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Rotational kinematics of pelvis and upper trunk at butterfly stroke: Can fins affect the dynamics of the system?

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ABSTRACT

The purpose of the present study was to investigate the rotational kinematics pattern of the upper trunk and the pelvis and the complexity-variability of their movement, during the sprint butterfly stroke between male and female swimmers with long fins (18–26 cm) and without fins. Two pairs of 3D accelerometers and gyroscopes were used to measure segments' flexion-extension angles. There were no gender differences apart from the record. The amplitude values at the pelvis were significantly larger when swimming without fins while at the C7 they were significantly larger when swimming with them. Autocorrelation coefficients of angles' time histories were higher when swimming with fins for both segments. The power spectrums revealed a dominant frequency representing the stroke period which grew significantly stronger for the fin condition. Correlation Dimension verified a lower dimensionality for the fin condition for the C7 segment movement pattern. Overall fin use seems to offer "strength" to the swimmer's movement pattern. This does not imply better movement coordination, but rather a trend toward a more stable attractor.

1. Introduction

Butterfly stroke is dominated by the body's undulatory movement in and out of the water. For the produced body wave to be effective for propulsion, it should always travel in a cefalo-caudal direction, and end with a whip-like leg kick (Sanders et al., 1995). Fins are supposed to enhance pelvis lift and body's undulation offering more torque for its facilitation. A task-specific constraint like swimming butterfly with fins, may affect the dynamics of the system both during initial learning and optimization of coordination phase (Newell 1986; Davids et al., 2008). Fins have been used in swimming training and learning for a long time. In elite swimmers' case, fins are used to amplify the swimming performance through strengthening the legs, adding speed and minimizing the energy cost during training (Zamparo et al., 2002, 2006).

Swimming is a cyclic movement where an underlying pattern is firmly repeating itself. Yet, according to Dynamic Systems Theory (DST) even such a pattern may vary between cycles depending on neuromuscular system's response to global (environmental) and local (internal e.g. joint flexibility) perturbations (Stergiou, 2004). This variability represents changes from stroke cycle to stroke cycle. Whether or not this phenomenon has a deterministic origin, it can be accessed through nonlinear tools (Stergiou, 2004).

The coordination pattern may be task-specific constrained (Newell, 1986) from the use of an implement like fins. Schnitzler et al. (2011) clearly showed that a task specific constrain, freestyle swimming with parachute (added resistance), modified the stroke's spatiotemporal organization. This may not always be the case with the use of implements. Gourgoulis et al. (2009) found that the use of hand paddles in freestyle imposes temporal changes in the duration of the stroke phases but does not change inter-arm coordination. Nakashima (2009) observed that when maximizing the velocity during underwater dolphin kick, trunk coordination during undulation shows an in-phase pattern. The trunk was modeled using five joints and the coupling between the joint angles was assessed. Other studies regarding swimming also confirm the allegation and accept velocity's repercussion on coordination (Seifert et al., 2004a; 2008, Nikodelis et al., 2005) Apart from task constraints, organism constraints such as sex may influence interlimb coordination in swimming (Seifert et al., 2004b). Overall the continuous interaction of all the constraints acting on the swimmer drives the exhibited coordination pattern (Seifert et al., 2014).

However, most of the studies in butterfly swimming refer to limb coordination patterns (Chollet et al., 2006; Seifert et al., 2007,

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2008) Different body parts' kinematics such as the upper trunk and the pelvis may also prove to respond to condition changes, such as fin use, while swimming the butterfly. The trunk, almost half of body mass with large inertia values and surfaces, during butterfly movement can enhance or reduce the body wave that passes through it, a great deal. This research tries to identify the rotational kinematics of the upper trunk and the pelvis and how these could be affected by the use of fins. Despite the fins' wide use in butterfly training, their repercussion on trunk movement pattern is not clear, although such information could be significant to researchers, swimming equipment-developing companies, trainers and athletes.

Advancements in MEMS technology (micro-electromechanic systems) allow the researcher to capture unconstrained continuous movements of the human body over prolonged periods of time, that could formerly be measured only as derivatives of locomotion parameters (Konstantakos et al., 2012). With the proper modifications and arrangements such sensors are used in swimming as well (Nikodelis et al., 2013; Davey and James, 2003; Silva et al., 2013; Stamm et al., 2013; Dadashi et al., 2012; Lee et al., 2011).

The purpose of the present study was to investigate the rotational kinematics pattern of the upper trunk and the pelvis and the complexity-variability of their movement during the sprint butterfly stroke, between male and female swimmers with long fins, (18–26 cm) and without fins.

2. Material and methods

Thirty four (34) young swimmers, nineteen (19) boys and fifteen (15) girls, voluntarily participated in this study. They were active national level swimmers, with at least 6 year of training experience, aged 15.62 ± 1.04 years old. A normal sample distribution was verified for each variable. The study was approved by the ethics comity of the institution and all participants signed an informed consent form before their participation.

The measurements were carried out in a 50 m indoor swimming pool. After a commonness warm up (600 m) in the pool, they were asked to perform 2×50 m sprint butterfly. One trial was without fins and the other with fins, 18–26 cm long, respectively, with a 15 min interval between the trials. No specific instruction about the breathing rhythm was given pants in order to avoid putting any constrains to the organization of their movement.

Kapa-Swim sensor (Kapa-Invent, © 2014) was used to investigate the kinematic pattern of the two segments. It comprises two IMUs, with a 3D accelerometer and a 3D gyroscope each, a micro SD data longer, a periodically lighten high density LED, and is controlled by a small scale microprocessor (Konstantakos et al., 2012) (Fig. 1). Some of the system's main advantages are reported in the following text (Konstantakos et al., 2012; Stamm et al., 2013):

- The sensors provide a high level of accuracy (digital step of the accelerometer is 4 mg/LSB, and of the gyroscope is 0.07°/s).
- The accelerometer can go up to 1600 Hz and the gyroscope can measure up to 8000 Hz. These sampling rates are more than adequate for the description of human movement.
- The system's small size (approximately $80\text{x}50 \times 30$ mm^3 for the main system and $30\text{x}20 \times 20$ mm^3 for each sensor module) and weight (120 g) do not restrain the participant's movement. Thus it can be performed without constrains, for a long period of time and almost at any environment.
- The system operates based on a battery, and is built by the need of low power consumption.
- External signals of synchronizing nature enable the combination of the acquired data with synchronized video data.
- The system's cost is relatively low in comparison with other systems of human motion analysis.
- Due to its' portability, it can be easily carried and utilized in an outdoor environment, or wherever necessary.
- Prolonged recording capacity: the sensors can collect data for quite a long period of time, or until the athletic motion is over.

On the other hand the system's disadvantages are:

- Error in measurement: errors can occur during measurement process due to measuring «noise» that can be normalized via a special handling of the collected data (Konstantakos et al., 2012).
- Skin fixation: skin is moving over other tissues of the human body, allowing error in collected data (Tik-Pui Fong, Chan, 2010).

The sensors were made waterproof and fixed on the swimmers' upper trunk (C7) and pelvis (midpoint of PSIS) (Fig. 1). The acquisition frequency was set at 200 Hz. The data were smoothed with a 2nd order low pass Butterworth filter with 5 Hz cutoff frequency.

A video camera was used to provide qualitative data which was also synchronized with sensors' data by using LED's light. Lap times were also recorded by a skilled timer.

Gyroscope smoothed data were integrated to provide angular displacement data. Systematic drift of the gyroscopes was removed using an optimization method that calculated the average inclination of the drift through least square linear approximation. Angular displacement drift was subtracted from the data according to this inclination that should ideally be zero. Data were originally separated to trials from visual inspection of angular velocity curves. Net oscillation phases and particularly flexion-extension angles of the upper trunk (C7) and the pelvis were stored for further analysis.

- Spatiotemporal parameters and especially peak to peak amplitude were used to describe the mobility and coordination of the selected segments.
- Autocorrelation analysis was used to investigate any possible fluctuations on the cyclic repetitive nature of each segment's movement. The mean values of the peaks were used.
- Power spectrums were used to investigate frequencies with different significance. Frequency amplitudes were normalized (%) with respect to the total power of the signals.
- Phase plots (angle vs angular velocity) of each segment were calculated to provide a qualitative view of how their moving pattern is evolving within the stroke cycles.
- Correlation Dimension (CoD) was assessed (Fraser and Swinney 1986; Cao 1997; Stergiou, 2004) to investigate the level of complexity (dimensionality) of the movement pattern.

All analyses were conducted in Matlab (Mathsoft, Natick, Massachusetts (U.S. A.). For all variables the average values of all cycles were calculated. An average stroke cycle was used for graphical representation which was normalized as a 100% of stroke cycle, using as start – end point the hands entry. A repeated, within subject, two-way ANOVA [2 Gender $\times$ 2 Trials] was used to determine the main effects and the possible interactions between the main effects. All tests were performed with SPSS 21 statistical package. For all tests, statistical significance was set at $p < 0.05$.

3. Results

The statistical analysis did not yield significant interactions for any of the selected variables. As expected the boys were

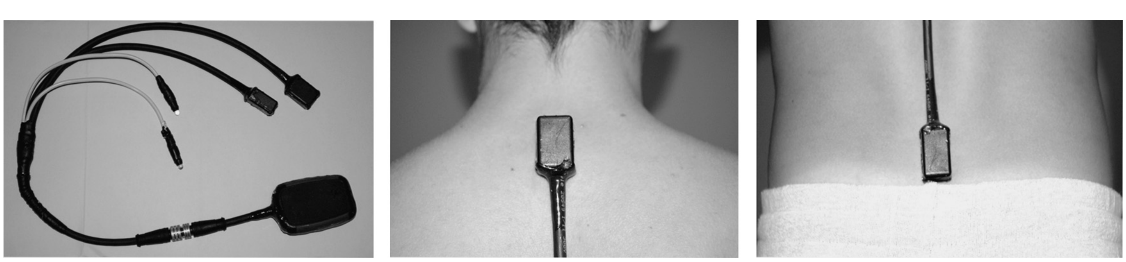

Fig. 1. KAPA SWIM sensors, placement of the sensor to C7 and to the midpoint of the PSIS (pelvis).

significantly faster than the girls, at both swimming conditions. Swimming with fins was also significantly faster for both groups ($p < 0.05$) (Table 1).

The rotational amplitude values at the pelvis were significantly larger when swimming without fins ($p < 0.05$) while at the C7 they were significantly larger when swimming with them ($p < 0.05$), for both boys and girls (Table 1). No significant difference was found between the two groups. No significant differences were found at the period values, neither between conditions, nor between groups (Table 1). The mean stroke cycle of a representative trial is imprinted in Fig. 2. The mean values of the correlation coefficients of the autocorrelation analyses were significantly larger when swimming with fins, for both pelvis and C7 ($p < 0.05$) (Table 1). No significant difference was found between groups. The power spectrums revealed a dominant frequency representing the stroke period, which was around 1 Hz at all cases. Representative trials from each test are presented in Fig. 3. The relative power of the dominant frequency revealed significant differences between the two conditions for pelvis amplitude values ($p < 0.05$), with both segments having larger relative amplitude values for the fins swimming condition (Table 1). The statistical analysis of the dominant frequency showed no significant differences for both segments (Table 1). No significant difference was found between groups.

Representative trials of the phase plots from each test are presented in Fig. 4. A distinct pattern was observed for the pelvis unrelated to the breathing rhythm while for the C7 there was a deviation for some cycles probably due to the breathing actions. The C7 segment had significantly lower dimensionality ($p < 0.05$), (CoD value) for the fins swimming condition for both groups, more evident for female swimmers (Table 1) but without any statistical interaction. Although not statistically checked under the original hypothesis, the CoD descriptive difference between pelvis and C7 was exemplar at all cases with the pelvis having lower values than the C7 (Table 1). This descriptive difference is in line with the qualitative observation mentioned at the beginning of this paragraph. The embedding dimension ranged from 3 to 4 at most of the cases.

Table 1
Descriptive values of the selected variables.

	Girls		Boys	
	No fins	Fins	No fins	Fins
Time (s)	37.99 ± 3.51	32.65 ± 2.62	34.84 ± 2.52	30.18 ± 2.41
Pelvis (peak to peak deg)	48.30 ± 10.86	46.50 ± 9.63	42.02 ± 7.42	41.31 ± 8.64
C7 (peak to peak deg)	34.08 ± 8.01	35.67 ± 7.56	36.72 ± 12.27	40.68 ± 12.82
Period (s)	1.28 ± 0.23	1.29 ± 0.21	1.25 ± 0.22	1.26 ± 0.24
Pelvis (autocor)	0.65 ± 0.12	0.77 ± 0.25	0.70 ± 0.26	0.74 ± 0.24
C7 (autocor)	0.45 ± 0.26	0.60 ± 0.23	0.50 ± 0.23	0.67 ± 0.24
Pelvis (power freqHz)	0.79 ± 0.12	0.80 ± 0.12	0.81 ± 0.13	0.81 ± 0.14
C7 (power freq Hz)	0.63 ± 0.25	0.70 ± 0.24	0.65 ± 0.24	0.70 ± 0.23
Pelvis (power ampl %)	26.12 ± 8.42	30.23 ± 8.20	26.07 ± 11.09	32.17 ± 10.49
C7 (power ampl %)	17.15 ± 8.27	23.24 ± 12.26	19.55 ± 12.73	26.01 ± 13.84
Pelvis (CoD)	1.382 ± 0.269	1.388 ± 0.289	1.383 ± 0.266	1.337 ± 0.205
C7 (CoD)	1.876 ± 0.343	1.686 ± 0.346	1.732 ± 0.308	1.723 ± 0.364

4. Discussion

The present study tried to unfold parts of the butterfly stroke technique that are not always obvious by examining the butterfly stroke under two conditions, with and without fins. The lack of a standard externally imposed breathing pattern, which was deliberate in order to capture individual technique characteristics, affected more the C7 segment and resulted in patterns not being identically the same from stroke to stroke.

Peak to peak amplitude values of flexion-extension angles at the pelvis were significantly smaller when swimming with fins. This observation comes in agreement with Zamparo et al (2002), who stated that fins are responsible for $\approx 10\%$ reduction in kick amplitude. This may occur from the increase in swimming speed (movements have to be made faster), the effort to take as much advantage as possible of the propulsive phases of the kick (smaller amplitude – more kicks), or even knee bending (Gautier et al., 2004), possibly as a compensation for the increased torques imposed by the fins. On the contrary, peak to peak amplitude values of flexion-extension angles were significantly larger at the C7 probably because of the extra push the fins are giving to the swimmer, which may make C7 segment's movement less constrained and the breathing easier while at the same time impose a more vertical undulation of the upper body due to excessive propulsion.

Either way although revealed, the imposed kinematic differences from the fins cannot be linked with the quality of technique. It is certain however that fins consist a strong external constrain which alters kinematic response at the segments rotation level. Does this affect the role of the two segments in the stroke pattern? The main anatomical role of the C7 segment is the facilitation of the breathing movements and the maintenance of a streamlined body position. The pelvis is used for the facilitation of the anterior-posterior rotation and the control of the trunk, the lower body and the legs, as well as in adopting a streamlined body position in water. In swimming the velocity is relatively slow for athletic movement, large masses are involved and the pattern is cyclic. Especially the last two characteristics should comprise a very stable kinematic pattern (Stergiou, 2004). The alteration of that kinematic pattern should put some skepticism to the people involved about the specificity of training with fins at least as far as

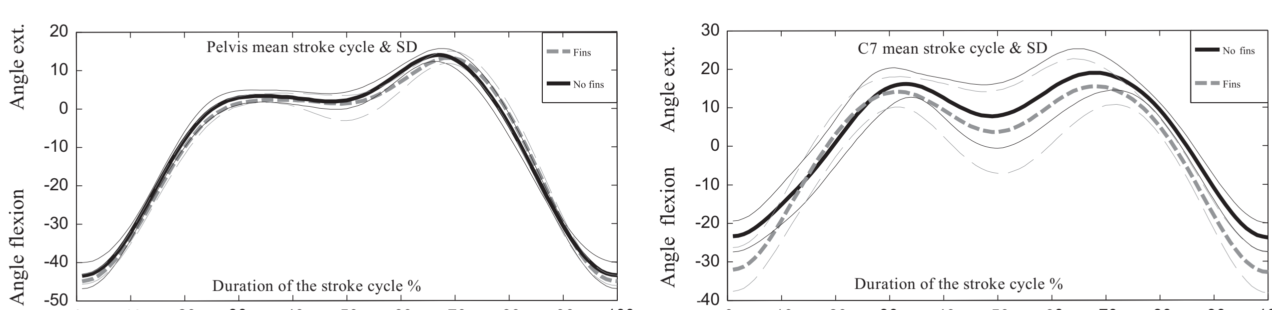

Fig. 2. Mean angle values of pelvis & C7 segment during the stroke cycle.

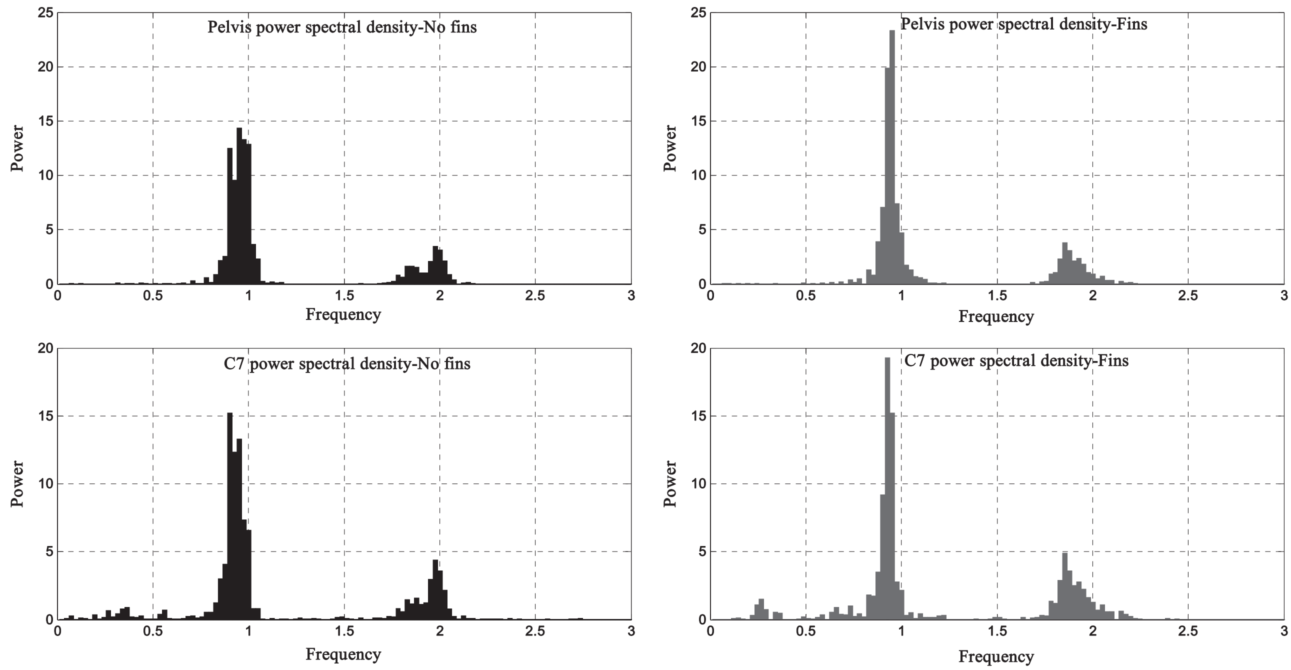

Fig. 3. Spectral content of segments' angular movement.

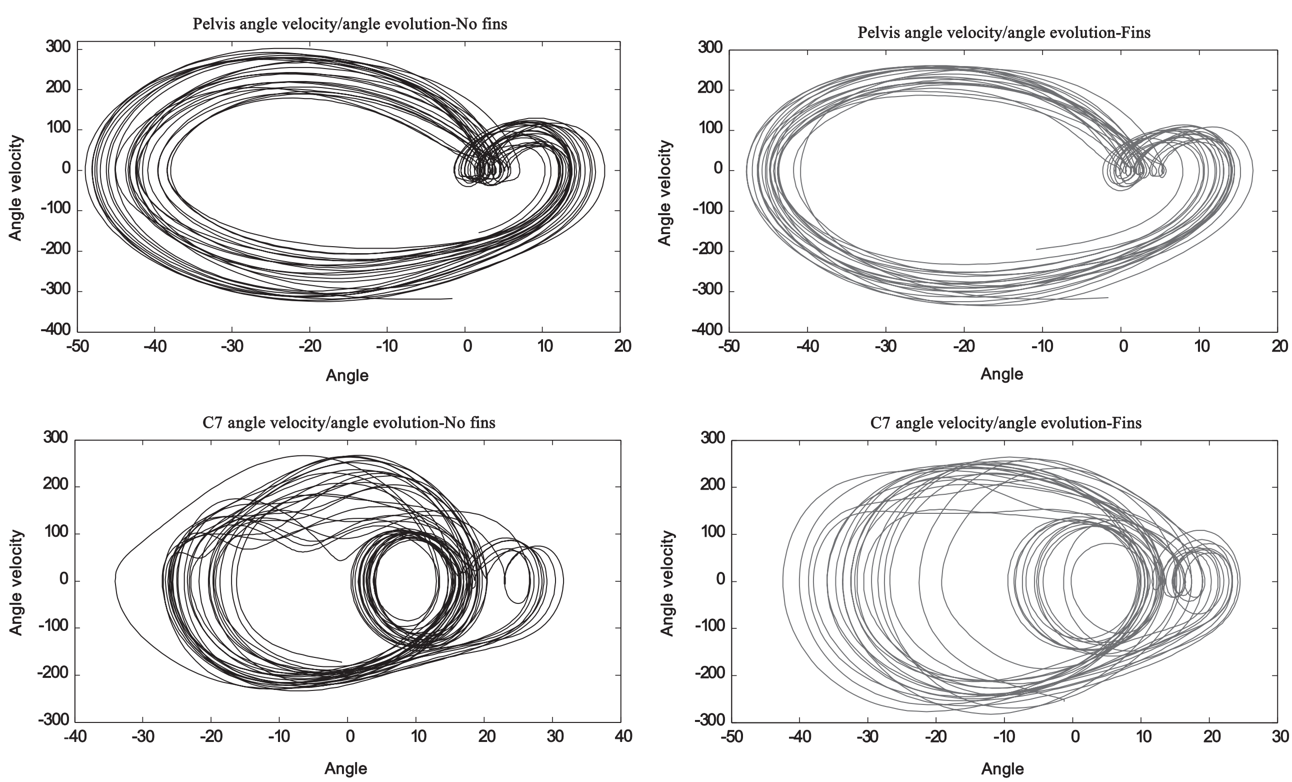

Fig. 4. Segments' phase plots.

technique training is concerned, since the two tasks are similar but not the same.

No significant differences were found between the two groups. However boys had a trend for smaller pelvis but larger C7 amplitude than girls at both conditions. Could there be a case of the system using its physical characteristics to maximize the swimming performance? Taking under consideration the fact that men are significantly stronger and more stiff than women in the trunk area (Magnusson et al., 1995) and are able to generate higher forces during arm pull (Seifert et al., 2008), one could assume that their "wave-like" swimming technique during butterfly stroke would look more like a "one piece" swimming technique without significant wave enhancement in pelvis segment, using arm strength to move forward. On the other hand, women that lack in strength compared to men ought to come up with other ways to maximize their performance. The possession of a flexible trunk can give a partial solution against lack in body strength. This idea may be indirectly supported by the study of Kolmogorov and

Duplisheva (1992) where they measured active drag values for men to be similar between butterfly and freestyle while for women the difference was greater, indicating a more "freestyle like" streamline position during butterfly for men.

The mean stroke period values were not affected by the use of fins. This is a positive effect on the stroke permitting the swimmers to maintain their established technique temporal pattern during training with fins. Fin-trial time was faster for both boys and girls but the number of strokes per trial was smaller, possibly due to increased propelling efficiency with fins (Zamparo et al., 2002). That fact allowed period values to stay unaffected. A crucial point may be the selected swimming distance. Things could be a lot different if only a few cycles were analyzed from the first 25 m of a sprint or from the last 25 m of a 200 m race. Fatigue undoubtedly affects spatiotemporal characteristics of the strokes (Barbossa et al., 2011).

Autocorrelation analyses revealed higher mean autocorrelation values when swimming with fins for both segments and C7's values were relatively smaller from pelvis. The stroke cycles looked more alike to each other within each trial, eliminating the spatial variability from one cycle to another. This is a strong indication that swimmers were able to maintain a more stable movement pattern during the fin-trial. The fact that swimmers were not instructed to use the same breathing pattern all along resulted in breathing pattern variation throughout and between the trials. C7's coefficient values were probably affected by that fact. What also could have affected the C7's values is the fact that head and hands are the first body parts that are confronted with the stationary water, experiencing higher drag forces (environmental constraint). As a result the entering in the water may not be identical from stroke to stroke.

Considering power spectrums, fins seem to have affected segments' power amplitude of the dominant frequency, indicating their contribution to a more "clear" swimming motion. The cyclic movements are organized so well that the majority of the power of the signal is gathered under the dominant frequency, without a lot of power spread at the frequency band (mechanical noise) (Stergiou, 2004).

Phase plots provide interesting information about the butterfly stroke. They can serve as a stroke print for comparative future research between differently skilled swimmers regarding intra-segmental coordination (Clark and Phillips 1993; Li et al., 1999) and imprint phenomena during the stroke that may have deterministic origin. Embedding dimension estimations are similar to those of other studies considering rhythmic extremity movements (Mitra et al., 1997; Dingwell and Cusumano, 2000). CoD analysis showed lower dimension for the C7 with the use of fins. At this case the specific constraint seems to decrease the dimension of movement (Newell and Vaillancourt, 2001). If we are to accept that the optimal amount of variability occurs during competitive butterfly stroke (no fins condition), the use of fins make the biological system more rigid, at least at the C7 level. That difference in movement regulation, between the two tasks should be seriously considered when using fins. Reduced or increased variability is a possible constraint-led change of the movement pattern (Haudum et al., 2012).

Nevertheless, the increased biomechanical demands by the use of fins do not affect the movement organization at the pelvis level. Furthermore at all cases the mean values of CoD are below 2, low enough to be considered as having deterministic origin. Especially at the pelvis level the non linear analysis indicates a strong resemblance with periodic orbit-low noise signal (Stergiou, 2004). Thus, overall CoD values indicate that the structural properties of the movement (butterfly stroke) are strongly preserved with the use of fins, at least at the pelvis level. This resemblance between fin butterfly and butterfly is important since swimmers using fins can get familiar with the "feeling" of higher velocities, greater drag forces (Toussaint et al., 1988) as well as strengthen the trunk and leg muscles (Marion et al., 2010), without seriously compromising the specificity of training at this level.

Overall fin use seems to offer "strength" to the swimmer's movement pattern. This does not imply better movement coordination, since we do not have a case of novice versus elite performers or a measured goal (Davids et al., 2008). It is rather a different movement pattern "channeled" toward a more stable attractor, possibly due to the large inertial changes in the movement properties from fins use, that allow less movement "flexibility". Besides the general evidence for increased variability in butterfly stroke compared to fin butterfly, which can have a functional role (Slifkin and Newell, 1998; Newell et al., 2006; Seifert et al., 2014), both tasks could be considered as movements of low variability. The fact is that fins represent a constraint that imposes some changes in the stroke compared to the competitive technique of butterfly and they should be used under this consideration.

Conflict of interest statement

There is no conflict of interest.

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