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# Front Crawl and Backstroke Sprint Swimming have Distinct Differences along with Similar Patterns Regarding Trunk Rotations

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## ABSTRACT

**Background:** Front crawl and backstroke share similar trunk rotating characteristics and tempt coaches to transfer teaching parts from one stroke to the other intuitively. However, the degree of similarity has yet to be determined. The coordination of the pelvis and the 7th cervical vertebrae (C7), during yaw and roll rotation, when sprint swimming front crawl, and backstroke was studied. **Methods:** Thirty-four swimmers were assessed on their performance in25m-sprint of each stroke. Using inertial sensors, each segment's time series of angular displacement was calculated. Their amplitudes, mean autocorrelation values, max cross-correlation coefficient, phase lag, and relative power at the main frequency were analyzed. For all comparisons, the p-value was set to <0.05. **Results:** Pelvis yaw and roll and C7 roll amplitudes were greater at backstroke, C7 yaw was greater at front crawl. Autocorrelations ranged from 0.79 to 0.82 except for the pelvis at front crawl in yaw which was 0.72±0.16. Relative power at the main frequency ranged from 47% to 52% except for the yaw pelvis' at the front crawl which was lower (32.81±14.09%). Backstroke had larger mean values in all cases and roll had larger mean values than yaw. Cross-correlation between the two segments yielded higher values at roll. At roll direction, the leading segment in the front crawl was the pelvis while in backstroke, it was the C7 which was true in all cases. In all cases, the coupling was slightly deviating from in-phase mode except from backstroke yaw which yield phase lag values of -13.35±1.14% of stroke cycle time. **Conclusions:** Although both strokes share similar characteristics their intersegmental coupling differs. The findings of the study imply that proper focus should be given to enhance only a positive transfer of learning between the two strokes.

**Key words:** Time Series, Sensors, Angular Displacement, Swimming Kinematics

## INTRODUCTION

Front crawl and backstroke, due to the alternating movements of the limbs facilitate a distinct roll of the torso along the longitudinal axis of the body (Gonjo et al., 2021). The torso which is usually analyzed as two segments (upper trunk or shoulder girdle and lower trunk or pelvis) (Psycharakis & Sanders, 2008;2010), also rotates around its sagittal axis (yaw rotation) (Kudo et al. 2019). As these two swimming techniques share similar characteristics (e.g. almost horizontal body position, extending – bending – extending the elbow, flutter kick, etc.), in practice, coaches tend to use the same tips for teaching the two strokes.

Yet, the existence of similarities must be proved because differences regarding limb actions also exist (Gonjo et al., 2020). Some are imposed by anatomical constraints when swimming in supine versus prone positions. Such examples are the restriction of the arm to move below the body during the propulsive phases, or the extra upward phase of the underwater stroke to facilitate release and recover in the surface during backstroke that possibly dictates the inter-limb coordination mode (Chollet et al., 2008). Another is the breathing constraint at front crawl, which imposes underwater stroke modifications (Vezos et al., 2007) and is associated with body roll (Payton et al., 1999).

Although when teaching front crawl and backstroke coaches tend to focus on the movements of the upper and lower limbs (Costa et al., 2017), it should not be overlooked that the fulcrums of their lever arms are located on the torso which interacts with them and rotates around its axes. Torso as the segment with the largest moment of inertia, exerts strong resistance or/and drive at rotational movements. Understanding these movements and teaching them properly can affect the hydrodynamics of the swimmer's body and swimming efficiency (Yanai, 2001; 2003; 2004).

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Movements of the torso are extensively studied for the front crawl, especially for roll rotation. Psycharakis & Sanders (2008) found that hips and shoulder roll asymmetry profiles, as indicated by the asymmetry index used, vary among 200m front crawl, with the shoulders and hips being out of phase for some of them. Thus, no dominant pattern could be identified. Cappaert et al. (1995), found that sub-elite swimmers rolled the two segments in anti-phase mode, compared to elite ones that rolled them in-phase. Moreover, when the velocity increased, swimmers reduced their shoulder and hip roll at front crawl, potentially minimizing the required torque and consequently maximizing efficiency (Yanai, 2003). In backstroke, swimmers showed a stable shoulder and hip roll amplitude regardless of the swimming velocity (Alves et al., 2004).

Nevertheless, the rotation of the two styles comparatively is only scarcely studied. Gonjo et al. (2021) reported an interaction in the rotational behavior of the torso between speed and style. They found that roll amplitudes for backstroke remained unaffected as velocity increased, which agrees with the findings of Alves et al. (2004), while for front crawl, they were reduced, as shown by Yanai (2003). Consequently, roll angles attained by the two strokes were not found to be different at maximal speed. On the other hand, as swim velocity increased, body roll was decreased for both strokes due to the buoyant torque. Thus, the two styles exhibit similar as well as different rolling behavior.

Recently, the study of stroke cycles has been dominated by analyzing a few strokes (Kudo et al. 2019; Gonjo et al. 2020; Gonjo et al. 2021), presenting some methodological limitations. The use of inertial sensors provides a valid solution to overcome this issue (Nikodelis et al. 2013; Averianova et al. 2016; Grigoriou et al. 2019), increasing the capability to capture many consecutive cycles and allowing the implementation of different data treatments like auto-correlation, frequency spectrum and cross-correlation analyses that can capture the repeatability and smoothness of the swimming pattern as well as inter-segmental coupling.

In addition, in most of the studies, the rotation of the torso around its sagittal axis (yaw rotation) has been overlooked. Recently, Kudo et al. (2019) described a substantial interdependency between the two rotational directions and the arm stroke characteristics during front crawl propulsive actions. These rotary movements may increase resistance, affecting thrust (Yanai, 2001; Kudo et al., 2017; Kudo et al., 2019). Since swimmers need to remain horizontal, and side aligned while speed increases (Maglischo 2003), yaw rotation may be considered a redundant dimension or an unavoidable reaction to applied torques.

Therefore, the inter-segmental relationship of pelvis and upper trunk rotation needs further research. The investigation of the behavior of the two segments at 2D rotation can assist in understanding the movement of the torso, identify possible similarities between the two strokes and provide information for developing teaching techniques and drills that exploit these similarities for learning purposes. The perspective of analyzing many consecutive stroke cycles instead of a limited number may offer new and more conclusive information since the intersegmental coordination of the two segments can be properly studied in such a dataset. The sprint condition, where mastering the degrees of freedom is challenged (Granata & England, 2006), seems suitable for investigation. The above features are endorsed to the present study design and reflect the literature gap and its methodological novelty.

Thus, the purpose of the current study was to investigate the inter-segmental coordination pattern of pelvis and the 7th cervical vertebrae (C7), regarding their yaw and roll rotation, at sprint front crawl and backstroke swimming using inertial sensors. It was hypothesized that the rotational behavior of the two segments around the sagittal (yaw) and longitudinal (roll) axis would have similarities as well as differences at amplitudes of biomechanical features and intersegmental synchronization characteristics between front crawl and backstroke.

## METHODS

### Participants and Study Design

Thirty-four (34) swimmers, nineteen (19) male and fifteen (15) female (15.62 ± 1.04 years old) voluntarily participated in this study. They were national-level age group swimmers with at least six years of training experience. The sample was built from all the available swimmers in the district of the city of Thessaloniki that formed the criteria of training experience and swimming level and were competing in the category of 14-16 years of age. A power analysis was conducted to justify the sample size. The power analysis was held with partial $\eta^2$ of 0.15, a significance level at.05 and desired power of 0.8 using G*Power 3.1 software (Faul et al. 2009). The study was approved by the Ethics Committee of the School of Physical Education and Sport Sciences of Aristotle University (approval number: 161/14-11-2013), and all swimmers and their parents signed an informed consent form. After warming up (600m) in a 50m indoor pool, all the participants performed 25m sprint of both front crawl and backstroke. The trials (one at each stroke) were executed in random order with at least 5-minute rest. No instruction concerning the breathing rhythm was given.

### Testing Procedures

Kapa-Swim sensor (© K-Invent), a system comprised of two IMUs, with a 3D accelerometer and a 3D gyroscope each, operating at 200Hz, was used to investigate the kinematic pattern of the swimmers' C7 and pelvis. According to the procedure explained by Averianova et al. (2016) rotation angles of C7 and pelvis around their longitudinal and sagittal axis (Figure 1) were obtained and the following were calculated:

- Peak to peak angular amplitude was used to describe the movement pattern of the selected segments. The mean values of all cycles were used.
- Autocorrelation analysis of the angular rotation for each segment in each direction was used to investigate possible fluctuations in their cyclic repetitive movement. The

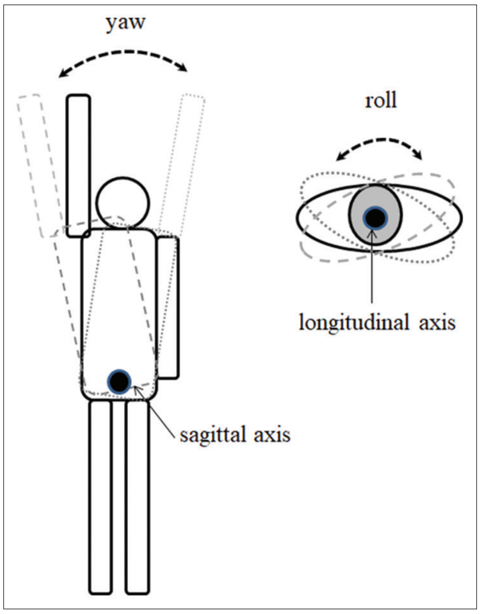

**Figure 1.** The yaw and roll rotations around the z-axis (sagittal) and y-axis (longitudinal), respectively

mean values of the peaks from the autocorrelation function were used.

- Power spectral density function was used to investigate the smoothness of the repetitive pattern. Power amplitudes were normalized (%) with respect to the total power of the signals. The relative power of the angular displacement of the pelvis and C7 at the main frequency was used.
- The cross-correlation function was used to express the inter-segmental coupling. Phase lags, expressed in percentage of the stroke cycle time, were used to describe the synchronization between the two segments, (see Figure 2 in the supplementary files for more details). When the phase lag is 0%, the pelvis and C7 move synchronously, and their coordination mode is in-phase. (Nikodelis et al., 2005).

### Statistical Analysis

The normal distribution criterion was satisfied after contacting the Shapiro–Wilk test. For peak-to-peak amplitude, auto-correlation and relative power amplitude in the main frequency Analysis of Variance were applied with three within subjects' factors (style: backstroke vs. front crawl, segment: pelvis vs. C7, direction: yaw vs. roll) and for cross-correlation Analysis of Variance was used with two within subjects' factors (style: backstroke vs. front crawl, direction: yaw vs. roll). P value was set at <0.05. All analyzes were held using SPSS 23 statistical package.

## RESULTS

### Spatiotemporal

A significant interaction between the three within factors was observed in peak-to-peak amplitude ($F_{1,\ 33=}$ 164.421; $p< 0.05$). Analyzing the simple main effects of "style" within each level combination of the "segment" and "direction" factors, significant differences were revealed between backstroke and front crawl in all combinations, except the peak-to-peak amplitude of pelvis in roll ($F_{1,\ 33=}$ 0.277; p= 0.602). In the backstroke swim, compared to the front crawl, the peak-to-peak amplitude of the pelvis was greater in yaw and of C7 was greater in roll. The value of C7 in the yaw was greater at front crawl than backstroke. Analyzing the simple main effects of "direction" within each level combination of the "segment" and "style" factors, significantly greater values were found in roll, rather than in yaw, in all combinations except the peak-to-peak amplitude of C7 in front crawl $F_{1,\ 33=}$ 0.166; p=0.687). Analyzing the simple main effects of "segment", in backstroke it was revealed a statistically significant greater peak-to-peak amplitude of C7, in comparison with pelvis, both in yaw ($F_{1,\ 33=}$ 91.403; $p< 0.05$) and roll ($F_{1,\ 33=}$ 92.362; $p< 0.05$), while in front crawl the values of C7 were significantly greater than the peak to peak amplitude of pelvis only in yaw ($F_{1,\ 33=}$ 457.826; $p< 0.05$), and had no significant difference in roll ($F_{1,\ 33=}$ 0.990; p= 0.327). The distributions of all variables along with the statistically significant differences, as appear in Figure 2. The angular displacements of a female swimmer that swims both front crawl and backstroke competitively appear in Figure 3.

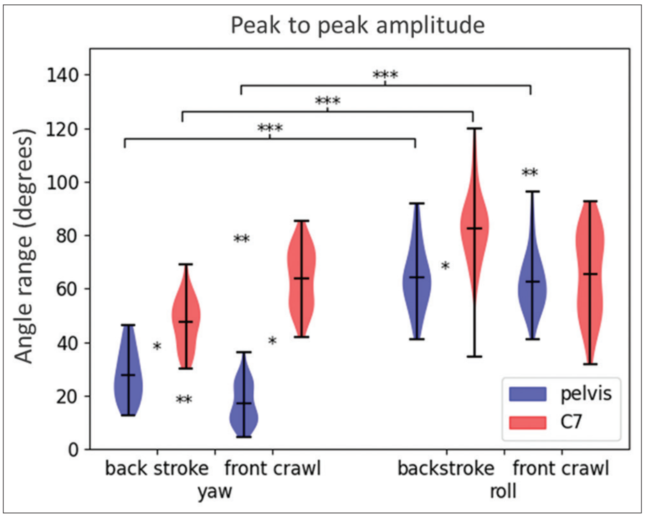

**Figure 2.** Peak to peak angular amplitude: The distributions of all variables and the statistically significant differences. Simple main effects for style (**) segment (*) and direction (***)

### Autocorrelation

All autocorrelation values ranged from 0.79 to 0.82 except the pelvis at front crawl in yaw rotation, which was 0.72± 0.16. A significant three-way interaction was found between the three within factors ($F_{(1,33)}$= 9.217; $p< 0.05$). The simple main effects analysis for "style" revealed significantly larger values for backstroke compared to front crawl fat pelvis in yaw ($F_{1,\ 33=}$ 8.717; $p< 0.05$). Analysis of the simple main effects for "direction" showed significant larger values for roll compared to yaw at pelvis in front crawl ($F_{1,33=}$ 13.379; $p< 0.05$). The simple main effects analysis of "segment" showed significant differences between the pelvis and C7 only in the

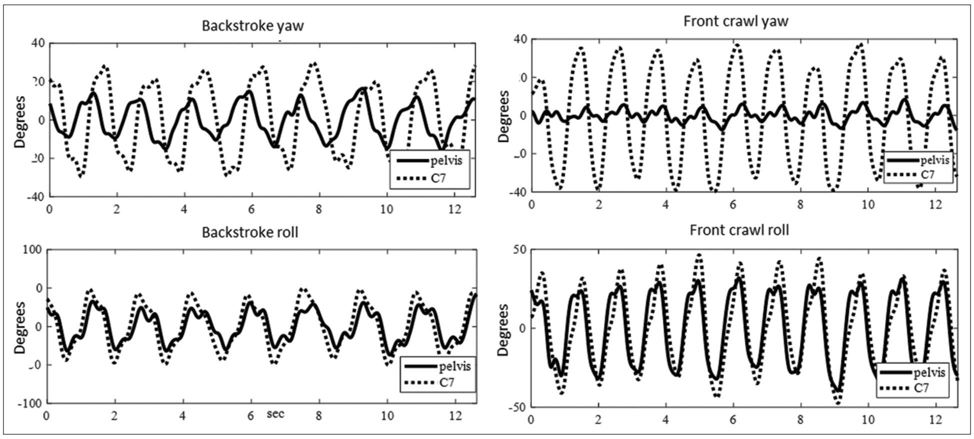

**Figure 3.** The angular displacements of a female swimmer that swims both front crawl and backstroke competitively

front crawl, where the autocorrelation value of the pelvis was significantly less in yaw ($F_{(1,33)}= 8.027$; $p< 0.05$).

### Power at the Main Frequency

Regarding the relative power amplitude of the angular displacement of the pelvis and C7 in the main frequency all values ranged from 47% to 52% except the yaw pelvis value in front crawl, which was relatively lower (32.81±14.09 %). Also backstroke had larger mean values in all cases, and roll had larger mean values than yaw in general.

A significant interaction between the three within factors was observed ($F_{1, 33=}$ 39.878; $p< 0.05$). Analyzing the simple main effects of "style", significantly larger values were found at backstroke compared to front crawl only in yaw rotation for the pelvis ($F_{1, 33=}$ 25.413; $p< 0.05$) and in roll rotation for C7($F_{1, 33=}$ 5.779; $p< 0.05$). Regarding the simple main effect of "direction" at backstroke, the power amplitude of C7 was significantly larger in roll compared to yaw ($F_{1, 33=}$ 20.396; $p< 0.05$), while at front crawl the same result was met at the pelvis level ($F_{1, 33=}$ 4.602; $p< 0.05$). Regarding the simple main effect of "segment" at backstroke, the power amplitude of C7 was significantly larger compared to that of the pelvis for both directions (yaw: $F_{1, 33=}$ 4.136; $p< 0.05$ and roll: $F_{1, 33=}$ 15.050; $p< 0.05$), while in front crawl, the power amplitude of C7 was significantly larger than the value of pelvis only in the yaw rotation ($F_{1, 33=}$ 58.176; $p< 0.05$) whereas no significant differences were observed in roll ($F_{1, 33=}$ 2.258; $p= 0.134$) between the two segments.

### Cross-correlation

Regarding the cross-correlation coefficients between the two segments (pelvis and C7) significant main effects of style ($F_{(1,33)}= 5.358$; $p< 0.05$) and direction ($F_{(1,33)}= 28.501$; $p< 0.05$) where noticed. For "style" irrespective of direction, backstroke had larger overall values while for "direction" significantly lower values were observed for yaw irrespective of "style". These results are imprinted in Figure 4.

Regarding the phase lag a significant two-way interaction was noticed between the factors "style" and "direction" ($F_{(1,33)}= 164.101$; $p< 0.05$). The simple main effects analysis for "style" revealed that the leading segment was the pelvis for front crawl in roll direction (negative phase lag) while for the backstroke was the C7 (positive phase lag) ($F_{(1,33)}= 111.964$; $p< 0.05$). The opposite was the case for the yaw direction ($F_{(1,33)}= 39.352$; $p< 0.05$). Analyzing the simple main effects of "direction" for each level of the "style" factor revealed that at backstroke yaw direction it was less in phase than roll ($F_{(1,33)}= 79.782$; $p< 0.05$). These results are imprinted in Figure 4 where it is clearly shown that the leading segment is different in each case and that phase lag for backstroke occupies larger part of the stroke cycle time deviating from in phase mode compared to the other cases.

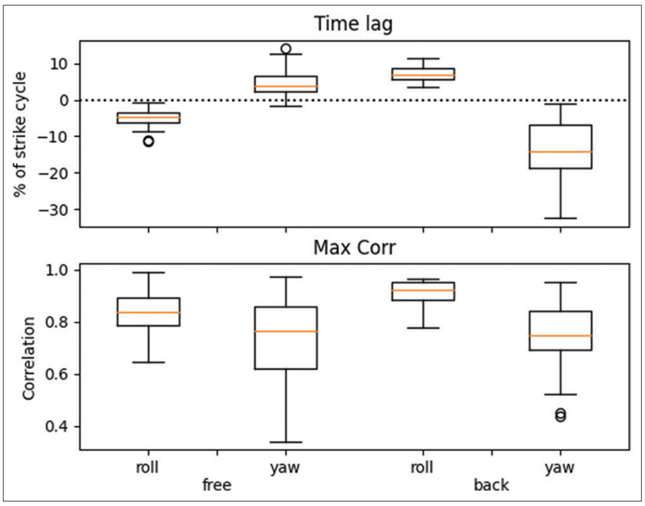

**Figure 4.** The cross correllation coefficients (lower part of the graph) and time lag of the cross correlation (expressed in % of the stroke cycle) of front crawl and backstroke at both directions. The results are imprinted in box plots

Regarding roll, at backstroke the leading segment was the C7 while at front crawl the leading segment was the pelvis. This observation was true for all participants.

## DISCUSSION

The main objective of this work was to study the rotational behavior of the pelvis and the 7th cervical vertebrae (C7) and their intersegmental coordination during sprint front crawl and backstroke swimming searching for similarities in order to provide practical implications for teaching. The main findings were that the pelvis rolls similarly at both strokes while the synchronization of the two segments at roll rotation is different as the upper part of the trunk leads the roll rotation at backstroke while the pelvis leads the roll rotation at front crawl.

More specifically, the roll of the pelvis was not found to be significantly different between the two techniques. This "similarity" implies that the coaches use drills oriented at the same amount of rotation both at the backstroke and at the front crawl, yet with different rotational frequencies (Conjo et al., 2021) and always at high intensity since the present study investigated only sprinting performance.

Backstroke at C7 in roll, has larger amplitudes than front crawl, exhibits slower rotation and has a lower main frequency. These findings are in line with the idea that body movements at lower frequencies may have larger amplitudes. This different behavior during movements with lower frequency has been shown by Yanai (2003) in the case of front crawl. Extensive roll in C7 at backstroke may also serve to overcome moments of inertia of the rest of the body and facilitate the placement of the hand in a more efficient position for propulsive action due to anatomical constraints. This is not the case at front crawl since the elbow can be flexed during the arm recovery and the arm can easily move medially during the underwater stroke. So, despite the absence of head rotation in backstroke, the values for C7 rotation are still larger. This finding is inconsistent with a recent study (Conjo et al., 2021), which found that shoulder roll was smaller at backstroke than front crawl. Yet, a different procedure was followed in the measurement, as it will be explained later in this section. Also, in the present study, most of the swimmers were young and not elite international athletes which may have played a role.

In backstroke, the yaw rotation for C7 is limited because it is probably not substantially influenced by the recovery of the arm, as this motion is executed mainly in the anteroposterior plane of the body and probably produces limited torque in yaw. Due to anatomical constraints of the shoulder joint, front crawl arm recovery as well as breathing actions, are not one-plane motions. Consequently, both may cause mediolateral movements of the trunk. Since the arms are directly linked to the shoulder griddle through the scapulars, C7 is mostly influenced (Kudo et al., 2019). This is apparent in the larger yaw rotation of C7 compared to the pelvis, especially in the front crawl.

Although the six-beat kick rhythm is not a "clear cut" in all cases, the intensive kicking action during sprint, especially at the front crawl, reduces the pelvis's freedom to rotate. This influence of kicking in the body's angular momentum, especially around its longitudinal axis, helps control body rotation (Andersen et al. 2020). Regarding the present findings, probably the reduced yaw at the front crawl compared to backstroke at the pelvis level could be attributed to more systematic six-bit kicking actions at front crawl where the speed is faster.

Pelvis rotation is less affected by the actions of the arms as they are not directly attached to it. Thus, even though inter-segmental differences follow the same rule in both swimming styles and in both directions, this is less apparent at front crawl in the roll direction, where the amplitudes of pelvis and C7 are almost equal, showing an in-phase mode and less twist. Actually, the fact that the leading segment is always the pelvis the idea that it has an active role in rolling is supported. Therefore, a direct teaching implication for swimmers is to learn to control the pelvis instead of focusing on performing the breathing from the head and the upper trunk. On the contrary, the leading of C7 in backstroke roll where the two segments are also strongly coupled, drives to a different behavior. Since twist is related to drag (Yanai 2001; 2003) and front crawl has lower active/passive drag ratios than backstroke (Kolmogorov & Duplisheva 1992) this may be an important difference.

Therefore, when teaching the backstroke technique, it should be emphasized that the roll starts from the upper part of the body, which was consistent for all the participants, as imprinted in the phase lag between the two segments. For front crawl the results prove the opposite. Rolling the body through the pelvis could help avoid anti-phase shoulder and hip coupling observed in sub-elite front crawl swimmers (Cappaert et al., 1995).

The smaller amplitude of pelvis in yaw compared to roll and the lower power at the main frequency, especially at front crawl, which also has the lower autocorrelation value, reveal the redundant role of yaw direction at this condition. Under this perspective the rotation in yaw could be considered a counteraction of the kicking and the mediolateral arm movements, which theoretically should be minimized in proper sprinting technique.

While C7 seems to follow a clear one-component sinusoid wave probably related to the arm stroke movements, pelvis control is poor, as it appears in the smoothness of the angular evolution, especially in yaw. As a result, this disparity between the two segments is also apparent in the lower cross-correlation values in yaw direction. Especially in backstroke, the coupling of the two segments is also out of phase for 13% of the stroke cycle. Perhaps the more complex down-up sweep motion (Formosa et al., 2014) and the need for the clearing phase that does not permit superimpose of the arm strokes at backstroke (Chollet et al., 2008; Lerda & Cardelli, 2013) have some effect on coupling. It appears that if there is a wave-like movement imposing mediolateral flexion of the spine, this is not actively controlled since the endpoints of the torso are not strongly coupled.

Power amplitudes at the main frequency are smaller than Kudo et al.'s study (2019). In the reported case Fast Fourier Transform (FFT) was used to calculate the unique power spectrum of the given signal, while in the current study the power spectral density of the signal was selected, which is a smoother metric (Stergiou, 2004). Also, the different sampling frequency, sampling length and thus step at the frequency axis play a role. More important is the fact that the adopted times series approach allowed multiple frequencies to unfold, as opposed to the limited number of cycles approach. The sum of the power at the main frequency and the peaks located right next to it would probably add up to similar values with the reported study. Nevertheless, the present findings partly question the credibility of selecting only one or two representative cycles for analysis (see Figure 3 and further discussion in the supplementary files).

### Limitations and Suggestions for Future Studies

The discrepancies in the roll rotation of C7 with the shoulder rotation calculated in other studies are attributed to the fact that the used local reference system was not formed using shoulder points but only aligned to the shoulder axis at neutral position. Therefore, theoretically only the rotation of the body of C7 was measured, although, as it is proved from a validation experiment (see supplementary files), yaw rotation of C7 partly accounts for the scapula movement also compared to single thorax rotation. Despite the effect that the sliding of the scapula might have on the measurement, the current method still differs from the previous ones. Moreover, this study investigated only sprint conditions, the participants were not elite high-level performers, and the majority specialized in front crawl. Consequently, future research should focus on multiple speeds and expert swimmers in both styles.

Swimming techniques are also related to the anthropometry and the duration that the upper limbs are above the water in relation to the cycle time. Individuals with different anthropometric characteristics from the participants of the current study might behave differently. Also, although swimmers theoretically perform similar kicking in both strokes, the mechanism may differ due to the distinct ventral and dorsal posture.

More comparative research is needed especially for yaw rotation in conjunction with stroke kinematics and propulsive forces to understand the role of the torso in these bilateral swimming techniques and integrate the findings in teaching.

### Strength and Practical Implications

The main strength of the study was that it managed to capture the nature of intersegmental coordination in 2D rotation using the whole trial, a combination not previously reported in the literature and revealed similarities of the two strokes in the rotation of the torso, as well as critical differences like the phase lag between the two segments. The fact that in backstroke the roll starts from the upper part of the body while in front crawl it starts from the pelvis gives a strong implication in teaching the synchronization of the intersegmental rotation differently for the two strokes.

## CONCLUSIONS

Conclusively, backstroke and front crawl have similar behavior for the pelvis in the roll direction, while coupling of the two segments seems to be different, especially in the leading segment. Using the pelvis for commencing the rotation in front crawl may be helpful for a more streamline position during breathing as lower trunk moment of inertial is larger than the head or the shoulder gridle and can facilitate rotation for the rest of the body more effectively.

## ACKNOWLEDGMENTS

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## CONFLICT OF INTEREST

None.

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