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Title: Upper-to-lower limb coordination dynamics in swimming depending on swimming speed and aquatic environment manipulations

Running head: Arm-to-leg coordination dynamics in swimming

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Abstract

Swimming is a challenging locomotion, involving the coordination of upper and lower limbs to propel the body forward in a highly resistive aquatic environment. During front crawl, freestyle stroke, alternating rotational motion of the upper limbs above and below the waterline, is coordinated with alternating lower limb pendulum actions. The aim of this study was to investigate the upper-to-lower limbs coordination dynamics of eight **male** elite front-crawlers whilst increasing swimming speed and disturbing the aquatic environment (i.e., pool vs. flume). Upper-to-lower limb frequency ratios, coordination, coupling strength and asymmetry were computed from data collected by inertial measurement units. Significant speed effect was observed, leading to transitions from 1:1 to 1:3 frequency ratios (1:3 over-represented), whereas 1:2 frequency ratio was rarely used. Flume swimming led to a significant lower coupling strength at low speeds and higher asymmetries, especially at the highest speeds, probably related to the flume dynamic environment.

Keywords

Upper-to-lower limb coordination, Phase coupling, Frequency coupling, Interlimb coordination dynamics

Introduction

Humans exhibit a large repertoire of patterns of locomotion, dependent on whether they are within a terrestrial or aquatic environment, including: walking or running, when on the ground; and at least four swimming strokes, when in water. According to an ecological dynamics approach, behavior of the swimmer within the aquatic environment emerges from a set of interacting constraints (i.e., task, environment, organism); therefore, the coupling between the organism and the environment is considered as the smallest unit in behavioral analysis (Araújo, Davids, & Hristovski, 2006; Davids, Araújo, Hristovski, Passos, & Chow, 2012). According to this theoretical rationale, the manipulation of these constraints would enable assessment and understanding of the stability of the coordination dynamics. For instance the manipulation of stroke frequency for oscillatory movement, and speed of locomotion, was used to investigate human coordination dynamics during walking-running (Donker, Beek, Wagenaar, & Mulder, 2001; O'Halloran, Hamill, McDermott, Remelius, & van Emmerik, 2012; Wannier, Bastiaanse, Colombo, & Dietz, 2001). Coordination of the **upper and lower limbs oscillators (i.e., large number of degrees of freedom)** involved in these multi-articular tasks of locomotion is a **challenge. At low walking speeds, upper and lower limbs oscillate with identical frequency relationships (Wannier et al., 2001) which changed with walking speed increased (Donker et al., 2001; Wagenaar & van Emmerik, 2000), leading to a reinforcement of the coupling between oscillators (Wagenaar & van Emmerik, 1994; 2000).** This coordination was generally described as 'absolute' or 'relative', depending on the eigenfrequencies of the oscillators (von Holst, 1939; 1973). More precisely, Kelso & Engström (2006) explained that the "absolute coordination is when the individual coordinating elements of a system are locked together in time. Relative coordination is when the coordinating elements lock in only transiently, and then break away from one another again, sometimes spontaneously and sometimes as circumstances change" (p. 141).

Typically, absolute coordination appeared more *stable* and *attractive* than oscillators moving without phase and frequency locking (Peper, Beek, & van Wieringen, 1995; Serrien & Swinnen, 1997; Treffner & Turvey, 1993). The coordination of the limbs may be characterized as a landscape of frequency ratios (i.e., the movement frequency of one limb expressed as a function of another, considered as reference) that could be hierarchically and mathematically structured in *Farey trees*. Such hierarchy helps in evaluating the coupling strength between oscillators (Hoffmann & Bardy, 2015). Therefore, the stronger the coupling strength, the higher the stability between studied oscillators (Hoffmann, Torregrosa, & Bardy, 2012). These findings highlighted that the increase of the degree of complexity of the frequency relationships was accompanied by a decrease in strength coupling, as stated by von Holst (1939; 1973).

Contrary to terrestrial locomotion, swimming is another cyclic task performed in an aquatic environment where water density ($\rho_{\text{water}} = 1000 \text{ kg/m}^3$) is 800 times denser than air, and viscosity ($\mu_{\text{water}} = 8.9 \times 10^{-4}$) is 50 times greater than air. This means that the resistive forces (i.e., passive and active drag) that the swimmer experiences are greater. Front crawl swimming also involves four-limbs locomotion, which challenges the arm-to-leg coordination since a 360° arm rotation around the shoulder and pendulum leg kicking actions are structurally and functionally different movements (Wannier et al., 2001). Moreover, the role played by the upper and lower limbs to propel the body forward is unbalanced, as the swimmers' upper limb actions on the fluid account for around 85-90% of the total propulsion, leaving only a potential 10-15% for lower limbs contribution (Andersen & Sanders, 2018; Gourgoulis et al., 2014). The lower limbs actions remain however essential to streamline the body by diminishing the trunk inclination (Gourgoulis et al., 2014), neutralizing any reaction of the body to the upper limb actions (Watkins & Gordon, 1983). Therefore, some authors suggest that lower limb action are not considered as perturbations of the upper limb

movements (Gourgoulis et al., 2014) or even favor appropriate upper-to-lower limb coordination (Deschodt, Arsac, & Rouard, 1999). Generally, upper-to-lower limb coordination is assessed as *frequency ratios* (i.e., 1:1, 1:2 and 1:3), with the number of arm stroke at the numerator and the number of leg kick at the denominator (e.g., 1:3 signifies that three leg kicks are observed during one arm stroke; Millet, Chollet, Chabies, & Chatard, 2002). These empirical and descriptive observations –mainly performed by coaches– suggested that the 1:3 frequency ratio could be more appropriate and performed more often at important speeds ranging from 1.4 to 1.9 m.s⁻¹ to ensure continuity of actions (Maglischo, 2003; Seifert, Chollet, & Allard, 2005). However, this suggestion was not fully experimentally tested and the way swimmers coordinate the upper and lower limbs as a function of a wide range of speeds remains unclear (Silveira, de Souza Castro, Figueiredo, Vilas-Boas, & Zamparo, 2017).

Aquatic locomotion is however not only restricted to pool swimming, leading individuals to face dynamic environments, coping with waves, turbulence and currents that are potentiated during open water events performed in the sea, a lake, or river. In those cases, fluid motion may become an additional challenge to upper-to-lower coordination by influencing the interaction between the swimmer and his/her environment. Although rarely used, a swimming flume can create comparable dynamic environmental constraints. Flumes are constrained channels of moving water that push the upper limbs of the swimmer backwards; through entrainment of air bubbles into the moving volume of water (in an unpredictable manner) a possible influence on both turbulence and buoyancy, challenging the horizontality of the swimmers body, can occur; see Guignard et al. (2017). Use of a flume offers the possibility to (i) apply a constraint that may directly impact the success of the task (swimmers are able/not able to sustain position in the moving volume of water) and (ii) directly modulate the environment through flowrate rather than increasing the swimming

speed (i.e., task constraint) that indirectly modifies the fluid flow. Limited previous researches highlighted that swimming in the flume revealed a slightly higher stroke rate at high velocities than in the pool (0.70 vs. 0.68 Hz, respectively; Wilson, Takagi, and Pease, 1998). This was associated with an increase in lateral upper limb accelerations, requiring the swimmers to control the three-dimensional positions of their limbs (Espinosa, Nordsborg, and Thiel, 2015).

The main purpose of the present work is to understand and explain how the challenging upper-to-lower limb coordination pattern emerges, persists and could be destabilized as a function of two major constraints of competitive swimming (i.e., speed and fluid flow). In this objective, the present study used the constraint-led approach initiated by Newell (1986) by comparing swimming in a stationary or displaced body of water, i.e., in pool and flume. As an underlying objective, the analysis of flume swimming will bring new insights in the potential role played by this device for training to constraints faced in competitions. It was first hypothesized that the 1:1 frequency ratio would lead to the most recurrent upper-to-lower limb coordination pattern, since one full upper limb rotation coincides with one full lower limb kick. According to literature, it would be reasonable to hypothesized a transition from 1:1 or 1:2 frequency ratios at slow speeds to a 1:3 frequency ratio at fast speeds, implying that the weight of the surrounding constraints is greater than the importance of maintaining stability between limb pairs. Assuming better continuity in leg kicks using 1:3, this transition would appear earlier in the flume due to a body of water moving in the same direction as the underwater arm rotation, that may lead to higher contribution of the lower limbs in propulsion. Finally, it could be assumed that the coordination of the four limbs would be strongly challenged in the flume dynamic environment (illustrated by chaotic and unpredictable water particles behaviors), leading to

potential asymmetries of strength coupling between right and left body sides in comparison to pool swimming.

Methods

Participants

Eight elite (national- to international-level) male swimmers (mean \pm SD age: 20.8 ± 2.96 years, height: 186.8 ± 3.37 cm, mass: 79.75 ± 7.81 kg) volunteered to participate in this study. Volunteers had no history of injuries and gave written consent. The investigative protocol was in accordance with the ethical standards of the Declaration of Helsinki and study approval was obtained from the Local Ethics Committee. The swimmers were all specialists of the 200 m front crawl event and trained more than ten times a week. Swimmers' level was expressed as a percentage of the current world record (WR) for the 200 m freestyle, in the manner of Seifert, Delignières, Boulesteix, and Chollet (2007): the participants' mean \pm SD best times represented $90.61 \pm 1.65\%$ of the WR (percentage of $WR = \text{time}_{\text{world record}} / \text{time}_{\text{subject}} \cdot 100$), corresponding to elite levels of performance.

Set-up

The first part of testing took place in a 50 m indoor swimming pool, before relocating to a specially designed swimming flume (recently used by Guignard et al., 2017) for the second part of the experimentation. Water is circulated through the flume (Italian National Olympic Committee, CONI, Italy), being pumped by an engine, at speeds from 0 to 40 Hz (0 to $1.9 \text{ m}\cdot\text{s}^{-1}$). The minimal increment between two speed levels was 1 Hz, corresponding to $0.05 \text{ m}\cdot\text{s}^{-1}$. Dimensions of the swimming volume was 6.20 m long, 2.90 m wide and 1.30 m deep; water temperature was fixed at 27°C . In the eventuality swimmers were unable to sustain the speed imposed by the flume flowrate, a safety net was positioned aft. Prior to testing, the

flume was calibrated and its performance was evaluated following a specific protocol: (i) flow speed was regularly measured with a one-dimensional Dostmann Electronic flux meter over 27 points distributed at different positions and depths in the water (water speed ranging from 0.5 to 2.1 m.s⁻¹); and (ii) the Italian Open Water National Team calibrated the flume and found the maximum error for a 100 m swimming time was 1.5 % (i.e., one second gap every 65 seconds). The procedure contributed to the better estimation of the water flow speed and optimization to a minimize wave formation at the flow surface. All swimmers were acquainted with swimming in this flume, as they (i) had already used the flume for training or (ii) had been familiarized with the flume prior to the present tests.

Procedure

After a standard 10 min warm-up performed in the pool, swimmers performed 8*50 m bouts at 76, 80, 84, 88, 92, 96, 100 and 104% of their mean speed as obtained during their best race time for 200 m front crawl. These percentages (determined from 2007 to 2014 French National Championships 200 m freestyle finals over more than 65 swimmers) were chosen to accurately account for the large speed fluctuations of speed generally observed in 200 m events (see McGibbon et al., 2018 that investigated pacing strategies). For each swimming speed, it corresponds to absolute values of 1.33 ± 0.05 ; 1.41 ± 0.04 ; 1.45 ± 0.03 ; 1.53 ± 0.02 ; 1.58 ± 0.05 ; 1.65 ± 0.03 ; 1.69 ± 0.04 and 1.77 ± 0.03 m.s⁻¹ (i.e., mean \pm SD values of all swimmers). Two experimenters imposed the target speeds, the first acting as a pacer and the second controlling the speed at the end of the pool, as extensively described in Guignard et al. (2017). Swimmers were tasked to globally follow the pace with a tolerance of 0.5 m from the position of a pole hold by the first experimenter. In the case where this criterion was not met, participants repeated trials until requirements of the task were satisfied. Without removing their testing equipment, swimmers were immediately transferred to the swimming

flume to commence the second testing session. The same incremental protocol was reproduced in the flume over eight swim speeds. For each speed bout in the flume, swimmers' performed forty stroke cycles; the first ten cycles corresponded to time necessary to overcome engine inertia, leaving up to thirty stroke cycles for coordination analyses. Notably, the swimmers globally had to swim above a positional marker on the bottom of the flume with a tolerance of 0.5 m. Both the pacer at the pool and the positional marker in the flume performed informative rather than restrictive **functions**. Swimmers were informed that they should globally follow the pacer, and stay above the positional marker, without denaturalizing their swimming. Moreover, no instruction was given regarding the breathing action, and all swimmers spontaneously adopted their own pattern (i.e., *right* (r) when they performed a swimming trial breathing *exclusively* on the right body side, *left* (l) when they performed a swimming trial breathing *exclusively* on the left body side or *both body sides* (b) when the breathing action is performed at least once on both body sides). Each swimmer was allowed one-minute rest between each bout in the pool and in the swimming flume.

Data collection

Swimmers wore four inertial motion units (Hikob Fox, HIKOB, Villeurbanne, France), positioned on the ventral side of the thighs and the dorsal side of the upper arms. Each inertial measurement unit (IMU) measured 45*36*17 mm and was composed of a three-dimensional accelerometer (± 16 G), a three-dimensional gyroscope (± 1200 °/s) and a three-dimensional magnetometer. Each sensor registered to an individual data logger with a sampling frequency of 100 Hz. A master logger, positioned at poolside, started and stopped the recordings to synchronize all IMUs. Due to the aquatic environment, sensors were placed within waterproof plastic bags. Sensors were then affixed to the skin with a therapeutic strap and adhesive tape (procedure similar to Dadashi et al., 2013a).

To obtain the sensor orientations in the three-dimensional field, the magnetometers were held above the pool and the flume for calibration, in order to reduce magnetic distortion during data processing. Other calibrations were performed during each rest period, to maintain alignment of sensor axes to the anatomical body axes (Dadashi et al., 2013a). These procedures consisted of three sequences of movements repeated five times. The upper limbs calibrations consisted of two movements performed with arms outstretched, rotating around the shoulder: flexion/extension around the transversal axis and pronosupination around the longitudinal axis. The lower limbs sequence comprised flexion and extension of the thigh around the transversal axis to get 90° angle between trunk and thigh. Such functional calibrations were necessary to obtain measurements that would not be sensitive to the IMU orientations despite the different body configurations in the swimmers' sample (Dadashi, Millet, & Aminian, 2013b).

Data analysis

Despite no instruction being given regarding the breathing action, qualitative control was performed on the video recordings (GoPro, San Mateo, California) to register the laterality of breathing for all swimmers. Angles between the sensors and the vertical axis (gravity vector) were computed using Matlab 2014a software (MathWorks Inc., Natick, MA, USA). Data from the accelerometers, gyroscopes and magnetometers were synchronized to create a common timestamp for all the devices. Then, the calibrations were used to reduce magnetic distortion following the method of Merayo, Brauer, Primdahl, Petersen, and Nielsen (2000). By combining the accelerometer, gyroscope and magnetometer data using the complementary filter of Madgwick, Harrison, and Vaidyanathan (2011), sensor orientations in the three-dimensional field were estimated. Madgwick's script computed quaternions and rotations matrices of the sensor positions for the whole test duration. From these parameters, segmental

angles (i.e., angles between the three-dimensional unit vector of the sensor positions and the gravity vector) were computed for all sensors. Segmental angles (Barela, Whittall, Black, & Clark, 2000; Kurz & Stergiou, 2002; van Emmerik & Wagenaar, 1996) were preferred to articular angles (i.e., angle between one sensor and another) since (i) a common reference was used for all the sensors (i.e., gravity vector) and (ii) it needs a single IMU to obtain an angular time series. Angular-time curves for both upper and lower limbs during front crawl swimming describe pseudo sinusoidal oscillations directly attributable to the segment on which the IMU is positioned. Hence, upper limb cycles were determined by recognizing maximal values of the upper arm/vertical axis angle. The leg kick can be broken down into two successive movements: the downbeat, **considered as the propulsive sequence of the movement (Andersen & Sanders, 2018)** and the upbeat, **respectively identified** from the high and low break points of the foot (Costill, Maglischo, & Richardson, 1992). Thus, each leg kick can be associated to a significant change in the slope of the values of thigh/vertical axis angle. Angle computations were obtained for all stroke cycles performed in the two test sessions. **After a residual analysis, angular data series were filtered** with a fourth-order Butterworth low pass filter, with a cutoff frequency of 6 Hz to remove noise in the signal that may alter real kinematics data (Winter, 1990). In the manner of Donker et al. (2001) for terrestrial locomotion or Wannier et al. (2001) for front crawl swimming, the frequencies of the rhythmic activity of upper and lower limb oscillators were then computed using a fast Fourier transform (FFT). The frequency component with the highest amplitude of the power spectrum (i.e., eigenfrequency) was taken as the cycle frequency of the limb: harmonics were not considered in the current study. Next, when the oscillators (here upper arms and thighs) possessing different eigenfrequencies are coupled, their interaction results in attraction to a certain *frequency ratio*, that corresponds to the ratio between the eigenfrequencies of the oscillators. These ratios were computed for both body sides, each swimming speed and in the

two aquatic environments and express the number of leg kicks performed during one arm stroke. The present analyses highlighted only three levels of frequency ratio (i.e., 1:3 or three leg kicks for one arm stroke; 1:2 or two leg kicks for one arm stroke and 1:1 or one leg kick for one arm stroke), corresponding to previous observations (Millet et al., 2002). The same conditions as detailed in Hoffmann and Bardy (2015) were precisely applied, since we considered that the observed ratios were bounded by intervals of the fifth level of the Farey tree, i.e., $[2:7, 3:8[$, $[3:7, 4:7[$ and $[4:5, 1:1]$, respectively. For instance, if the real coefficient falls into the $[2:7, 3:8[$ interval (e.g., 0.342), it will correspond to the 1:3 frequency ratio. Following this procedure, low-order ratios have wider interval than high-order ratios.

To avoid any start and finish effects, and keep only the stabilized swimming sequences, two cycles at the beginning and one at the end of the 50 m bouts were systematically removed from the swimming pool analyses. Similarly, two stroke cycles were systematically removed from the thirty analyzed cycles in the swimming flume. For each participant, the number of analyzed stroke cycles in the flume was then matched to the number of stroke cycles performed in the swimming pool (ranging from 13 stroke cycles for swimmer 3 during Speed 3 in the pool to 20 stroke cycles for swimmer 2 during Speed 1 in the pool).

Discrete relative phase between upper limb and lower limb movements from both sides of the body was computed by:

$$RP_{i,R(p)} = \frac{t_{i,R(p)}}{T_i} \cdot 360^\circ \quad (1)$$

where $RP_{i,R(p)}$ represents the relative phase at the leg kick i for the corresponding frequency ratio (determined thanks to the help of previously described FFT-based analysis), $t_{i,R(p)}$ represents the distance from the leg kick i to the end of p arm stroke, and T_i represents the time between two consecutive leg kicks i (see Hoffmann & Bardy, 2015 and Figure 1).

Following Donker et al. (2001) investigations in walking, discrete relative phase was preferred to continuous relative phase since the goal was to investigate the coupling between *punctual* events of the stroke cycle (i.e., the number of leg kicks performed over one arm cycle). A return map between the relative phase i and the relative phase $i + q$ was plotted (here q corresponds to the number of leg kicks, either 1, 2 or 3 in the present study), allowing determination of the variability of coupling between the two oscillators. “This method tests for a deterministic structure in the dynamics by grouping discrete relative phase values into pairs (RP_i and RP_{i+q}) and plotting it as a point over time” (p.19; Jeka & Kelso, 1989). A phase coupling index (PC) was then computed in the manner of Hoffmann and Bardy (2015). PC is a function of the variations of pairs of relative phase points from the line of identity in the returns maps. These points are paired based on the periodicities of the data identified within the return maps (McDermott, van Emmerik, & Hamill, 2003). Therefore, PC expresses the dispersion of the relative phase d_f by calculating the Euclidean distance d_n of each point from the identity line and then summing the weighted distances wd_n :

$$wd_n = \begin{cases} 1 - \frac{|d_n|}{40 \cos(45)}, & d_n \leq 40 \\ 0, & d_n > 40 \end{cases} \quad (2)$$

$$PC = \frac{\sum_{n=1}^m wd_n}{m} \cdot 100 \quad (3)$$

where m is the number of points of the return maps (McDermott et al., 2003). This measure (equation 2) weights each point with the distance that separates it from the line of identity (Ebert, Ressler, & Hefter, 2000). Distances greater than or equal to 40° are weighted by zero and distances less than 40° are computed differently (equation 2). Finally, their sum is expressed as a percentage of highest possible sum (equation 3). $PC = 100\%$ when all points fall exactly on this line, representing a perfect phase locking between the movements of the

upper arms and the movements of the thighs. PC decreased proportionally to the increase in phase coupling variability (whole procedure described in Figure 1). PC dynamics have then been evaluated as a function of swimming speed increase and changes in frequency ratios to characterize the potential effects of these parameters on coupling strength for both body sides in the pool and flume environments. Precisely, this was done using mathematical fittings based on linear regressions (PC values against absolute speeds) and comparing slopes of the models in each tested conditions.

Finally, the Absolute Symmetry Index (ASI) was computed to estimate the differences in PC values as a function of the swimmer's body side (Karamanidis, Arampatzis, & Brüggemann, 2003). ASI enabled the comparison of different swimmers from the same population:

$$ASI = \frac{|PC_{right} - PC_{left}|}{\frac{1}{2}(PC_{right} + PC_{left})} \cdot 100 \quad (4)$$

with ASI the Absolute Symmetry Index in percentage, PC_{right} and PC_{left} the phase coupling values for right and left body sides, respectively. Contrary to the initial Symmetry Index developed by Robinson, Herzog, and Nigg (1987), ASI values ranged from 0 to 100%, and $0\% \leq ASI \leq 10\%$ indicates symmetry whereas $100\% > ASI > 10\%$ indicates asymmetry (Herzog, Nigg, Read, & Olsson, 1989).

Statistical analysis

For all following analyses, the normality of the distribution (Shapiro-Wilk test) and the variance homogeneity (Hartley's F_{max} test) of the data were checked before using parametric statistics. However, none of these tests followed the assumption of normality. It implied the use of non-parametric statistics for frequency ratios (Friedman's ANOVA on the ranks). When appropriated, *post hoc* tests were conducted using Wilcoxon signed-rank tests (test results T is the smaller of the two sums of ranks for each test). For these non-parametric

statistics, the effect size, noted r , was computed as follows: $r = z\sqrt{n}$, with z the result of the Wilcoxon signed-rank test and n the total number of observations (Field, 2013). Regarding PC dynamics as a function of speed manipulation in both environments, a logarithmic transform was applied to meet the normality assumption and to test data with more powerful parametric ANOVAs. Sphericity was verified by the Mauchly test (Winter, Eston, & Lamb, 2001). When the assumption of sphericity was not met, the significance levels of F -ratios were adjusted according to the Greenhouse-Geisser procedure (adjustments were performed when $\epsilon < .75$). Two-way repeated measures ANOVAs [environment (2 levels: pool and flume) \times swimming speeds (8 levels from low to high)] tested for differences in PC values. Then, pairwise *post hoc* tests were performed by Bonferroni tests. Partial eta squared (ηp^2) statistics were calculated as indicators of effect size, with $\eta p^2 = .01$ indicating a small effect, $\eta p^2 = .06$ a medium effect, and $\eta p^2 = .15$ a large effect (Cohen, 1988). For all tests, the level of significance was fixed at $P < 0.05$, using SPSS software (SPSS Statistics 21.0, SPSS Inc., IBM, Chicago, IL, USA).

Results

Frequency ratios

The use of inertial sensors leads to the computation of frequency ratios and relative phase over 3780 stroke cycles for the eight swimmers involved in the tests.

As stated previously, the analysis performed on segmental angle data revealed three typical frequency ratios (i.e., 1:1, 1:2 and 1:3), which remained stable over the duration of each trial (i.e., no significant intra-trial variability, as indicated by angular vs. time series; Figure 2).

The distribution of the three frequency ratios **for all tested conditions and both body sides revealed that 1:3 is used in majority in both environments: 64.8 % and 57.0 % of all chosen frequency ratios in the pool and the flume, respectively.** Then, 1:1 is solicited (32.1 % in the

pool; and slightly higher in the flume, with 38.5 %) with 1:2 the least used ratio throughout the tests (only 3.1 % in the pool and 4.5 % in the flume). However, on average, when progressing in the flume, swimmers solicited the 1:1 frequency ratio more often for both body sides than they did in the pool. For the right body side, a significant effect of the increase of speed on frequency ratios was observed in the pool ($\chi^2(7)=31.045$, $P=0.000$): there was a switch from lower ratios (i.e., use of 1:1 or 1:2) at the slowest swimming speeds to use of 1:3, predominantly at highest speeds. This effect was however not observed in the flume ($\chi^2(7)=11.406$, $P=0.122$). Statistically, there was an effect of the environment ($\chi^2(1)=9.8$, $P=0.003$) on the selection of frequency ratios. Therefore, it appeared that the frequency ratios are on average higher (i.e., 1:3, statistics of $T=0.00$, $r= -0.22$) in the pool than in the flume for Speed 7 and Speed 8 ($P=0.031$ and $P=0.016$, respectively). For the left body side, the increase of speed is concomitant with a significant increase of the frequency ratios both in the pool ($\chi^2(7)=30.930$, $P=0.000$) and in the flume ($\chi^2(7)=20.340$, $P=0.005$). These effects of speed mimic the results observed for the right body side in the pool. The transition from one swimming environment to the other also conditioned these values ($\chi^2(1)=4.571$, $P=0.033$). *Post hoc* tests emphasized that this effect was noted for Speed 7 exclusively ($P=0.031$, statistics of $T=0.00$, $r= -0.12$): 1:3 remained the only frequency ratio used in the swimming pool by all swimmers, whereas they used both 1:3 and 1:1 frequency ratios in the flume. It was likewise observed that swimmers switched from low frequency ratios to high frequency ratios, but not vice versa (Figure 3). Finally, the 1:2 frequency ratio pattern was never used for the left body side, leading to a body asymmetry in both environments.

Phase coupling

On average, PC values were 64.5% in the pool and 62.8% in the flume. Values of PC for each speed level obtained in both environments are displayed in **Figure 4**. For the right body side, neither a speed effect ($F(2,674,18.718)= 1.486, P=0.252 \eta p^2= 0.175$) nor an effect of the fluid flow modification ($F(1,7)= 0.021, P=0.890, \eta p^2= 0.003$) was observed on PC values. Moreover, there were no statistically significant effects of the interaction between these two factors (i.e., speed*environment) since F values were $F(7,49)= 0.740, P=0.639, \eta p^2= 0.096$. For the left body side, the increase of speed, the effects of swimming in the pool vs. in the flume and the interaction between these two factors led to no effect on the PC values. The results of the parametric analyses were $F(2.803,19.618)= 1.638, P=0.215 \eta p^2= 0.190$; $F(1,7)= 1.075, P=0.334, \eta p^2= 0.133$ and $F(7,49)= 1.514, P=0.185, \eta p^2= 0.178$, respectively.

Interpreting the dynamics of PC as a function of frequency ratio choice offered different results. Therefore, equations of linear regression (**Figure 5**) highlighted that the selection of 1:2 and 1:1 ensured an increase of PC values associated with speed increase (excepted for the right body side in the pool when using 1:1). **On the contrary, the** adoption of the 1:3 frequency ratio led to a stabilization in the PC values despite the speed increase, as shown by the slopes of the models.

Absolute Symmetry Index

Results for phase coupling ASI computation are displayed in Table 1 for pool swimming and in Table 2 for flume swimming. The swimming asymmetry was not directly related to the swimming speed increase throughout the tests. For all tested conditions, 50% of the PC values were asymmetrical in the pool, whereas this number rose to 67.9% in the flume. Swimmer 2 in the pool was highly asymmetrical for 6 of 8 swimming speeds in which he was involved. In the flume, this swimmer was once again very asymmetrical regarding his PC values, as swimmer 3 for whom the ASI values were systematically above the 10% limit

whatever the swimming speed. Finally, it may be considered that the main asymmetries were found for swimmer 7 at the highest swimming speeds in the pool. Highest values of ASI were not systematically associated to specific breathing conditions (i.e., laterality, see Tables 1 & 2).

Discussion

The main aim of this study was characterization of upper-to-lower limb coordination dynamics of elite swimmers when facing different task and environmental constraints; in particular the effect of swimming in a stationary (swimming pool) vs. a dynamic fluid flow (flume). The main findings were: firstly, three frequency ratios emerged between upper and lower limbs, mainly related to the speed increase and in a lesser extent to changes in aquatic environment (i.e., 1:1; 1:2 and 1:3) and both 1:1 and 1:3 frequency ratios were over-represented. Secondly, the effect of swimming speed increase **was responsible of a significant transition from low- to high-order frequency ratios in the pool and for the left body side in the flume (for the right body side in this environment, only a qualitative transition between low- and high-order ratios was observed for 6 out of 8 swimmers). These transitions were associated with** a general decrease of phase coupling. Additionally, swimming in the flume seems to develop on average a higher phase coupling asymmetry in comparison to pool swimming, and especially for three swimmers over the eight involved in the tests.

As is usually observed in competitive swimming (Millet et al., 2002), swimmers exhibited three different upper-to-lower limb frequency ratios in testing: 1:1, 1:2 and 1:3. These three frequency ratios represented the first three levels of the *Farey tree*, a mathematical construct that reveals the organization of frequency ratios as predicted by the sine circle map (Hoffmann & Bardy, 2015). To go further, each of the three frequency ratios

was spontaneously adopted at the beginning of a trial and maintained until its completion, despite the manipulation of task (i.e., speed increase) and environmental (i.e., stationary vs. displaced body of water) constraints (Newell, 1986). In this sense, the three frequency ratios used by swimmers in the current study reflected stabilized absolute coordination patterns to functionally achieve the task goal.

Among the three frequency ratios, 1:1 and 1:3 were the most present in all conditions (1:1 in a lesser extent than 1:3), whereas the 1:2 frequency ratios was less recurrent, and appearing exclusively on the right body side (only 3.1% in the pool and 4.5% in the flume). It was not surprising to observe such a preponderance of these two ratios, since 1:1 is mainly involved **in the maintenance of a horizontal body position** at slow speeds (i.e., **the kicking action counterbalances the legs sinking**), while 1:3 provides a significant contribution to the propulsion for sprint events (Silveira et al., 2017). Additionally, the proportion of 1:3 was higher than of 1:2 frequency ratio for two possible reasons. **Firstly**, each downbeat of the lower limbs is coordinated with one of the three hand sweeps that composes an underwater arm stroke (Maglischo, 2003; Seifert et al., 2005). **Precisely, considering one arm stroke, the sweep to move the arm into position for the catch is concomitant with the downbeat of the leg of the same body side. Then, the sweep of the arm towards the midline of the body is coordinated to the downbeat of the contralateral leg, and finally, the upsweep is performed at the same moment as the last downbeat of the leg of the same body side (Maglischo, 2003).** **Secondly**, the turning effect of fluid forces around the body's longitudinal axis for a complete stroke cycle has three sinusoidal components that exactly match those expected from the 1:3 frequency ratio (Yanai, 2003). According to those considerations, the 1:3 ratio would possibly be assimilated to a 1:1 frequency ratio, since each arm sweep fits with a leg kick. At highest speeds where flow turbulence and disturbances may impact and perturb catch action, buoyancy and body horizontality, the functional role of leg kicks avoids the risk of lower

limbs sinking, whilst simultaneously decreasing active drag (Osborough, Daly, & Payton, 2015; Watkins & Gordon, 1983). This appears a particular issue when swimming in a flume. Precisely, the action of the arms becoming highly impacted by the fluid flow (e.g., important hand speed increase throughout the stroke cycle; Monteil, 1992), an important help to propulsion is provided by the action of the lower limbs, which is considerable when using the 1:3 frequency ratio. The only potential limitation in the use of 1:3 frequency ratio is that this leads to higher internal work and requires more energy to be sustained (Zamparo, Pendergast, Termin, & Minetti, 2002). At the slowest speeds, where the propulsion may be fully performed by the actions of the upper limbs, the internal work may be decreased with larger solicitations of the 1:1 frequency ratio. **In quasi-static fluid flow, it was showed that swimmers were able to take advantage of the vortices created in the swimming pool during the downbeat to produce a reaction force in the swimming direction (Andersen & Sanders, 2018). By analogy, elite swimmers of the present study were able to take advantage of the body of water travelling in the same direction as arm rotation underwater in the flume, to further use 1:1 frequency ratio (+5 and +8% on the right and left body sides in comparison to the pool values, respectively) in order to minimize energy expenditure through leg kicking.**

Two swimmer profiles could thus be identified when the swimming speed is increased: (i) swimmers using a 1:3 frequency ratio from the slowest to the fastest speeds and (ii) swimmers beginning at a lower frequency ratio, but then switching to higher ratio by the end of the tests. Osborough et al. (2015) already described such profiles, revealing that swimmers who performed low-speed trials with a 1:3 frequency ratio would remain in this configuration despite an increase of speed. On the other hand, the recurrence of this 1:3 frequency ratio was increased for swimmers who started the incremental protocol with 1:1 or 1:2 frequency ratios. In the current study, the second profile of swimmers exhibited transition of frequency ratios associated with speed increase. This speed effect was previously reported

between 800 m and 50 m paces, where swimmers used, with almost no exception, the 1:3 frequency ratio (i.e., 91%) in swim sprint events (Hue, Benavente, & Chollet, 2003). For swimming speeds ranging from $1.22 \text{ m}\cdot\text{s}^{-1}$ to $1.82 \text{ m}\cdot\text{s}^{-1}$ (i.e., similar to the speeds investigated in the present study), Millet et al. (2002) showed that the 1:3 remained the most recurrent frequency ratio at the highest speeds, despite associated higher swimming drag resistances (drag resistance being a function of speed squared; Vorontsov & Rummyantsev, 2000). Additionally, due to the large amplitude of upper limb movement, cycle duration of the upper limbs commonly superseded that of the lower limbs (Wannier et al., 2001). In Wannier et al. (2001), this feature became particularly evident when participants were asked to swim rapidly, leading to the solicitation of the 1:3 frequency ratio. Lastly, it was shown that the 1:2 frequency ratio was less recurrent than the others, whereas it remains stable until the end of the trial once selected. Therefore, at the scale of the different swimming speeds, the 1:2 was used punctually, swimmers switching rapidly to the selection of the 1:3 frequency ratio. Moreover, the 1:2 frequency ratio was systematically performed on the right body side, either associated with the use of the 1:1 or 1:3 frequency ratio on the left body side. Theoretically, both lower limbs act in a sequential manner, the downbeat of one leg corresponding to the upbeat of the other (Maglischo, 2003). Rather, results from the present study suggest that the combination of 1:2 frequency ratio on one leg with another frequency ratio on the other leg would possibly induce a pause in the movement or, more broadly, coordination asymmetries. In the present study, these asymmetries were more recurrent in the flume, but surprisingly, not directly related to the breathing action: swimmers 2 and 3 used either right or left body sides to inhale throughout the trials, whereas swimmer 7 performed the breathing action at least once on both body sides during a trial. **Therefore, it could be reasonably suggested that the selection of the 1:2 frequency ratio may appear essential for the enhancement of body balance or streamlining, which could be weakened due to the moving**

flow of water acting on the swimmers in the flume (Espinosa et al., 2015). Theoretically, our analyses showed that the emergence of the different modalities of arm-to-leg coordination is continuously shaped by (i) the constraints manipulated in the present study and (ii) the specificities of the swimming behavior (i.e., movements of the limbs structurally different, prone position, performed in a resistive environment). The modification of the perceptual–motor landscape of these elite swimmers organize their repertoire in multiple frequency ratios for which individuals were able to switch in-between, without compromising the completion of the trial. Since we observed no performance destabilization, our results highlight that swimmers exhibited properties of functional adaptability (Seifert, Button, & Davids, 2013): at slow speeds, the task goal was mainly satisfied by a *stable* use of the 1:1 frequency ratio, but with the increase of the level of constraints associated to speed increase and environment change, swimmers exhibited *behavioral flexibility* (a possibility to switch to another coordination mode to maintain performance output; 1:3). More precisely, these elite swimmers were sensitive to the information surrounding them (Araújo, Davids, & Bennett, 2004), e.g., the fluid flowing around their body in the flume or the sensation of gliding in the pool. This emphasizes an increase of the flexibility of the coordination dynamics between the oscillators of the upper and lower limbs, even in an environment as specific as water, where the propulsion emerged from the use of the dense and viscous properties of the fluid, that also act as major resistances. Interestingly, we can learn from the results of the present study that individualized motor patterns may still arise even under a strong level of interacting constraints and for an elite sample of swimmers: there is no prescription of the behavior that rather emerge spontaneously as a function of the constraints, showing inter-subject behavioral variability (Seifert et al., 2013), as exemplified on Figure 3.

Phase coupling (PC) was previously used for terrestrial activities to assess local stability of two oscillatory systems: in McDermott et al. (2003), or O'Halloran et al. (2012) studies, the heel strike for each walking/running stride is coupled with the end of exhalation; more recently, Hoffmann and Bardy (2015) solicited this method to couple expiration and pedaling strike. In this study, PC values expressed the strength of the coupling between upper and lower limbs during front crawl swimming. On average, PC reached near 64.5% in the pool and 62.8% in the flume, which could be considered as high coupling levels between limbs. In other words, it indicates a large tendency for lower limb kicking to occur at a particular phase of the upper limb stroke cycle during consecutive lower limb oscillations. These averaged PC values appeared greater than those generally reported in the literature: between 9 and 23% for Hoffmann and Bardy (2015); around 20% for McDermott et al. (2003) and near 25% for O'Halloran et al. (2012). Such a difference may potentially be explained by the fact that (i) phase coupling was computed from both behavioral signals, whereas previous studies mixed different sources of data (i.e., locomotion and physiology) and (ii) only three levels of frequency ratios were identified, while up to ten were referenced by Hoffmann and Bardy (2015), leading to higher variability.

The effect of constraints manipulation on phase coupling dynamics were tested, and the coordination stability appeared not statistically impacted by these factors (i.e., swimming speed, fluid flow and interaction of both factors). Put another way, it highlights that speed neither had a positive nor a negative impact on whole PC values whatever the swimming environment, leading to general phase stability between upper and lower limb oscillations. Despite such general results, it would be interesting to connect PC values with frequency ratios used by swimmers to complete the trial. Since frequency ratios were not directly manipulated, only some assumptions can be made regarding the dynamics of the PC values: it would seem that 1:1 frequency ratio was mainly used at lowest speeds, corresponding to a

higher stability (i.e., a stronger movement attractor; Treffner & Turvey 1993). At highest speeds, it was observed that a recurrent selection of the 1:3 frequency ratio was generally associated with lower levels of phase stability. Qualitatively, switching between 1:1 and 1:3 frequency ratios is associated to a negative jump of PC values, either in the pool or in the flume. In the flume, these assumptions may explain the general tendency to a delayed selection of this 1:3 frequency ratio (i.e., higher levels of the Farey tree) in comparison to the pool. Indeed, swimmers conserved a larger upper-to-lower limbs coordination stability that allow them to face the dynamic fluid flows in the flume. This corroborates the previous conclusions of Hoffmann and Bardy (2015): average values of PC were near 21% when the 1:2 coupling was selected, whereas this value dropped to 17% when participants used a 1:3 frequency ratio. In other words, despite the increase of speed forcing swimmers to use the 1:3 frequency ratio, the prevalence of the 1:1 ratio was shown, since it appears to offer larger coupling strength between the propulsive limbs; essential to resist the moving body of water in the flume. **Indeed –even not directly highlighted in the present study–** swimmers have to deal with flow turbulence and disturbances in this particular environment, alongside rotational speed components of water that may immediately compromise performance **by pushing individuals into the safety net if they do not coordinate themselves properly**. The flow characteristics within the flume therefore have potential to strongly alter the general swimming motion and the stroke frequency of the upper limbs (Espinosa et al., 2015; Wilson et al., 1998). **Considering that the flume simulates some turbulent fluid flows that could appear naturally (e.g., in sea or river), we highlighted that the adaptation to temporary perturbations in aquatic environments may compromise the stability between propulsive oscillators (i.e., decrease of PC values) without impacting the task goal.**

The motor outputs in aquatic environments were still associated with difficulties of swimmers in maintaining symmetry between phase coupling values when the interaction of

constraints was maximal (i.e., at the fastest speeds in the flume). Thus a tendency was observed for larger asymmetry in the flume environment in comparison to the average values observed in the pool. This was despite swimmers being able to satisfy task goal and maintain PC values in the flume regardless of swim speed. In this condition, an incompressible moving body of water is mechanically driven around a swimmer in a confined volume: as a consequence, it is hypothesized that the hydrodynamic forces experienced by a flume swimmer are altered, affecting movements from both body sides to a larger extent than in the pool. As suggested by Seifert et al. (2005), elite swimmers coordination asymmetry could appear as functional behavior to achieve the task when it did not impact the performance outcome. Interestingly, three of the eight swimmers seemed more asymmetrical (i.e., 2, 3 and 7), corresponding to swimmers who used the 1:2 frequency ratio at least once during the tests. More precisely, this 1:2 ratio appeared systematically for the right body side, the symmetry of PC values was therefore perturbed since the second leg was using a different frequency ratio (i.e., 1:1 or 1:3). The results finally emphasized that breathing laterality was not related to swimming asymmetry in the present study. Other conceivable hypothesis can be found in the swimmers' arm dominance: literature indeed revealed that arm dominance may lead to coordination asymmetry (Seifert et al., 2005; Seifert, Chehense, Tourny-Chollet, Lemaitre, & Chollet, 2008). Consequently, a promising perspective would be to enrich this study with a rigorous control of this parameter for future works interested in upper-to-lower limbs coordination investigations in swimming. From a more practical and general perspective, flume swimming conditions a bimodal behavior to achieve the task goal: the *failure* associated with premature ends of the trial in the safety net during the first training attempts will progressively lead to *success* when an adapted coordination pattern will emerge to help swimmers to face the constraining fluid flow. Therefore, future studies should now consider the flume as a valuable training device for swimmers with precarious coordinative

behaviors that may be destabilized by a sudden increase of resistances in competition (e.g., the wave coming back from the wall or from a close opponent).

Conclusion

By manipulating task (swimming speed) and environmental (stationary vs. moving body of water) constraints, the present work simulated ecological swimming constraints that might be encountered in a lesser extent in competition or in natural aquatic environments. This constraint-led approach enabled to understand the upper-to-lower limb coordination dynamics of elite swimmers in various environments. As expected, three different frequency ratios emerged (i.e., 1:1, 1:2 and 1:3), corresponding to different modes of propulsion in water, mainly related to the increase in swimming speed. 1:1 frequency ratio was the most recurrent in the flume, mainly related to the effects of the moving body of water and allowing high phase coupling values to be maintained. Moreover, with speed increase, PC values remained on average stable regardless of change in swimming environment. To go further, a potential impact of the selection of the frequency ratio on the values of PC was observed in the present study, even though this variable was not directly manipulated. In this regard, it is suggested that future studies be conducted to evaluate the precise role of frequency ratios on PC, determining the accurate role of these ratios on the stability of the coordination of the four limbs in front crawl swimming. We may expect from the present results that the mechanisms responsible of an effective coordination in constraining swimming environments suggest the use of the 1:3 frequency ratio to reach high propulsion, despite decrease of the arm-to-leg stability and increase of the level of energy expenditure. Finally, flow turbulence and disturbances in the flume led to major phase coupling asymmetries, especially for swimmers 2, 3 and 7. This was potentially related to how the swimmer interacted and exploited the aquatic environment characteristics, as to their arm dominance, though not

controlled in the present study. In all cases, this work emphasizes that elite swimmers functionally adapted their upper-to-lower coordination to mixed task and environmental constraints operating in the flume, as they were never swept into the safety net behind them. **Indeed, swimmers exhibited stable behaviors but were not locked in these modes of coordination since an increase of the level of constraints generally coincides with behavioral flexibility.** From this fundamental approach, coaches should consider training swimmers in the flume to develop and enrich their motor repertoire when faced with sudden changes in fluid flow, that may transfer to a competitive performance context. Last, a potential limitation was identified and must be considered for the design of future research: the tests were systematically conducted in the pool before the flume (because the targeted speeds were first set in the pool), causing a possible order effect between the two tested situations.

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Figure captions

Figure 1. The different steps used to obtain the phase coupling (PC) from a 1:3 frequency ratio. (1) Detection of the main frequency of angular data (in black, the upper arm angle plotted against the y-left axis, in gray the thigh angle plotted against the right y-axis) registered during the swimming trial. (2) A zoom of the portion of the angular data highlighted with the rectangle in (1). It illustrates the assessment of the relative phase between the upper arm and the thigh angles for a 1:3 frequency ratio. (3) Depiction of the computed relative phase. (4) Relative phase at time (i) plotted against relative phase at time (i+3). The PC is then computed by analyzing the distance of each point from the identity line (in gray).

Figure 2. Qualitative representation for a better understanding regarding the computation of the three typical frequency ratios (from top to bottom, 1:1; 1:2 and 1:3) for different conditions performed by a single participant. Angular displacement and schema of the corresponding Power Spectral Density (PSD) of the upper arms (in gray) and the thighs (in black) are proposed.

Figure 3. Distribution of the three frequency (1:3; 1:2 and 1:1) ratios as a function of speed increase in both environments for the eight swimmers.

Figure 4. Mean \pm SD of phase coupling values (in %) as a function of speed increase for all swimmers in both environments and body sides. Pool values are displayed in black whereas flume swimming is plotted in light gray.

Figure 5. Phase coupling (PC) dynamics as a function of absolute speed increase in the two tested conditions for both body sides. Each dot represents the values of PC averaged over a single trial for one speed and one swimmer. Phase coupling values have been differentiated from each frequency ratios (1:1 in dark gray dots, 1:2 in light gray squares and 1:3 in black triangles) and corresponding linear regressions are used as indicative of PC values dynamics (models' equations are displayed on the right of each graph).