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Upper-body muscle activity and synergies in front crawl: comparison between submaximal and maximal swimming speed under breath-holding condition

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Title: Upper-body muscle activity and synergies in front crawl: comparison between submaximal and maximal swimming speed under breath-holding condition

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Abstract

Swimming speed is a primary biomechanical constraint shaping muscle activity through modulation of stroke timing and coordination. However, how variations in speed influence both individual muscle activation and its organization into motor modules remains poorly understood. This study investigated the effect of swimming speed on upper-body muscle activation and muscle synergies during front crawl performed under breath-holding conditions. Surface electromyography was recorded bilaterally from six upper-body muscles in nine trained male swimmers while performing 25-meter trials at 80% and 100% of their maximal speed, after exclusion of three participants whose EMG recordings did not meet predefined signal-quality criteria. Muscle activity was analyzed using envelope-based methods and muscle synergies extracted through Non-Negative Matrix Factorization. Statistical non-Parametric Mapping (SnPM) was applied to examine amplitude- and timing-related differences across the stroke cycle. At maximal speed, muscles showed widespread increased activation amplitude and systematically earlier recruitment compared with the submaximal condition, as supported by SnPM analyses. Muscle synergy analysis identified four and six motor modules at 80% and 100% of maximal speed, respectively. Four synergies were preserved across conditions, but exhibited systematic anticipatory shifts. Two additional synergies were required to reconstruct muscle activity at maximal speed, primarily involving external oblique and anterior deltoid activity. These findings suggest that increasing swimming speed under breath-holding condition is associated with both earlier activation of shared muscle synergies and a reorganization of synergy modules.

1. Introduction

Quantitative assessment of muscle activation in sport enables the characterization of task-specific motor patterns, including timing, intensity of muscle contraction, fatigue, and coordination (Clarys, 2000). In swimming, surface bipolar electromyography (sEMG) clarifies the role of individual muscles across different phases of the stroke cycle (Andersen et al., 2023). Beyond traditional single-muscle analysis, muscle synergy analysis provides a higher-level perspective on neuromuscular control.

Muscle synergies describe how the central nervous system organizes muscles into functional modules (Chvatal & Ting, 2012; Tresch et al., 2006), identifying subsets of muscles consistently activated together during specific phases of a movement. Each module reflects a coordinated recruitment pattern, characterized by relative contributions of individual muscles and their temporal activation and associated with specific biomechanical functions (Ghislieri et al., 2023). Within the swimming research field, current literature mainly describes motor control underlying specific swimming techniques (Matsuura et al., 2020; Morais et al., 2026) or compares populations, such as elite vs. recreational swimmers (Vaz et al., 2016; Yamakawa et al., 2022) or swimmers with and without shoulder pain (Matsuura et al., 2022a, 2024). Nevertheless, muscle synergies hold the potential to evolve from a descriptive tool into a more informative role in the development of training programs (Scano et al., 2024).

Swimming speed results from the interplay between propulsive and resistive factors, representing a primary biomechanical constraint that modulates stroke timing (Seifert et al., 2004) and inter-limb coordination (Seifert et al., 2010). At the level of individual muscles, higher swimming speed has been associated with increased muscle activation and earlier onset of activity (Olstad et al., 2017; Yamakawa et al., 2022), while evidence from butterfly swimming suggests that speed-related changes may primarily affect the timing of muscle synergies rather than their spatial organization (Yamakawa et al., 2026). However, no study has specifically addressed speed-dependent changes in muscle activation patterns and muscle synergy organization in front crawl.

This study aimed to investigate changes across swimming speed conditions in upper-body muscle activation and muscle synergies during front crawl performed under Breath-Holding Conditions (BHC), to minimize breathing-related confounding effects (Yamakawa et al., 2025). Importantly, swimming speed was intentionally manipulated as an experimental constraint to generate distinct task demands. Therefore, comparisons across speed conditions inherently involve concurrent changes in effort level and overall neuromuscular demand. We hypothesized that maximal swimming speed would be associated with: (i) increased upper-body muscle activation amplitude and earlier activation timing; and (ii) speed-dependent modulations in muscle synergy organization. By combining envelope and muscle synergy analysis, the present study aims to link single-muscle level adaptations with higher-level control strategies, thereby contributing to a better understanding of speed modulation in front crawl swimming.

2. Methods

2.1 Participants

Twelve regional-to-national level swimmers were initially recruited for the study. Eligible participants were experienced front crawl swimmers, free from injuries in the previous six months, and consistently completing at least six training sessions per week. However, due to the technical challenges associated with underwater electromyographic recording, several sEMG recordings exhibited excessive noise (Rojas et al., 2018; Severini et al., 2018). As a result, complete datasets suitable for muscle activity analysis were obtained for nine male swimmers (age: 24±4 years; height: 183±6 cm; body mass: 77±4 kg), who constituted the final experimental group. Their anthropometric, training and performance characteristics are summarized in **Table 1.** All participants provided written consent. The study was approved by the Bioethics Committee of the University of Bologna (Approval code: 0312138, 10 October 2024).

2.2 Experimental protocol

Data were collected in a 25-meter indoor swimming pool. Swimmers performed a 1000-meter warm-up and preliminary underwater undulatory swimming trials to determine the appropriate underwater phase and configure the light pacer system (Bosetto et al., 2025).

Target speeds were set at 80% and 100% of each swimmer's maximal speed (v_{max}). Maximal speed was determined during a preliminary 25-meter front crawl trial performed in the same experimental session, with the swimmers instrumented with sEMG sensors and IMUs, thereby accounting for the additional resistance associated with the experimental setup.

Swimmers performed two 25-meter front crawl trials at 80% of v_{max} (BHC80%) followed by two all-out trials (BHC100%), guided by the light pacer system. Recovery intervals of one and two minutes were allowed between repetitions, respectively, in accordance with previously reported work-to-rest ratios for repeated sprint swimming and short-duration high-intensity efforts (Papadimitriou et al., 2025). The testing order was intentionally not randomized, as the submaximal trials were not expected to induce fatigue or learning effects capable of influencing subsequent maximal performance in this population of highly trained swimmers.

A posteriori verification was performed to assess the agreement between target speed and actual swimming speed. The mean absolute error (MAE), expressed as percentage of target speed, was computed for each participant. Across swimmers, the mean deviation from the target speed was 0.05±0.02 m/s for BHC80% and 0.05±0.04 m/s for BHC100%.

2.3 Data acquisitions and processing

Swimming motion was recorded in the sagittal plane using a video camera (Panasonic HC-V770, Kadoma, Japan). Maximal speed was determined via video analysis (Bosetto et al., 2025) and only the clean swimming phase was considered for speed computation. An underwater light pacer (Indico Technologies, Turin, Italy) was installed on the pool bottom to guide athletes at the target speeds.

Two Inertial Measurement Units (IMUs; WaveTrack, Cometa, Italy, 285 Hz) were attached to the wrists to assist stroke segmentation using Co-Plus LF elastic bandages (BSN Medical) (**Figure 1**). Stroke cycles were defined by right-hand water entry, detected via angular jerk (Fantozzi et al., 2022). Left-hand entries were also identified, occurring at 49%±7.84% (BHC80%) and 50%±6.57% (BHC100%) of the right stroke cycle.

Muscle activity was recorded bilaterally using a wireless waterproof surface electromyography system (Cometa MiniWave Waterproof, Cometa, Italy, 2000 Hz) from six upper-body muscles: External Oblique (EO), Biceps Brachii (BB), Triceps Brachii long head (TB), Anterior Deltoid (AD), lower Pectoralis Major (PM), and upper Latissimus Dorsi (LD) (**Figure 1**). Electrode placement followed SENIAM recommendations (Hermens et al., 2000) for BB, TB, and AD, and previous literature for EO, PM, and LD (Okubo et al., 2010; Stirn et al., 2011). Before electrodes attachment, skin surface was shaved and rubbed with an abrasive paste (Merletti & Cerone, 2020). Electrodes were secured using Fixomull transparent adhesive tape (BSN Medical). sEMG and IMU data were acquired with the same system and stored on board. Stroke cycles were time-normalized to 1000 samples (0-100%), and left-hand entries aligned at 50% of the cycle, enabling comparisons across cycles and swimmers.

2.3.1 sEMG envelope extraction

Raw sEMG signals from all repetitions were band-pass filtered (20-450 Hz, zero-phase 4^{th}-order Butterworth), full-wave rectified, and low-pass filtered (12 Hz, zero-phase 5^{th}-order Butterworth) to obtain sEMG linear envelopes (Ghislieri et al., 2020; Merletti & Cerone, 2020). Envelopes were segmented into stroke cycles and normalized, for each subject, to the maximum activation value of the corresponding muscle across all repetitions and conditions. To ensure consistency across participants, a fixed number of ten stroke cycles per subject was used, corresponding to the minimum number of valid cycles available across all included swimmers, producing a (10x1000)x12 sEMG envelope matrix.

Mean temporal anticipation and mean amplitude increase were computed, for each condition, at the subject level from individual average envelopes. Temporal anticipation was defined as the difference in peak timing between BHC100% and BHC80%, expressed as a percentage of the stroke cycle, with positive values indicating earlier activation at higher speed. Amplitude increase was defined as the percentage change in peak amplitude between the two speed conditions.

2.3.2 Muscle synergy analysis

Muscle synergy extraction. Muscle synergies were extracted using Non-Negative Matrix Factorization (NNMF) (Lee & Seung, 1999), implemented through the MATLAB function '*nnmf*'. The factorization decomposed the sEMG envelope matrix into muscle weight vectors (W), representing the contribution of each muscle to the synergy, and activation coefficients (C), describing the temporal activation pattern of the synergy (Ghislieri et al., 2020). According to Ghislieri *et al.* (Ghislieri et al., 2020), the algorithm was run with a maximum of 100 iterations, 15 replicates, and a termination tolerance to 10^{-6}. Weight vectors were initialized using a sparse constraint, while activation coefficients were randomly initialized (Soomro et al., 2018). For each subject and speed condition, NNMF was iteratively performed by varying the number of synergies

from 1 to 12, corresponding to the total number of recorded muscles (N), to explore different solution spaces.

Optimal number of synergies. The optimal number of synergies was determined using the plateau criterion described by Berger and D'Avella (2014) (Berger & d'Avella, 2014), applied to the curve of R^2 (coefficient of determination) values as a function of N. To ensure comparability across athletes and speed conditions, a fixed number of synergies was imposed for each condition, defined as the mode of the optimal values obtained across repetitions and subjects.

Muscle synergy sorting and matching. Since NNMF returns arbitrarily ordered synergies, a within-subject two-step realignment procedure was applied. *K*-means clustering was performed on the W vectors obtained across stroke cycles, grouping synergies based on muscle composition (Ghislieri et al., 2020). Activation coefficients were then sorted accordingly. Subsequently, clustered synergies were temporally sorted based on the position of the peak activation in C.

Inter-subject matching was performed to enable meaningful comparisons across participants. For each subject, an average W matrix was obtained by averaging the weight vectors across all stroke cycles. A Pearson's correlation matrix was computed between each subject's averaged W matrix and that of a randomly selected reference participant. Synergies were then iteratively matched using a best-first strategy by assigning, at each step, the pair with the highest correlation and removing it from further iterations until all synergies were paired.

Correspondence of muscle synergies between speed conditions was evaluated by computing Pearson's correlation (r) between W vectors, allowing the identification of shared synergies, preserved across speeds, and speed-specific synergies. Synergies were considered shared between conditions when the Pearson correlation coefficient between their W vectors exceeded the critical value of 0.58, following the statistical approach described in Chvatal et al. (2011) for synergy matching.

The above-described procedures were conducted in MATLAB (R2023b, The MathWorks Inc., Natick, MA, USA).

Nonlinear registration. To account for the cyclic nature of the swimming stroke and avoid boundary effects, sEMG envelopes and activation coefficients were extended (-50% to +150%). Nonlinear registration was applied following Pataky (2022) (Pataky et al., 2022), separating amplitude modulation (registered curves) from timing shifts (displacement fields). This procedure was performed in Python 3.8.19.

2.4 Statistical analysis

Speed-related differences in sEMG envelopes and activation coefficients were tested using Statistical non-Parametric Mapping (SnPM) (Nichols & Holmes, 2002), implemented in the '*spm1d*' MATLAB toolbox (https://spm1d.org/) on the original 0-100% stroke cycle region of interest. In all analyses, the participant was considered the statistical unit, with stroke cycles first averaged within each participant and condition. A multivariate Hotelling's T^2 paired test was applied to the combined dataset of registered curves (amplitude component) and displacement fields (timing component). *Post-hoc* univariate SnPM paired *t*-tests were conducted separately on the two components to determine whether the observed differences between speed conditions were driven by changes in signal amplitude, timing, or a combination of both, and to identify the stroke phases where neuromuscular activation differed between speeds (Pataky et al., 2022).

The distribution of the optimal number of muscle synergies was assessed with the Shapiro-Wilk test. Since the assumption of normality was not satisfied, differences between speed conditions were evaluated using the Wilcoxon signed-rank.

Statistical analyses were conducted in MATLAB (R2023b, The MathWorks Inc., Natick, MA, USA), with significance set at α=0.05. The effect size of statistically significant differences was determined using Hedges' g statistic, including correction for small sample sizes (Hedges, 1981). According to Hedges et al. (1981), effect sizes were interpreted as small, medium, and large effect size if g values were 0.2, 0.5, and 0.8, respectively.

3. Results

Group mean swimming speeds were 1.58±0.07 $m \cdot s^{-1}$ at BHC80% and 1.88±0.08 $m \cdot s^{-1}$ at BHC100% (p=0.0039, |g|=5.4).

3.1 sEMG envelopes

Average sEMG envelopes of the twelve recorded upper-body muscles during front crawl (**Figure 2**) showed a clear modulation throughout the stroke cycle associated with higher speed condition. A detailed descriptive statistics including peak amplitude, peak timing, amplitude increase, and temporal shift for each muscle are reported in **Table 2**.

SnPM analysis confirmed significant speed-related differences in sEMG envelopes across the stroke cycle for all muscles (p=0.002), due to both amplitude and temporal changes (**Figure 3**).

3.2 Muscle synergies

Four and six synergies were extracted at BHC80% and BHC100%, respectively. With this selection, R^2 and Variance Accounted For (VAF) exceeded 90% for all participants (**Table 3**). A statistically significant difference in the optimal number of synergies was observed between speed conditions (p=0.0039, |g|=2.4). To facilitate comparison across conditions, reconstruction metrics obtained using both four and six synergies in each condition are additionally reported in **Table 3**.

Four synergies were shared between speeds (r=0.91-0.98), and two additional synergies emerged at maximal speed (**Figure 4**). These speed-specific synergies showed moderate similarity with submaximal ones (r=0.45 and 0.46 with the 3rd and 1st submaximal synergy, respectively).

At BHC80%, the first shared synergy was mainly active at approximately 0-20% and 90-100% of the stroke cycle, with higher contributions from left BB and PM. The second shared synergy occurred between 0-30% of the cycle and mainly involved right TB and LD. The third shared synergy was active around 40-60%, with major contributions from the right BB and PM. Finally, the fourth shared synergy spanned between 40-80% of the stroke cycle, with predominant contributions from right TB and LD. At BHC100%, two additional speed-specific synergies emerged, primarily characterized by EO and AD activity and mainly active between 10-40% and 60-90% of the stroke cycle.

With increasing speed, shared synergies preserved their functional role and muscle weight (W) composition, while exhibiting a systematic anticipation in activation timing (15%, 11%, 12%, and 8% of the stroke cycle). An increase in peak amplitude was also observed (8%, 25%, 37%, and 31%), although amplitude-related differences were not consistently present across all conditions. When present, these differences were mainly localized around peak activation. SnPM analysis of shared synergies revealed significant differences across the stroke cycle (**Figure 5**; p<0.05). *Post-hoc* tests indicated that these differences were mainly attributable to a systematic effect on activation timing.

4. Discussion

This study investigated how upper-body muscle activation and coordination are modulated by swimming speed during front crawl, analyzing both sEMG envelopes and muscle synergies. Submaximal (80% v_{max}) and maximal (100% v_{max}) speeds were compared. Although previous research reported speed-related changes in muscle activity, no study has examined how swimming speed influences upper-body muscles and their synergistic organization in front crawl.

Breathing has been shown to alter inter-arm coordination and introduce asymmetries related to breathing laterality and head turning (Seifert et al., 2008). Evidence from butterfly swimming also indicated that breathing can affect muscle activation and synergies organization (Yamakawa et al., 2025), suggesting that respiratory patterns may influence neuromuscular control. To minimize these confounding effects, swimmers performed front crawl under Breath-Holding Condition (BHC), allowing direct assessment of speed-related effects. Moreover, it should be noted that, although the experimental design targeted differences in swimming speed, the comparison inherently involved changes in effort level and overall neuromuscular demand; therefore, the observed changes should be interpreted as responses to the combined demands of the experimental conditions rather than being attributable exclusively to swimming speed.

4.1 sEMG envelopes

Results showed speed-dependent modulation of upper-body muscle activity, with the largest differences observed in the propulsive muscles (BB, TB, PM, and LD) (Kwok et al., 2022; Pink et al., 1991). The anticipatory activation observed at maximal speed is likely associated with adaptations in the temporal organization of muscle activation, which may facilitate more rapid force production during faster swimming conditions. Comparable trends have been reported in previous studies, although methodological differences limit direct quantitative comparison. Lim (2023) reported increased sEMG activity of anterior and posterior deltoids with increasing front-crawl pace (Lim et al., 2023), while Yamakawa (2022) described an increased and earlier muscle activation in the lower-limb during underwater undulatory swimming, as speed increased. Similar findings were also reported by Olstad (2017) in breaststroke swimming, comparing upper-body muscle activation at submaximal and maximal intensities (60%, 80%, and 100% of maximal effort) in elite swimmers (Olstad et al., 2017). Despite methodological and technical differences, the overall pattern observed in previous studies is consistent with the present results and suggests that higher speeds are associated with greater activation magnitude and anticipatory recruitment of propulsive muscles.

Although no formal symmetry analysis was performed, sEMG envelopes qualitatively showed an alternating bilateral recruitment strategy for the main propulsive muscles, with peak activations of homologous muscles occurring approximately half a stroke cycle apart. A dedicated quantitative analysis of symmetry will be addressed in future work.

4.2 Muscle synergies

A front crawl stroke cycle is typically characterized by four main phases: hand entry, pull, push, and recovery (McCabe et al., 2011). The four synergies identified at submaximal speed were qualitatively consistent with these functional phases, alternating between the two upper limbs (left-arm pull, left-arm push, right-arm pull, and right-arm push, each corresponding to the entry and recovery phases of the contralateral arm). This interpretation remains indirect, as inferred from upper-limb EMG patterns without direct kinematic or hand trajectory measurements. However, muscle weight composition of these modules was coherent with the expected muscular demands of ~~each functional phase~~ the corresponding phases, with BB and PM muscles predominantly contributing during pull phases and TB and LD during push phases (Figueiredo et al., 2012; Rouard & Billat, 1990). At maximal speed,

the same four main phases were preserved, while two additional modules emerged. High coefficients of correlation between shared synergies (r>0.91) indicated strong preservation of the underlying structures and coordination patterns, despite changes in timing and activation magnitude. The additional speed-specific synergies were mainly active around the end of the push and during recovery, with dominant contributions from EO of the lengthening arm and AD of the recovering arm. Given their moderate similarity with submaximal synergies, these components may reflect a splitting of the existing modules observed at lower speed, rather than the emergence of entirely distinct functional modules. A similar speed-related ~~speed-dependent~~ increase in the number of recruited muscle synergies has been reported in other locomotor contexts (Yokoyama et al., 2016). These findings, however, originate from terrestrial gait tasks, which differ substantially in terms of mechanical constraints and propulsion mechanisms. Therefore, while not directly transferable, the present results are consistent with the broader notion that increased speed may influence modular motor organization.

Synergy activation coefficients further confirmed the pattern observed for sEMG envelopes, namely, consistent earlier activation at maximal speed. However, whereas most individual muscles showed significant increases in activation amplitude, this effect was less evident at the synergy level, likely due to the redistribution of muscle contributions across a larger set of synergies. Moreover, bilateral alternation can also be observed at the synergy level. Although bilaterality may appear inherent to the cyclic nature of front crawl, side-related differences in activation and coordination may exist between the dominant and non-dominant sides (Kwok et al., 2022).

Comparison with previous work on front crawl muscle synergies by Matsuura and colleagues (2024) partially supports the present findings. That study identified two monolateral upper-body synergies active during pull and push phases and characterized by major contributions from BB, TB, PM, LD, and EO muscles, consistently with the composition of the propulsion-related synergies identified in the present study. However, differences in recorded muscles and methodological choices, such as the use of a VAF threshold to determine the number of synergies, limit direct comparison. Moreover, although the mean swimming speed reported by Matsuura (1.75±0.09 $m \cdot s^{-1}$) closely matches the maximal speed condition of the present protocol, swimming speed was not explicitly manipulated, preventing analysis of speed-related reorganization. Results are in agreement with evidence from butterfly swimming, where higher swimming speed is mainly associated with earlier synergy activation (Yamakawa et al., 2026).

The following limitations should be acknowledged. The sample size was limited ~~but~~ and restricted to a specific group of highly trained male swimmers, which may limit the generalizability of the results to other populations, including female swimmers and or populations with a different competitive level. However, the sample size was comparable to previous studies investigating muscle synergies in swimming (Matsuura et al., 2020; Olstad et al., 2017; Vaz et al., 2016). Additionally, only six bilateral upper-body muscles were recorded. Although these muscles were chosen based on their primary and well-established role in propulsion during the front crawl (Kwok et al., 2022), this selection provides a partial representation of the overall neuromuscular coordination. Recording a large number of muscles in aquatic environments remains technically challenging and the present protocol is in line with similar in-water studies (Matsuura et al., 2020, 2022a, 2022b, 2024; Vaz et al., 2016; Yamakawa et al., 2025). Finally, trials were performed under BHC to reduce respiratory-related confounding. Therefore, the present findings should be interpreted within this specific condition and may not fully extend to front crawl swimming involving breathing.

4.3 Practical implications

Speed-specific synergies observed at maximal speed were characterized by a strong contribution of EO and AD. Greater EO involvement may reflect increased trunk demand under high-speed

(Andersen et al., 2023) and BHC, although a specific role in trunk stabilization cannot be inferred from the present data given the limited muscle set and experimental constraints. On the contrary, swimming speed is primarily modulated by Stroke Rate (SR) (Takagi et al., 2023), which can be increased by reducing the recovery phase (Pink et al., 2011) while maintaining the propulsion (Carmigniani et al., 2020). Therefore, AD-focused training may be relevant in the context of stroke rate modulation, potentially by supporting upper-limb coordination strategies associated with a shorter recovery phase.

5. Conclusion

This study investigated speed-related effects on upper-body muscle activation and coordination during front crawl performed under breath-holding conditions. By combining sEMG envelope analysis with muscle synergy analysis, we demonstrated that increasing swimming speed from 80% to 100% of maximal speed was associated with systematic and structured adaptations. Consistent with our hypotheses, recorded muscles exhibited consistent earlier recruitment and widespread greater activation amplitude within the stroke cycle. Furthermore, speed-dependent modulations in muscle synergy organization were observed. Four and six synergies were respectively identified at submaximal and maximal speed. Four modules were preserved across conditions, while two speed-specific synergies were required to reconstruct muscle activity at maximal speed, primarily involving EO and AD activity during late push and recovery phases. Importantly, synergy timing was also systematically shifted toward earlier activation at maximal speed across conditions. Overall, these results suggest that increasing swimming speed is associated with both an earlier activation of shared muscle synergies and a reorganization of synergy modules, emphasizing the adaptive nature of muscle synergy organization in response to task demands such as speed.

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Captions

Figure 1. Experimental setup and sEMG and IMU placement. Bilateral placement of sEMG electrodes (red) on the upper-body muscles and IMUs (black) positioned on wrists, with the x-axis oriented toward the shoulder.

Figure 2. sEMG envelopes. Average sEMG envelopes of twelve bilateral upper-body muscles during front crawl during BHC80% (blue) and BHC100% (red) conditions. The solid line represents the mean across participants, while the shaded area indicates the standard deviation error band.

Figure 3. Statistical non-Parametric Mapping: sEMG envelopes. Statistical non-Parametric Mapping (SnPM) results for the muscle envelopes. Panels (a-c) correspond to the right side muscles, and panels (d-f) to the left side. (a/d) Hotelling's T^2 multivariate test simultaneously applied to nonlinearly registered muscle envelopes (amplitude component) and their associated displacement fields (temporal component). Post hoc analysis isolating (b/e) amplitude-related and (c/f) temporal differences between speed conditions. Dashed red lines indicate the significance threshold set at $\alpha = 0.05$.

Figure 4. Muscle synergies. Comparison of average muscle synergies between submaximal and maximal front crawl swimming speeds. Activation coefficients (C) are shown as average curves with standard deviation error bands across participants. The black vertical line represents the instant of left-hand water entry. Weight vectors (W) are presented as average values with standard deviations. Shared synergies across speed conditions are aligned on the same rows.

Figure 5. Statistical non-Parametric Mapping: activation coefficients. Statistical non-Parametric Mapping (SnPM) results for the activation coefficients of shared synergies between speed conditions. (a) Hotelling's T^2 multivariate test simultaneously applied to nonlinearly registered activation curves (amplitude component) and their associated displacement fields (temporal component). *Post-hoc* analysis isolating (b) amplitude-related and (c) temporal differences between speed conditions.

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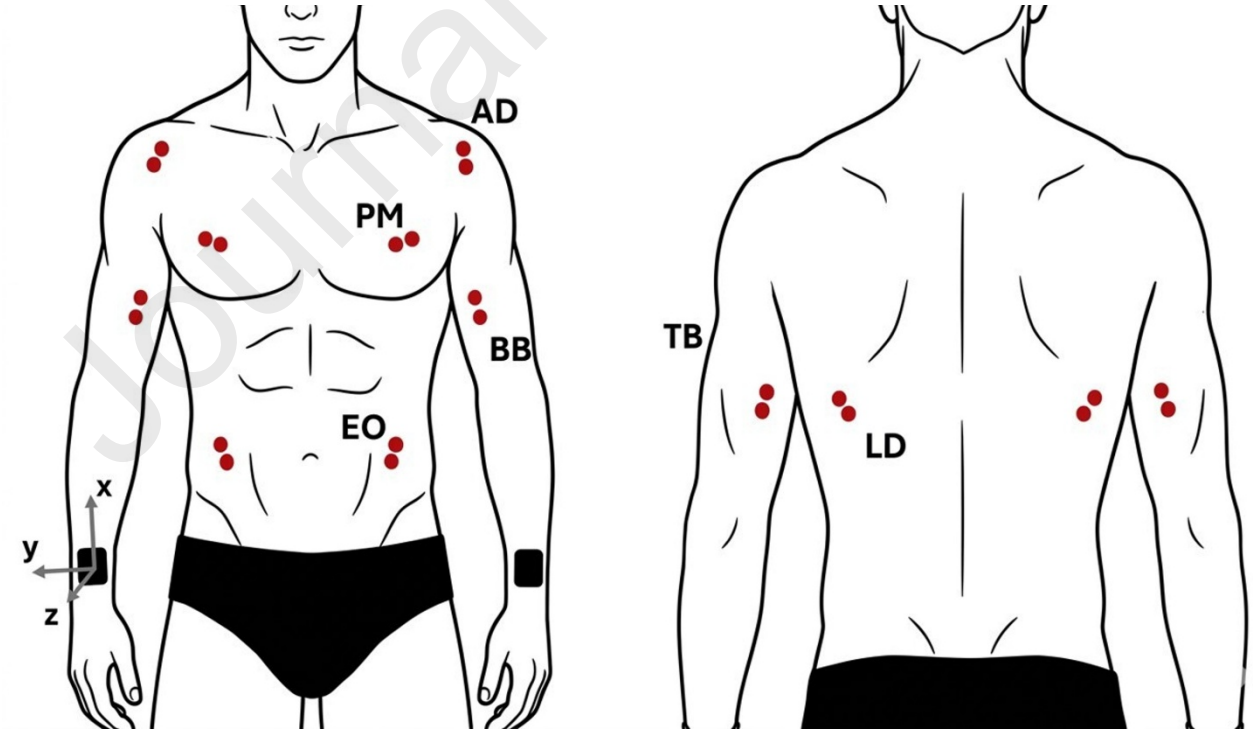
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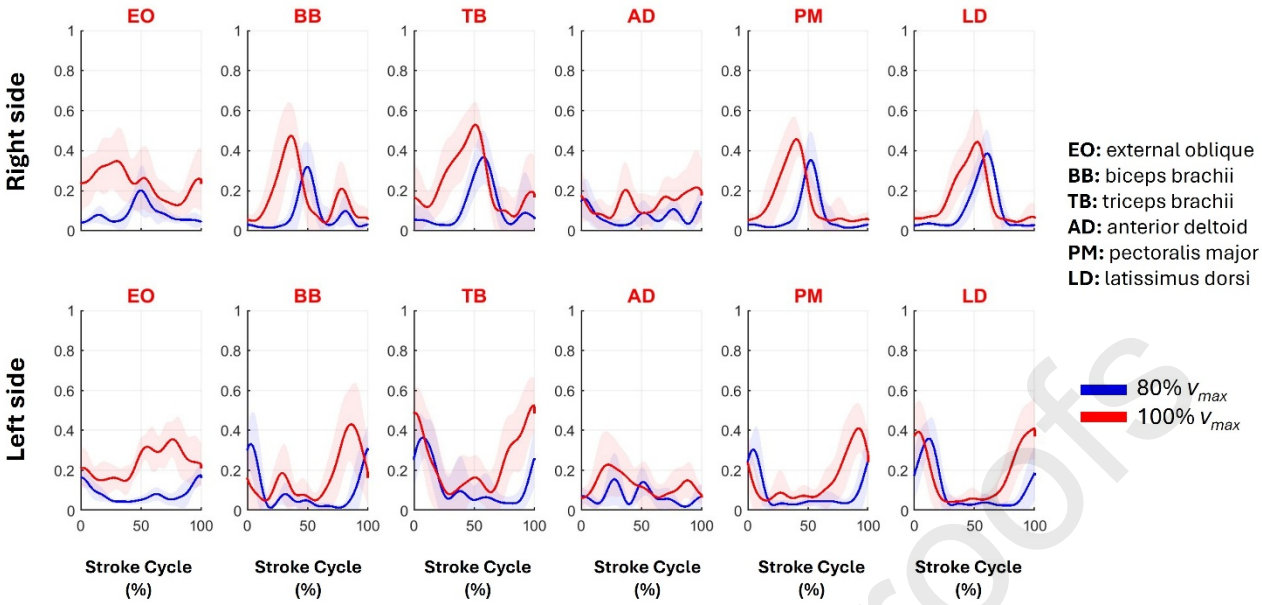
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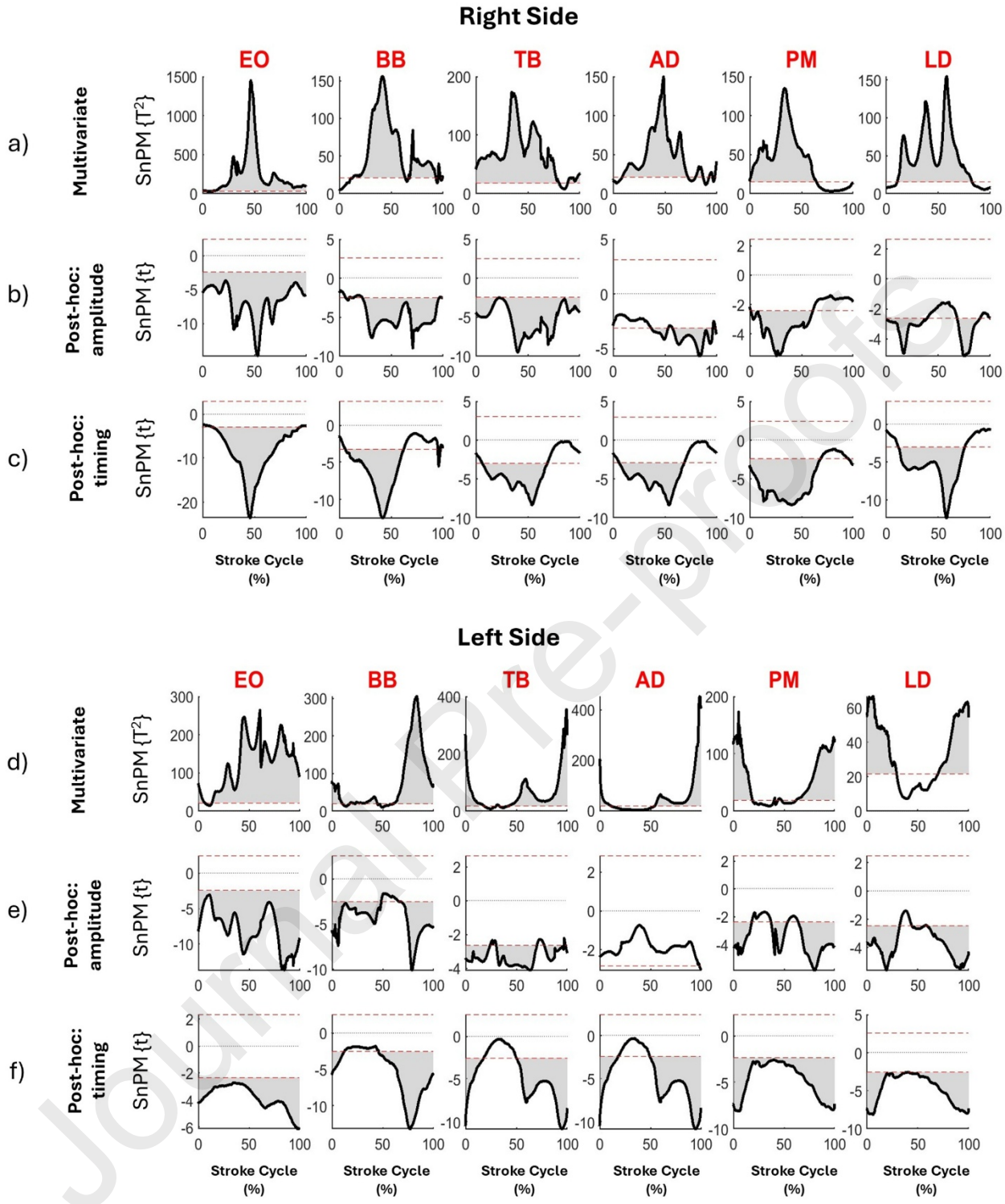
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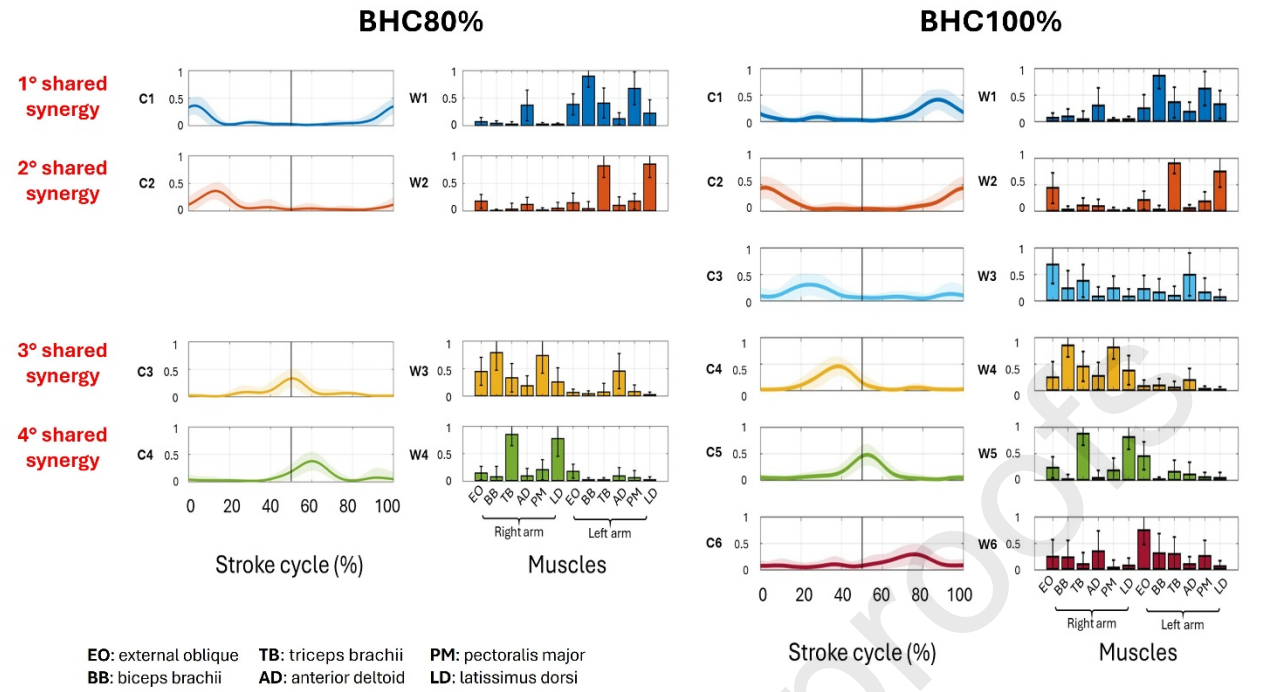
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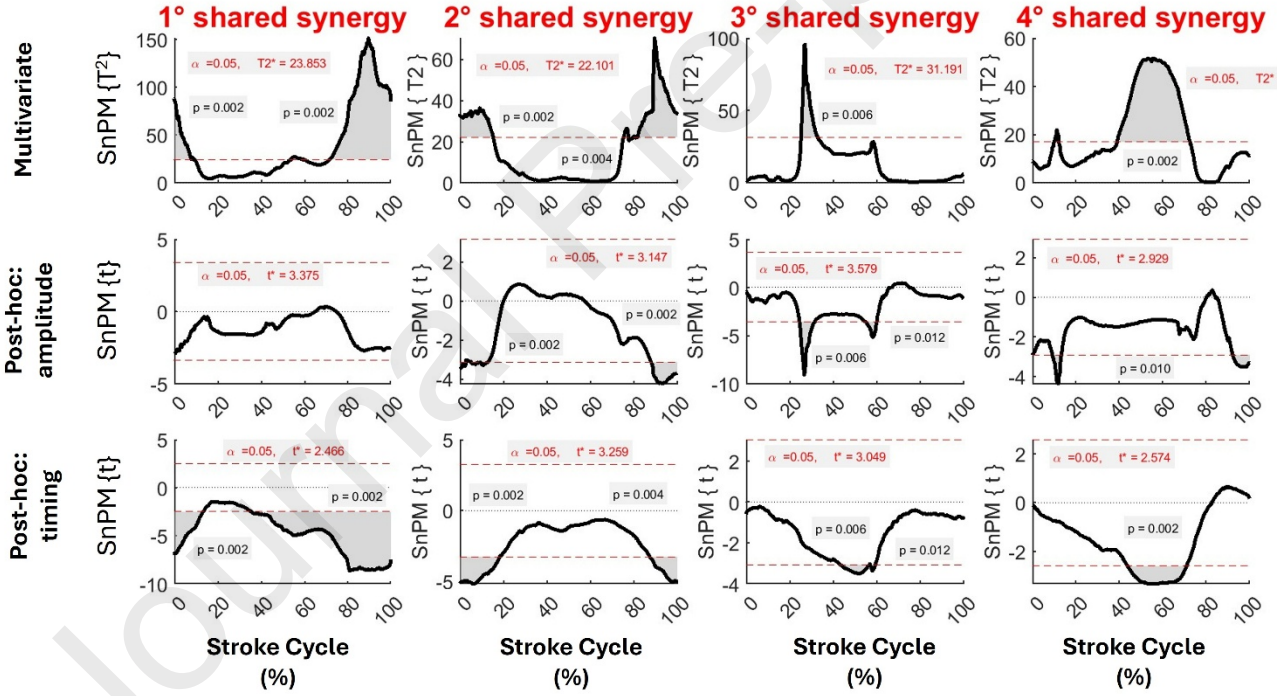


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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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