A comparison of the kinematics of the dolphin kick in humans and cetaceans

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ABSTRACT

Prerecorded video footage of 9 female and 13 male Olympic level athletes swimming underwater by using the dolphin kick was analyzed and comparisons of the stroke kinematics were made with a previous analysis of cetacean swimming conducted by Rohr and Fish (Rohr, J. J., & Fish, F. E. (2004). Strouhal numbers and optimization of swimming by odontocete cetaceans. The Journal of Experimental Biology, 207, 1633–1642). The velocities of the swimmers ranged from 1.12 m/s to 1.85 m/s which corresponded to a range of effort levels. While some swimmers performed the dolphin kick on their backs (dorsal), others employed the prone (ventral) or the side (lateral) position and no distinctions were made between these positions when considering the results. The raw quantities measured were body length \( L \) (from the fingertips of the outstretched arms to the tips of the toes), time \( T_L \) taken by the swimmer to traverse a body length, kick amplitude \( A \) at the toes, and the number of video frames per kick. These allowed us to determine the average velocity \( U \) of the swimmer, the kick frequency \( f \), the reduced or length-specific velocity \( U/L \) (body lengths traversed per second), and the non-dimensional quantities kick amplitude \( A/L \), the Strouhal number \( fA/U \) (ratio of tip or toe speed to forward speed) and the quantity \( fL/U \) (kicks per body length traversed). Trends of these dimensional and non-dimensional quantities were examined for the swimmers and compared to the cetaceans. Results showed that humans and cetaceans have comparable non-dimensional kick amplitudes, but kick frequency in humans was greater than for cetaceans swimming at equivalent speeds. Human swimmers required up to five kicks per body length traveled, while cetaceans require only 1.3. Length-specific
velocities reached a maximum of 0.81 for humans and this was about half that of cetaceans. Human swimmers had a mean Strouhal number of 0.80, which was above the range considered optimal for underwater undulatory propulsion.

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1. Introduction

The underwater dolphin kick in competitive swimming is used following entry as well as turns in freestyle, back stroke, and butterfly (Clothier, 2004; Colwin, 1992; Counsilman, 1968; Sanders, Cappaert, & Devlin, 1995). The use of this stroke in competitive swimming is relatively new (see Arellano, Pardillo, and Gavilán (2002) for a chronology of this stroke in competitive swimming). The appearance of this stroke in competitive swimming is a direct consequence of the fact that swimming underwater diminishes wave drag (Counsilman, 1968; Toussaint & Truijens, 2005) and can therefore give a competitive edge to the swimmer.

The dolphin kick consists of simultaneous vertically oriented motions of the feet. Displacements of the feet and body are normal to the coronal or frontal plane and have minimum magnitude at the hands, and increase along the length of the body, reaching a maximum at the toes. It was suggested that in this stroke, a traveling wave moved caudally along the body and legs (Gavilán, Arellano, & Sanders 2006; Sanders et al., 1995; Ungerechts, 1983). However, due to the limited number of rotational joints available in humans, the increase of displacement along the length of the body is not smooth. Cetaceans (whales and dolphins), on the other hand, have many vertebrae leading up to the end of the tail, which allow them to pass a much smoother wave with a smooth increase in displacement (Fish, 1993). This movement is used to oscillate the tail, which is expanded laterally into two wing-like flukes. Cetaceans also maintain a minimum displacement along the length of the body until the wave reaches the caudal peduncle, the necked portion anterior of the flukes. The displacement increases sharply across the short distance of the caudal peduncle and reaches a maximum at the tips of the flukes (Fish, 1993, 1998; Fish, Peacock, & Rohr, 2003).

Lighthill (1975) postulated that small displacements along the body anterior to the caudal peduncle avoid large recoil forces. The anterior portion of the body of cetaceans presents a large projected area. Oscillations of this area would produce substantial energy losses due to the development of large recoil forces to stabilize the body (Fish et al., 2003; Webb, 1992). For the same reason, the caudal peduncle, which sees the greatest increase in displacement, is necked to avoid presenting a large projected area and the resulting recoil forces. The flukes on the other hand provide a large area, combined with vertical displacements, resulting in large propulsive forces. Cetaceans have effectively separated their bodies into a drag producing part (anterior of the caudal peduncle) and a thrust producing part (posterior of the caudal peduncle) (Fish, 1993; Fish, 1998).

The thrust produced is associated with the momentum shed by the swimmer into the water (Lighthill, 1975). The manifestation of this shed momentum is the wake, which is composed of a thrust producing jet and alternating pairs of vortices (Triantafyllou, Triantafyllou, & Gopalkrishnan, 1991; Triantafyllou, Triantafyllou, & Grosenbaugh, 1993; Weihs, 1972). The distance between vortex cores is closely approximated by the amplitude of the trailing edge. The optimal creation of thrust associated with the jet and vortices lies in a narrow range of dimensionless frequencies referred to as the Strouhal number, St (Rohr & Fish, 2004; Triantafyllou et al., 1991, 1993). This parameter is related to how fast the vortices are being generated and the space between them. St has also been associated with maximum efficiency (Anderson, Streitlien, Barrett, & Triantafyllou, 1998; Rohr & Fish, 2004; Triantafyllou & Triantafyllou, 1995; Triantafyllou et al., 1993). The predicted St range occurs between 0.25 and 0.4, peaking near 0.3 for maximum efficiency of swimming and flying animals (Rohr & Fish, 2004; Taylor, Nudds, & Thomas, 2003; Triantafyllou & Triantafyllou, 1995; Triantafyllou et al., 1991, 1993). Kinematic analysis of a large number of cetaceans by Rohr and Fish (2004) provided insights into the nature of the cetacean stroke and performance related quantities,
such as efficiency and thrust. Cetaceans generally swam within the optimal range of $St$ with maximum efficiency within $St$ values of 0.25–0.35 (Rohr & Fish, 2004).

It is therefore only natural to compare the dolphin kick in humans with that of the originators, cetaceans. It is expected that the dolphin kick of humans will inevitably be inferior to that of cetaceans. Compared to cetaceans, humans have constraints on musculo-skeletal kinematics and a relatively small propulsive area (i.e., feet). Indeed, a number of patents have been issued for monofins based on dolphin flukes to improve human swimming performance by expanding the propulsive surface area (Evans, 1994; Lewis & Lorch, 1979; Meyer, 2001; Nicolas, Bideau, Colobert, & Berton, 2007; Soloviev, 1993; Wenzel, 1985). However, because of differences in the manner of data collection used to estimate propulsive efficiency, comparisons of swimming modes of humans and cetaceans are difficult. However, the basic physics of swimming is similar and therefore certain hydrodynamic parameters based on the kinematics can be used to make direct comparisons. The number of strokes required per body length traveled is expressed by the non-dimensional kinematic parameter $fl/U$, where $f$ is the stroke frequency (Hz), $L$ is the body length (m), and $U$ is the swimming velocity (m/s). This parameter is indicative of efficiency and thrust production.

The dolphin kick in humans has been the subject of a number of investigations in the past. Of particular note is the work of Ungerechts (1983), Ungerechts, Daly, and Zhu, (1998). In his study, Ungerechts compared the swimming of dolphins to the butterfly kick of seven elite swimmers. It should be noted that the swimmers were swimming on the surface (and not underwater) using the butterfly stroke and were performing the stroke in the ventral position. It is expected that the fly kick on the surface will generally be performed differently from the underwater dolphin kick due to the difference in the motion of the upper body between the two strokes as well as the presence of the air-water interface in the fly kick. Nevertheless, these studies are of relevance to the current study. The key conclusion of these studies was that although kinematics features such as length-specific body wave velocity and stroke frequency were not different, the movements of the dolphin flukes were more symmetrical than the feet of the swimmers.

Arellano and colleagues (Arellano, Pardillo, & Gavilán, 2003; Arellano et al., 2002) also performed extensive studies of the kinematics of the dolphin kick (also termed underwater undulatory swimming (UUS) in those studies). His analysis was based on a set of 32 swimmers of skill level ranging from national juniors to international seniors where all swimmers swam at maximum effort using the dolphin kick in the ventral position. Comparisons of mean values of various dimensional and non-dimensional kinematic parameters were made between swimmers of different levels. The primary conclusions and observations regarding the kinematics were that the mean Strouhal number for the swimmers was about 0.81 and that lower Strouhal numbers correlated with higher swimming speeds. Similar to Ungerechts et al. (1998), the study focused mainly on mean values of parameters and did not delve deeply into the observed trends.

In the current study, we perform a comprehensive analysis of the underwater dolphin kick in elite, Olympic level swimmers and compare the key dimensional and non-dimensional kinematic parameters to the large database on cetaceans developed by Rohr and Fish (2004). Both male and female swimmers are included in this study and we did not attempt to categorize the swimmers based on

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
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<tr>
<td>$L$</td>
<td>body length from fingertips of outstretched arms to toes</td>
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<tr>
<td>$A$</td>
<td>peak-to-peak toe amplitude</td>
</tr>
<tr>
<td>$T_L$</td>
<td>time taken to cover one body length</td>
</tr>
<tr>
<td>$U$</td>
<td>average velocity</td>
</tr>
<tr>
<td>$f$</td>
<td>kick frequency</td>
</tr>
<tr>
<td>$St$</td>
<td>Strouhal number, ratio of tip (toe) speed to body speed</td>
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<tr>
<td>$U/L$</td>
<td>reduced velocity, body lengths covered per second</td>
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<tr>
<td>$A/L$</td>
<td>non-dimensional kick amplitude</td>
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<td>$fl/U$</td>
<td>kicks per body length traversed</td>
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</table>
their stroke specialization. The swimmers in the current study swim in ventral, dorsal, or lateral orientations and also perform the kick at various effort levels. This leads to a larger range of parameters and allows us to go beyond mean values and examine trends in the variation of these parameters. Comparison of these trends with cetaceans over this large parameters space is expected to provide a better understanding of the performance gap between humans and cetaceans.

2. Methods

2.1. Experimental procedure

Prerecorded footage of 9 female and 13 male Olympic level athletes swimming underwater by using the dolphin kick was examined. The videos were recorded during practice sessions and while some swimmers were in a dorsal position, others were recorded performing the dolphin kick in the ventral or lateral body position. No distinctions were made between body positions. In all cases, the arms were held cranially so that propulsive movements were confined to vertically oriented oscillations of the body and legs.

The motions of the swimmers were recorded underwater with a Lorex brand camera, model CVC-6991. The frame resolution was 720 × 480 pixels, and the temporal resolution was 30 frames/s. Videos were taken from the side of the swimmers in the sagittal plane (Fig. 1). The cameras capturing the footage were either in motion parallel to the swimmers or fixed in place. Only video sequences were used in which the swimmers were moving horizontally and at an approximately constant speed (the largest variation in swimmer velocity about its mean value was about 8%) and 4–8 cycles were used to extract the kinematical data for each swimmer. The video footage provided by USA swimming was analyzed using the software Darttrainer (version 2.5.3.62; Dartfish Inc., Friburg, Switzerland). Using this software, visual landmarks (such as the finger tip and toes) were manually identified and digitized. Swimmers moved at the center of the swimming lane which resulted in distances from the camera that ranged from 1.3 m to 1.8 m.

Height measurements of all swimmers were provided by USA Swimming. The heights were recorded in normal standing posture and measured as the distance between the ground and the top of the head. These measurements were used as the reference length for each swimmer. When swimming, video frames of the athletes in which the body and legs were held in a position resembling the straight, standing posture were used to assign the reference length. The reference length enabled the conversion of distances measured on the computer screen to actual distances. The distance from the soles of the feet to the top of the head was assigned the given height and all measurements were made using this reference length. As mentioned previously, all videos were prerecorded and the authors had no influence over the runs. Thus it was not possible to use measurements, such as limb lengths, as reference lengths.

2.2. Kinematic parameters

The morphometrics and kinematic parameters, including body length (\(L, \text{m}\)), kick frequency (\(f, \text{Hz}\)), kick amplitude (\(A, \text{m}\)), and mean swimming speed (\(U, \text{m/s}\)), were derived from the videos. The body length \(L\) was defined as the distance from the toes to the fingertips of the outstretched arms. The frequency \(f\) was determined by dividing the frame rate by the number of frames to complete one kick cycle. The amplitude \(A\) was measured as the distance between the maximum and minimum vertical displacements of the toes (distance from the peak of the toes at the upstroke to peak of the toes at the downstroke, see Fig. 2). The velocity \(U\) was determined by dividing the body length \(L\) by the time elapsed between the fingertips and the toes passing the same reference mark (i.e., the time taken for the swimmer to traverse one body length, \(T_L\)). Due to differences in size between the swimmers, amplitude \(A\) and velocity \(U\) were scaled to length-specific parameters \(A/L\) and \(U/L\).

Estimates of swimming efficiency were provided through the derived parameter of \(St\), according to the equation

\[St = \frac{fa}{u}\]

and the kinematic parameter \(fl/u\).
2.3. Uncertainty analysis

With the given video frame resolution measurement error was conservatively estimated at ±0.1 m across the dataset. This uncertainty was primarily a result of deterioration of visibility due to entrainment of bubbles in some of the videos. Time was determined through use of the frame rate of 30 frames/s with a corresponding maximum uncertainty of ±1/30 s. Both the frame rate and the uncertainty in length measurements affected the velocity, the frequency, and the kick amplitude measurements. However, for measurement of the amplitude $A$, a full frame ambiguity at the maximum and minimum toe positions was considered negligible, as the velocity of the toes was low when changing direction. Only the uncertainty in length measurement affected the body length measurement, as this required only one static frame.
Uncertainties also propagated through to the combined parameters $U/L$ (body lengths traveled per second), $A/L$ (amplitude reduced by body length), Strouhal number $St$, and $fL/U$ (kicks per body length traversed) and this propagation was determined according to Kline and McClintock (1953) and Beckwith, Marangoni, and Lienhard (1993). Maximum uncertainties in body length $L$, velocity $U$, frequency $f$, and kick amplitude $A$ were 5%, 7%, 7%, and 28%, respectively. Maximum uncertainties in the combined parameters $U/L$, $A/L$, $St$, and $fL/U$ were 8%, 28%, 29%, and 10%, respectively. All results are considered to have 95% coverage.

Comparisons of the kinematics of the human dolphin kick and cetaceans (i.e., whales and dolphins) were made using data from Rohr and Fish (2004). The kinematic data for cetaceans was obtained from seven species for 267 swimming trials. Differences in the kinematics between swimmers were analyzed by Student’s $t$-test (Data Desk). Trends in data were determined by regression analysis. Variation about means was expressed as $\pm$ one standard deviation (SD). Results were considered significant at the $\alpha = .05$ level.

3. Results

All measured and calculated data for male and female swimmers are listed in Table 1. Only differences in body lengths were determined to be statistically significant ($t$-test, df = 20, $p < .05$) between males and females. Therefore, data for males and females were pooled for analysis of all kinematic variables.

The average velocity $U$ ranged from 2.08 to 2.51 m/s, which corresponded to less than one body length per second ($U/L = 0.48–0.81$). No relationship was found between body length $L$ and velocity $U$ for the submerged dolphin kick. The amplitude $A$ remained as a relatively constant proportion of $L$ at $A/L$ of $0.23 \pm 0.04$ (Fig. 3). The kick frequency $f$ varied from 1.66 to 2.66 Hz, but was not found to be correlated with swimming speed (Fig. 4).

The non-dimensional parameters $fL/U$ (number of kicks per body length traversed) and Strouhal number $St$ both displayed significant indirect relationships with $U/L$ (Figs. 5 and 6). The regression equations were

$$fL/U = 6.58 - 4.85 \frac{U}{L}$$

with a correlation coefficient of .65 (df = 20; $p < .01$), and

$$St = 1.46 - 1.04 \frac{U}{L}$$

with a correlation coefficient of .65 (df = 20; $p < .01$). $St$ values were generally high, ranging from 0.45 to 1.08 with a mean value of $0.80 \pm 0.15$ (the standard deviation is 0.15). These values were above the
optimal range of 0.25 to 0.4 (Triantafyllou & Triantafyllou, 1995; Triantafyllou et al., 1991, 1993) for fish and cetaceans. In fact, analysis of the data of Rohr and Fish (2004) indicates the following regression equations for the cetaceans.

### Table 1

<table>
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<tr>
<th></th>
<th>L (m)</th>
<th>U (m/s)</th>
<th>f (Hz)</th>
<th>A (m)</th>
<th>U/L (1/s)</th>
<th>A/L</th>
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Fig. 3. Length-specific amplitude, A/L, as a function of length-specific swimming speed, U/L. Closed symbols represent female swimmers and open symbols are male swimmers. The line is the mean kick frequency for pooled values of males and females.
Mean and maximum values of $\frac{U}{L}$ for humans were only 39% and 18% of cetaceans. Mean values of the amplitude $A$ were significantly different ($t = 3.25, df = 287, p < .01$) between humans and cetaceans. When scaled as $A/L$ (Fig. 7), a significant difference was also found ($t = 3.19, df = 287, p < .01$), despite similar mean values of $0.23 \pm 0.04$ and $0.21 \pm 0.03$ for humans and cetaceans.
respectively. As opposed to the trend for cetaceans of increasing kick frequency $f$ with increasing $U/L$, the $U/L$ for the human dolphin kick was relatively constant (Fig. 8) with frequency. This difference probably reflected the limited range of swimming speed $U$ for humans in comparison to cetaceans. Based on the regression equation from Fig. 2 in Rohr and Fish (2004) for a cetacean swimming at $U/L$ of 0.63, the kick frequency $f$ for the human dolphin kick was 1.9 times greater.

A significant difference was found for the Strouhal number $St$ between humans and cetaceans ($t = 34.07$, df = 287, $p < .001$). $St$ for humans was three times greater than that for cetaceans with mean values of 0.80 ± 0.15 and 0.27 ± 0.06, respectively. Whereas $St$ for humans inversely varied with $U/L$, $St$ was nearly constant for cetaceans (Fig. 9).

Fig. 6. Relationship of Strouhal number, $St$, and $U/L$ from pooled data of male and female swimmers. The line represents the best fit of the data. The regression equation is provided in the text.

Fig. 7. Plot of distribution of length-specific amplitude, $A/L$, to length-specific velocity, $U/L$, for humans using a dolphin kick (closed symbols) and cetaceans (open symbols). Data on cetaceans provided from Rohr and Fish (2004).
4. Discussion

This study examined the kinematics of swimmers using the dolphin kick. As mentioned previously, swimmers used a variety of body positions (dorsal, ventral, and lateral) and no distinctions were made between body positions. Variables, such as frequency and amplitude of the stroke, are of particular importance in determining propulsive performance. The frequency determines the time course of the acceleration provided to a mass of water in the wake, whereas the amplitude, in conjunction with the area of the feet, contributes to the volume and mass of water being affected. Collectively, these
factors interact to impart a force on the water, which generates a reaction force to derive thrust. The propulsive interaction between the body and the water is mainly confined to the trailing edge (i.e., the feet) (Lighthill, 1975). When swimming without use of the arms, it is at the broad trailing edge that propulsive movements are fastest and largest, and produce the greatest amount of thrust along the body.

Studies of unaided swimming using the dolphin kick generally have not focused on the kinematics over a range of speeds. Sanders et al. (1995) examined wave characteristics of butterfly swimming between 1.2 and 1.7 m/s with respect to amplitude, velocity, and acceleration. The wave motions propagated along the body contributed to propulsion from the kick in a whip-like manner (Gavilán et al., 2006; Ungerechts et al., 1998). However, Sanders et al. (1995) and Gavilán et al. (2006) confined their analysis to the ankles as the caudal-most point. Maximum amplitude $A$ at the ankle for a typical butterfly swimmer was approximately 0.29 m. International senior swimmers in a prone position using solely the dolphin kick for propulsion had an average amplitude $A$ of 0.62 m and frequency $f$ of 2.14–2.17 Hz (Arellano et al., 2002; Gavilán et al., 2006). These data were comparable to the results found in the present study (see Table 1 and Figs. 3 and 4), although the amplitude $A$ in this study was 15% lower than the value from Arellano et al. (2002).

As mentioned before, the swimmers’ body positions varied between dorsal, lateral, and ventral, but no distinctions were made when considering results. Arellano et al. (2006) studied the influence of varying between the three body positions and found significant kinematical differences. These differences were, however, attributed to the swimmers lack of familiarity with and past training of the different positions. The current authors believe that given enough familiarity and training, there should be no significant differences between dolphin kicking in different body positions.

In this study, frequency and amplitude for the humans remained relatively constant across the range of $U/L$ (Figs. 3 and 4). In contrast, organisms that swim by undulation or oscillation of the body and caudal fin are known to increase frequency with increasing speed, but maintain constant amplitude over a range of speeds (Bainbridge, 1958; Fish, Innes, & Ronald, 1988; Hunter & Zweifel, 1971; Rohr & Fish, 2004; Videler, 1993; Webb, 1975). The lack of correlation between the frequency and $U/L$ for the human swimmers may have been the result of a limited speed range that was near the maximal effort of many of the swimmers. It is expected that at lower speeds the frequency will decrease. When examined on a length-specific basis, the constant amplitude ($A/L = 0.23 \pm 0.04$) was near the typical value for body and caudal fin undulators and oscillators. These organisms maintain their amplitude at about 20% of body length (Rohr & Fish, 2004; Webb, 1975). Modulation of frequency with constant amplitude would prevent excessive distortion of the body, which would increase overall drag and decrease locomotor efficiency.

The Strouhal number $St$ is related to the ratio of tip speed to overall body speed. Among human subjects, the Strouhal number varied considerably, yet velocities were comparable, indicating a substantial variation of kinematics from subject to subject. The Strouhal number was found to decrease with increasing $U/L$. However the slope of the linear regression line (Fig. 9) for humans is much steeper than that of the cetaceans. This clearly indicates that whereas even slight reduction in Strouhal number for cetaceans leads to impressive increase in length-specific velocity, a similar increase is not seen for the human swimmers. This is clear reaffirmation of the fact that the swimming apparatus of humans is not as effective as that of cetaceans. In fact, the data seems to indicate that the limiting value of length-specific velocity $U/L$ for humans at $St = 0$ is about 1.4. It should also be pointed out that the values of $St$ for the human swimmers were outside the optimal range, where propulsive efficiency is considered to be maximal (Triantafyllou & Triantafyllou, 1995; Triantafyllou et al., 1991, 1993). Only one swimmer (F3) with $St = 0.45$ came close to the optimal range (Table 1). Arellano et al. (2002) showed swimmers using a dolphin kick also had high Strouhal number values of 0.79 and 0.95. The Strouhal numbers reported in the current study are also in line with those reported by Arellano et al. (2006) where Strouhal numbers of 0.95, 0.86, and 0.95 were reported for the three different body positions.

As expected, human swimmers using the dolphin kick were outperformed by their cetacean counterparts. Specifically, cetaceans’ velocities were approximately three times greater and their length-specific velocities, or body lengths covered per second, more than double those of human
subjects. In addition cetaceans required less than half of the kicks to travel one body length than most of the human swimmers, and less than a third of the kicks than some. Unexpectedly, the human swimmers and the cetaceans had comparable kick amplitudes and non-dimensional kick amplitudes. This implies that the subjects, both human and cetacean, are limited to a relatively narrow range of kinematics when performing the dolphin kick effectively.

The basic movements of the body and feet of human swimmers using the dolphin kick have similarities with the propulsive movements of actual dolphins (Arellano et al., 2002; Clothier, 2004; Nicolas et al., 2007; Sanders et al., 1995; Ungerechts, 1983; Ungerechts et al., 1998). However, considerable differences are displayed between the human dolphin kick with the actual swimming stroke of a dolphin. The number of joints available and their range of movement are lower in humans compared to dolphins (Long, Pabst, Shepherd, & McLellan, 1997). Ungerechts et al. (1998) noted the inflexibility of the human ankle, which required compensatory movements to increase swimming performance. The inability to hyperextend the knee and ankle limit symmetrical movements of the foot during upstroke and downstroke with a steady generation of thrust by humans (Arellano et al., 2002). Using particle image velocimetry for dolphin kicking in the prone position, Miwa, Matsuuchi, Shintani, Kamata, and Nomura (2006) demonstrated that the development of periodic vortex rings with the downstroke produces more useful jet flow than the upstroke. Asymmetrical vortices were visualized using bubble injection (Arellano, 1999; Arellano, Terrés-Nicol, & Redondo, 2006; Arellano et al., 2002). The vortex shed at the termination of the downstroke was larger than for the upstroke. In contrast to this Fish (1993) found that dolphins had a symmetrical stroke in which the angle of attack of the flukes could be adjusted to maintain steady thrust production through both upstroke and downstroke.

The underperformance (as measured by number of kicks per body length travel) of human swimmers when compared to cetaceans is a consequence of their anatomy and musculature. Additional indications of the lowered proficiency of the dolphin kick by humans are their higher Strouhal numbers. This implies that the human feet are producing less thrust than the flukes of cetaceans, as they must keep them moving at higher velocities to maintain relative comparable body speed. Although the amplitude was similar in humans and dolphins, the kick frequency of humans for an equivalent swimming speed was higher resulting in higher Strouhal numbers. In addition, the combined projected area of the feet is smaller than that of the flukes of dolphins (Fish, 1993, 1998). Propulsion is more efficient when a large mass of water is accelerated slowly than to rapidly accelerate a small mass of water (Alexander and McNeill, 1983). Furthermore, the flukes produce highly efficient lift-based propulsion as an oscillating wing (Lighthill, 1975). This assertion is supported by the fact that underwater swimmers using a dolphin kick augmented with a monofin swim faster than freestyle swimmers using all four limbs (Matsuuchi et al., 2006). Monofin swimmers had the highest velocities, high efficiencies, and lowest active drag at Str = 0.34 (Nicolas et al., 2007). A peak efficiency of 0.82 occurred at Str close to 0.4. These results are comparable with the efficiency and Str for cetaceans. The maximum mechanical efficiency ranged from 84 to 90% for swimming cetaceans within the range of Str of 0.25–0.35 (Fish, 1998; Rohr & Fish, 2004).

5. Conclusions

Examination of a large dataset of dolphin kick in humans and cetaceans has provided some additional insights into the limits of human performance in this swimming stroke. In conclusion, human swimmers using the dolphin kick are underperforming and underpowered compared to cetaceans. Even though some kinematic variables such as normalized amplitude and frequency are similar, unaided human swimmers are unable to match the locomotor performance of cetaceans. The Strouhal numbers for humans are above the range associated with optimal performance and high efficiency for oscillatory swimming. Equally important is the observation that the increase in length-specific speed with decrease in Strouhal number is significantly lower in humans indicating that there is a severe limit on the fastest speeds that can be attained in humans using this stroke.
References


