5	5.90	9	0.00*
Mean knee ω ($deg.s^{-1}$)	22.53	14.01	4.43	7.7	5.09	9	0.00*
Peak knee ω ($deg.s^{-1}$)	342.64	31.13	9.84	6.7	34.80	9	0.00*
Mean hip ω ($deg.s^{-1}$)	6.02	10.62	3.36	9.0	1.79	9	0.11
Peak hip ω ($deg.s^{-1}$)	-56.09	39.76	12.57	5.9	-4.46	9	0.00*

Disadvantageous anatomy and musculature has been said to restrict the effectiveness of the upkick (Atkison et al. 2013). Although the downkick produced greater peak acceleration, the resultant change in velocity was the same as the upkick. This suggests that although the downkick produces more thrust than the upkick, there is also a greater resistive impulse, causing the net change in velocity to be equivalent to the upkick. The long duration of the upkick compared to the downkick also suggests the upkick is used as a recovery phase.
Significant negative correlations to both performance parameters were found for mean hip angular velocity ratio, with values of 0.89 to 1.33. The greatest performance was achieved by the participant with a ratio of 0.89, all other participants had ratios greater than 1.00, with values increasing for poorer performances.
Phase duration correlated positively to V_{COM} and approached significance when correlated to nV_{COM} ($p = 0.056$). Phase duration ratio values were between 0.67 and 1.01, with greater values being related to superior performances.
The remaining phase ratios did not show a significant correlation to performance (Table 2).

Table 2
Correlations between downkick/upkick ratios and performance. Angular velocity is represented by ω. Significance was reported at the p < 0.05 level, indicated by *.

Ratio (Downkick/Upkick)	V_{COM}	nV_{COM}
Change in V_{COM}	0.042	0.236
Peak acceleration	0.520	0.579
Duration	0.643*	0.620
Vertical toe velocity	0.302	0.311
Body wave velocity	-0.411	-0.365
Mean knee ω	-0.164	-0.200
Peak knee ω	-0.345	-0.340
Mean hip ω	-0.792*	-0.688*
Peak hip ω	0.120	0.176

The correlation between the upkick/downkick ratio of mean hip angular velocity and performance highlights the importance of the hip action. The participant with the highest mean COM velocity had a mean hip angular velocity ratio of 0.89. This value shows that mean hip flexion angular velocity (downkick) was less than mean hip extension angular velocity (upkick). All other participants had ratios greater than one, showing that mean hip flexion angular velocity was greater than mean hip extension angular velocity, with ratios increasing with poorer performances up to 1.33. This finding suggests that elite performers should aim to maximise hip angular velocity during the upkick, in order to achieve a ratio less than 1.00, and also to maximise contribution of the large musculature associated with hip action.
The values of the phase duration ratios were less than 1.00, highlighting that upkick duration was greater than downkick duration. Larger duration ratios were related to superior performances, so it follows that more equal phase durations are favourable, as supported by a recent study (Atkison et al. 2013). Therefore, in order to maximise frequency and achieve a temporal balance, swimmers should aim to minimise the duration of the upkick.

CONCLUSION: The current findings have implications for training, as focusing on hip extension will alter programming and prescription of exercises both in the pool and on land, and an emphasis on temporal phase balance should be included in monitoring procedures. Knowledge gained from this study can be directly used in training to improve UUS performance and therefore improve race outcomes in swimming.

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