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Arm – leg coordination profiling during the dolphin kick and the arm pull-out in elite breaststrokers

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Abstract

In breaststroke races, the dolphin kick could finish before, at the same time, or during the arm pull-out, but it is unclear how swimmers perform this technique. The aim of this study was to investigate whether swimmers glide between the dolphin kick and arm pull-out, favour continuity or even overlap those two phases, as it would impact the active underwater sequence. Fourteen international and national male swimmers performed 100-m breaststroke with all-out effort in a pre-calibrated 25 m swimming pool. A multi-camera system with five underwater and five above water cameras positioned at the side of the pool tracked the head of the swimmers throughout the trial and provided the two-dimensional displacement of the head. Key points of the active underwater sequence were obtained from notational analysis in order to assess the coordination between the dolphin kick and the arm pull-out, the mean speed, the relative time and distance covered by the head. A hierarchical cluster analysis identified three coordination profiles. All swimmers started their dolphin kick before the arm pull-out. However, one swimmer started the arm pull-out before the end of the dolphin kick (i.e. '*superposition*' pattern of coordination), seven swimmers started the arm pull-out after the end of the dolphin kick (i.e. '*glide*' pattern of coordination), and four swimmers synchronised the beginning of the arm pull-out and the end of the dolphin kick (i.e. '*continuity*' pattern of coordination), while two other swimmers mixed two coordination profiles among the start and the three turns. Those different profiles allow achieving similar performance outcome, suggesting individual training regarding the underwater phase.

Key words: coordination, cluster analysis, underwater sequence, swimming, biomechanics

1. Introduction

Previous researches in swimming biomechanics have emphasized the importance of the start and turns segments in swimming races. A recent study examining the key factors related to short course 100-m breaststroke performance showed that turns were the largest time contributor to the finishing time (44.30 ± 0.58%), followed by clean swimming (38.93 ± 0.50%), start (11.39 ± 0.22%), and finish (5.36 ± 0.18%) (Olstad, Wathne, & Gonjo, 2020). Both in start and turn-outs, the underwater phase has a great influence on the 15-m start and turn-out time (Vantorre, Chollet, & Seifert, 2014). This suggests the importance of managing the time spent and the distance travelled during the glide as well as the appropriate timing to start underwater movements (e.g. dolphin kick) in order to maximize the speed during the underwater phase (Vantorre et al., 2014; Vantorre, Seifert, Fernandes, Vilas-Boas, & Chollet, 2010; Veiga, Cala, Frutos, & Navarro, 2014). For instance, Veiga et al. (2014) observed greater distance and speed during the underwater phase of the start than of the turns during 200-m breaststroke and between national compared to regional level male swimmers. Veiga et al. (2014) also observed greater speed during the underwater phase of the start and turns in 100-m breaststroke for national compared to regional level male swimmers.

While some studies investigated the drag force during the first and second gliding positions of the breaststroke underwater stroke (e.g., Costa et al., 2015; Vilas-Boas et al., 2010), only two published studies investigated the coordination between the arm pull-out and the dolphin kick in breaststroke (Adams, Scharbrough, & McLean, 2018; Hayashi, Homma, & Luo, 2015). Adams et al. (2018) compared the time spent and the distance travelled between an early-initiation (performed before the initiation of the arm pull-out) and late-initiation (performed at the completion of the arm pull-out) of the dolphin kick during the turn sequence in fourteen collegiate swimmers performing four 50 yards (i.e. 47.5 m) breaststroke. Their findings exhibited a 0.12 s shorter time to 6 m from the wall when performing a late-initiation (3.06 ± 0.31 s) compared with an early-initiation (3.18 ± 0.24 s) of the dolphin kick. However, the arm pull-out with the late-initiation of the dolphin kick occurred 0.22 m closer to the wall (3.33 ± 0.52 m) than with the early-initiation (3.55 ± 0.47 m) (Adams et al., 2018). Therefore, to provide a more equitable comparison between the variations, the analysis was repeated using time measured from the initiation of movement. Thus, the time to reach 3.5 m from initiation of movement was 0.27 s shorter when performing the early-initiation (3.79 ± 0.42 s) than the late-initiation (4.06 ± 0.44 s) of the dolphin kick. Swimmers travelled nearly 1 m further underwater when using the early-initiation (3.44 ± 0.53 m) than the late-initiation (2.50 ± 0.53 m) of the dolphin kick. These findings suggested that the early-initiation of the dolphin kick was better for covering distance in less time after initiation of movement, leading to an increase in the distance travelled underwater (Adams et al., 2018). However, this study was limited to collegiate swimmers and short distance race, and the knowledge in top elite swimmers, as well as that in medium and long race events, is lacking. In another study, Hayashi et al. (2015) investigated the optimal timing between the dolphin kick and arm pull-out in the active underwater sequence in breaststroke through computational simulation modelling. The simulation indicated that swimmers should perform the dolphin kick 0.4 s earlier than the arm pull-out to maintain a streamlined position during each sequence (Hayashi et al., 2015). Nevertheless, this modelling involved only one swimmer from a university team and its validity should be tested before any application to elite swimmers.

Previous research investigating intra-cyclic velocity variations in breaststroke revealed that the highest velocity peak could occur either during leg propulsion (corresponding to ‘leg propulser’ profile) or during arm propulsion (corresponding to ‘arm propulser’ profile) (Seifert, Leblanc, Chollet, Sanders, & Persyn, 2011). This suggests that ‘leg propulser’ swimmers might generate a strong dolphin kick and might use a *glide* pattern of coordination between the dolphin kick and the arm pull-out, while ‘arm propulser’ swimmers might favour a strong arm pull-out and minimise the glide between the dolphin kick and the arm pull-out (i.e. using *continuity* or *superposition* patterns of coordination). However, it remains unclear how elite swimmers organize the set of arm pull-out and dolphin kick motion.

Moreover, the dolphin kick and the arm pull-out are not the only actions of the active underwater sequence, as swimmers perform arm recovery and leg kicking until the head breaks the water surface. Thus, it is reasonable to hypothesise that the timing between the dolphin kick and the arm pull-out could influence the following arm and leg actions during the active underwater sequence until the head breaks the water. For instance, Seifert et al. (2007) compared the arm-leg coordination at different key points of the active underwater sequence between an international and ten national swimmers; the analysed variables included (i) the time spent with the arms close to the thighs after the completion of the arm pull-out, (ii) the time-gap between the end of the arm recovery and the beginning of the leg propulsion during the pull-out phase and at the first swim stroke, and (iii) the time-gap between the end of leg propulsion and the beginning of arm propulsion. The results showed that the international swimmers had a shorter 15-m start time than the national swimmers due to shorter times in the swim phase, longer times in the underwater phase, longer times spent with the arms close to the thighs and in glide with the body in extension (Seifert et al., 2007). The whole population showed a negative superposition of leg propulsion with arm recovery at the pull-out phase (i.e. leg propulsion started before the arms completed their recovery), which was not observed at the first swim stroke (Seifert et al., 2007). According to the fact that the arm-leg coordination differs between the pull-out phase and the first swim stroke, it was crucial to understand and explain how elite swimmers coordinate their arms and legs actions during the active underwater sequence until the first swim stroke.

Therefore, the aim of this study was to investigate whether swimmers glide between the dolphin kick and arm pull-out, favour continuity or even overlap those two phases, as it would impact the active underwater sequence. On one hand, from a motor control point of view, performing one action after another could be less complex than controlling a partial superposition of two different actions (i.e. when arm pull-out starts before the dolphin kick finishes). On the other hand, from a biomechanical perspective, separating arm pull-out from the dolphin kick would require swimmers to manage the gliding time between those two actions in order to minimise velocity variations of the centre of mass. Based on these motor control and biomechanical aspects, we hypothesised that swimmers might favour glide and continuity patterns of coordination, which would be associated to similar performance outcome of the active underwater sequence.

2. Methods

2.1. Participants and testing procedures

Fourteen international and national male breaststroke swimmers (mean age: 19.13 ± 2.45 yr, mean height: 184.37 ± 5.88 cm, mean body mass: 80.34 ± 7.72 kg) performed 100-m breaststroke with maximal effort within 64.54 ± 3.11 s, which was 2.5% slower than their best record for Short course 100-m breaststroke (62.95 ± 2.65 s, which corresponded to 88.48 ± 3.69% of the current world record). All participants were qualified for the National Senior Swimming Championships. The protocol and data collection procedures were approved by the local ethical committee and the National Data Protection Agency for Research according to the Declaration of Helsinki. The protocol, benefits, and potential risks of the testing were explained to the swimmers, who then gave their written informed consent to participate.

2.2. Data collection

A synchronised multi-camera system consisting of five underwater (0.7 m below the water surface) and five above water (approximately 5 m above the floor) cameras (AIMSys Sweden AB, Lund, Sweden) recorded the swimming trials. Each camera was positioned and zoomed to observe the centre lane of the pool with an approximate field of view of 6 - 8 m in the swimming direction. The cameras were calibrated in the manner described by Haner, Svärm, Ask, and Heyden (2015), and the mean calibration error was 2.0 pixels corresponding to 0.025 degrees and 0.006 m of angular and linear error, respectively. After recording, the lens distortion, exposure, and the chromatic aberration were corrected in the AIMSys software, and camera images were joined by matching the global coordinate points of the subsequent cameras to produce a panning video image of the entire swimming trial (Haner et al., 2015).

The system was equipped with an automatic colour tracking algorithm, based on a support vector machine and a non-linear colour transformation, which detects a yellow colour object with a disc radius of 5-50 pixels and provides the coordinates of its centre (Haner et al., 2015). All swimmers were instructed to wear a plain yellow silicon cap so that the system would track their head throughout the trial and calculate the displacement of the centre of the head relative to the global coordinate system. For further analysis, the panning video file and the head displacement data were exported as the format of MPEG-4 Part 14 and Excel Macro-Enabled Workbook, respectively (and was recently used for race analysis, Olstad, Wathne, & Gonjo, 2020). The timeline of the exported video and displacement data were synchronised with the sampling frequency of 50 Hz.

2.3. Data analysis

Performance outcomes

The performance outcomes were determined as i) the time; ii) the distance travelled by the head and iii) the mean speed during the active underwater sequence, which was defined as from the first arm or leg action to when the head breaks the water surface. Moreover, the time of the whole event and each lap was measured with an electronic timing system (Omega, Bienne, Switzerland) in order to attest that swimmers were engaged in the testing with their maximal effort.

Key points and phases of the active underwater sequence of the start and turn out

Six key points for arm actions (A to F) and seven key points for legs action (1 to 7) were defined as shown in Figure 1: (A) First arm action, when the hands start to separate to break the initial streamlined position, (B) Start of pull-out, when the hands start to move backwards following the initial streamlined position, (C) End of pull-out, when the hands stop moving backwards at the thigh, (D) Start of the recovery, when the elbows start flexing which leads the hands to move forward from the thigh, (E) End of recovery, when the arms are fully extended to make the second streamlined position before the breakout, (F) The first arm action following the second streamlined glide (beginning of the first cycle of the surface swimming); (1) Start of dolphin kick recovery, when the knees actively start flexing and feet go upward, (2) Start of dolphin kick, when the knees actively start extending which leads the feet to move downward, (3) End of dolphin kick, when the feet reach their deepest position, (4) Start of leg recovery, when the knees actively start flexing which leads the feet to go upward, (5) Start of leg propulsion, when the feet move backward after the knees show their maximum flexion, (6) End of outsweep, when the legs are fully extended, (7) End of insweep, when the feet are maximally closed after the leg extension.

Insert figure 1 about here

Based on the underwater side and aerial views, five expert operators visually analysed the key points for the active underwater sequence of the four laps with a blind technique, that was, without knowing the analyses of the other four operators (as previously done for arm and leg stroke phases in breaststroke; Chollet, Seifert, Leblanc, Boulesteix, & Carter, 2004; Leblanc, Seifert, Baudry, & Chollet, 2005; Seifert & Chollet, 2005). To ensure that all operators shared the same interpretation of the key points, all five operators obtained the key points from all four laps of one swimmer. Intra-class correlation was then computed to assess inter-operator variability for each key point. Despite a high coefficient of intra-class correlation (between 0.999 and 1; $p < 0.05$), when the five operators compared their analysis, a mean discrepancy of 0.12 s was observed for the assessment of the start of the arms pull-out and a mean discrepancy of 0.17 s was observed for the assessment of the start of the arm recovery. Therefore, for key points that showed a difference between the five operators of over 0.04 s, all operators together discussed the definition of the points again and redid the assessment in order to validate the key point of each phase. After all operators agreed on the interpretation of all key points, each operator assessed the key points of the four laps once again and confirmed that all operators shared the same quantitative definition (the largest inter-operator error was $\leq$ 0.04 s).

The five operators were then randomly paired and analysed the key points for the other twelve swimmers with the blind technique. When the difference between the two video analyses did not exceed a discrepancy of 0.04 s, the mean of the two analyses was accepted to validate the key point of each phase. When the discrepancy exceeded 0.04 s, the two operators discussed their differences and proceeded to a new assessment of the key point. A previous study has shown that expert operators can analyse motion key points subjectively with high accuracy in comparison to data obtained by a quantitative method using video footage and manual digitising (Seifert et al., 2006).

Arm – leg coordination during the active underwater sequence

Three time-gaps (T1-T3) were computed to assess the arm-leg coordination during the underwater sequence (Chollet et al., 2004; Seifert & Chollet, 2005): T1: *Glide duration* with arms at the thigh; T2: *Synchronisation between the beginning of arm and leg recovery*; and T3: *Synchronisation between the end of arm and leg recovery*. These time-gaps were expressed in absolute time (s) and relative time (% of the active underwater sequence duration).

When T1 is zero, there was no glide motion, and if positive, it shows the duration of the glide with the arms at the thigh. When T2 is zero, it indicates that the leg and arm recovery started at the same time, if negative and positive, the time-gap indicates that the arm recovery started respectively earlier and later than leg recovery. T3 being zero means that the leg and arm recovery ended at the same time, and when T3 is smaller or larger than zero, it shows that respectively the leg propulsion overlapped the arm recovery action or the arms were fully extended while the legs were still performing their recovery.

Following previous research (Adams et al., 2018; Hayashi et al., 2015), the two time-gaps (T4 and T5) were also computed and expressed in absolute (s) and relative (%) time to assess the *coordination between the dolphin kick and the arm pull-out*. T4 is a time-gap between the end of the dolphin kick and the beginning of the arm pull-out. A positive or negative time-gap means respectively that the dolphin kick finished before or after the beginning of the arm pull-out (the negative time-gap shows an overlap between the arm pull-out and dolphin kick). T5 is a time-gap between the end of the arm pull-out and the beginning of the dolphin kick, in which the positive time-gap corresponds to the glide duration of the body with the arms and legs fully extended. This means that the dolphin kick started after the end of the arm pull-out.

On the other hand, negative T5 shows that the beginning of the dolphin kick was before the end of the arm pull-out, and zero T5 means that the arm pull-out and the dolphin kick were performed continuously. In summary, the dolphin kick occurred before the arm pull-out when T4 > 0 and T5 < 0; and after the arm pull-out when T5 > 0. The dolphin kick overlapped the arm pull-out when T4 and T5 < 0.

The duration of the downward *dolphin kick* (from the highest to the deepest position of the feet), and the duration of the *arm pull-out* (when the hands started to move backwards until they stopped at the thigh) were also quantified.

The absolute (m) and the relative (%) of the head distance travelled during the active underwater sequence and the mean speed were computed to assess the arm-leg coordination during the five time-gaps, the dolphin kick, and the arm pull-out of the active underwater sequence.

2.4. Coordination profiling

Cluster analysis

Cluster analysis is a common technique to detect hidden groups within high dimensional datasets. One significant advantage of coordination pattern clustering is that no prior assumptions about the structure of the dataset are required to identify similar patterns (Rein, Button, Davids, & Summers, 2010). Cluster analysis is a means to investigate coordination variability and thus potentially be able to define performance profiles for individuals. For example, if all laps of one swimmer are in the same cluster, it suggests a low intra-individual variability. Similarly, when different swimmers are allocated to the same cluster, it indicates a low inter-individual variability. A previous study (Chow, Davids, Button, & Rein, 2008) employed a cluster analysis to detect inter-individual differences of coordination patterns to perform a shot in soccer. Rein, Davids, and Button (2010) also used cluster analysis to explore inter-individual differences of performers with different skill levels performing the basketball hook shot.

In our study, cluster analysis was chosen because the active underwater sequence is composed of several phases (i.e. arm and leg actions described in Figure 1) that must be well temporally sequenced to be effective. Assuming that an ineffective arm-leg coordination at each moment (identified by our five time-gaps) of the sequence can destabilise the whole active underwater sequence, the cluster analysis would be useful to identify which time-gaps classify various arm-leg coordination profiles during the active underwater sequence. For this purpose, a hierarchical cluster analysis (HCA) with the Euclidean distance dissimilarity measure and the complete linkage method was used (Duda, Hart, & Stork, 2001; Hastie, Tibshirani, & Friedman, 2009). The cluster analysis was performed on the basis of 24 features that are the relative duration, the relative distance, the mean speed of the five time-gaps, of the dolphin kick and of the arm pull-out, as well as the absolute duration, the absolute distance and the mean speed of the active underwater sequence. Relative duration and relative distance were preferred to the absolute duration and distance to express the data in reference to the active underwater sequence. Moreover, each feature was scaled to zero mean and unit variance in order to give the same weight to each feature. As each swimmer performed four underwater active sequences (one start and three turns), 56 data (four active underwater sequences x 14 swimmers) were considered in the HCA.

Cluster validation

The Calinski-Harabasz (CH) index was used to estimate the number of clusters that best fitted the data and thus best classified the participants in each cluster (Calinski & Harabasz, 1974):

$$CH(k) = \frac{B(k) \cdot (n-k)}{W(k) \cdot (k-1)} \qquad (1)$$

where n represents the number of participants, k denotes the number of clusters, and $B(k)$ and $W(k)$ denote the between- and within-cluster sums of squares of the partition. The highest CH among all potential cluster combinations indicates the optimal ratio between inter-cluster distance (*i.e.* inter-cluster separation) and intra-cluster distance (*i.e.* intra-cluster compactness) and in turn, an optimal number of clusters (Duda, Hart, & Stork, 2001; Everitt, Landau, & Morven, 2001; Hastie, Tibshirani, & Friedman, 2001; Zhao & Karypis, 2005). The CH index was calculated from two to ten potential clusters with Cluster Validity Analysis Platform (CVAP) (Version 3.7) (Wang, Wang, & Peng, 2009) and Matlab (R2014a, 1994–2014, MathWorks Inc, Massachusetts). According to the sample size (fourteen swimmers x four turn-outs = 56 observations), we did not look for more than ten potential clusters.

The Fisher information was then computed for each of the 21 features to understand which feature(s) significantly differentiated the clusters. Fisher information corresponds to the ratio between inter-cluster and intra-cluster distances (J_b / J_w).

Inter-cluster distance (J_b) corresponds to:

$$J_b = \sum_g N_g \cdot d^2(\mu_g, \bar{X}) \qquad (2)$$

where N_g is the number of elements in the cluster g, d is the chosen distance, μ_g is the centre of cluster g (*i.e.* the mean of all points in g) and $\bar{X}$ is the centre of all the points (*i.e.* mean of all the points).

Intra-cluster distance (J_w) corresponds to:

$$J_w = \sum_g \sum_{i \in C_g} d^2(x_i, \mu_g) \qquad (3)$$

where C_g is the number of observations in cluster g, and x_i is the value of each observation. The higher the Fisher information, the more discriminative are the features, notably because a Fisher information of > 1 means that the inter-cluster distance is greater than the intra-cluster distance.

3. Results

The CH index exhibited its highest breakpoint value when the participants were classified in three clusters (C1, C2 and C3) (Figure 2), which was also displayed in the dendrogram (Figure 3).

Insert Figures 2 & 3 about here

Cluster C1 was composed of 19 data: four swimmers, S1, S2, S4, S9, whose start and the three turns were all characterised in this cluster; one swimmer, S8, had the three turns in C1. The swimmers in C1 exhibited a negative relative duration for T5, meaning that the dolphin kick started before the end of the arm pull-out. However, those swimmers also demonstrated a relative duration of T4 of approximately 0%, showing continuity between the dolphin kick and the arm pull-out, i.e., no time-gap between two propulsive actions.

Cluster C2 included 30 data: seven swimmers, S3, S5, S6, S7, S11, S12, S14, whose start and the three turns were included and two swimmers, S8, S13, who had only the start in C2. The swimmers in C2 had a negative relative duration of T5 that shows the start of the dolphin kick before the end of the arm pull-out, and a positive relative duration in T4, which means that the dolphin kick finished before the beginning of the arm pull-out.

Cluster C3 comprised seven data: one swimmer, S10, who had the start and the three turns in this cluster and one swimmer, S13, whose three turns were included in C3. The swimmers in C3 showed a negative relative duration in both T5 and T4, suggesting that the dolphin kick started before the end of the arm pull-out, and the beginning of the arm pull-out overlapped with the end of the dolphin kick.

In summary, eleven swimmers, S1, S2, S3, S4, S5, S6, S7, S9, S10, S11, S12, S14, used the same coordination profile throughout the 100-m, whereas two swimmers, S8 and S13, had different coordination profiles during the start and turns; S8 switched from C2 to C1 and S13 switched from C2 to C3 from the start to turns, respectively. The features with the highest

Fisher information (near 1) that distinguish the three clusters were the relative duration spent in T1, T4 and T5, the relative distance travelled during T1, T4, T5 and the dolphin kick. The Fisher information of the relative time, the relative distance travelled by the head and the mean speed during the active underwater sequence were very low, meaning that the intra-cluster distance is close to the inter-cluster distance, and suggest that the three clusters did not differ in terms of performance outcome.

Insert Tables 1, 2 and 3 about here

4. Discussion

The main aim of this study was to investigate whether swimmers glide between the dolphin kick and arm pull-out, favour continuity or even overlap those two phases, as it would impact the performance outcome of the active underwater sequence of the start and three turn-outs in 100-m breaststroke. According to the Fisher information displayed in Tables 1 to 3, our findings highlighted (i) three coordination profiles (‘*continuity*’, ‘*glide*’, ‘*superposition*’) to manage the timing between the dolphin kick and the arm pull-out (i.e. dolphin kick performed before, during or after the arm pull-out), which were mainly distinguished by T4 and T5, but not by T2 and T3, (ii) various relative duration of the glide with the arms at the thighs (assessed by T1) which was also related to those three profiles, and (iii) those different coordination profiles exhibited similar performance outcome, as they did not differ in terms of relative time, relative distance and mean speed during the active underwater sequence. Another finding is that ineffective synchronisation of the arm and leg recovery (assessed by T2 and T3) occurred before the first swimming arm stroke for all participants.

4.1. Timing between the arm pull-out and the dolphin kick

While Adams et al., (2018) distinguished an early- and a late-initiation of the dolphin kick (performed before the initiation of the arm pull-out versus at the completion of the arm pull-out), our findings highlighted that all swimmers started their dolphin kick before the initiation of the arm pull-out (measured by negative T5 values). However, three profiles were distinguished concerning the initiation of the arm pull-out: '*continuity*', '*glide*' and '*superposition*'. Four swimmers (C1) performed a '*continuity*' pattern of coordination as they synchronised the beginning of the arm pull-out and the end of the dolphin kick (T4 = 0%). The swimmers with a '*glide*' pattern of coordination (C2) were the most represented in the sample and started the arm pull-out after the end of the dolphin kick (T4 > 0%). In C2, the absolute duration of T4 was around 0.36 s (10.5% of the duration of the active underwater sequence that took 3.44 s), which supports the findings of the case study of Hayashi et al., (2015), who advised performing the dolphin kick 0.4 s earlier than the arm pull-out to maintain a streamlined position during the active underwater sequence. Then, one swimmer performed a '*superposition*' pattern of coordination as he started the arm pull-out before the end of the dolphin kick (T4 < 0%). The positive effect of overlapping the beginning of the arm pull-out before the end of the dolphin kick could be to cover a greater distance during the dolphin kick (in our study 0.38 m, which was 8.3% of the distance covered during the 4.6 m active underwater sequence). However, further investigation of the instantaneous speed would help to understand whether the partial overlap of the arm pull-out to the dolphin kick could add speed to the leg kick or if it is wasted because the dolphin kick is not performed with the upper limbs in a streamlined position (as suggested by Hayashi et al., 2015). Lastly, two swimmers, S8 and S13, exhibited a mixed coordination profile at start and turns, as they used a '*glide'* pattern of coordination (C2) during start, then S8 and S13 respectively switched to C1 and C3 for their three turns. They might prefer a glide pattern of coordination during the active underwater sequence of the start to take advantage of the high speed reached from the dive start. On the other hand, because the wall push-off provides less speed than the dive start, the swimmers probably switched to another coordination pattern to adjust the active underwater sequence of the turn-outs. As only two swimmers mixed two coordination profiles, further research is needed to understand whether a mixed profile could relate to the effect of speed and/or fatigue (for instance, by comparing the sprint pace with 200 m pace or investigating differences between seven turns in the 200 m).

4.2. Glide phase with the arms at the thighs

T1 showed that swimmers in C2 glided less (in terms of relative time and relative distance) than swimmers in C1 and C3 before starting the dolphin kick. This was probably because (i) they glided more after the wall push-off (Hayashi et al., 2015), and (ii) they already glided between the dolphin kick and the arm pull-out. The absolute duration of T1 (16% of the active underwater sequence 3.44 s = 0.55 s) for the swimmers in C2 is aligned with previous findings exhibiting a glide duration with arms at the thighs ranging from 0.30 - 0.52 s in French national swimmers to 1.06 s in the bronze medallist of the Athens 2004 and the Beijing 2008 Olympics (Seifert et al., 2007).

4.3. Synchronisation of the arm and leg recovery before the first swimming arm stroke

Regarding the synchronisation of the arm and leg recovery before the first swimming stroke, which were assessed by T2 and T3, the three clusters exhibited negative T2 and T3. The relative duration of T2 ranged from -5.9 to -8.4% (absolute duration between 0.20 and 0.29 s), meaning that the arm recovery started earlier than the leg recovery. This coordination was also observed in an Olympic bronze medallist (Seifert et al., 2007), but not in elite and non-expert swimmers (Chollet et al., 2004; Leblanc et al., 2005; Seifert & Chollet, 2005).

However, although the arms started their recovery earlier than the legs, it did not help to have a streamlined position of the upper limbs when the legs start their kicking action, which was supported by the negative relative duration of T3. The range of T3 was between -4.5 and -4.7% (absolute duration between 0.14 and 0.16 s), meaning that the legs started their propulsive kicking before the arm recovery reached full extension. This arm – leg coordination was not effective because the arms are not in a streamlined position when the legs initiate their propulsion, as already observed more than 10 years ago in national and international swimmers (absolute duration of T3 was between -0.1 and -0.16 s; Seifert et al., 2007). Those authors also mentioned that T3 came closer to 0% from the first swim stroke and stayed near 0% throughout the regular swimming, as observed in other studies (Chollet et al., 2004; Leblanc et al., 2005; Seifert & Chollet, 2005). This strategy is likely effective because the arm recovery does not interfere with the leg propulsion (Takagi, Sugimoto, Nishijima, & Wilson, 2004). The fact that swimmers can perform a complete arm pull-out (i.e. pull and push until reaching the thighs) instead of stopping the arm action at the chest level as during the regular swimming, might explain this overlap between the end of the arm recovery and the beginning of the leg propulsion because the arms must travel a longer distance than during regular swimming.

In conclusion, although three patterns of coordination (i.e. glide, continuity and superposition) were used to synchronise the dolphin kick and the arm pull-out, the swimmers mainly used the glide and continuity patterns of coordination. Surprisingly, two swimmers changed the way they synchronised their dolphin kick and arm pull-out between the start and the three turns. The three patterns of coordination led to similar performance outcome of the active underwater sequence. Therefore, it is recommended that coaches and swimmers should seek an individually advantageous pattern among the three rather than focusing on only one way of coordinating the dolphin kick with the arm pull-out. Our findings also exhibited that all swimmers initiated the leg propulsion while the arms did not finish their recovery, probably because the hands had to travel a longer backward distance relative to the body than during regular swimming. This finding suggests practitioner to train specifically the synchronisation of the leg and arm recoveries following the arm pull-out as the overlap of two contradictory actions (i.e. leg propulsion started before arms finished their recovery) affect the performance outcome of the active underwater sequence.

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Declaration of interest

The authors declare no conflict of interest.

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Table 1. Relative duration (in % of the active underwater sequence) of the five time-gaps, the dolphin kick and the arm pull-out for each cluster.

	T1 (%)	T2 (%)	T3 (%)	T4 (%)	T5 (%)	Dolphin kick (%)	Arm Pull-out (%)	Active Underwater Sequence (s)
Cluster 1	23.5 ± 3.7	-6.2 ± 2.6	-4.7 ± 1.5	0.0 ± 3.5	-21.6 ± 3.5	5.1 ± 1.0	16.5 ± 3.4	3.34 ± 0.51
Cluster 2	16.0 ± 4.8	-9.0 ± 6.1	-4.5 ± 1.3	10.5 ± 5.0	-32.1 ± 4.7	5.2 ± 0.7	16.3 ± 2.8	3.44 ± 0.34
Cluster 3	23.3 ± 3.3	-6.5 ± 2.2	-4.6 ± 0.9	-19.9 ± 1.1	-5.6 ± 1.6	5.5 ± 0.6	20.0 ± 2.1	3.08 ± 0.17
Fisher Information	0.78	0.08	0.01	5.81	4.85	0.03	0.17	0.09

Table 2. Relative distance travelled by the head (in % of the active underwater sequence) of the five time-gaps, the dolphin kick and the arm pull-out for each cluster.

	T1 (%)	T2 (%)	T3 (%)	T4 (%)	T5 (%)	Dolphin kick (%)	Arm Pull-out (%)	Active Underwater Sequence (m)
Cluster 1	27.8 ± 4.7	6.05 ± 2.5	3.1 ± 1.3	3.4 ± 2.5	28.2 ± 4.8	5.7 ± 1.2	22.3 ± 5.0	4.9 ± 1.0
Cluster 2	18.9 ± 5.4	8.8 ± 5.3	2.9 ± 1.2	11.9 ± 5.2	39.6 ± 4.9	6.5 ± 0.9	21.3 ± 3.7	5.1 ± 0.6
Cluster 3	29.0 ± 4.4	6.5 ± 2.4	2.9 ± 0.8	25.8 ± 1.3	8.5 ± 2.4	8.3 ± 0.9	26.0 ± 3.1	4.6 ± 0.4
Fisher Information	0.88	0.09	0.01	2.92	5.12	0.63	0.14	0.07

Table 3. Mean speed reached by the head (in $m.s^{-1}$) of the five time-gaps, the dolphin kick and the arm pull-out for each cluster.

	T1 ($m.s^{-1}$)	T2 ($m.s^{-1}$)	T3 ($m.s^{-1}$)	T4 ($m.s^{-1}$)	T5 ($m.s^{-1}$)	Dolphin kick ($m.s^{-1}$)	Arm Pull-out ($m.s^{-1}$)	Active Underwater Sequence ($m.s^{-1}$)
Cluster 1	1.84 ± 0.06	1.54 ± 0.10	0.88 ± 0.15	1.84 ± 0.45	1.91 ± 0.12	1.73 ± 0.15	2.00 ± 0.11	1.47 ± 0.10
Cluster 2	1.85 ± 0.09	1.57 ± 0.11	0.87 ± 0.12	1.62 ± 0.12	1.82 ± 0.09	1.82 ± 0.21	1.97 ± 0.12	1.49 ± 0.10
Cluster 3	1.86 ± 0.04	1.60 ± 0.08	0.79 ± 0.07	1.57 ± 0.05	1.78 ± 0.05	1.70 ± 0.17	1.91 ± 0.11	1.48 ± 0.07
Fisher Information	0.01	0.04	0.05	0.17	0.29	0.06	0.06	0.01

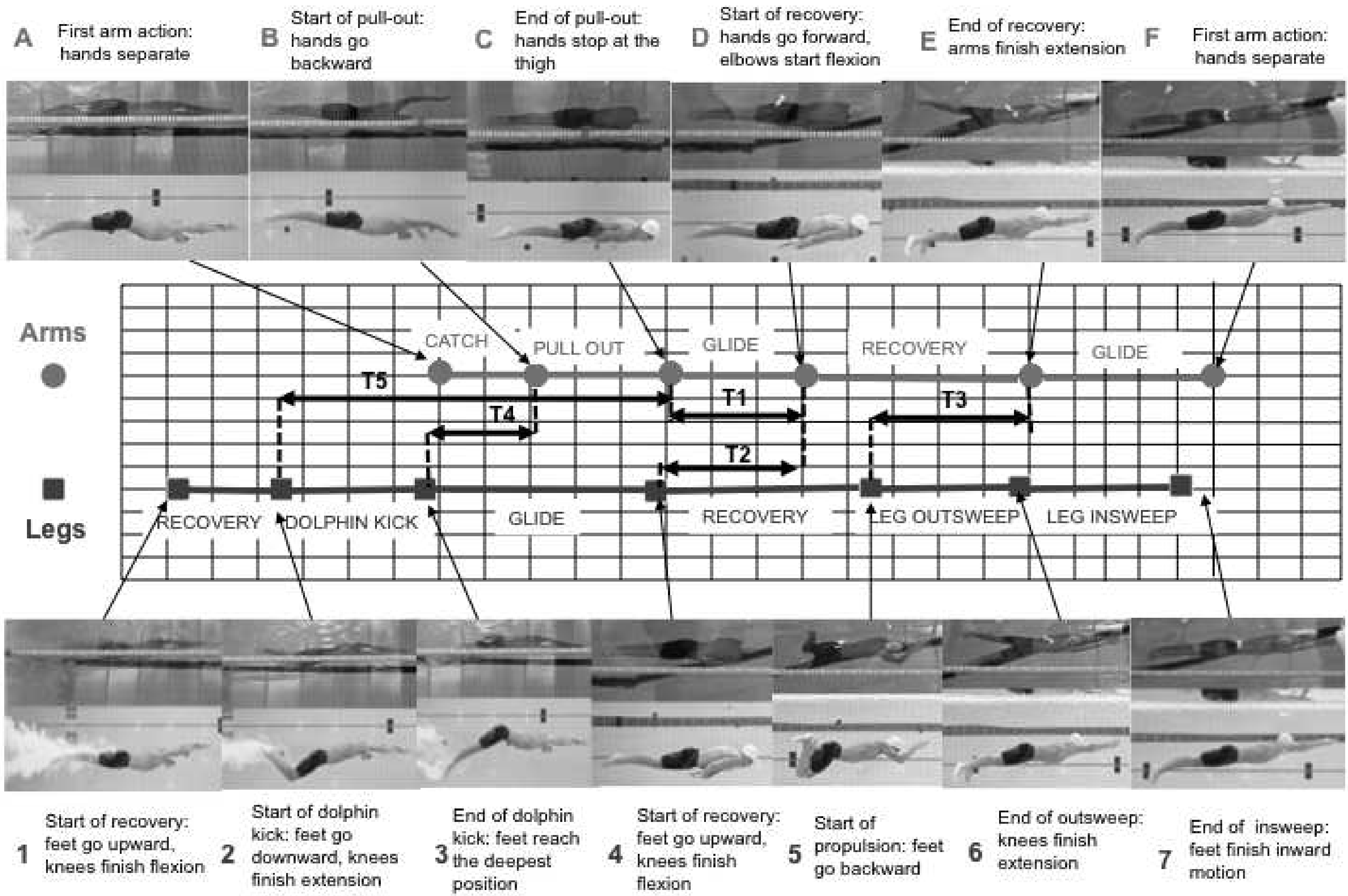
Figure Legends

Figure 1. Key points and phases of the active underwater sequence of the arms and legs

Figure 2. Values of Calinski-Harabasz (CH) index in relation with the number of clusters.

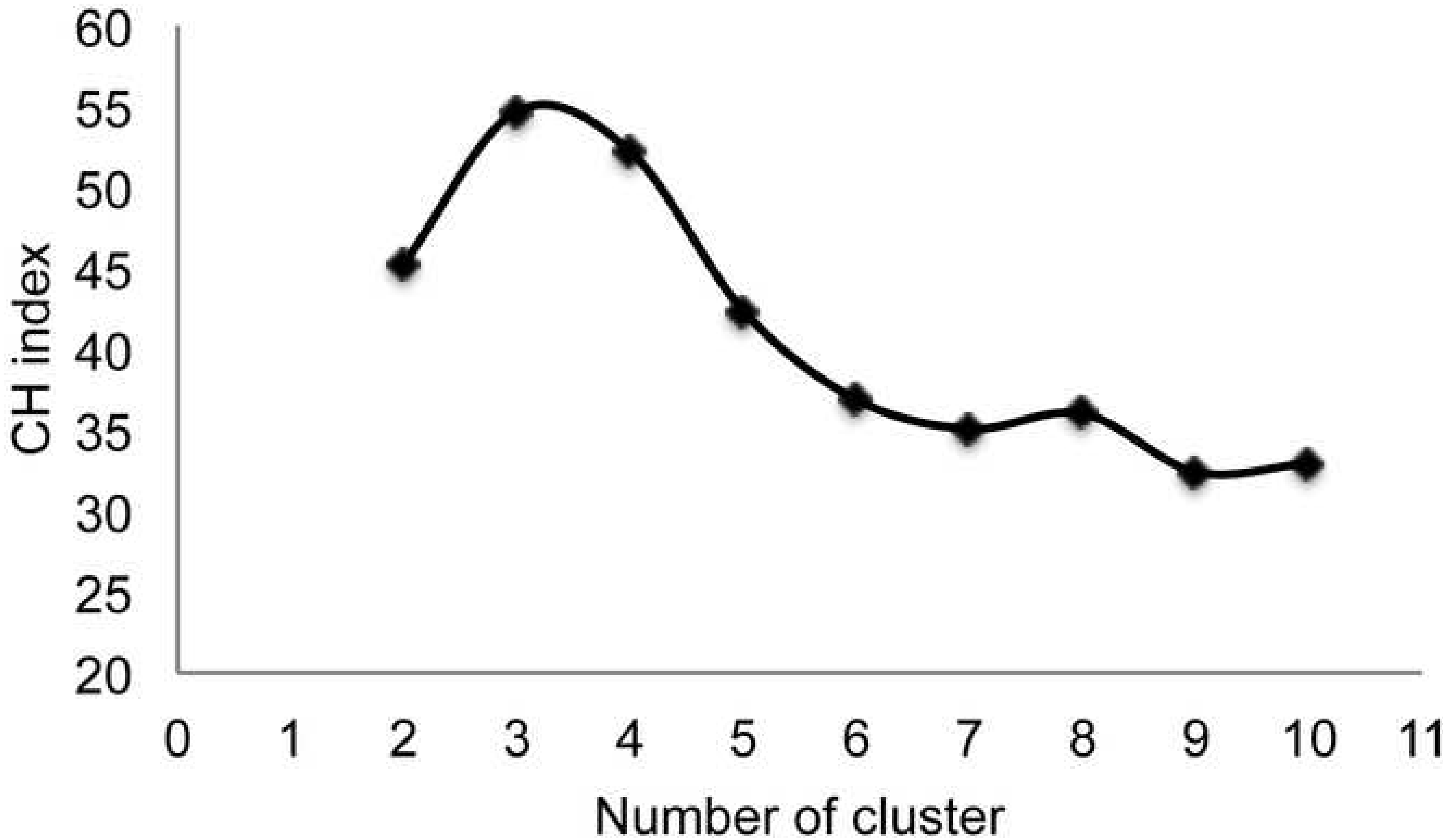
Figure 3. Dendrogram showing the distribution of the data relative to the active underwater sequence, showing three clusters on the basis of the Euclidean distance similarity (here 50).

Figure 1



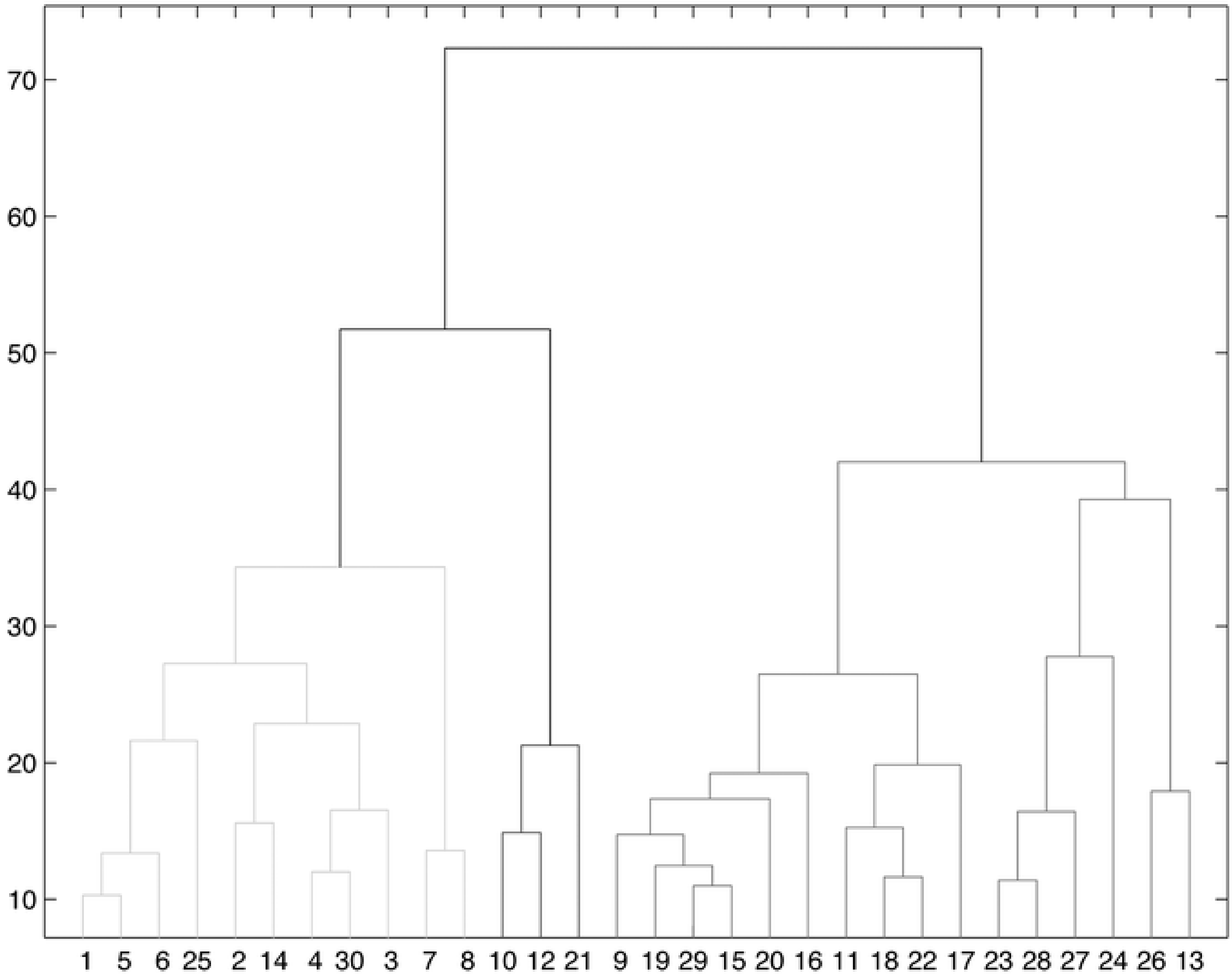
A First arm action: hands separate
B Start of pull-out: hands go backward
C End of pull-out: hands stop at the thigh
D Start of recovery: hands go forward, elbows start flexion
E End of recovery: arms finish extension
F First arm action: hands separate
Arms
Legs
CATCH
PULL OUT
GLIDE
RECOVERY
GLIDE
T5
T4
T1
T2
T3
RECOVERY
DOLPHIN KICK
GLIDE
RECOVERY
LEG OUTSWEEP
LEG INSWEEP
1 Start of recovery: feet go upward, knees finish flexion
2 Start of dolphin kick: feet go downward, knees finish extension
3 End of dolphin kick: feet reach the deepest position
4 Start of recovery: feet go upward, knees finish flexion
5 Start of propulsion: feet go backward
6 End of outsweep: knees finish extension
7 End of insweep: feet finish inward motion

Figure 2



60
55
50
45
40
35
30
25
20
CH index
0
1
2
3
4
5
6
7
8
9
10
11
Number of cluster

Figure 3 B&W



70
60
50
40
30
20
10
1 5 6 25 2 14 4 30 3 7 8 10 12 21 9 19 29 15 20 16 11 18 22 17 23 28 27 24 26 13

Figure 3 color