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# EVALUATION OF ARM-TO-LEG COORDINATION IN FREESTYLE SWIMMING

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## ABSTRACT

This study proposes a new method to evaluate arm-to-leg coordination in the freestyle swimming. Eight international-level youth swimmers were tested on a 50m swim at the speed of their 400m personal best (V400), and recorded at 60Hz bilaterally. The discrete relative phase angles between the arm-to-leg movements were identified by video analysis, using four key points adapted from Maglischo (2009): the hand entry corresponding to the lowest point of the ipsilateral kick (C1), the arm catch corresponding to the lowest point of the ipsilateral kick (C2), the lowest point on the arm pull corresponding with the lowest point of the contralateral kick (C3), and the hand exit corresponding to the lowest point of the ipsilateral kick (C4). International-level youth swimmers showed arm-to-leg discrete relative phase values of 355.9°±32.7°, 0.5°±38.7°, 352.9°±35.1° and17.5°±33.0°, respectively, for each of the four key events on the freestyle swimming cycle. This coordinative parameter allowed evaluating if the arm-to-leg movements of the swimmer were coordinated in-phase (between 330° and 30°), anti-phase (between 150° and 210°) or out-of-phase on the different phases of freestyle swimming. Therefore, it represented a practical tool to be used by coaches and researchers to quantitatively evaluate their swimming technique.

**Key words**: motor control, biomechanics, performance, crawl

# EVALUACIÓN DE LA COORDINACIÓN BRAZOS-PIERNAS EN EL NADO A ESTILO LIBRE

## RESUMEN

El presente estudio propone un nuevo método para evaluar la coordinación brazos-piernas en el nado a estilo libre. Ocho nadadores jóvenes de nivel internacional fueron filmados (60 Hz) durante 50m nadados a la velocidad de su marca personal en 400m libre. Los ángulos de fase relativa discreta entre los movimientos de brazos y piernas fueron cuantificados utilizando cuatro eventos clave del ciclo de nado (Maglischo, 2009): la entrada de la mano al agua correspondiente con el punto más bajo del primer batido de la pierna ipsilateral (C1), el agarre correspondiente con el punto más bajo del segundo batido ipsilateral (C2), el punto más bajo del tirón correspondiente con el punto más bajo del segundo batido contralateral (C3), y la salida de la mano del agua correspondiente con el punto más bajo del tercer batido ipsilateral (C4). Los nadadores mostraron valores de fase relativa discreta brazos-piernas de 355.9°±32.7°, 0.5°±38.7°, 352.9°±35.1° y 17.5°±33.0°, respectivamente, para cada uno de los cuatro eventos clave en el ciclo de nado. Este parámetro coordinativo permitió evaluar si los movimientos brazos-piernas del nadador se realizaban en fase (entre 330° y 30°), anti fase (entre 150° y 210°), o fuera de fase. Por tanto, se propone como una herramienta práctica para ser utilizada por entrenadores e investigadores con el fin de evaluar cuantitativamente la técnica de nado.

**Palabras clave:** control motor, biomecánica, rendimiento, crol

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## INTRODUCTION

In sports, traditional biomechanical analysis focuses on the data of a particular joint or segment of the body during key events of the sports movement. This information is then compared to a theoretical technical model in order to look for possible areas of improvement in the pattern of movement. Moving away from the technical model imposed would imply a loss of performance and a greater risk of injury (Robertson, Caldwell, Hamill, Kamen and Whittlesey, 2004).

However, in the learning of movements there is no "ideal pattern of movement", but a "common pattern of coordination" (Zanone & Kelso, 1997). The theories on dynamic systems and the ecological model approach have advocated that individuals should not replicate an ideal model of movement but they should look for an optimal solution to the motor tasks according to their specific individual conditions (Chow, Davids, Button and Koh, 2008). The individual motor response or motor behaviour would be dependent on organism, task and environmental constraints (Newell, 1986) and it would be characterized by a certain degree of variability, also known as the range of coordinating patterns needed to complete a task (Robertson et al., 2004). In this context, the analysis of a particular joint or segment during the pattern of movement would not completely characterize the movements. Instead, the pattern of coordination between different body parts would allow understanding how the individual is interacting with different constraints to perform the specific movement. Indeed, the patterns of coordination are very stable, and can be used to distinguish different levels of performance in subjects (Nikodelis, Kollias and Hatzitaki, 2005).

Theoretically, there are two possible patterns of coordination (in-phase and anti-phase) between moving limbs in a cyclic movement which indicate how the body parts are interacting with each other (Robertson et al., 2004). The in-phase mode corresponds to the movement of two limbs in a synchronous manner with non lag time between the maximum or minimum angular position of both segments. On the other hand, the anti-phase mode corresponds to limb movements in opposite directions indicating that the maximum angular position of one segment will correspond to the minimum position of the other segment, and vice-versa (Robertson et al., 2004). Any other mode of coordination between moving limbs on a cyclic movement is considered out-of-phase, indicating the absence of a systematic lag time between the angular positions of the moving segments. In the area of motor control and biomechanics different techniques have been developed to measure the patterns of coordination between moving limbs, usually employing grades to quantify the lag in angular position or phase angle (Robertson et al., 2004). However, the use of discrete measurements of the moving limbs on key events of the sports techniques (discrete relative phase angles) has become a useful tool for coaches and researchers in order to evaluate patterns of coordination (Robertson et al., 2004).

In swimming, the interaction between moving limbs has been extensively analyzed by the use of the so-called index of coordination (Chollet, Chalies and Chatard., 2000; Millet, Chollet, Chalies and Chatard, 2002; Seifert, Chollet and Bardy, 2004; Telles, Barbosa, Campos and Júnior, 2011; Castells and Arellano, 2012). This index employs discrete relative phase measurements to calculate the lag time between the propulsive phases of both alternative moving arms in freestyle (Chollet et al., 2000) and backstroke (Chollet, Seifert and Carter, 2008) strokes. In this way, a precise quantification of the inter-limb pattern of coordination is provided and three typical models of swimming coordination are proposed (Chollet et al., 2000): catch-up, opposition and superposition mode, from a longer to a shorter lag time between the propulsive phases of both moving arms. The index of coordination has been shown to act as a control parameter that increases as a function of the swimming velocity, the competitive level of swimmers, the stroke rate, the stroke rate to length ratio (Seifert et al., 2004) an even the use of training equipment (Telles et al., 2011). That is, a faster swimming velocity will indicate a shorter lag time between the two moving arms. The interaction between the swimmers' moving limbs has been also characterized between arms and legs when swimming simultaneous techniques such butterfly and breaststroke (Seifert, Delignieres, Boulesteix and Chollet, 2007; Chollet, Seifert, Leblanc, Boulesteix and Carter, 2004). With similar measurements as the index of coordination, the lag times between the propulsive phases of legs and arms were measured and changes according to velocity, stroke rate and expertise (Seifert et al., 2007) were encountered. Those swimmers employing an in-phase coordinative mode between the key events of arms and legs decreased swimming speed fluctuations and reduced the energy cost of swimming (Barbosa, Keskinen, Fernandes, Colaco, Carmo and Vilas-Boas, 2005).

However, little is known yet about the inter-limb coordination between arms and legs during alternative strokes (freestyle and backstroke). Classic technical swimming manuals describe qualitative patterns of coordination when swimming freestyle (Counsilman, 1983; Maglischo, 2003) and outline the importance of the arm-to-leg coordination in order to increase swimming efficiency (Maglischo, 2009). However, no previous research has precisely quantified the interaction between arms and legs when swimming at different swimming paces. Leg kicking during freestyle swimming has been shown to play a singular role on stabilizing body roll during the stroke (Yanai, 2003), maintaining the streamline of the body (Gourgoulis et al., 2014), improving the propulsion (Sanders & Psycharakis, 2009) and enhancing the effectiveness of the arm stroke (Deschodt, Arsac and Rouard, 1999). Therefore, in the present research we applied discrete relative phase measurements to analyze the interacting movement of arm and leg when swimming freestyle. The main aim was to propose a new method to evaluate arm-to-leg coordination in the freestyle swimming.

## MATERIAL AND METHODS

### *Participants*

Eight youth swimmers (4 men and 4 women) including six of them competing at the international level (762.4±31.1 FINA points) and with a weekly training volume of 20 hours (approximately 60km) of swimming per week gave an informed written consent to participate in this study. The study methodology and ethics were approved by the board of the Universidad Politécnica de Madrid. The main characteristics of the participants are presented in Table 1.

TABLE 1
Characteristics of the male and female swimmers participants in the present research (mean ± SD).

| Sex | Age (yr) | Mass (kg) | Height (m) | Experience (yr) |
|---|---|---|---|---|
| Men | 16.5±1.35 | 62.3±7.2 | 1.73±0.07 | 7.12±2.35 |
| Women | 15.5±1.29 | 50.5±6.5 | 1.6±0.05 | 5.9±1.68 |

### *Swim trials*

A GoPro Hero 4 video camera at 60 Hz, mounted on a monopod (Stick Luxebell) at a depth of 0.5m, was used to track the underwater movements of the swimmers in a 50-m Olympic size swimming pool. The lateral view recordings enabled the determination of key points in both arm and leg movements and thus facilitated the delimitation of the coordination between the different arm and leg phases. The video was synchronized with a chronometer to find out the time between the different key points. Each swimmer performed a swim trial of 25+25 m at velocity of 400 m race pace from the middle of the pool in order to allow for a lateral view of both swimming sides. The trials were self-paced and subjects were asked to hold their breath in order to avoid modifications in coordination due to breathing.

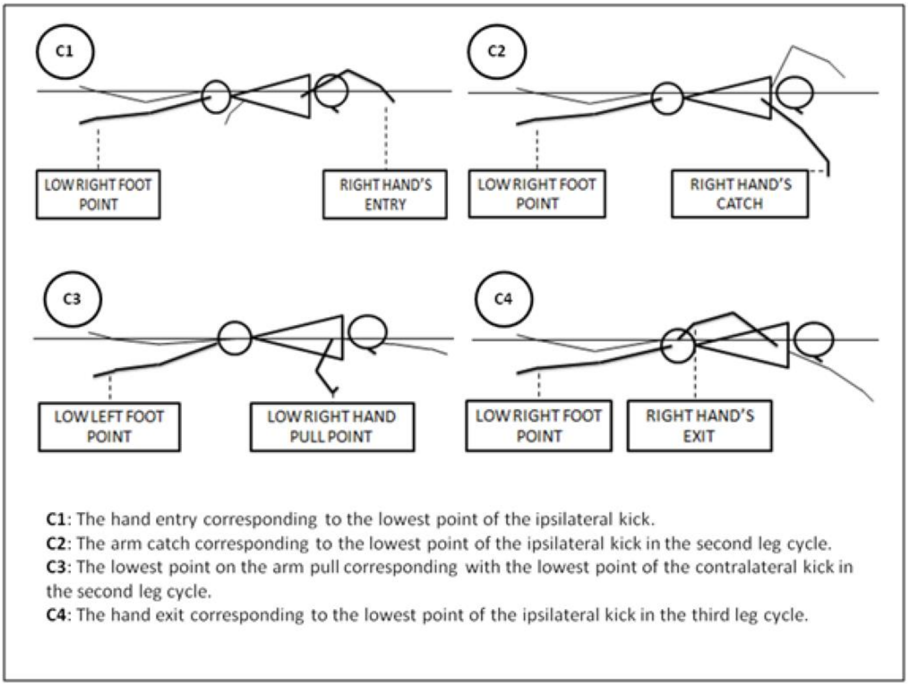
*Arm stroke and leg kicking times*

The arm stroke was divided into four distinct phases by two operators who analyzed the key points of each phase at 0.016s intervals without any knowledge of the analyses of the other operator. The two analyses were compared, and when the difference between the analyses did not exceed an error of 0.032s, the mean of the two analyses was used to validate the key point of each phase. When the error exceeded the 0.032s, the two operators met for the accomplishment of the analyses together. The four key events of the freestyle stroke cycle were defined as follow: 1) the hand entry in the water, as the first video frame where hand touches the water after the aerial movement, 2) the arm catch or the first video frame when the hand begins moving backwards, 3) the deepest point of the arm pull when the hand is in the vertical plane of the shoulder and 4) the hand exit from the water, as the first video frame where the hand is out of the water. According to these key events, the following stroke phases were defined (Chollet et al., 2000): entry and catch phase (Phase A), from to the instant of the hand's entry into the water to the beginning of its backwards movement; the pull phase (Phase B), from the beginning of the hand's backwards movement to the instant the hand is located below the shoulder; the push phase (phase C), from the instant the hand is located below the shoulder to its release from the water and the recovery phase (Phase D), from the hand's release from the water to its following entry for the beginning of the next stroke. One stroke in which the swimmer did not take a breath was selected for analysis on each side, and the time intervals of each phase were calculated. The sum of the phases B+C represented the propulsive phases of the stroke whereas the sum of the phases A+D represented the non-propulsive phases of the stroke (Chollet et al., 2000).

The leg kicking consisted in two phases, 1) the downward kick, which corresponded to the time between the highest and lowest point of the foot and 2) the upward kick, which corresponded to the time between the lowest and highest point of the foot during the kicking movement. The swimmers were asked to perform a six-beat kicking (three ascending and three descending movements of legs, or three complete leg cycles) on each complete arm stroke (Maglischo, 2003) during swimming trials. Therefore, the following leg kicking times were measured: first time interval (F1), the difference between the lowest point of the first ipsilateral kick linked with the hand entry and the previous lowest point of the opposite kick; second time interval (F2), the time interval between the first lowest point of the ipsilateral kick and the next lowest point of the contralateral kick and, subsequently, the third, fourth, fifth and sixth time intervals (F3, F4, F5 and F6) corresponding to the remaining time intervals in a six beat kicking. All kicking time intervals were expressed as a percentage of the complete 6 beat cycle time.

*Arm-to-leg coordination*

Following the coordination model proposed by Maglischo (2009) in international level freestyle swimmers, four key instants were established where the coordination (C) between the arm phases and the leg phases could be evaluated (Figure 1): C1, represented by the hand entry corresponding to the lowest point of the ipsilateral kick, C2, represented by the arm catch corresponding to the lowest point of the ipsilateral kicking on the second leg cycle, C3, represented by the lowest point on the arm pull corresponding with the lowest point of the contralateral kick on the second leg cycle and C4, as the hand exit corresponding to the lowest point of the ipsilateral kicking the third leg cycle.



**C1**: The hand entry corresponding to the lowest point of the ipsilateral kick.
**C2**: The arm catch corresponding to the lowest point of the ipsilateral kick in the second leg cycle.
**C3**: The lowest point on the arm pull corresponding with the lowest point of the contralateral kick in the second leg cycle.
**C4**: The hand exit corresponding to the lowest point of the ipsilateral kick in the third leg cycle.

FIGURE 1: Key instants on the freestyle swimming arm-to-leg movements according to the coordinative model proposed by Maglischo (2009).

The arm-to-leg coordination was assessed by the discrete relative phase procedure proposed by Robertson et al. (2004). This Relative Phase (RP) illustrates the relative timing of the key events, in a movement cycle. So, in the freestyle swimming, a concrete point in the arm stroke time will correspond with another point in the leg stroke time. The formula is expressed in degrees:
RP = (difference between events / time of a complete cycle of arm stroke)*360°

$$[RP = ((T_1 - T_2)/(Tc - T_0))*360°]$$

For the four relative phases during freestyle swimming, $T_c$-$T_0$ represents the duration of the complete cycle of arm stroke from the first entry of the hand until the next one. RP1 represented the time difference between the entry of the hand ($T_1$) and the lowest point of the ipsilateral feet ($T_2$), divided by the time to complete an arm cycle, expressed in degrees. RP2 represented the time difference between the catch ($T_1$) and the lowest point of the ipsilateral feet ($T_2$), divided by the time to complete an arm cycle, expressed in degrees. RP3 represented the time difference between the instant when the hand is in the lowest point on the arm pull ($T_1$) and the lowest point of the contralateral feet ($T_2$), divided by the time to complete an arm cycle, expressed in degrees and RP4 represented the time difference between the exit of the hand ($T_1$) and the lowest point of the ipsilateral feet ($T_2$), divided by the time to complete an arm cycle, expressed in degrees.

TABLE 2
Key events of the four discrete relative phase measurements (RP) in the arm-to-leg coordination during the freestyle swimming.

| | First key event | Second key event | End of stroke cycle | Beginning of the stroke cycle |
|---|---|---|---|---|
| RP1 | Hand entry | Lowest point ipsilateral kick (1st cycle) | Hand entry (2nd stroke) | Hand entry (1st stroke) |
| RP2 | Arm catch | Lowest point ipsilateral kick (2nd cycle) | | |
| RP3 | Deepest point of pull | Lowest point contralateral kick (2nd cycle) | | |
| RP4 | Hand exit | Lowest point ipsilateral kick (3rd cycle) | | |

Three coordination modes were used to evaluate the arm-to-leg movements of each swimmer on the four relative discrete measurements (Bardy, Oullier, Bootsma and Stoffregen, 2002; Diedrich & Warren, 1995; Seifert et al., 2007): in-phase mode (between 0° and 30° or 330° and 360°), anti-phase mode (between 150° and 210°), and the remaining phase angles considered as out-of-phase mode.

*Arm to arm coordination*

The arm-to-arm index of coordination (IdC) was measured as described by Chollet et al. (2000), calculating the difference of time between the beginning of the propulsive phase of one arm (pull phase) and the end of the propulsive phase of the other arm (push phase). This was calculated with both arms, and expressed as a percentage of the mean duration of the stroke. When the result was lower than 0 (IdC <0), the stroke coordination was called catch-up mode, indicating a lag time between the propulsive phases. When the beginning and the end of the propulsive phases of both arms matched each other, it was considered opposition mode (IdC = 0). Finally, when the propulsive phases of both arms overlapped, the coordination mode was superposition (IdC > 0).

## RESULTS

The arm stroke % times (Table 3) indicated that youth swimmers at a V400 spent longer in the entry and catch stroke phase (phase A) respect to the others three phases (a mean of 33%±3.5% of the total time of a complete arm stroke). In conjunction with the recovery time, this represented a non-propulsive proportion of time in the complete stroke cycle of 60%±3.5%. For the leg kicking times, the first time interval of the kick (F1), corresponding with the entry of the hand to the water, represented the shortest proportion of time (F1=15%±2%) respect to the rest of the kicks. As an average, the time employed to complete a leg cycle (downward and upward movement) was 0.44±0.03 s.

TABLE 3
Mean (± SD) values of the % arm stroke and leg kicking times for youth international-level freestyle swimmers at V400.

| Stroke Phases | Entry and catch | Pull | Push | Recovery | Propulsive | Non propulsive |
|---|---|---|---|---|---|---|
| % time | 33.0±3.5 | 15.0±2.5 | 25.0±2.0 | 27.0±3.5 | 40.0±2.25 | 60.0±3.5 |
| Leg kicking phases | F1 | F2 | F3 | F4 | F5 | F6 |
| % time | 15%±2% | 18%±2 | 17%±3% | 17%±2% | 16%±2% | 17%±1% |

The mean arm-to-leg coordination indexes for the participants in the present research were RP1=355.9°±32.7°, RP2=0.5°±38.7°, RP3=352.9°±35.1° and RP4=17.5°±33.0°, respectively, at each of the four key instants of the freestyle arm stroke and leg kicking movements. As an average, the arm-to-leg coordination index of the complete freestyle swimming cycle was 1.7°±33.9°, corresponding to an in-phase coordinative mode. On the other hand, the average arm-to-arm index of coordination was -9.27% ± 1.87% in correspondence to a catch-up coordination model.

TABLE 4
Mean (± SD) values of arm-to-leg discrete relative phase values in the four key events of youth international-level freestyle swimming cycles.

| | Right arm | Left arm | Mean |
|---|---|---|---|
| Relative Phase 1 | 350.4°±28.8° | 1.5°±36.6° | 355.9°±32.7° |
| Relative Phase 2 | 1.8°±37.7° | 359.2°±39.7° | 0.5°±38.7° |
| Relative Phase 3 | 345.4°±37.0° | 0.38°±33.3° | 352.9°±35.1° |
| Relative Phase 4 | 14.1°±34.3° | 20.9°±31.7° | 17.5°±33.0° |
| Mean | 357.9°±33.5° | 5.5°±34.2° | 1.7°±33.9° |

## DISCUSSION

The aim of the present research was to develop a new method to quantitatively evaluate the arm-to-leg coordination in the freestyle swimming. Discrete relative phase angles between the key events of arms and legs movements were identified in youth international-level swimmers when swimming freestyle at 400m race pace. The results indicated an in-phase mode of coordination at four distinct key events of the freestyle swimming cycle according to the model proposed by Maglischo (2009), although some variations were observed depending on the swimmer.

Youth international-level swimmers in the present research swam in an inter-arm catch-up mode at the V400, in concordance with previous data from Seifert et al. (2004), who proved that the catch-up coordinating pattern predominated between the velocities of V3000 and V200. However, some differences were found between the group of youth international-level swimmers (IdC = -9.27%±1.87%) and those by Seifert's et al. (2004) (IdC = -7.8%±4.5%) at the V400, indicating a greater catch up mode of coordination for participants in the present study. This may be explained by the event distance specialization of both groups, as the swimmers by Seifert et al. (2004) were specialists on short events (50-100 m) whereas swimmers in the present research were specialists on middle distance events (200-400 m). As Potdevin, Bril, Sidney and Pelayo (2006) and Seifert et al. (2004) reported, swimmers who are specialists in longer distances usually adopted a greater catch-up mode of coordination when compared to sprinters to reduce the active drag and to maintain a higher stroke length.

For the arm stroke % times, youth international-level swimmers in this study spent a 60.0%±3.5% of time of the stroke cycle with non-propulsive stroke phases whereas previous studies with elite swimmers (Millet et al., 2002) showed 52.7%±2.1% for the same non-propulsive actions. In the same line, the entry and catch % time (33.0%±3.5% vs. 26.3%±2.6%) and the recovery % time (27.0%±3.5% vs. 26.2%±1.7%) were also greater in the present research and, consequently, the propulsive phase % times were lower (40.0%±2.25% vs. 47.3%±2.6%). This probably implied a better swimming efficiency by reducing energy cost and the hydrodynamic resistance to maintain the V400 (Chollet et al., 2000). For the leg kick % times, swimmers in the present research were capable to perform a six beat kick during the swimming trials and they spent as an average 17.0%±1.0% time on each kicking. The average time employed by swimmers to complete a kicking leg cycle (downward and upward movement (0.44±0.03 s) was similar to that found by Gatta, Cortesi and Di Michele (2012) with high-level swimmers (0.42 s), corresponding to a leg-kick frequency close to 2.4 Hz.

For the arm-to-leg coordination, data in the present study indicated an in-phase mode of coordination at the four key points of the stroke (at the entry, the catch, the lowest point of the hand on the arm pull and the exit of the hand) following previous qualitative descriptions proposed by Maglischo (2009). Values from the present research cannot be compared with literature as no previous studies had ever conducted this type of coordinative analysis in swimming. However, previous researches in simultaneous swimming strokes indicated that the reduction of lag times between the selected key events of the stroke and kick phases ensured a greater propulsive continuity and lower velocity fluctuations during the swimming cycle (Seifert et al., 2007; Seifert, Boulesteix, Chollet and Vilas-Boas, 2008). Therefore, this pattern of coordination would be characteristic at different performance levels to maintain swimming efficiency at selected race paces (Chollet et al., 2004; Seifert & Chollet, 2005). In freestyle, Craig and Pendergast (1979) found that maximum and minimum of velocity fluctuations during the swimming cycle were lower in alternative strokes (15-20%) compared to the simultaneous strokes (45-50%). However, this percentage still remains a window of opportunity for improving the swimming efficiency especially at the elite level. For this reason, the analysis and quantifying of the arm-to-leg coordination on the alternative strokes could represent a practical way to evaluate the skill level of swimmers.

Despite similar arm-to-leg coordination when swimming freestyle, some differences in the discrete relative phase angles were observed between swimmers, according to their level or their specialty.

Those swimmers specialists on freestyle events were able to show values of discrete relative phase closer to the in-phase mode of coordination when compared to those non-freestyle specialists. This is in agreement with previous data by Chollet, Seifert, Boulesteix and Carter (2006), who found that the best butterfly swimmers reduced their lag times between the key arms-to-legs events below 5%, indicating a greater synchronization between the key arm-to-leg movements. Also, Seifert et al. (2007) observed that the more expertise butterfly swimmers, the closer values of their arm-to-leg coordination indexes to an in-phase model of coordination. For example, values of the present research with a freestyle swimmer (the highest ranked of the present research with a personal best of 2:01,99 on the 200m freestyle event) showed discrete relative phase values of 351.5°, 5.6°, 345.8° and 8.5°, respectively, for the C1, C2, C3 and C4 coordinative indexes. This represented an in-phase mode of arm-to-leg coordination at V400 with values close to 0° or 360° and it was accompanied by an arm-to-arm index of -12.9%, indicating a catch up mode. The greatest deviation from the in-phase coordination mode was observed on the lowest point on the arm pull corresponding with the lowest point of the contralateral kick on the second leg cycle (C3). At this key event, the relative duration of the arm pull in this swimmer was lower than the average values in the present research (11% compared to 15%±2.5%). Therefore, a further evaluation of the pull phase would be needed in order to optimize the arm-to-leg movements in this swimmer. On the other hand, another swimmer specialist on the backstroke events showed discrete relative phase values of 36.8°, 76.5°, 62.3° and 82.2°, respectively, for the C1, C2, C3 and C4 arm-to-leg coordination indexes. In this case, the swimmers showed out-of-phase values beginning on the arm catch corresponding to the lowest point of the ipsilateral kicking on the second leg cycle (C2). In this entry catch stroke phase, he spent a longer time proportion (41%) than the remaining group of swimmers (33%±3.5%) which probably caused the out-of-phase angle between the movement of arm and legs. Therefore, the exposure of the swimmers to different learning environments where the constraints of the entry catch phase were modified (for example, by the use of training equipment) could allow him to seek for different solutions to the arm-to-leg coordination at this point.

As reflected, the discrete relative phase angles allowed measuring the arm-to-leg coordination of youth international-level swimmers when swimming freestyle. The quantification of the four key events during the freestyle swimming cycles proposed by Maglischo (2009) showed an in-phase mode of coordination and revealed some differences according to the swimmer level and specialty. Little deviations from the in-phase coordination at key events provided researches with data to accurately identify areas of improvement during the freestyle swimming of participants in the present research. Therefore, this seems to provide an accurate and practical tool for researches and coaches when seeking to evaluate the swimmers movements.

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