

Coordination Pattern Variability Provides Functional Adaptations to Constraints in Swimming Performance

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Abstract In a biophysical approach to the study of swimming performance (blending biomechanics and bioenergetics), inter-limb coordination is typically considered and analysed to improve propulsion and propelling efficiency. In this approach, ‘opposition’ or ‘continuous’ patterns of inter-limb coordination, where continuity between propulsive actions occurs, are promoted in the acquisition of expertise. Indeed a ‘continuous’ pattern theoretically minimizes intra-cyclic speed variations of the centre of mass. Consequently, it may also minimize the energy cost of locomotion. However, in skilled swimming performance there is a need to strike a delicate balance between inter-

limb coordination pattern stability and variability, suggesting the absence of an ‘ideal’ pattern of coordination toward which all swimmers must converge or seek to imitate. Instead, an ecological dynamics framework advocates that there is an intertwined relationship between the specific intentions, perceptions and actions of individual swimmers, which constrains this relationship between coordination pattern stability and variability. This perspective explains how behaviours emerge from a set of interacting constraints, which each swimmer has to satisfy in order to achieve specific task performance goals and produce particular task outcomes. This overview updates understanding on inter-limb coordination in swimming to analyse the relationship between coordination variability and stability in relation to interacting constraints (related to task, environment and organism) that swimmers may encounter during training and performance.

1 Introduction

Expertise in swimming has traditionally been associated with the capacity of athletes to reproduce a specific movement or coordination pattern consistently and to reduce attention demands during performance in this cyclic activity by increasing movement automaticity [1]. Stroke kinematics (e.g. stroke rate and stroke length) and inter-limb coordination have typically been investigated regarding the averaged cycle of experts versus non-experts [2, 3], fast versus slow speed [4–6], males versus females [7, 8]. Through averaging data within or between individuals, coordination variability has been smoothed and considered as noise in movement data which should be minimized or eradicated to enable high performance levels [9–11]. Similarly, from a metabolic point of view, less variability in

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displacement pace is preferred as slightly variable paces are considered less economical than constant ones [12]. However, recent studies analysing stroke kinematics and coordination in elite swimmers have revealed high variability within individuals throughout 100- and 200-m front-crawl events [13–15]. The data might induce more precise thinking about movement and coordination variability and why elite swimmers show such variability.

In that sense, research in ecological dynamics has shown that movement system variability should not necessarily be construed as noise, detrimental to performance [9, 16], nor should it always be viewed as error, or a deviation from a putative expert model, which should be constantly corrected in learners by coaches [17]. A key idea is that coordination pattern variability can be viewed as a functional property in skilled performers which helps them adapt their movement behaviours to changing performance constraints [18, 19]. Different categories of constraints (related to task, environment, and organism [20]) are resources that limit or set the boundaries for the emergence of coordination patterns in human movement systems. These ideas suggest the need to reconsider learning and training of inter-limb coordination in swimming. The assumption that there is one general optimal pattern of coordination towards which all developing learners in swimming should aspire, is rejected. Instead expertise in swimming can be re-considered as the emergent, rapid and efficient adaptation to a range of interacting constraints that shape the competitive performance environment [21]. An important implication of our work is that reaching a high skill level in sports such as swimming (e.g. performed in an ‘unnatural’ environment for humans, being submitted to different external forces) does not involve athletes following a universal and linear pathway. Rather non-linear neurobiological system characteristics suggest that coordination pattern variability might be functional in enhancing performance at different levels (e.g. intra-cyclic, inter-cyclic and inter-individual level) [17, 22]. These ideas have implications for pedagogical practice in swimming. Chow et al. [23] presented the key concepts of a ‘non-linear pedagogy’ based on characterising athletes as complex non-linear dynamical systems. A non-linear pedagogy highlights how a learner’s coordination behaviours emerge from self-organisation under interacting constraints. It advocates that instances of movement variability or exploration are an inherent part of the learning process. Therefore, during motor skill acquisition, coordination pattern variability plays a functional role in encouraging learners to explore the relationship between spatial-temporal parameters of the movements and the interacting constraints, which impinge on him/her.

Following an ecological dynamics framework, the goal of this overview is to update existing knowledge on inter-limb coordination in swimming by integrating relevant research in

the sub-disciplines of biomechanics and motor control. We sought to achieve this aim by undertaking two independent database searches (in PubMed, ISI Web of Knowledge, Index Medicus, MEDLINE, Scopus, SPORTDiscus and EBSCO) from 1970 to 2014. Our first database search concerned biomechanical approaches to studying coordination in swimming, through the key words ‘coordination’ and ‘competitive swimming’, yielding 110 articles. The second database search concerned coordination dynamics through the key words ‘movement coordination’ and ‘dynamical systems’, providing around 50 articles. The criteria of inclusion to select an article was its relevance for integrating ideas and methods in biomechanics and motor control, in order to highlight the functional role played by coordination variability in helping swimmers to adapt to a set of interacting constraints rather than seeking to imitate a putative expert model.

This overview has two main sections: the first presents recent studies that have stimulated debates about the existence of an ‘ideal’ coordination pattern in swimming. The next section explores the functional role played by coordination pattern variability as a mark of adaptation of a complex, dynamical system to a set of interacting constraints. Our overview aims to stimulate thinking on how sport scientists, movement scientists, coaches, educators and teachers might re-consider variability in swimmers’ movement patterns and manipulate major constraints to stimulate emergent adaptive behaviours in learners.

2 Is There an Ideal Pattern of Coordination in Swimming?

More traditional approaches to the study of expert performance in swimming have led scientists and coaches to search for a putative ‘ideal’ inter-limb coordination pattern that would provide a biomechanical profile (swimming kinematics and swimming kinetics), thereby enhancing swimming economy and performance. Previous research has attempted to highlight the links between inter-limb coordination, propulsive and drag forces, propulsive efficiency, power output generation, intra-cyclic speed variations and energy cost of locomotion in swimming [24–26]. According to Barbosa et al. [24], when swimming at constant speeds, the cycle average of mechanical power remains constant. However, the swimmer does not typically displace with uniform motion because variations in arm, leg and trunk actions can lead to intra-cyclic speed variations and changes in mechanical power output. Moreover, gross efficiency (e_g) depends upon the conversion of power input (P_i) to mechanical power output (P_o) [Eq. 1]; the power input is also called metabolic power and represents the rate of energy expenditure (\dot{E}) [24, 27]:

$$e_g = P_o / P_i = P_o / \dot{E} \quad (1)$$

Total mechanical power output (P_o) may be considered the sum of two components (Eq. 2): (1) internal (P_{int}), i.e. mechanical power associated with the mechanical energy changes relative to the centre of mass due to limb movements; and (2) external (P_{ext}), i.e. mechanical power associated with the mechanical energy changes of the centre of mass as well as power on the surrounding environment, i.e. power to overcome drag (P_d) and power on propelled masses of water (P_k) [24, 27]:

$$P_o = P_{ext} + P_{int} = P_d + P_k + P_{int} \quad (2)$$

For the sake of simplicity, several researchers have considered internal mechanical power as negligible in swimming. Thus, in order to minimize mechanical power to allow swimmers to enhance their speed and/or swim more efficiently, intra-cyclic speed variations of the centre of mass should be minimized towards a more constant speed. Theoretically, the energy cost of locomotion would be lower when reducing the magnitude of acceleration and deceleration variations within a stroke cycle [28, 29]. Nigg [28] showed mathematically that changes in speed of 10 %, within a stroke cycle, resulted in an additional work demand of about 3 %. This additional work may result when swimmers have to overcome inertia and drag forces. Thus, for a given average speed, intra-cyclic speed variations would lead to higher drag forces that swimmers can notably minimize by increasing continuity between propulsive actions [30]. According to Chollet et al. [2], in front crawl a stroke cycle can be decomposed into the hand entry and catch, pull, push and recovery phases. In backstroke, the push phase finishes with the hand around 30 cm below the water level, so a cleaning phase is dedicated to exit the hand from the water before undergoing the aerial recovery [31]. Thus, pull and push phases are usually considered as propulsive actions in front crawl and backstroke. In breaststroke, the arm and leg stroke has been divided into the glide, outswEEP, insweep and recovery phases [31]. Last, in the butterfly stroke, the arm stroke has been divided into the entry and catch, pull, push and recovery phases, while the leg stroke is composed of the downward and upward phases of the kick [31]. Chollet and Seifert [31] proposed an index of coordination for front- and backstroke to assess the time gap between the propulsive actions of the arms. They calculated a time gap between the propulsive actions of the arms and legs for breaststroke and butterfly. Depending on whether a lag time, continuity or overlap occurred between propulsive actions, the patterns of coordination were respectively called the 'catch-up' or 'glide', 'opposition', and 'superposition' [31]. As explained later in this section, one cannot rule out that the fatigue-induced decrease in

muscular rate of force development would lead to longer propulsive durations without any increase in propulsive efficiency [32, 33]. From the perspective of classical mechanics, a uniform motion emerges whenever the sum of all external forces is null. In swimming, two major external forces are at work: drag (D) [opposite to the displacement direction] and propulsion (Fp) [in the displacement direction]. Assuming that a cycle-averaged balance between drag and propulsive forces is needed to swim at a cycle-averaged constant speed (Eq. 3) [27], swimmers have to organize their inter-limb coordination patterns in order to overcome drag (D), which is associated with speed (v) squared (Eq. 4):

$$Fp + D = (m_b + m_a) \cdot a \quad (3)$$

where m_b is the swimmer's body mass, m_a is the mass of water and a is the body's acceleration;

$$D = K \cdot v^2 \quad (4)$$

where K is the drag constant that depends on body size, body shape and fluid density.

Experimental and computational simulations have indeed reported a non-linear relationship between active drag and speed. Again, assuming that, in the swimming speed range of 1.2–1.8 m s⁻¹, active drag relates to speed squared [27] on average, as arm coordination does, at least in front-crawl sprinters [34], Seifert et al. [35] demonstrated that stroke cycle changes in arm coordination are linked to variations in aquatic resistance. This observation emerged when swimmers were tested in a series of swimming bouts in which speed was varied and rest was provided between each bout. A positive linear regression between the index of arm coordination (measuring the degree of continuity between two propulsive actions [2]) and active drag with 95 % explained variances has been observed in 20 front-crawl specialists [35]. These data suggest that coaches should seek to promote and train 'opposition' or 'continuity' patterns of inter-limb coordination in order to help swimmers to overcome high levels of active drag and minimize speed variations within a stroke cycle [24, 30, 36]. Moreover, using 'superposition' patterns of inter-limb coordination signifies that the overlap of two propulsions occurs, during which doubling the propulsive surface area would enable athletes to achieve higher swimming speed and/or lower intra-cyclic speed variations [2, 6, 37], but with a higher metabolic cost and/or muscle fatigue. Similar results have been reported in studies of other swim strokes (e.g. butterfly [38–40] and breaststroke [3, 4, 8, 41]). The key idea that high continuity between propulsive actions is correlated with high speed and low intra-cyclic speed variations seems to be an assumption accepted by scientists and coaches regarding front crawl.

Minimizing intra-cyclic speed variations appears to be a valuable goal in front crawl. However, in breaststroke, intra-cyclic speed variations is a challenge due to under-water arm and leg recoveries that the swimmer must take into account to organize inter-limb coordination in order to minimize active drag and maximize swimming speed. Achieving a high average speed and, more broadly, a high level of effectiveness, cannot be automatically equated with low intra-cyclic speed variations [41]. For instance, through analysis of arm to leg coordination patterns of breaststroke swimmers, in relation to intra-cyclic speed variations of centre of mass and effectiveness (i.e. horizontal distance of the centre of mass for each phase of the cycle), Komar et al. [41] revealed that both expert and recreational swimmers decreased intra-cyclic speed variations and their glide time when they were required to swim faster. Unsurprisingly, expert breaststrokers reached higher values of swim speed than recreational swimmers, notably because they coordinated their limbs in a more effective way than recreational swimmers (i.e. higher acceleration peak during propulsion: 2.4 m s^{-2} for experts and 1.6 m s^{-2} for recreational swimmers, and higher distance covered by the centre of mass during each phase of the cycle). More surprisingly, this performance outcome was achieved without any differences in intra-cyclic speed variations between the two groups [41]. Since the task-goal in sprinting is to swim as fast as possible for a short distance, swim effectiveness appears a more important goal to be achieved by a competitive swimmer than minimizing intra-cyclic speed variations. However, it remains to be determined whether this is also the case for long-distance swimming. Indeed, in long-distance swimming, the goal cannot be simply to swim at maximum speed. There is the need to select a speed that matches metabolic capacity over the duration of the exercise, such that fatigue prohibits further exercise only when the finish line has been reached.

These data inform us that the link between propulsion and coordination is clearly related to specific task constraints and the intentions of performers. In particular, sprint and distance swimming may not result in the same inter-limb coordination patterns, swim effectiveness, intra-cyclic speed variations and energy cost [42]. Although high continuity between propulsive actions seems to overcome high drag force and consequently ensure achievement of high swim speeds with reduced intra-cyclic velocity variation, numerous recent studies have highlighted intra- and inter-individual adaptations for a given task-goal [34, 43, 44]. These findings negate the view that ‘opposition’ (continuity between propulsive actions) and ‘superposition’ (overlap between propulsive actions) patterns of coordination are ‘ideal’ performance behaviours that all swimmers need to adopt. More precisely, Schnitzler et al. [45] showed that expert swimmers exhibited greater glide times

between two propulsive actions for higher values of swim speed and stroke length than recreational swimmers when swimming the 400-m front-crawl event. They suggested that a catch-up pattern of coordination could be acceptable for performance in mid- and long-distance races (as previously observed in distance swimmers [42]).

3 Functional Variability of Coordination Patterns

According to Bartlett et al. [46] and Davids and Glazier [22], coordination variability in neurobiological systems can produce (1) the relative stability of motor functions undergoing internal and external disturbances; (2) behavioural flexibility in response to changes in the environment; and (3), the emergence of new behaviours in order to enhance task performance. When coordination variability leads to a similar or higher performance outcome, Davids and Glazier [22] and Seifert et al. [17] have suggested that variability could correspond to functional adaptations that reveal neurobiological system properties such as degeneracy. Edelman and Gally [47] originally defined degeneracy as “the ability of elements that are structurally different to perform the same function or yield the same output”. In fact, the property of degeneracy can exhibit several forms in neurobiological systems. For instance, degeneracy can occur through parcellation, when an initial structure is subdivided into smaller units that can still perform the initial function and can also be functionally redeployed [48]. Another form of degeneracy may emerge through organisation of a coordinative structure that realises a function in combination [48]. This means that whether a structure is able to perform an initial function independently or not, another one is available for modification. Last, degeneracy can be observed when two or more independent structures converge upon the same function [48]. Moreover, the concept of degeneracy captures not only the ability of the structurally different components of a neurobiological system to perform the same task under certain conditions but also the ability of these components to assume distinctly different roles in other conditions [47, 49]. Degeneracy refers to two types of relationship: many structures-to-one function and one structure-to-many functions [50]. In other words, the same function can be performed by two different architectures, each involving different joints (i.e. many structures-to-one function), as well as by several joints working together (i.e. one structure-to-many functions), all the while leaving some joints free for future involvement [50]. This last characteristic is known as pluri-potentiality [48]. Pluri-potentiality corresponds to a surplus of structures for future situations, which means that during task performance, some limbs may be only slightly mobilized, but they may potentially be far

more mobilized in the future [48]. The last form of degeneracy could be exhibited through redundancy. In particular, redundancy can create the opportunity for degeneracy to arise as the function of the original structure is maintained by one copy, while other copies are free to diverge functionally [48, 50]. Indeed, redundancy refers to how something functions, whereas degeneracy is an attribute of structural elements in relation to a function. Price and Friston [50] have suggested that degeneracy is necessary for redundancy. In other words, for redundancy to occur there must be multiple system structural configurations that can support the same function [50]. In summary, degeneracy signifies that an individual can vary motor behaviour (structurally) without compromising function, providing evidence for the adaptive and functional role of coordination pattern variability at different levels of organization (i.e. intra-cycle, inter-cycle and inter-individual), in order to satisfy task, environmental and organism constraints.

3.1 Inter-Limb Coordination Variability Within a Cycle

Analysis of inter-limb coordination within a cycle provides a useful way to understand degeneracy, for instance by highlighting different limb-coupling patterns or different limbs involved in motor organization in response to a task-goal. For example, swimming breaststroke could be achieved by a circular arm action where the arms are mostly extended at the water surface (which usually reflects novice behaviours) or where the hands move downward by elbow flexion (which reflect a higher skill behaviour). In both cases, the forearms and arms are involved in upper-limb coordination, but with a different coupling. Traditionally, intra-cyclic variation in limb coordination was assessed by analysing continuous relative phase [51]. The calculation of continuous relative phase enables an analysis of the spatial and temporal relationships between joints within a cycle for cyclic tasks, as demonstrated in the paradigmatic work of Kelso [51] on finger oscillation coupling. In contrast, pioneer studies analysing inter-limb coordination in swimming have calculated time gaps between key points marking the beginning and end of propulsive actions (for an overview see Chollet and Seifert [31, 52] and Seifert et al. [31, 52]). As outlined by Glazier et al. [53] and Hamill et al. [54], this discrete method was based on temporal data and could be complemented with analyses of spatial data (such as the angular positions of the limbs) to enable a spatial-temporal perspective. Nikodelis et al. [55] first proposed methods to study the spatial-temporal relations between the upper limbs in front crawl by means of recording the peak amplitude and time lag of the cross-correlation function

between the right and left arm's endpoint trajectories. They observed a strong anti-phase coupling between the two arms without any differences between elite and novice swimmers. Nikodelis et al. [55] concluded that in front crawl, the intrinsic anti-phase pattern of coordination is strongly preserved despite environmental constraints (i.e. aquatic resistance), as this pattern is not affected by skill level. Thus, a more accurate method was needed to examine intra-cyclic variations of coordination that could occur, especially when limb actions alternate between air and water; in particular, continuous relative phase provides information on inter-limb coordination from angle and angular velocity data to facilitate examination of coordination dynamics through a complete cycle [51, 54]. Moreover, using continuous relative phase, inter-limb coordination could be captured with only one macroscopic order parameter, while in breaststroke for instance, arm to leg coordination has been traditionally analysed by recording four time gaps at four key points of the cycle [3, 4, 8]. Recently, continuous relative phase was used to assess skill level effects and the individual profile of arm to leg coordination variability in breaststroke. Data revealed that the topography of the curve of novices resembled a 'W-shape', whereas an 'inverse U-shape' was noted for competitive swimmers [44, 56]. These curve shapes, and the degree of variability of these curves, provided fruitful information on homogeneous or heterogeneous muscular actions of legs and arms; for instance, in-phase coordination patterns correspond to simultaneous flexion of the knee and elbow or simultaneous extension of these two joints (resembling an 'accordion' movement), while anti-phase coordination patterns correspond to simultaneous flexion of a joint and extension of the other joint (resembling a 'windscreen wiper' movement) [56]. Interestingly, Komar et al. [41] reported that recreational and expert swimmers exhibited the same glide relative duration, whereas the latter swam faster and covered a greater distance during the glide period. Continuous relative phase has also been used in front crawl to assess the degree of coupling between the right and left arm, providing insights on coordination asymmetry [57]. It appears helpful to detect coordination asymmetry because it often relates to handedness, breathing pattern (bilateral breathing vs. breathing preferential side) or force dominance.

3.2 Inter-Cycle Variability of Coordination Patterns

Neurobiological degeneracy effects could be observed when inter-cycle variability of coordination patterns was studied. Rein [58] overviewed several methods to study inter-cycle variability, such as the computation of root-mean-squared-error and the Cauchy criterion. Root-mean-squared-error assesses the deviations between the pattern of

one cycle and the mean pattern, while the Cauchy criterion measures the differences between two successive coordination patterns. Traditionally, variance between cycles could be assessed by calculating standard deviation values that Kelso [51] measured by a moving window over the data to highlight critical fluctuations around transition between two coordination patterns. In swimming, our research assessed stroking kinematics (e.g. swim speed, stroke rate and stroke length) and coordination pattern variability within and between 25-m laps composing a 100-m swim course to explore how swimmers coped with fatigue [14, 15]. Variability within a lap was assessed by decomposing the 25-m lap into five 5-m zones (on average each composing two or three cycles) [14, 15]. Seifert et al. [15] showed that to maintain swimming speed as stable as possible through a 100-m front-crawl race, swimmers used different strategies of arm coordination adaptation according to their skill level, perhaps revealing neurobiological degeneracy when it led to performance maintenance. In particular, experts display a superposition pattern of arm coordination, which is stable between laps but increasing in propulsive continuity within laps due to the turn out. Non-expert swimmers also increased propulsive continuity within laps; however, they switched from an opposition to superposition pattern of arm coordination (due to longer relative durations of propulsive actions) in the second part of the 100-m race [15]. This motor adaptation to fatigue appeared less effective because, unlike in the expert swimmers, stroke length continued to decrease both between and within 25-m laps [15]. According to Toussaint et al. [59], the longer relative duration of the propulsion actions found by Seifert et al. [15] for non-expert swimmers could relate to their lower hand speed and a decrease of 20 % of the power output generation between the first and the fourth 25-m lap [59]. Similarly, during time to exhaustion tests, Alberty et al. [33] showed that fatigue could lead the swimmer to slow the movement of the hand during the propulsive action and to exhibit a higher continuity between propulsive actions without equivalent efficiency because he/she is not able to generate a high mechanical impulse [33]. However, a high hand speed did not guarantee effective propulsion and arm coordination. For example, fatigue could result in the hand slipping through the water (i.e. increase transfer of the kinetic energy to water mass and thus decrease propelling efficiency [59]), meaning that although hand speed remained high, force generation was low or not well orientated to overcome drag. Thus, muscular fatigue does not induce similar adaptations toward a specific kinematical coordination pattern, muscular recruitment pattern and force production pattern, suggesting how neurobiological degeneracy can be harnessed to maintain a high level of performance [59–62]. In other words, varied motor

organizations can emerge with fatigue that might suggest that coaches and teachers need to focus on how learners achieve a task-goal rather than on the reproduction of an ‘ideal’ coordination pattern. Last, recent studies using inertial measurement units (IMU) associated with data mining for front crawl and breaststroke coordination pattern recognition have revealed a promising way to explore inter-cycle coordination variability [63, 64]. IMUs can combine tri-dimensional accelerometers, tri-dimensional gyroscopes and tri-dimensional magnetometers from which raw data is processed for change point detection [63, 64] or for rotation matrix, and for computations of the Euler angle (i.e. yaw, pitch and roll) and quaternion [65, 66]. For instance, Dadashi et al. [64] automatically detected the start and the end of the arm pull and push phases in front crawl from accelerometer and gyroscope signals, in order to assess the index of arm coordination without using an optic system. It is an affordable, less time-consuming (collecting and handling the data) technique that in addition provides almost immediate ‘on the spot’ feedback to coaches and swimmers, being used as an interactive tool. Specifically as a new window of investigating inter-cycle variability, the use of IMUs allowed the assessment of arm-leg coordination in breaststroke during the entire learning process [67]. In this experiment, a cluster analysis was applied to the coordination patterns assessed during every cycle performed throughout 2.5 months of practice. Each cycle of each trial was recorded (Fig. 1) and each individual, therefore, presented a series of approximately 2,000 cycles representing 16 learning sessions that, taken together, allowed the investigation of exploratory learning strategies (Fig. 2). In particular, the Fisher-EM cluster analysis showed that the learner visited 11 coordination patterns throughout the learning protocol, each of them showing more or less stability within and between sessions [67, 68].

3.3 Inter-Individual Variability of Coordination Patterns

Characteristics of neurobiological system degeneracy could be understood by studying inter-individual variability of coordination patterns. In water, the human body is subjected to an upward buoyant force or ‘Archimedes lift’ (equal to the weight of the water volume displaced by the body) and gravity. Coping with these interacting forces in an aquatic environment means that the swimmer’s focus is not just limited to assembling coordination patterns for propulsion (e.g. moving forward to overcome drag as explained previously). The swimmer must also ensure an appropriate balance of forces in the vertical direction that is influenced, for example, by breathing, by how much of the body is immersed or the partial location of the limbs (i.e. position of the segments). Differences in, for example, lung

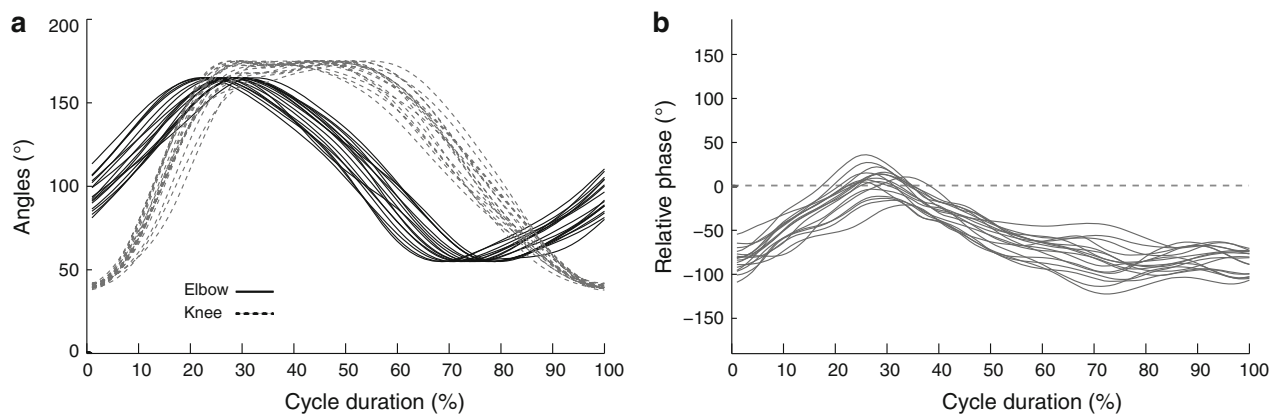


Fig. 1 Examples of (a) knee and elbow angles and (b) continuous relative phase between knee and elbow for one trial of 17 cycles. A cycle began from a position of maximal leg flexion (feet at the buttocks) and ended at the return to this position. A value close to -180° (i.e. anti-phase relationship) indicates that the elbows are at their maximal extension when the legs are at their maximal flexion prior to

starting their extension. A value closer to 0° indicates that the elbows are flexed when the knees are at their maximal flexion. The time spent in the in-phase pattern of coordination indicates an identical motion of both arms and legs (i.e. flexion or extension of both pairs of limbs). For instance, the time spent in simultaneous extension of arms and legs indicates the body glide duration

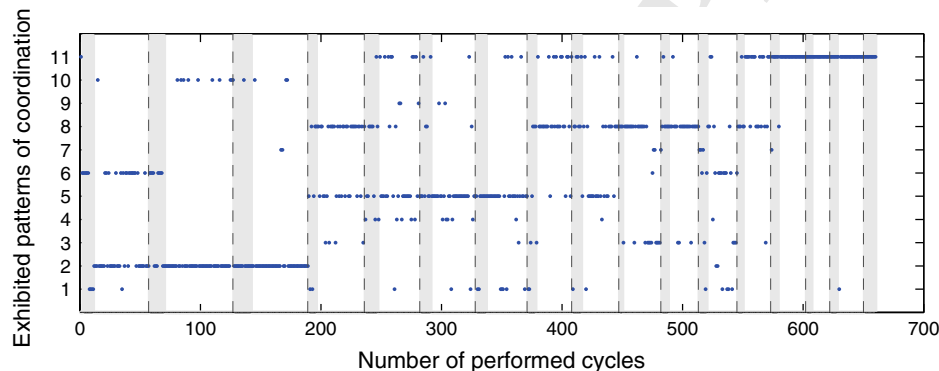


Fig. 2 Inter-cycle variability in the dynamics of breaststroke learning. Each *point* represents a cycle performed by an individual during 16 learning sessions (sessions are delimited by a *broken line*). All cycles were individually labelled in terms of their belonging to a

specific cluster (between 1 and 11) which represents a typical coordination pattern. Motor exploration is represented by the diversity of exhibited patterns during learning (sometimes cycle-to-cycle) and highlights the functional role of inter-cycle variability during learning

volume, tissue density and stroking style will induce different levels of flotation, creating variability in the movement problem to be solved by the swimmer, especially in beginners who are not familiar with this environment. Inter-individual variability has been identified in several physical activities and its analysis is important to determine coordination profiles.

A paramount issue in the study of inter-individual variability is the absence of a priori knowledge about the nature and structure of variability in a sample of individuals under study. In this task, the use of statistical tools and procedures derived from data mining and knowledge discovery principles offers interesting alternatives to more common analysis of variance measures. Tools such as cluster analysis [69, 70], neural networks [71, 72] or principal component analysis [73, 74] have been used in order to investigate inter-limb coordination. They can be

used to explore the potential existence of similar patterns between individuals (i.e. low inter-individual variability), as well as potential differences between these groups of similar patterns (i.e. high inter-group variability), without any a priori knowledge about the structure of the initial dataset (e.g. sex, level of expertise, swim specialty). For example, Chow et al. [75, 76] employed cluster analysis to detect inter-individual variability of coordination patterns to perform a chip in soccer. Rein et al. [77] also used cluster analysis to explore inter-individual variability of coordination patterns for basketball shooting. In swimming, cluster analysis has already been used to classify the backstroke start as regarding the body segment vector of the swimmers [78]. Other recent swimming studies have used cluster analysis to identify coordination patterns in different starting phases [79, 80]. For instance, based on take-off and entry angles, arms-trunk and trunk-legs angles,

Seifert et al. [79] distinguished four start profiles (flat, pike, flight and Volkov) in expert front-crawl swimmers, which led to similar 15 m start times, suggesting the need to consider the inter-individual variability during training in relation to start time before favouring a unique strategy. Cluster analysis was also used to classify speed range in relation to coordination range for 63 front-crawl swimmers with different characteristics (e.g. sex, performance level, specialty) [34]. Interestingly, the cluster analysis exhibited four profiles of swimmers: (1) national distance male swimmers with a high maximal speed but a low continuity between propulsive actions; (2) international male sprinters with the highest maximal speed and maximal continuity between propulsive actions and the widest range of speeds and coordination patterns; (3) the third profile was marked by sex differences; in particular, males exhibited a superposition pattern of coordination while females only reached an opposition pattern of coordination; and (4) lowest level of performers, who exhibited low maximal speed and continuity between propulsive actions. However, in-depth analysis of beginners also reveals the functional role of variability at this skill level. Notably, some swimmers used an in-phase pattern of arms-legs coordination to keep their body close to the water surface, while others used an out-of-phase pattern to overcome aquatic resistance [44]. Coordination variability is viewed as ‘functional’ and ‘adaptive’ in helping swimmers to organize the distribution of movement in water and air over time, forwards and backwards (e.g. the underwater recovery actions of the legs and arms as well as the propulsion of arms and legs in breaststroke). Thus, Seifert et al. [44] showed that cluster analysis supported the distinction between some beginners in breaststroke who were just beginning to apply Newton’s third law (i.e. learning about action-reaction force processes), while others had already begun to exploit aquatic resistances, distinguishing propulsion and recovery, creating acceleration and glide. The study of inter-individual variability with a limited cluster analysis [44] also highlighted which sections of a swimming cycle were the most discriminating in the clustering process. For instance, in breaststroke swimming, Komar [67] highlighted key points of the breaststroke cycle that were highly discriminative between individuals, therefore representing key features of inter-limb coordination in breaststroke.

4 Individual Adaptation to Interacting Constraints

To correctly and efficiently respond to a performance goal, the motor system must be coordinated under the influence of internal neuroanatomical forces and external environmental forces that act on each individual [52] (e.g. in the aquatic environment: gravity and buoyant forces, the latter

dependent on the percentage of body volume immersed, water density and temperature). The motor system also produces forces in response to body parts that move relative to water creating propulsion and drag. According to the constraints-led approach [18], instead of prescribing a specific coordination pattern to adopt, constraints channel emergent behaviours of each individual performer. Newell [22] defined three categories of constraints that act on and channel behaviour—related to the environment, organism and task.

In swimming, *environmental* constraints refer to water properties such as the temperature and density and viscosity of the fluid, the direction and type of water flow (laminar vs. turbulent, quantified with Reynolds number), underwater visibility, and waves on the surface of the water (e.g. assessed with Froude number). As mentioned previously, body parts that move relative to water will induce drag, so that a certain amount of propulsion is needed to balance or overcome drag [27]. Environmental and organism constraints are in interaction and cannot be considered separately. A good example is breaststroke, for which arm and leg recoveries must be realised underwater, explaining why breaststroke exhibits the highest level of active drag among the four stroke techniques [81, 82]. For instance, at a velocity of 1.25 m s^{-1} , active drag was close to 20 N in front crawl and 40 N in breaststroke, and at 1.45 m s^{-1} , active drag was close to 25 N in front crawl and 95 N in breaststroke [81]. Previously, Kent and Atha [83] studied passive drag of the body position at five key points of the breaststroke cycle. They showed that, for a velocity of 1.5 m s^{-1} , passive drag equalled 92 N in the glide position, 165 N in the breathing position, 222 N during the arm and leg recoveries position, 214 N when the legs begin their propulsion and 205 N when the legs finished their propulsion in the extended position. These variations in resistance indicated the importance of organizing the arm-leg coordination effectively in order to minimize the influence of these environmental constraints on performance. To investigate the dynamical nature of coordination, and its adaptation to environmental constraints, it seems useful to artificially increase aquatic resistance by using, for example, a parachute, and investigate the influence on inter-limb coordination patterns [84]. In particular, Schnitzler et al. [84] identified a higher continuity between propulsive actions, a higher propulsive phase duration and mechanical impulse, and a lower stroke rate when athletes swam with added resistance (i.e. towing a parachute), in comparison to free swimming.

Organism constraints refer to the personal characteristics of each individual. They may include passive drag and flotation parameters (hydrostatic lift, sinking force acting at the ankle) [85] that could be artificially modified by wearing a wetsuit and influence arm coordination in front

crawl [86]. Other body characteristics such as strength, endurance and laterality (handedness and the preferred breathing side) [87–89] can also influence inter-limb coordination. All organism constraints can be included in larger categories related to age and sex and showed individual adaptation of inter-limb coordination [90]. Regarding sex differences on inter-limb coordination, the greater fat mass, a different distribution of this mass, lower arm strength and greater difficulty in overcoming forward resistance in females (than in males) may explain their lower propulsive continuity between the propulsion of the two arms in front crawl [7, 90] and their longer glide between legs and arm propulsion in breaststroke [8]. Organism constraints could also be functional (e.g. fatigue), for example related to a swimmer's speciality event (e.g. sprint vs. mid-distance [42, 91–93]; swimmer vs. triathlete [94]). When disabilities and/or impairment such as Down syndrome were explored, swimmers exhibited lower propulsion generation and lower continuity between the propulsive actions of the arms in front crawl [95–98], which reflects a combination of physical and cognitive limitations due to differences in the cerebellum [99]. Marques-Aleixo et al. [95] noted that the breathing action amplifies the catch-up pattern of arm coordination. Additionally, Osborough et al. [97] showed that unilateral arm-amputee swimmers used a catch-up coordination pattern with higher discontinuity between propulsive actions to their affected-arm side compared with their unaffected-arm, suggesting that this organism constraint led them to use an asymmetrical strategy for coordinating their arms in front crawl. Interestingly, asymmetric coordination between arms was marked in swimmers with unilateral breathing patterns and/or arm strength dominance [87, 89]. Indeed, swimmers performing unilateral breathing patterns (every two, four, or six arm strokes) showed a style known as 'rickety swimming'. This is characterized in non-expert swimmers by a prolonged catch with the arms extended forward to assist the head's rotation during breathing, leading to the emergence of catch-up coordination pattern on the breathing side [87, 100]. Conversely, swimmers with bilateral breathing patterns (breath every three or five arm strokes) tended to balance the arm coordination [87, 88]. Moreover, when breathing patterns (unilateral vs. bilateral) were manipulated in front crawl, breathing to the preferential side led to an asymmetry of arm coordination, in contrast to the other breathing patterns. The asymmetry was even greater when the swimmer breathed on the non-preferential side [88]. Conversely, arm coordination was symmetric in patterns with breathing that was bilateral, in the longitudinal axis (as in breathing with a frontal snorkel), or removed (as in apnoea) [88]. Finally, as arm coordination asymmetry was observed both in swimmers with disabilities and in able-body swimmers with unilateral

breathing pattern preference, it suggests that similar coordination adaptations (i.e. asymmetry between left and right arm) could reflect different organism constraints. Thus, it is reasonable to say that similar organism constraints could lead to the adoption of different coordination solutions, and different organism constraints could shape similar emergent patterns of inter-limb coordination in different individuals, exemplifying the degeneracy of human movement systems.

Task constraints are generally more specific to a particular context of performance than environmental constraints. To test how variable a swimmer's coordination patterns are, a 'scanning task' can be used where swim speed, stroke rate and stroke length (i.e. number of cycles per lap) are progressively increased from a minimal to a maximal value that can be sustained by a swimmer. This type of task goal explores the range of a swimmer's functional capabilities. For example, when stroke rate increases above a critical value (i.e. 50 cycles per minute), only the superposition pattern emerges [43]. For instance, a possible instruction could be to 'use different coordination patterns for a given swim speed' in order to determine the effective bandwidth of coordination variability. For this purpose, Seifert et al. [101] asked breaststroke and front-crawl swimmers to swim with 'maximal' or 'minimal' glide after a trial with self-selected glide duration, while maintaining the same controlled speed during each of these three coordination conditions. In this experiment, the flexibility of swimmers' coordination patterns appeared highly dependent on individuals and their swimming style. Less flexible swimmers exhibited a range of flexibility in freestyle close to 5.6 % of a freely chosen pattern, and the most flexible swimmers in breaststroke showed a range of flexibility close to 94.3 % of the freely chosen pattern [101]. Interestingly, the adoption of unusual patterns of coordination was sometimes 'counter-balanced' (e.g. by an uncommon eight leg-beat-kick when swimmers were instructed to glide for maximal duration in front crawl). In addition, the freely chosen pattern of coordination was more economic than the two imposed patterns, which was associated with a metabolic energy-saving mechanism, since the freely chosen pattern was the most trained. Although an increase in glide duration led to an increase in the energy cost of locomotion, swimmers did not spontaneously adopt an 'opposition' or 'continuity' pattern of coordination in the freely chosen condition but a catch-up or glide pattern of coordination. These results highlighted the idea that actual adopted patterns did not really fit an 'ideal' theoretical model promoting a 'continuity' pattern of coordination in order to minimize intra-cyclic speed variations, but rather emerged in order to satisfy interacting constraints (e.g. gliding capabilities have been shown to relate to body characteristics [85]). However, the effect of

the metabolic constraint on inter-limb coordination seemed real, specifically as the onset of blood lactate concentration (i.e. the transition from a dominant aerobic pathway to a dominant anaerobic pathway) showed a strong correspondence with the inflection point in the index of coordination curve during incremental speed protocol [102]. As highlighted previously, metabolic constraints were often used to test coordination pattern variability in relation to the development of fatigue, by using time to exhaustion tests [33, 103], assessing race pacing [15] or analysing repetitions of intensive efforts [32].

Finally, it must be emphasized that coordination emerges not from a selection or addition of constraints, but rather from the continuous *interaction* of the many constraints acting on the individual [17, 18, 104]. It sometimes may be difficult to distinguish between varied influences of the different types of constraints. For example, changes in swimming speed (swimming at 1.5 m s^{-1} then 2 m s^{-1}) are variations in an environmental constraint in that increasing the speed causes an exponential increase in active drag force. In contrast, changes in the pace [swimming at 75 % of maximum speed (1.5 m s^{-1}) and then at 100 % (2 m s^{-1})] is a variation in a task constraint because, in this case, the amount of drag force is not defined, but rather there is clarity on the task that the swimmer must perform. In addition, constraints acting on performance and training behaviours are more often temporary than permanent, and their influence can be strengthened or reduced according to different time scales [105]. In summary, constraints on an individual are dynamic, interacting and fluctuating over time (e.g. with learning, age or development); therefore, as advocated by Reed and Brill [106], performance dexterity is not a function of the movements themselves, but rather emerges from the ability to adapt to dynamic, emerging external constraints.

5 Conclusion

This overview of inter-limb coordination in swimming attempted to show how inter-limb coordination is an emergent behaviour under varied interacting constraints. It sought to highlight that, even if the continuity between propulsive actions usually increases with increments in swimming speed and/or active drag, the ‘opposition’ or ‘continuous’ patterns of coordination are not putative ‘ideal’ patterns of coordination toward which all swimmers must converge or seek to imitate. Instead, coaches and teachers may consider that the inter-limb coordination pattern exhibited by a swimmer is an emergent behavioural response to a set of interacting constraints, which the swimmer has to satisfy in order to achieve specific task performance goals and produce particular task outcomes.

Our overview suggests that coaches, teachers and instructors need to focus on the careful implementation of task goals with specific individuals instead of favouring an ‘ideal’ coordination pattern based on a putative expert model that all learners should imitate. A favoured strategy might be to implement a varied range of interacting constraints, which each individual needs to satisfy during training in order to achieve the task goal of swimming faster for longer durations in competition. A good implication for coaches could be to manipulate environmental constraints such as drag by artificially applying added resistance using a small parachute in order to invite swimmers to explore a new coordination pattern or to maintain the current coordination pattern as long as possible. Coaches can also manipulate task constraints such as stroke rate management by giving verbal instructions or using an auditory pacer (i.e. a metronome) that may induce the emergence of various coordination patterns. Another last example could be to manipulate task constraints by using towing equipment that increases the swim pace artificially, or using different combinations of paddles and/or fins.

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