Underwater undulatory swimming: study of frequency, amplitude and phase characteristics of the 'body wave'

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The purpose of this study was to analyze wave motions of underwater undulatory swimming (UUS) and to compare these whip-like actions with previous studies developed in butterfly and breaststroke. UUS is characterized by vertical displacements of the body parts such that a wave progresses along the body with most of its power contained in a single sinusoidal harmonic (H1). Progresion of the H1 wave from hip to ankle raises the possibility that energy is transmitted along the whole body in butterfly swimming and from the hips in USS. In UUS upper body segment movements were not part of the body wave and would be used to stabilize position. Increasing values of vertical velocities caudally from hip to knees to ankles appears to be related to maximising horizontal velocity of the CM in UUS. A future analysis of the wake structure generated by UUS and its relationship to wave characteristics seems a logical step for further understanding propulsive mechanisms in UUS.

Key Words: *Fourier Transform, harmonic, technique, hydrodynamics.*

INTRODUCTION

When swimming underwater undulatory swimming (UUS) the swimmer's body parts are displaced horizontally and vertically through the kick cycle. These motions have been likened to oscillations or wave-like motions (2,3,5). When dolphins and butterfly swimmers were compared, based on body wave (BW) velocity and duration of the up beat, BW velocities were similar while the duration of the up beat was different (5). Harmonic or Fourier analysis[1] was applied by Sanders et al. (2,3) to determine the frequency, amplitude and phase characteristics of the vertical undulations of the swimmer's body parts. They found differences in phase between body parts in butterfly swimming such that a body wave travelled caudally and suggesting that energy gained by raising the CM was transmitted caudally and contributed to a propulsive whip-like action, while in breaststroke the range of vertical motion of the hips was large relative to the vertical motion of the CM. It was proposed that these vertical motion differences reduced the need to do work to raise the CM and the transmission of a body wave enabled energy

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[1] Any periodic signal can be broken down into its harmonic components. The sum of the proper amplitudes of these harmonics is called Fourier series (7).

accrued by the upper body to be reused to raise the caudal half of the body to a streamlined position in which drag is reduced.

The purpose of this study was to analyze wave motions of UUS and to compare these whip-like actions with previous studies developed in butterfly and breaststroke.

METHODS

Subjects: Twenty international and national ranked swimmers, ten male and ten female, were videotaped performing UUS for a 15m sprint after a water start. The distance was covered in the horizontal direction and at approximately one meter in depth to avoid wave resistance.

Instrumentation: One camera (S-VHS sampling at 50 Hz) with its optical axis perpendicular to the line of motion of the swimmer recorded each trial through an underwater window. To avoid the influence of impulse from pushing off the wall, the camera recorded the movement from 7.5 to 12 m from the wall. As this study was two-dimensional, a symmetrical 13 points model was digitized after each video-capture using Kinematical Analysis System developed by R. Schleihauf at San Francisco State University (www.kavideo.sfsu.edu). Coordinates of the CM were determined. The digitised coordinates of the body landmarks were exported to a set of MatLab routines (developed by R. Sanders). The program steps were: 1) Raw data was smoothed and interpolated to 100 samples per second. 2) Stick figures of the kick cycles were produced. 3) A kick cycle was selected based on the vertical displacement of the ankle 4)The cycle time was normalised to percentiles of the total cycle time. 5) Data and graphs of vertical displacement, vertical velocity and vertical acceleration versus % of kick cycle were obtained. 6) Fundamental harmonic (H1, H2, …Hn) velocity of body segment were calculated and graphically displayed. 7) A graph of wave amplitude of first five harmonics and their power contribution was displayed. 8) Phase analysis of the two first harmonics (H1 and H2) was performed. 9) Joint angles, angle velocity and angle acceleration evolution of hip, knee and ankle were determined for the kick cycle.

Variables: Distance of the body per kick (KL, m (cyc^{-1}), kick frequency (KF, Hz) and mean CM horizontal velocity (CMHV, m (s^{-1}) were the basic variables to describe the UUS technique (see table 1). Vertical position data were input to the Fourier analysis software to obtain the fundamental frequency and its harmonics. Amplitude of each frequency was calculated by $C_n=(A_n^2+B_n^2)^{0.5}$, were A_n and B_n are cosine and sine coefficients for the nth frequency (harmonic). The contribution of each harmonic to the power of the signal, that allows us to know its influence in the movement, was given by $2C_n^2$. Average velocity of the travel of the wave along the body was determined for the fundamental harmonic (n=1) for the vertex to shoulders, shoulders to hips, hips to knees and knees to ankles (m/s) by $u=d/t$ where u is the velocity of travel along the body, d is the displacement between adjacent landmarks and t the time taken to achieve the same phase as the previous landmark.

RESULTS AND DISCUSSION

Table 1 shows mean swimmers UUS kick characteristics. On average the group took approximately 0.46 s to complete a kick cycle. This was less than half of the that obtained in the studies of the butterfly stroke (2) and breaststroke (3).

Table 1: Means and SD for the displacement of the body per kick (KL), kick frequency (KF), kick index (KI) and CM velocity (v).

	KL ($m\bullet cyc^{-1}$)	KF (Hz)	CM v (ms^{-1})
Mean	0.76 (±0,14)	2.17 (±0,324)	1.63 (±0,17)

Figure 1 shows the vertical velocity (VV) of each body landmark and CMHV. Upper values of absolute VV were found in the downward kick compared with the upward kick in the knee and ankle. This produces a small increment in the CMHV at the end of the downward kick. Peak values of VV increase progressively from shoulder to hip to knee to ankle. CMHV showed a small range of variation during the cycle, this low variability demonstrates a likely contribution of different kind of propulsive mechanisms appropriately combined in a period of body oscillation. A wave transmitted in a cephalo-caudal direction along the body can contribute to conservation of mechanical energy. The vertical movement of the body parts was almost entirely comprised of one low-frequency waveform (Table 2) and it suggests a truly harmonic or wave-like pattern, as Ungerechts (6) and Sanders (2) suggested. This means that vertical movements of the body landmarks are phases of a simple sinusoid oscillation with very rhythmical motion. Upper body segment results were more variable. Our H1 results of the vertex and shoulder were similar than the obtained in butterfly (2) and breastroke (3) however, hip, knee and ankle showed values about 100% of power contribution different than the previously obtained (2,3) where the H1 and H2 harmonics contribution was very differently distributed in butterfly (about 50%) and breaststroke (about 70% for H1). The arm strokes performed during these strokes explained the differences found in UUS, where the arms are stretched and fixed forward in horizontal position.

The increasing amplitude of oscillation from hip to ankle suggested a 'whip-like' action. It can be hyphothesised that there is a relation between this action and the production of a wake with rotating vortices that can be propulsive, as UUS visualized wakes suggested (1). Each time the tip of the feet change direction, it sheds a stop/start vortex. As the feet move to the other side, a low-pressure region develops in the posterior half of the legs, sucking a bolus of fluid laterally (as Tytell and Lauder (4) proposed in eel propulsion).

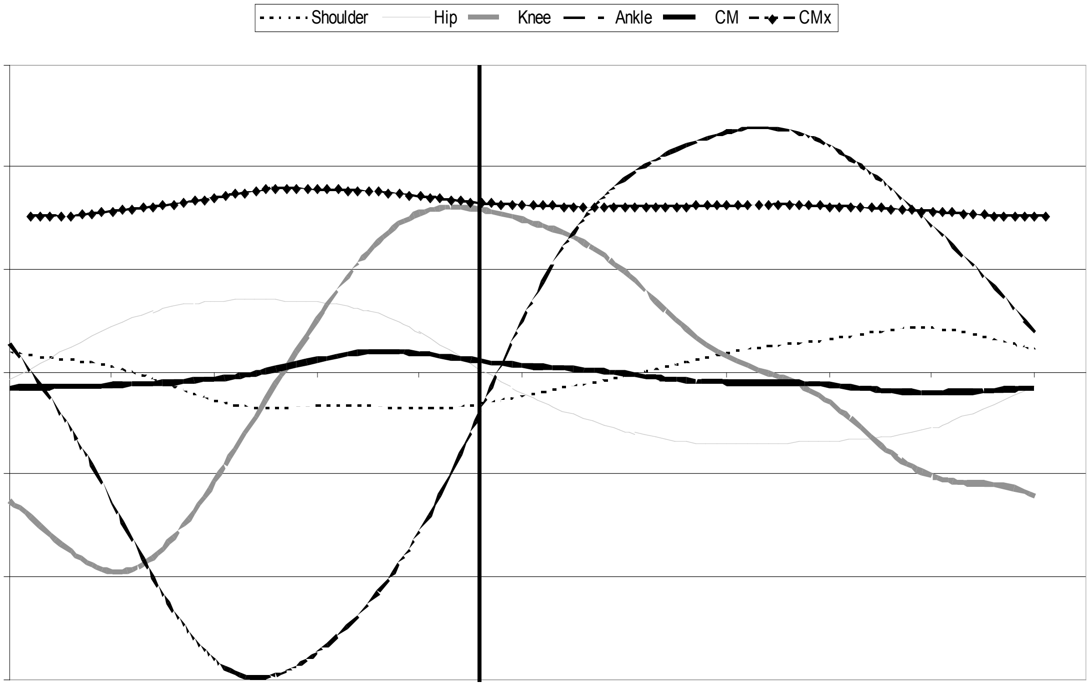

Figure 1: Average vertical velocity for each body landmark and CM horizontal velocity (m/s).

Table 2: Mean Percentage Power Contributions of H1 and H2 to waveform power.

Body Landmark	H1		H2	
	Mean	SD	Mean	SD
Vertex	91,28	9,02	6,29	8,50
Shoulder	94,34	5,63	3,15	3,41
Hip	96,89	3,15	2,43	2,91
Knee	96,77	1,84	2,77	1,82
Ankle	98,94	0,60	0,93	0,66

Table 3: Mean and SD for Fourier amplitude H1 wave and range of vertical motion (m).

	Amplitude	Range
Vertex	0,013 (±0,005)	0,102 (±0,04)
Shoulder	0,015 (±0,003)	0,066 (±0,02)
Hip	0,029 (±0,007)	0,068 (±0,016)
Knee	0,059 (±0,013)	0,136 (±0,031)
Ankle	0,099 (±0,02)	0,239 (±0,056)
CM	0,007 (±0,004)	0,041 (±0,021)

The range of vertical motion produced by the calculated waveforms was about four times that of the Fourier amplitudes presented. Mean Fourier amplitudes for H1 and range of vertical motion are presented in Table 3. Mean Fourier amplitudes of H1 and range, increased progressively from vertex to ankle showing the lowest vertical movement in CM. The obtained results were similar to those obtained in studies of butterfly (2) and breaststroke (3) in hip, knee, ankles and CM.

CONCLUSIONS

UUS is characterized by sequential vertical displacements of the body parts such that a fundamental sinusoidal wave harmonic (H1) dominates the waveform power and travels caudally from hip to ankle. This raises the possibility that energy is transmitted mainly from the hips in USS rather than along the whole body as in butterfly swimming. Upper body segment movements appear to be used only to stabilize the body and to maintain a horizontal position. Increasing values of vertical velocities of hip, knees and ankles appears to be associated with horizontal velocity of the CM in UUS. A future analysis of the wake structure generated by the underwater undulatory swimmer and its relationship to wave characteristics seems a logical step for further understanding propulsive mechanisms in UUS.

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