

EVIDENCE OF ENERGY REUSE THROUGH BODY WAVE MOTION IN BUTTERFLY SWIMMING

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INTRODUCTION

In butterfly swimming the upper body is raised above the water during the stroke cycle. An obvious purpose of this process is to raise the head to breathe and to assist in recovering the arms for the next stroke. However, it is apparent that skilled butterfly swimmers have rhythmical undulations of all body parts. There are at least two possible advantages of these undulations. The first is that if the hips and other body parts oscillate out of phase with the upper body the vertical displacements of the centre of mass (CM) may be minimised, thereby reducing the energy requirement to raise the CM. A second possibility is that the undulations actually contribute to propulsion. In this instance it is possible that energy gained by raising the CM may be used to aid propulsion and therefore may not constitute wasted effort.

The purpose of this study was to investigate the possibility that performance is related to minimisation of the amplitude of CM oscillation and the possibility that propulsion is aided by reuse of energy through body wave motion.

METHOD

Digitised video data were made available for analysis by the International Center for Aquatic Research (ICAR) in Colorado Springs. These data were from six males and four females competing at the 1991 World Championships in Perth, Australia, and two males and four females swimming at maximum butterfly pace at a United States National Team Swimming Camp in Indianapolis. Four synchronised video cameras operating at 30Hz recorded the swimmers motion (two cameras were above water and two cameras below water) at the 40m mark of both pools. Separate direct linear transformations (DLT, Abdel-Aziz, 1971) of the digitised body landmarks were conducted for the above and below water views. Continuous records of above and below water views were subsequently obtained and smoothed at 6Hz by a 2nd order recursive Butterworth digital filter. The CM was calculated using Peak Performance Technologies Incorporated software using the anthropometric data of Dempster (1955). Vertical and horizontal position data of the CM, vertex of the head, shoulders, hips, knees, and ankles were extracted from the ICAR records and input to a FORTRAN program 'flyosc' developed at ICAR by the first author to perform the analysis. The data were analysed over the period corresponding to one stroke cycle defined as the instant of hand entry to the following hand entry.

Average velocity of the CM (dependent variable) was calculated as the difference in the horizontal displacement of the CM from the first to the last samples of the stroke cycle divided by the period of the cycle.

For the purpose of investigating whether elite butterfly swimmers may conserve energy by minimising the vertical movement of the CM maximum and minimum CM displacement over the stroke cycle were obtained from the CM/time records of each swimmer and the vertical displacement/time records of the CM, shoulder, hip, knee, and ankle paths were plotted.

For the purpose of investigating the possibility that vertical motions of the body parts contributed to a body wave that transmitted energy to aid propulsion the amplitude and phase characteristics of the fundamental frequency (equivalent to stroke frequency =1/period of the stroke cycle) and its integer harmonics were determined by Fourier analysis. The average velocity of wave travel between landmarks was obtained for the fundamental frequency (H1) and the second harmonic (H2) by dividing the average displacement between the landmarks by the difference in time. Time was calculated as the difference in phase angle of adjacent landmarks expressed as a ratio of a whole cycle and multiplied by the period of the stroke cycle. The same procedure was used to calculate the average wave velocity of H1 from vertex to ankle. In this case the difference in phase of the vertex and ankle was used in the calculation.

Angular kinematic data were obtained for the trunk (shoulder to hip), thigh (hip to knee), and shank (knee to ankle) to investigate the timing of body segment rotations.

RESULTS

1.Evidence for minimising vertical movement of the CM

The average vertical movement of the CM from its minimum to maximum position was .106m (S.D.=.019m) for the males and .089m (S.D.=.014) for the females. There was no relationship suggesting that performance was associated with small vertical movement of the CM for either males ($r=.12$) or females ($r=.57$). In fact, the correlations were positive rather than negative.

The CM path and the paths of the shoulders, hips, knees, and ankles with respect to the mean CM position of a typical subject show that the hips were not moved directly out of phase with the shoulders in order to minimise vertical CM movement. The hips were moving rapidly upwards prior to the shoulders reaching their highest position. At the time of peak CM displacement shoulders, hips, knees and ankles were all in relatively high positions.

2.Evidence for reuse of energy transmitted by a 'body wave'.

For the vertex and shoulders a very high percentage of the total power in the waveform (males: vertex=95.2%, S.D.=2.2%; shoulders=93.5%; S.D.=4.4%; females: vertex=95.3%, S.D.=2.5%; shoulders=88.1%, S.D.=10.3%) was contained in the fundamental frequency H1. This indicated that the vertical motion of the vertex and shoulders were simply particular phases of a sinusoid oscillation.

For the hips, knees, and ankles the waveform was comprised almost entirely of H1 and H2. This reflected the introduction of a two beat pattern associated with the two beat dolphin kick. The two beat pattern (H2) was superimposed on the H1 waveform.

Amplitudes of H1 and H2 oscillation of vertex, shoulder, hip, knee, ankle, and CM are presented in Table 1. These were variable among subjects but similar for males and females although males tended to have greater amplitudes of oscillation of knee and ankle for both H1 and H2 (significant at $p<.05$ for H2). For the H1 oscillations the vertex had the greatest average oscillation. The oscillation of the hips was the smallest of all the body oscillations (males: .025m; females .029m). None of these amplitudes were significantly related to CM velocity.

Table 2 shows the average phase differences and average velocities of H1 wave travel between each segment and their correlations with CM velocity. The phase relationships among the H1 oscillations of the body parts was such that a definite cephalo-caudal sequence of wave travel was evident. The rate of travel of the wave was positively correlated with performance for all body segments except vertex to shoulder (significant at $p<.05$ for the knee to ankle). A particularly strong relationship ($p<.01$) was found between the average velocity of wave travel and CM velo-

city (males: $r=.88$; females: $r=.96$). In every case the absolute velocity of the wave was slightly faster than the swimmer's forward motion with the average difference between H1 velocity and CM velocity being $.34\text{m}\cdot\text{s}^{-1}$ (S.D. $=.22\text{m}\cdot\text{s}^{-1}$) for the males and $.17\text{m}\cdot\text{s}^{-1}$ (S.D. $=.06\text{m}\cdot\text{s}^{-1}$) for the females.

Table 1
Mean Amplitude* of Oscillation of H1 and H2

Body Landmark	Mean H1 Amplitude		Mean H2 Amplitude	
	Males	Females	Males	Females
Vertex	0.083 (0.023)	0.081 (0.021)	0.015 (0.003)	0.012 (0.006)
Shoulder	0.068 (0.009)	0.064 (0.009)	0.011 (0.004)	0.011 (0.006)
Hip	0.025 (0.009)	0.029 (0.006)	0.025 (0.008)	0.026 (0.004)
Knee	0.055 (0.018)	0.049 (0.009)	0.054 (0.010)	0.040 (0.011)
Ankle	0.050 (0.018)	0.041 (0.009)	0.066 (0.016)	0.050 (0.011)
CM	0.016 (0.006)	0.013 (0.005)	0.012 (0.003)	0.012 (0.003)

Note: Standard deviations in parentheses.

* Fourier amplitude given is 1/4 of the range from maximum to minimum.

Table 2
Mean H1 Phase Differences and Velocities of H1 Wave Travel Between Body Landmarks

Body Landmarks	Phase Difference (degrees)		Absolute Velocity of H1 Travel (m/s)		Correlations*	
	Males	Females	Males	Females	Males	Females
Vertex	35.0	30.6	2.2	2.0	-0.09	0.18
Shoulder	(7.5)	(8.5)	(0.8)	(1.6)		
Shoulder	142.8	135.6	1.5	1.2	0.56	0.36
Hip	(48.6)	(19.7)	(0.4)	(0.1)		
Hip	44.4	60.2	1.8	2.2	0.47	0.46
Knee	(38.4)	(13.8)	(2.0)	(0.7)		
Knee	26.2	46.3	3.8	2.1	0.77	0.77
Ankle	(8.9)	(16.8)	(1.4)	(0.5)		
Vertex	248.4	246.9	1.9	1.6	0.88	0.96
Ankle	(17.3)	(46.7)	(0.3)	(0.2)		

* Correlation between velocity of H1 travel and CM velocity

In general there was a definite progression of a wave of frequency H2 from the hip to the knee (males: $2.39\text{m}\cdot\text{s}^{-1}$; S.D. $1.05\text{m}\cdot\text{s}^{-1}$; females: $2.48\text{m}\cdot\text{s}^{-1}$; S.D. $1.48\text{m}\cdot\text{s}^{-1}$). However, this was more variable and less distinct than that of H1. Correlations between hip to knee velocity of H2 and CM velocity displayed a trend towards increasing CM velocity with increasing velocity of

wave travel but did not reach significance at the $p=0.05$ level (males: $r=0.64$; females: $r=0.61$). The progression of the H2 wave from knee to ankle occurred with smaller velocity than hip to knee velocity (males: $1.177\text{m}\cdot\text{s}^{-1}$, $S.D.=0.115\text{m}\cdot\text{s}^{-1}$; females: $1.099\text{m}\cdot\text{s}^{-1}$, $S.D.=0.191\text{m}\cdot\text{s}^{-1}$) but was much less variable across subjects than the velocity of H2 from hip to knee. There was a trend towards greater CM velocities with increasing velocity of the H2 wave from knee to ankle (males: $r=0.73$; females: $r=0.60$) but, like the hip to knee velocity, did not reach statistical significance at the $p<0.05$ level.

Analysis of the angular velocity profiles of the trunk, knee, and ankle showed that rotations with increasing magnitude occurred in a sequence from trunk to thigh to shank and was particularly apparent in the prelude to the downbeat of the shanks that occurred in the middle of the cycle. This sequence was initiated by the negative (downward) rotation of the trunk at the end of the previous cycle. The downbeat of the shanks tended to coincide with an acceleration peak in the acceleration/time profiles of subjects. However, this acceleration was also influenced by the latter stages of the arm pull and the acceleration cannot be attributed solely to the downbeat of the kick. Towards the end of the stroke cycle another acceleration of the CM occurred which coincided with high angular velocity during the downbeat of the shanks.

DISCUSSION AND CONCLUSIONS

The analysis of the vertical motion of the selected body segment endpoints showed that the motions of elite butterfly swimmers were largely comprised of low frequency waveforms and were truly 'wavelike' as has been suggested by Ungerechts (1982). However, there was no evidence that small CM vertical movement was associated with performance or that the oscillation of the body parts was timed to minimise the vertical movement of the CM.

There was evidence that the mechanical energy required to rotate the trunk and to raise part of the body mass above the water was reused to assist in propelling the body forward. First, the undulations of the body were timed in a way that indicated the existence of a body wave travelling in the caudal direction. Because waves transmit energy it is possible that this timing was developed as a means of assisting propulsion. There was also strong evidence that the velocity of the H2 wave was associated with CM velocity.

A 'whip' action was indicated by the sequencing of vertical movements in the caudal direction and the increasing magnitude of vertical movement from hip to ankles. This was further supported by the sequencing of rotations and increasing angular velocity of segment rotations in the caudal direction. Because accelerations of the CM coincided with large angular velocities of the shank it appeared likely that propulsion was gained from this whip action.

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