TADPOLE, TROUT OR TUNA: THE EQUIVALENCE OF ANIMAL AND HUMAN AQUATIC UNDULATORY LOCOMOTION.

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The purpose of this study was to examine the kinematics of human undulatory underwater swimming and compare the principle components of the propulsive waveform to those generated in the various modes of animal undulatory locomotion. Results indicated a similarity to a sub-carangiform mode of locomotion, with minimal undulation in the anterior aspects of the body and less than one wavelength present on the swimming body. A sub-cariangiform mode of locomotion suggests that swimmers' arms are acting as inertial dampers, reducing dorso-ventral movements (pitch) in the anterior aspects of the body, and thereby minimising form drag and allowing a more efficient transfer of the propulsive wave along the caudal aspects of the swimmer.

KEY WORDS: swimming, hydrodynamics, inertial recoil.

INTRODUCTION:

Undulatory underwater locomotion is accomplished via the production of a propulsive force, generated by temporally sequenced (wave-like) oscillations passing caudally along the length (*or part*) of the swimming body. According to McHenry, Pell & Long (1995) to enable a comprehensive understanding of the factors that determine undulatory swimming speed, the mechanical determinants of the shape and speed of the propulsive waveform must be established. Assessments of morphology (Webb, Kostecki & Stevens, 1984), tail-beat frequency / amplitude (Bainbridge, 1957; Hunters & Zweifel, 1971) and body flexibility/rigidity (McHenry, Pell & Long, 1995) have been undertaken to identify the principle factors which influence the propulsive waveform in animal aquatic undulatory locomotion. Similarities between animal undulatory locomotion (AUL) and human undulatory underwater swimming (UUS) have been recognised, and the hydrodynamic principles used to explain efficient and effective animal undulatory locomotion applied when analysing UUS (Ungerechts, 1983; Arellano, Pardillo, & Gavilan, 2002; Lyttle & Blanksby, 2000; Lyttle & Keys, 2004). However, AUL occurs in many forms or *modes* (Table 1), primarily as a consequence of interspecies morphological differences and differences in predatory/avoidance behaviours. The fundamental characteristics of AUL (wavelength, body amplitudes, tail-beat amplitude/ frequency, etc) have been used to classify the various *modes* (Table 1). Chopra, (1976) suggests that anguilliform undulatory locomotion with a wave travelling caudally along the *entire* length of the body is found in animals with relatively low hydrodynamic efficiency. According to Dewar & Graham (1994) anterior sections of the body are ineffective in the production of a propulsive force, and more effective/efficient thrust is produced with undulations occurring in the latter half/third of the body. However, Lighthill, (1977) demonstrated that a major source of inefficiency associated with this mode of undulatory locomotion is inertial recoil. Inertial recoil occurs as a consequence of the relatively large oscillations of the caudal aspects of the undulatory swimming body resulting in a pitching motion. As is apparent from Table 1 anguilliform locomotion is characterised by the inclusion of one or more wavelengths per body length, which acts to minimise this inertial recoil, by balancing the dorso-ventral forces along the whole length of the body. It would appear that each mode of undulatory locomotion has advantages and disadvantages in the production of effective/efficient propulsion. The aim of the present study was to examine the kinematic characteristics of skilled UUS and compare them to those apparent in the various modes of AUL. The considerable morphological disparities evident between humans and specificallyadapted aquatic animals may limit the direct application of *all* the different modes of undulatory locomotion to accurately describe UUS. However, establishing which mode of AUL best approximates a human form of UUS would provide further information as to which characteristics of UUS influence performance, and identify areas for improvements in technique.

Table 1 Modes of Undulatory Locomotion and their Fundamental Characteristics

Undulatory Locomotion	Fundamental Characteristics
Anguilliform	• Purely undulatory, almost the entire body participates in the waveform. • Short wavelength - 1 or more wavelengths per body length. • Amplitude of the body movements are relatively large along the entire length of the body • E.G. Tadpole, Eel
Sub-Carangiform	• Similar to *anguilliform*, except posterior aspects of the body are emphasised in the production of propulsion. • Between ½ and 1 wavelength per body length. • E.G. Trout
Carangiform	• Only the posterior sections (final third) of the body oscillate. • Less than ½ a wavelength per body length • Minimal oscillations occur in the anterior aspects of the body. • E.G. Salmon
Thunniform	• Long propulsive wavelength • Majority of propulsive force generated in extreme caudal regions • Minimal oscillations occur in the anterior aspects of the body. • E.G. Tuna

N.B. Table 1 only presents four from a range of modes of undulatory locomotion. It should be noted that the modes are not exclusive – a more or less developed version of each can be attained

METHODS:

Fifteen skilled male swimmers (Mean ± S.D: Age 19 ± 3.3 years, height 181.6 ± 0.05m, weight 74.8 ± 8.6kg, competitive swimming experience 9.4 ± 3.2 years) from the Edinburgh University swimming team participated in the study. An initial practice session was held one week prior to data collection to familiarise the swimmers with the requirements of the experimental protocol. Participants were required to swim 15m underwater using UUS technique. A two dimensional cinematographic technique was employed to collect (position-time) data. Subjects were filmed with a stationary underwater camera (KY32 CCD, JVC Corporation, Japan) at fifty fields per second. The optical axis of the camera was perpendicular to the plane of motion of the swimmer. The camera was fixed at a distance of 12m from the plane of motion of the swimmer, 1m below the surface of the water. The camera was adjusted to enable a capture window of 4m in the line of horizontal travel, ensuring that a minimum of two complete kick cycles could be captured. Two cycles per trial were captured to allow the between cycle fluctuations in swimming kinematics (velocity, kick amplitude, etc) to be assessed. In accordance with common convention the swimmers were instructed to swim from left to right through the filming area. Subjects were marked at the joint centres of the shoulder, hip, knee, ankle and 5th metatarsal phalangeal joint (5th MPJ) of the foot on the right side of the body with a 3cm diameter circle of black oil based body pain. Prior to data collection swimmers undertook a standardised twenty minute warm-up. Swimmers were instructed to use a push start from the wall to achieve the correct depth (between 0.8m-1.2m) and orientation (horizontal-with respect to the camera) in the water. Once at the correct depth and orientation swimmers were required to accelerate from the wall to a marker on the pool floor 10m away, which represented the start of the filming area. Subjects were instructed to maximise swimming velocity as they passed over the first marker and maintain maximal velocity until they passed over a second marker, a further 5m ahead. Three trials were conducted to collect a total of six cycles of data. Segment endpoint data from two consecutive kick cycles from each trial were digitised using Ariel Performance Analysis System (APAS-2000 Arial Dynamics, 2000). A kick cycle was defined from the video data as the frame corresponding to the initiation of an upward movement at the 5th MPJ, through a complete kick cycle, to the frame immediately prior to the frame corresponding to the initiating of an upward movement at the 5th MPJ for a second kick cycle. Additional frames either side of the observed start and end of the two kick cycles were digitised to enable the accurate identification of the start/end points of each cycle. For the purpose of this analysis bilateral symmetry was assumed and only the side of the body facing the camera was digitised to define a five segment model of the swimmers body comprising the arm, trunk, thigh, shank and foot. The raw coordinate data from the APAS system were then transformed to produce the displacement data, using a subject derived two-dimensional linear scale (Clothier *et al.,* 2004). Prior to filtering, the data were demeaned and detrended to satisfy the prerequisite conditions for the Fourier transform. The digitised coordinates of the raw 2D segment endpoint data were filtered using a Fourier transform with a cut-off frequency of 7Hz. Propulsive wave velocity (*U*) was derived using the methods employed in Sanders *et al.,* (1995). Wavelength (λ) was calculated as *U*/kick cycle frequency.

RESULTS & DISCUSSION:

Average swimming velocity and preferred kicking frequency showed similar values to those found in Arellano, *et al.,* (2002), albeit with slower swimming velocities (a consequence of swimmers performance levels). The results presented in Table 2 indicate that UUS most closely resembles the sub-carangifrom mode of animal undulatory locomotion. This is evidenced by the minimal vertical oscillations present in the anterior aspects of the body (wrist / shoulder) and the λ present being between half and one λ per body length.

Table 2 Kinematic Variables and Waveform Characteristics

Derived Kinematic Variables	Mean (S.D.)
Preferred Kicking frequency (Hz)	2.11 (0.03)
Average Swimming Velocity ($m.s^{-1}$)	1.24 (0.47)
Joint Centre Amplitudes	
Wrist (cm)	7.69 (2.27)
Shoulder (cm)	7.51 (1.46)
Hip (cm)	13.21 (1.54)
Knee (cm)	30.23 (2.35)
Ankle (cm)	47.9 (3.57)
5th MPJ (cm)	62.9 (4.21)
Waveform Characteristics	
Wavelength (λ per BL)	0.88 (0.19)
Propulsive Wave Velocity ($m.s^{-1}$)	3.86 (1.25)

It has previously been demonstrated (Vorontsov & Rumyantsev, 2000) that the arms act to present a more streamlined shape in an attempt to minimise form drag. It has also been asserted that the anterior aspects of a body (in this instance the hands/arms) may serve to induce minor turbulence along the anterior section of the body, thus serving to delay flow separation along the length of the swimming body (Bushnell & Moore, 1991). In addition, the λ and joint centre amplitude values provide evidence (table 2) to suggest another potential role for the hands and arms in the performance of UUS. As previously mentioned inertial recoil in the anterior aspects of the swimming body can be caused by the large amplitude vertical oscillations of the feet and ankles, which produce a concomitant oscillation or 'recoil', at the wrist/shoulder. The joint amplitudes of the wrist and shoulder indicate that comparatively small amounts of vertical movement is occurring in the those locations, indicating that the arms may also be acting as an inertial damper in a similar manner to the anterior fins present on fast swimming fishes. If the arms are acting as an inertial damper this will minimise form drag, as the frontal cross-sectional area perpendicular to the swimming direction is reduced on the anterior portion of the body. Again, this 'stabilisation' of the anterior aspects of the body may also act in accordance with the hydromechanics observed in AUL, whereby the anterior segments provide a stable platform from which the undulation is initiated. This would enable a more effective transmission of the propulsive waveform along the caudal aspects of the body (Lighthill, 1977), facilitating a more powerful whip-like kicking action.

CONCLUSION:

Tadpole, Trout or Tuna? It would appear that sub-carangiform mode of locomotion displayed by Trout exhibits the greatest commonality in undulatory swimming style with UUS. If the notion of the arms acting as an inertial damper holds true, this may provide information as to the most appropriate techniques for UUS performance. Specifically, if an area perpendicular to the dorso-ventral motion is increased i.e. the hands orientated accordingly and held slightly wider, this may enable a more effective kicking action. Whilst the morphological disparities compromise a direct comparison of animal with human undulatory swimming, the results of the present study invite further analysis to ascertain the efficacy of manipulating the properties of such an inertial damper in an effort to improve performance.

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