MECHANICS OF BODY ROLL IN FRONT-CRAWL SWIMMING

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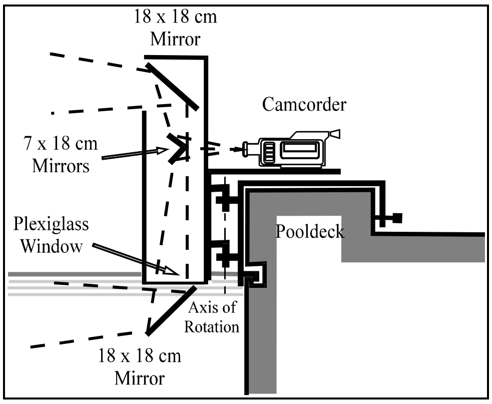
INTRODUCTION: The rolling action of the body about the long-axis of the body (bodyroll) has been known to have important functions in front-crawl swimming. Attainment of an appropriate amount of bodyroll facilitates the breathing action, enhances the medio-lateral movements of the stroking hand (Hay et al., 1993 and Liu et al., 1993) and reduces the possibility of developing "swimmer's shoulder" problems (Ciullo and Stevens, 1989, McMaster, 1986, Neer and Welsh, 1977, Penny and Smith, 1980, and Richardson et al., 1980). There has been, however, no quantitative attempt made to determine how swimmers generate and maintain bodyroll. The purpose of this study was to identify the mechanical factors that would explain the mechanics of bodyroll in front-crawl swimming. The major goal of this study was to describe how elite swimmers maintain rolling action of the body by means of mechanical quantities, so that the mechanical cause of the bodyroll could be hypothesized.

METHODS:
Eleven male competitive swimmers performed front-crawl swimming at a self-determined sprinting speed for two lengths of a 22.9 m pool. The subjects were asked to take a breath for every two stroke cycles on their preferred sides, so that the effect of breathing action on the bodyroll could be investigated. The performances were recorded using two panning periscopes (see figure). A Panasonic camcorder mounted on each of the two periscopes was used to record the performances at 60 Hz. The videotapes of the performances were digitized using a Peak Motion Measurement System (Peak Performance Technologies, Denver, CO, USA) and the resulting sets of two-dimensional coordinate data were used as input to custom software that generated the corresponding three-dimensional coordinates (Yanai et al., 1996). The determined three-dimensional coordinates were smoothed using a Butterworth filter with an estimated optimum cut-off frequency of 7.4 Hz (Yu, 1988). The subject's body was modeled as fourteen simply-linked cylindrical rigid segments. The inertial parameters of each body segment were adopted from the studies of Hinrichs (1990) and Whitsett (1963). Angular momenta of the body segments were computed relative to a translating reference system attached to the center of mass of the subject using the procedure described by Dapena (1978), and summed to determine the angular momentum of the whole body. The component of the determined angular momentum about the long-axis of the trunk was then used for analysis. The first time-derivative of the angular

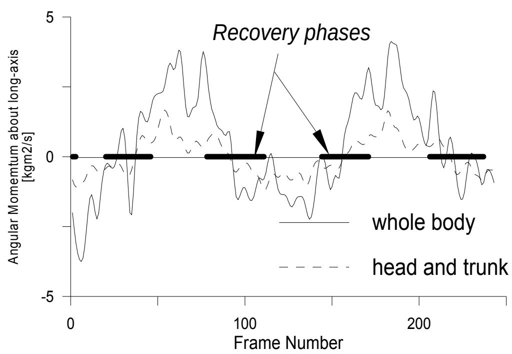


momentum of the whole body was numerically computed to determine the magnitude of the external torque acting on the body. The data analysis procedure consisted of the computation of means and standard deviations, and a repeated-measures ANOVA to test the difference between breathing side (both with and without breathing action) and non-breathing side at the significant level of 0.05. Post-hoc tests (Tukey's HSD) were also conducted to evaluate the significance of the effect of breathing pattern.

RESULTS AND DISCUSSION:

Kinematics

General: In many cyclic activities, such as walking and running, upper and lower limbs move in opposing directions, and the angular momentum of whole body about the long-axis of the trunk is kept near zero. Such movements are considered efficient because no effort is required to generate an external torque to create and change the angular momentum of the body. In front-crawl swimming, the angular momentum of the whole body about the long-axis of the trunk was found to change in a systematic manner (see figure). The angular momentum changed from the mean value of 4.15 (left) to -4.39 kgm^2/s (right) in a systematic manner. The mean value for the maximum amplitude of the angular momentum over all subjects was significantly greater than zero ($p < 0.00$) for both sides. These results indicate that an external torque was acting on the body to maintain the rolling action of the body. Of the angular momentum of whole body, 40% was due to the rolling action of the head and trunk, and 60% due to the actions of the upper and lower limbs.

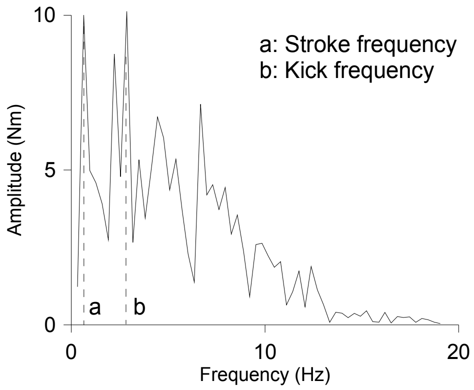


Coordination of upper and lower limbs: The angular momenta of the upper and lower limbs were directed in opposing directions for 56% of the stroke time. Such counter-movements of the limbs were often observed while the trunk was rolling without twist. When the lower limbs rotate in one direction (say clockwise) against fluid resistance, the trunk must receive a torque from the lower limbs in the other direction (counter-clockwise) through the hips. This torque consists of the torque due to fluid resistance and the reaction of the torque that generated the lower limb rotation. At the same time, the upper limbs rotate in opposing direction to the lower limbs (counter clockwise). The fluid resistance and the reaction of the torque (clockwise) that generated the upper limb rotation, in turn, act on the trunk through the shoulders. These opposing torques act at the upper and lower ends of the trunk did not result in a twist of the trunk. It suggests that the trunk acts as a rigid link to transfer the reactions of the torques that generated the angular momenta in upper and lower limbs against the fluid resistance.

Effect of Breathing action: The mean values of maximum angular momenta toward the breathing side (4.50 & 4.33 kgm^2/s for the strokes with and without a breathing action, respectively) were significantly greater ($p < 0.00$) than that toward the non-breathing side (3.51 kgm^2/s). No significant difference was, however, found in the mean values of maximum angular momentum of the head and trunk between breathing (both with and without breathing action) and non-breathing sides (2.00, 1.94, & 1.69 kgm^2/s, respectively). These results indicate that the increase in the angular momentum toward the breathing side is due to an increase in the angular momentum of upper and/or lower limbs. It also indicates that a greater magnitude of the external torque must be applied toward the breathing side than toward the non-breathing side.

Kinetics

External torque: The external torque acting on the body about the long-axis of the trunk attained its peak value (mean = ± 64 Nm) at, or around, the instant that the arm exited the water and also in the middle of the recovery phase of the stroke. A Fourier analysis (see figure) was conducted and the frequency and the amplitude of the transformed components of the external torque-time curve were examined. The signal that had the same frequency as the stroke frequency (mean: 0.63 Hz) or the kicking frequency (mean: 1.92 Hz) attained one of the highest amplitudes of all signals (means: 11 Nm and 8 Nm, respectively). The peak amplitudes of the former signal were attained during the recovery phases of the stroke. The latter signal attained its peak values harmoniously with the kicking actions. Other signals with relatively high frequencies (> 5 Hz) for the given motor skill were found to attain a large amplitude (< 23 Nm) in some trials. No obvious relationship between these signals and the stroking pattern could, however, be observed clearly.



Hypothesizing mechanical cause of bodyroll: An assumption was made to isolate and hypothesize the mechanical cause of bodyroll. That is, the lift force generated by arm and leg actions contributes entirely to the propulsion, and thus, it has no effect on bodyroll. With this assumption, the angular momenta of the limbs could be related to the generation of the external torque in the following argument: When the right arm has entered the water in front of the right shoulder and moves vertically downward, the angular momentum of the arm about the long-axis of the body is directed in counter-clockwise from an observer in front. The fluid force acting on the right arm is directed upward (drag) and/or forward (lift). This fluid force generates clockwise torque about the long-axis of the body. When the right arm moves medially in the middle of the pull phase (inward pull), the angular momentum of the right arm is directed in clockwise. The fluid force acting on the right arm is directed outward (drag) and forward (lift). This fluid force generates counter-clockwise torque about the long-axis of the body. With the assumption, the torque generated by a limb action must be acting in the opposing direction to the angular momentum of the limb. This characteristic and the results of the Fourier analysis suggest the following hypotheses:

Kicking action was hypothesized to be a major drive in generating the large torque at, or around, the instant that the arm exited the water, which apparently helped the body to attain a large bodyroll angle. The kicking action in this period is distinct and is almost always greater than the other two kicking actions. The other large torque observed in the middle of the recovery phase was hypothesized to be generated by the force due to inward pull of the stroke and the buoyant force acting at a position located laterally (away from the recovery side) with respect to the center of gravity of the body. The resultant torque of these two forces apparently stopped the bodyroll and initiated the roll toward the other side.

CONCLUSIONS: The findings of this study support the following conclusions:
1. External torque was necessary to maintain the rolling action of the body.
2. While rolling, the trunk acted as a rigid link to transfer the twisting torques.
3. The external torque was hypothesized to be generated by the kicks at, or around, the instant of arm exit, inward pull of the stroke, and the buoyant force acting on those body segments immersed in water during the recovery phase.

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