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FRONTCRAWL PROPULSIVE PHASE DETECTION USING INERTIAL SENSORS

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Front crawl is an alternating swimming stroke technique in which different phases of arm movement induce changes in acceleration of limbs and body. This study proposes a new approach to use inertial body worn sensors to estimate main temporal phases of front crawl. Distinctive features in kinematic signals are used to detect the temporal phases. These temporal phases are key information sources of qualitative and quantitative evaluation of swimming coordination, which have been assessed previously by video analysis. The present method has been evaluated upon a wide range of coordination and showed a difference of 4.9% with video based system. The results are in line with video analysis inter-operator variability yet offering an easy-to-use system for trainers.

KEY WORDS: swimming phases, arm coordination, accelerometer, gyroscope.

INTRODUCTION: A reliable data capture technique based on scientifically sound principles is a key to carry on all human motion studies. Human motion analysis in the water comprises complications as the water element avoids using many classical techniques of motion capture. Traditionally, assessment of swimming technique has been performed based on frame-by-frame video analysis (Callaway et al., 2009). The video footage allows evaluation of both qualitative and quantitative features of swimming such as the ratio of arm strokes, stroke length, angles of arm joints etc. However, the method is burdensome to be fully automated and entails demanding data post-processing. The functionality of the system can be affected by various factors such as restricted field of view, water-air interface turbulence, refraction of light in the water and image blurring (Schechner & Karpel, 2004). In 3D analysis the field of view of video based system provides only 2 or 3 cycles that can hardly be representative of a lap containing more than 15 cycles and makes video based inter-cycle variability assessment misleading.

Consequently, there is a need for an easy-to-use system with short set up time that can be used openly by coaches in swimming pool. A new emerging alternative to video based swimming analysis equipment is inertial sensor, which can be placed on different sites on swimmers body. Pansiot et al. (2010) and Bächlin et al. (2009) used 3D accelerometer data in order to provide information such as stroke counts, turn and wall push-off detection and some spatial parameters. According to the current knowledge of the authors, Ohgi (2002) have performed the only study on front-crawl arm cycle phase-detection based on inertial signals. He used wrist-worn sensor containing 3D accelerometer and 3D gyroscope. Since he did not consider the orientation information during phase detection, he was not able to determine the beginning of recovery phase.

The interaction between intrinsic dynamics of body and water mechanical properties results in coordination between arms and legs as well as inter-arm coordination. A widespread metric to quantify arm stroke coordination is index of coordination (IdC), which was introduced by Chollet et al. (2000). The index is based upon lag time between the propulsive phases of each arm and to date is assessed by human operators using video based systems. We hypothesized that there are temporal features in kinematic signals of swimming from which we can calculate IdC. The objective of this study was to present an automated inertial system in order to detect main stroke temporal features for IdC calculation. The data from 3D accelerometer along with 3D gyroscope was used in data fusion filters to discriminate arm propulsive and non-propulsive phases to describe arm coordination.

METHODS: Seven elite swimmers (18.7 ± 5.3 yr, 177.4 ± 4.8 cm, 67.7 ± 5.7 kg) have participated in this study. Trials were performed as three 300-m front crawl in a 50-m indoor pool. The athletes were asked to maintain their coordination as long as possible in three different modes: one freely-chosen, one catch-up mode (with a lag time between two propulsions as in long-distance paces) and one in superposition mode (with an overlap between two propulsions, as in sprint events). So we can ascertain that the system was tested in broad range of coordination. Subjects were filmed by two synchronised sagittal and frontal underwater cameras (25 Hz). Two inertial units (Physilog®, BioAGM, CH) including 3D accelerometer (±10g) and 3D gyroscope (±1200°/s) recording data at 500Hz and synchronized with video cameras, were placed on the forearms of each swimmer. A push-button, which started the sensors' data acquisition, also provided a flashlight in front of video cameras to synchronize the two systems. The sensors' axes were aligned to the anatomical body axes by performing a functional calibration procedure similar to Favre et al. (2009). Kinematics signals (acceleration and angular velocities) were expressed in the sensor frame $X_SY_SZ_S$ (after alignment with anatomical frame). The transformation of these kinematics signals in the fixed inertial frame $X_FY_FZ_F$ was obtained by using the method proposed by Favre et al. (2006). Fig.1 illustrates the coordinate frames and directions used in this study.

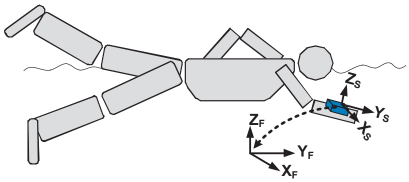

Figure 1: Orientation of arm obtained in Fixed frame ($X_FY_FZ_F$) from Sensor frame ($X_SY_SZ_S$).

In order to detect the beginning of pull and recovery phases using inertial sensors, we considered the definition of Chollet et al. (2000). Based on their definition each arm stroke can be divided into four distinguishable phases i.e. entry and catch, pull, push and ultimately recovery. Distinctive features on kinematic signals discriminate these phases. A complete stroke cycle (ΔT_C) has been determined as the time interval between two successive peaks ($t_{\omega p+}$) of pitch angular velocity of arm (see also Fig.2a in Results). We considered that pull phase starts after a relatively motionless period of the arm in the catching phase. This period is observable in pitch angular velocity ($\omega_{S,pitch}$) and the forward acceleration ($a_{S,f}$ in Fig.2b) of the arm expressed in sensor frame, where thereafter the slope of both signals changes drastically and corresponds to the backward and downward movement of the forearm. The beginning of the pull at each stroke has been determined by detecting this slope change. For this purpose primarily, the first negative peak ($t_{\omega p-}$) of the $\omega_{S,pitch}$ was detected. Then the change in the slope of both signals ($\omega_{S,pitch}$, $a_{S,f}$), were detected in the interval [$t_{\omega p+}+0.2\Delta T_C$, $t_{\omega p-}$] using the cumulative sum algorithm (Gustafsson & Firm, 2000). The beginning of the pull (t_{PUL}) was computed as the average of detected instant on both signals.

To detect the beginning of recovery phase, we considered that it starts with a local maximum acceleration in arm as the arm gets unloaded from the resistive drag force when it exits the water. Consequently, first the acceleration was computed in the fixed frame (a_{fix}) and then the gravity component was removed. Then, the local maximum on the norm of acceleration of the arm which is denoted by $||a_{fix}-g||$ was detected (see Fig.2c) during the interval [$t_{\omega p+}+0.8\Delta T_C$, $t_{\omega p+}+\Delta T_C$] and considered as the beginning of the recovery phase (t_{REC}).

Two operators under supervision of an experienced coach performed the video analysis to extract the beginning of the pull and recovery phases for each stroke cycle. The comparison between the operators and inertial system merely carried out upon the cycles, which were detectable by camera.

For each stroke cycle *k*, coordination was quantified based on the index of coordination (IdC) as defined in Chollet et al. (2000) by considering the instant of t_{PUL}, t_{REC} obtained for the Right and Left arms:

$$IdC^k = \frac{t^k_{REC,Left} - t^k_{PUL,Right}}{\Delta T^k_{C,Right} + \Delta T^k_{C,Left}} + \frac{t^k_{REC,Right} - t^{k+1}_{PUL,Left}}{\Delta T^k_{C,Right} + \Delta T^k_{C,Left}}$$

For each cycle stroke t_{PUL}, t_{REC} and IdC were estimated by inertial sensors and compared to values obtained by video analysis (reference system). A test-retest process has been done to evaluate the reliability of our video analysis. Statistical test and interclass correlation coefficient were used for test-retest reliability assessment.

RESULTS: Fig.2 depicts a typical result of phase detection where the starts of pull and recovery phases found on right (Fig.2 a,b,f) and left arm (Fig.2 d,e,c) signals by applying our algorithms. In addition, this figure illustrates different time intervals to estimate IdC. By considering all trials in which both pull and recovery instants were detectable for the operators, we had a total of 126 video-extracted cycles to compare with the same parameters estimated by the inertial system.

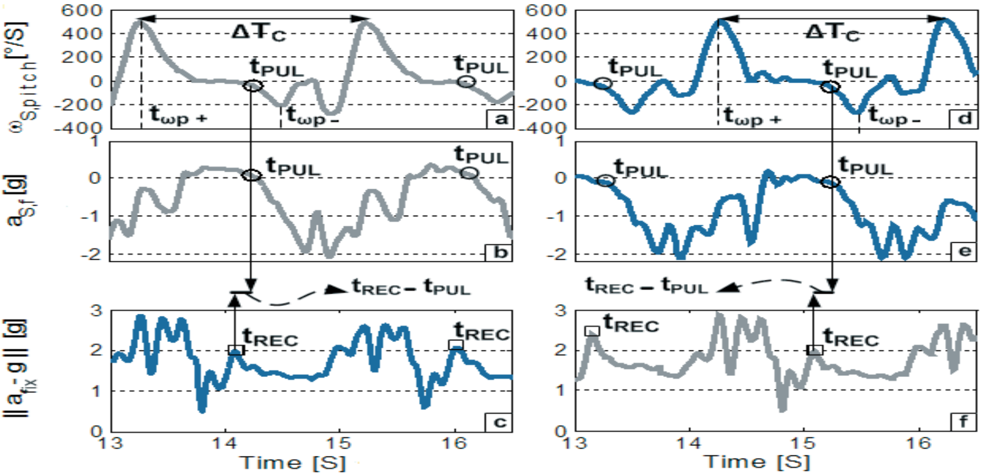

Figure 2: The beginning of pull (circles) and recovery (squares) phases using proposed algorithm on right and left arms. Pitch angular velocity of the right (a) and left (d) arms in sensor frame with relatively motionless period before t_{PUL}. Forward acceleration of the right (b) and left (e) arms in sensor frame with motionless period before t_{PUL}. Detection of recovery on the left (c) and right (f) arms on local maximum of $||a_{fix}-g||$ as explained in the method.

Table 1 summarizes the difference between time parameters (expressed in number of frames) and IdC (in %) estimated by operators (using video), each operator and Inertial system, and test-retest for one operator. With the video footage we had only 3 cycles per lap. Five laps out of 18 laps of each subject used for test-retest process. No significant difference between the test and retest video analysis was observed. The ICC(1,1) for test-retest of operator was 0.97. The comparison of IdC has been performed upon a broad coordination range (IdC=-16 to15.7) on video footage.

Table 1: Mean ± Standard Deviation of difference in Cycle Duration (ΔT_C), start of Pull (t_{PUL}) and Recovery (t_{REC}), in frames and IdC in %

Difference	ΔT_C	t_{PUL}	t_{REC}	IdC
Operator1 - Operator2	0.0±0.7	-0.8±2.3	-0.2±0.9	1.8±4.2
Operator1 - Inertial system	0.1±1.2	-0.7±3.1	-0.2±1.4	1.3±4.5
Operator2 - Inertial system	0.2±1.1	0.0±3.6	0.0±1.7	-0.5±4.9
Operator1 Test - Retest	0.0±0.5	-0.1±1.0	0.0±0.6	0.2±2.4

DISCUSSION: In this study we confirmed our hypothesis that inertial sensors can be used for automatic temporal phase detection during swimming. The high value of ICC indicates the consistency of our video analysis and thus, can be used as a reference to evaluate the proposed algorithm. Table 1 showed that the standard deviation of the difference between the two systems (video and inertial) was in accordance with standard deviation of inter-operator difference. Therefore, the precision (expressed by Standard Deviation) of inertial system can be considered as good enough compared to video analysis. The mean difference of inertial system and video based system is always lower than 0.8 frames which is in the range of resolution of video analysis (i.e. 1 frame) and casts the accuracy of the inertial system. Table 1 shows also that the main source of difference between the two systems originates from detection of t_{PUL}. This problem could come from confusion during video analysis to find out whether the hand is moving downward or downward and backward (Seifert et al., 2006). The later results in a propulsive force and considered as pull phase. Whilst, our algorithm is more reliable since we used the end of motionless part of the signal on two different signals (acceleration and angular velocity). Besides, our data capturing method enables us to address the problem of inter-cycle variability as we can have cycle to cycle analysis whereas the field of view of video based system (when calibrated for 3D analysis) is restricted to 2 or 3 cycles. Finally, our results showed that inertial system provides similar results to video analysis in a wide range of coordination.

CONCLUSION: In this study we introduced a new system based on inertial sensors with dedicated algorithms that can be used easily by the coaches to assess automatically the main temporal phases of arm stroke in front-crawl. The proposed algorithms inspired from dynamics of swimming have shown to be enough accurate and precise and avoid the long and time-consuming video-analysis. Therefore, the method offers a promising technique for investigating the biomechanics of swimming. The system has been validated in different coordination modes and provided an error lower than 5% in IdC. To our knowledge, this is the first time that IdC is estimated automatically with inertial sensors.

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