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Importance of sagittal kick symmetry for underwater dolphin kick performance

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The purpose of this study was to determine how sagittal kick symmetry in the underwater dolphin kick (UDK) between the downkick and upkick phases is related to UDK performance. Fifteen adult male competitive swimmers ranging from provincial to international level were filmed performing three trials each of maximum effort UDK over 15 m using an underwater video camera. Video frames were manually digitized and each subjects' single fastest trial was evaluated for between-subject comparisons. Kinematic variables were calculated for each individual and Pearson product-moment correlations between the average horizontal centre of mass velocity (V_x) and all kinematic variables were calculated. Horizontal velocity during the downkick, horizontal velocity during the upkick, relative time spent in each phase, maximum chest flexion angle, maximum knee and ankle extension angles, the ratio of flexion/extension for chest, knee and ankle angles, and maximum vertical toe velocity during the upkick phase correlated significantly with V_x ($p < 0.05$). The ratio of downkick vertical toe velocity/upkick vertical toe velocity was significantly negatively correlated with V_x ($p < 0.05$). These results indicate the importance of kick symmetry for UDK performance, and indicate that performing the upkick phase well appears to be most important for UDK performance.

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1. Introduction

There is a growing research interest in the underwater dolphin kick (UDK) in competitive swimming due to the apparent advantages that can be gained by successfully performing UDK sequences following starts and turns. The major difference between swimming below versus on the surface of the water is improved propulsive efficiency through reduced resisted drag force (Lyttle, Blanksby, Elliott, & Lloyd, 1998). This is accomplished through the reduction of wave drag, as it is minimized at a depth of 0.6–0.7 m at speeds experienced by elite swimmers following turns and starts (1.9–3.1 m/s; Lyttle et al., 1998; Vennell, Pease, & Wilson, 2006). It is legal for swimmers to remain underwater for 15 m following a start or turn in butterfly, backstroke, and freestyle (FINA, 2009); equal to 30% of the total race distance in a 50 m long course (Olympic size) pool, and 60% of the total race distance in a 25 m short course pool. Since nearly a third of the race distance in long course and two thirds in short course competition can be covered underwater, an effective UDK can benefit swimming race performance.

The underwater dolphin kick is a cyclic motion where the toes oscillate in a regular fashion with one spatial maximum (up-peak) and one spatial minimum (down-peak) in the vertical direction occurring over the course of one cycle. It has been suggested that a wave travels caudally from the torso to the toes, increasing in amplitude at each body segment in a whip-like action, whereby momentum is transferred from the larger body segments to the smaller body segments (Gavilán, Arellano, & Sanders, 2006; Sanders, Cappaert, & Devlin, 1995; Ungerechts, 1983). Underwater dolphin kick can be broken down into two phases; the downkick and upkick. In a ventral body position, the downkick is characterized by hip flexion and knee extension and occurs from the up-peak position and ends in the down-peak position; the upkick is characterized by hip extension and knee flexion and occurs from the down-peak position and ends in the up-peak position. Figs. 1 and 2 respectively demonstrate a swimmer over the course of one complete kick cycle and the corresponding toe marker path during that cycle.

Previous studies have compared the kinematics of human undulatory propulsion to the kinematics of dolphins/cetaceans (Ungerechts, 1983; Von Loebbecke, Mittal, Fish, & Mark, 2009a, 2009b). Ungerechts (1983) compared the kinematics of the butterfly stroke with dolphins and found that the primary difference between the human swimmers and dolphins was that dolphins were able to perform symmetrical downkick and upkick phases; in contrast, the human swimmers were relatively less effective at the upkick phase, and he concluded that only swimmers who were able to hyperextend their knees would be able to perform the upkick phase effectively. Despite similarities between the butterfly stroke and UDK, butterfly is performed on the surface and involves propulsion with the arms and legs. Von Loebbecke et al. (2009a) and Von Loebbecke et al. (2009b) compared the kinematics of the UDK in humans with odontocete cetaceans (class of mammalian swimmers, including dolphins, toothed whales, porpoises, etc.), finding that humans were less propulsively efficient and slower than cetaceans over the range of kicking frequencies and kicking amplitudes selected by the human swimmers. The differences between humans and cetaceans were attributed to the disadvantageous anatomy and musculature of humans, such as narrow feet and less-flexible joints, which especially limit the performance of the upkick phase.

Kicking symmetry in the UDK is defined as the ability to produce equivalent propulsion during the downkick and upkick phases. This is accomplished through similar kinematics between the downkick and upkick phases. Theoretically, symmetry between downkick and upkick phases should result in more consistent CM velocity as there are two equivalently propulsive phases, compared with one propulsive and one resistive phase in an assymetrical kick cycle. Von Loebbecke et al. (2009a) evaluated the propulsive efficiency of human underwater dolphin kicking using Computational Fluid Dynamics (CFD) and found that parameters evaluating the entire kick cycle could not predict propulsive efficiency in UDK, but is connected to overall swimming style. Kinematics between downkick and upkick were compared by Arellano, Pardillo, and Gavilán (2000), but in this study the upkick phase was broken into two phases, which is inconsistent with the rest of the literature. Furthermore, data such as kick displacement and toe velocities were reported for the whole kick cycle, not for the individual downkick and upkick phases. Given their anatomical differences, symmetry between the downkick