Speed-Dependent Upper-Limb Control Asymmetries in Backstroke Swimming during Psycho-Neuro-Motor Training

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Abstract

Introduction. *Upper-limb asymmetries in backstroke swimming can affect stroke efficiency and performance, yet their dynamics with respect to execution speed are not fully understood. This study extends previous research on lower-limb asymmetries to investigate speed-dependent upper-limb asymmetries and the potential of simulator-based training to improve interlimb coordination.*

Materials and Methods. *An elite 100 m backstroke swimmer performed two sessions on the "C.S.N. Simulator for Water Sports" (C.S.N. Simulator), executing 30 repetitions per arm at progressive motor-assisted velocities (0, 0.5, 1.2 m/s) with constant brake intensity (15%). Force–position data were recorded in real time across catch, traction, and push phases.*

Results. *At lower speeds, the left arm dominated during catch and traction, while higher speeds increased variability and shifted dominance toward the right arm in the push phase. Inter-session improvements demonstrated reduced asymmetry and more balanced force application, though variability remained at higher velocities.*

Conclusions. *Upper-limb asymmetries are speed- and phase-dependent. Simulator-based training with real-time feedback can enhance coordination, reduce asymmetry, and potentially improve performance, complementing prior findings on lower-limb asymmetries.*

Keywords: *interlimb asymmetry, psycho-neuro-motor control, execution speed, backstroke swimming*

JEL Classification: I10, I20, I23

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1. Introduction

Guiard proposed a taxonomy of sports based on motor-action characteristics, distinguishing among unilateral sports, bilateral antisymmetric sports, and bilateral symmetric sports. This taxonomy serves as a critical framework for understanding

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how asymmetries in motor control and morphological traits manifest under different sporting demands. (Guiard, 1987).

Humans, by virtue of their bilateral anatomy, exhibit functional and morphological asymmetries. As documented by Stagi, such asymmetries, influenced by genetic and environmental factors, manifest in size, strength, and functional capacities between left and right limbs. Dominant limbs, often the right upper extremity, typically display greater muscle mass and strength in both sexes, whereas differences in body fat or composition are less marked. In sports with strong unilateral demands (e.g., tennis, fencing, football), these side-to-side differences are magnified. Conversely, more symmetrical activities, such as walking, promote closer bilateral equivalence. (Stagi, 2023).

Krzykała underscored how sport-specific training loads drive somatic adaptation: unilateral sports tend to result in measurable lateral imbalances in strength, morphology, and functional output (Krzykała, 2023). Croitoru added that even in sports traditionally considered "symmetric" (running, skiing, swimming), the nature of movement often remains antisymmetric because limbs perform alternating actions (Croitoru, 1999). Within swimming, freestyle and backstroke are paradigmatic bilateral antisymmetric strokes; by contrast, breaststroke and butterfly demand synchronous, symmetric limb actions.

A considerable body of research has focused on asymmetries in upper limb function in swimming. Khudik demonstrated that substantial asymmetries in stroke execution may degrade stroke efficiency, emphasizing the importance of non-dominant limb training (Khudik, 2018). Jaszczak highlighted that hand trajectory, entry angle, and underwater path are critical for propulsion (Jaszczak, 2008), and that asymmetry increases under aquatic conditions compared to dryland simulations (Jaszczak, 2011). Morouço found that among elite freestyle swimmers, two-thirds exhibited force asymmetries correlated with breathing laterality, and that the dominant arm tends to lose force more quickly in maximal efforts (Morouço, 2015). In freestyle swimming, swimmers aim to maintain a constant force level in the water, resulting in minimal variation in speed during the stroke cycle (Borbosa, 2010).

Recent studies have reinforced and extended these findings. For example, Morouço showed that most high-level swimmers present asymmetrical force profiles during maximal front crawl efforts, often linked to unilateral breathing patterns (Morouço, 2015). Similarly, Evershed found that while ~85 % of athletes exhibited clinical strength asymmetries, about half could compensate in force output, suggesting that kinematic or neuromuscular adaptation may mediate asymmetry (Evershed, 2014).

More specifically, research into coordination and motor flexibility has revealed that increasing speed or manipulating environmental constraints (e.g. swimming in a flume vs a pool) leads to greater upper limb asymmetry and altered interlimb coupling dynamics. Guignard found that as swimmers' speed increases, their index of coordination and stroke rate change non-linearly, and higher asymmetries emerge, particularly under perturbed environmental conditions

(Guignard, 2020). Also, Bartolomeu compared propulsive force symmetry across strokes and found backstroke to be among the most asymmetric, especially under limb-segmental manipulations (Bartolomeu, 2022)

A recent systematic review mapped 60 studies: asymmetry values in in-water testing ranged widely (2.7-60 %), with many studies reporting significant between-limb differences; however, only a few found clear associations between those asymmetries and overall performance outcomes (Knihs, 2023).

This literature, however, has focused predominantly on lower limb or whole-body coordination, or has considered upper limbs in freestyle/front crawl strokes. What remains less well explored is how control asymmetries in upper limbs behave in backstroke swimmers under psycho-neuro-motor training paradigms, particularly how speed, environmental constraints, and neuro-motor control demands (e.g., rhythm, coordination, feedback) interact to modulate asymmetry.

Our prior work on ankle joint extension demonstrated that control asymmetry is sensitive to movement speed: at higher speeds, the non-dominant leg sometimes becomes functionally dominant, while in slow, strength-based tasks, the dominant leg often prevails. Moreover, as speed increases, movement becomes more ballistic and less controlled, indicating that neuromotor control capacity can be exceeded (Iacobini, 2025). These results underscore the value of investigating how such asymmetries evolve under increasing task demands. Analogously, the present study seeks to extend these observations to the upper limbs in swimmers, specifically in the context of backstroke, under psycho-neuro-motor training conditions.

Therefore, this study aims to investigate the dynamics of control asymmetries in the upper limbs of backstroke swimmers during psycho-neuro-motor training, with particular attention to how speed, coordination demands, and neural control influence asymmetry. We hypothesize that asymmetries will increase with speed and neuromotor challenge, and that psycho-neuro-motor training can modulate these asymmetries, potentially informing strategies to optimize performance and reduce injury risk.

2. Methods and Materials

This sstudy on upper-limb control asymmetry was conducted with an elite swimmer, qualified for the World Championships in the 100-meter backstroke event. Data collection and training interventions were carried out using the "C.S.N. Simulator for Water Sports[2]" (hereafter referred to as the C.S.N. Simulator), which

[2] The C.S.N. Simulator constitutes an advanced system, as detailed by Angelescu, combining both hardware—comprising an inertial disk, force sensors, an electromagnetic braking mechanism, and a computing unit—and software components. Its design is grounded in the five core principles guiding the development, implementation, and application of training and assessment equipment, thereby enabling effective interaction between the athlete and the device. The simulator provides a graphical representation of the movement on a computer interface, allowing the athlete to continuously monitor and adjust the applied force in real time across different resistance settings. This functionality is

provides accurate measurement conditions and real-time feedback. The simulator is specifically designed for controlled, intentional movements that demand sustained attentional focus from the athlete. Such tasks aim to enhance coordination and refine motor control by targeting psycho-neuro-motor development.

The experimental protocol spanned one week, during which the athlete completed two simulator sessions prior to their regular in-water training. This structure was intended to facilitate the immediate transfer of motor control strategies and kinesthetic feedback acquired on the simulator to swimming practice in water.

Training consisted of replicating the backstroke arm movement in a supine position on the simulator bench. The athlete's hands were fitted with paddles connected to the simulator cables, enabling resistance and motor control to be precisely regulated. Each execution was recorded and displayed in real time on a monitor, allowing the athlete to analyze and reorganize their movements from repetition to repetition, adjusting technique based on direct visual feedback.

On each training day, the athlete performed backstroke-specific movements under three distinct exercise conditions, which systematically varied simulator parameters:

- *Exercise 1 (E1):* The simulator's brake intensity[3] was set to 15%, with the motor speed[4] at 0 m/s. This configuration produced a nonlinear braking effect analogous to resistance encountered in fluid environments, with braking force proportional to the square of movement velocity.
- *Exercise 2 (E2):* The simulator's brake intensity was set to 15%, and the motor speed was 0.5 m/s. This condition increased task speed while ensuring a baseline velocity supplied by the simulator.
- *Exercise 3 (E3):* The simulator's brake remained at 15%, with the motor speed set to 1.2 m/s, further elevating task velocity while preserving a minimum motor-assisted speed.

For each exercise, the athlete completed 30 repetitions per arm, executed alternately to replicate the technical dynamics of the backstroke stroke cycle.

The three exercise conditions were selected to progressively increase neuromotor demands while preserving ecological validity by simulating water-like resistance. The nonlinear braking at 0 m/s replicated natural drag forces, while the

specifically adapted to meet the objectives of individualized training programs (Angelescu, 2014, p. 118).

[3] The C.S.N. simulator incorporates an electromagnetic braking mechanism designed to produce speed-dependent nonlinear resistance. This is achieved through a configuration that links the mean intensity of the magnetic field to the velocity of movement. At full (100%) intensity, the magnetic field remains continuous, whereas lower settings generate a pulsating magnetic field, with its strength represented as a percentage of the maximum attainable intensity. Accordingly, the braking levels are expressed in relative percentages, corresponding to the maximum achievable electromagnetic braking force.

[4] The Simulator's motor provides the athlete with a minimum baseline speed that requires no effort to maintain. Any force exerted by the athlete is applied only at velocities exceeding this motor-assisted minimum, placing the athlete in a condition where the movement must be initiated and controlled under increased speed demands.

addition of baseline motor-driven speeds (0.5 m/s and 1.2 m/s) allowed us to assess control under higher task velocities, conditions in which asymmetries are hypothesized to become more pronounced. The structure of alternating repetitions mirrors the biomechanical pattern of backstroke, ensuring that training closely matches sport-specific movement dynamics. This design thus provides a controlled yet realistic framework to investigate how speed and resistance modulate upper-limb control asymmetries in elite backstroke swimmers.

3. Results

The following section presents observations regarding the dynamics of upper-limb control asymmetries in relation to execution speed during the training sessions conducted on the *C.S.N. Simulator*. For each analyzed movement, graphical representations illustrate both symmetrical and asymmetrical patterns. In these figures, the Y-axis represents position (in meters [m]) and the X-axis represents force (in decanewtons [daN]).

3.1 First training day (T1)

In the initial session, the force model displayed on the monitor corresponded to the backstroke movement, adapted to the athlete's current capacity. The model required a baseline threshold of 1.5 daN (1.52 kg-force), progressively increasing to 5.5 daN (5.60 kg-force) at the terminal "explosion" phase.

E1 (0 m/s, 15% braking). As shown in Figure 1, the left arm (green) displayed dominance during the catch (1.1) and traction (1.2) phases. By contrast, the push phase (1.3) was executed symmetrically, with both arms generating comparable peak forces.

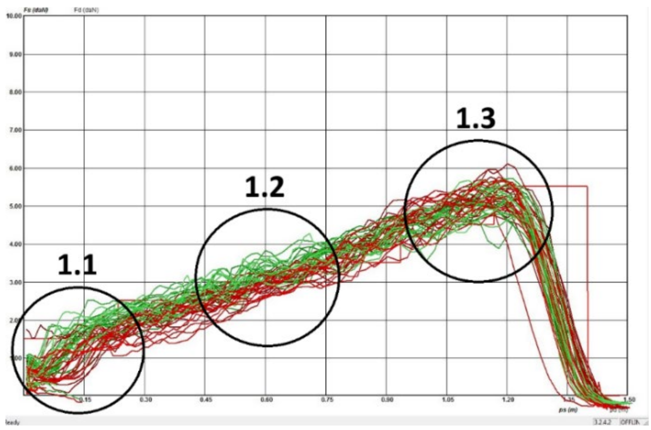

Figure 1. Force based on position T1-E1

E2 (0.5 m/s, 15% braking). At the slightly elevated baseline speed (Figure 2), asymmetry persisted in the initial phases (2.1–2.2), with the left arm maintaining dominance. However, in the push phase (2.3), the right arm produced a more pronounced explosive force. The transition between traction and push (2.2-2.3) was marked by a discontinuity, reflected in an abrupt increase in force output.

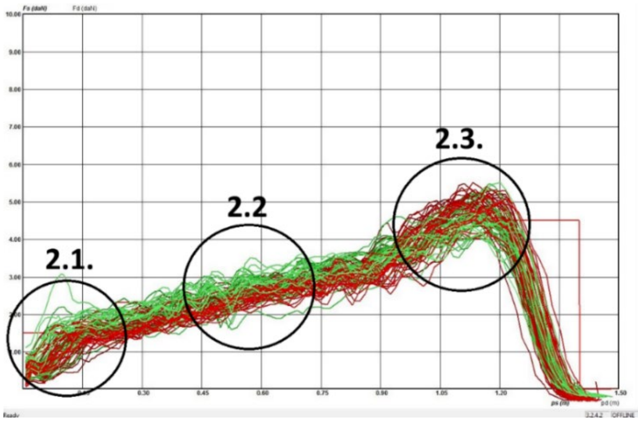

Figure 2. Force based on position T1-E2

E3 (1.2 m/s, 15% braking). At higher velocity (Figure 3), both arms exhibited reduced control during the catch phase (3.1), with delayed force application and substantial variability. Effective force generation was achieved only at the onset of traction (3.2), although this was inconsistent. Toward the end of traction, dominance shifted to the right arm (red), while in the push phase (3.3), the left arm regained slight superiority, indicating a reversal compared to lower-speed conditions.

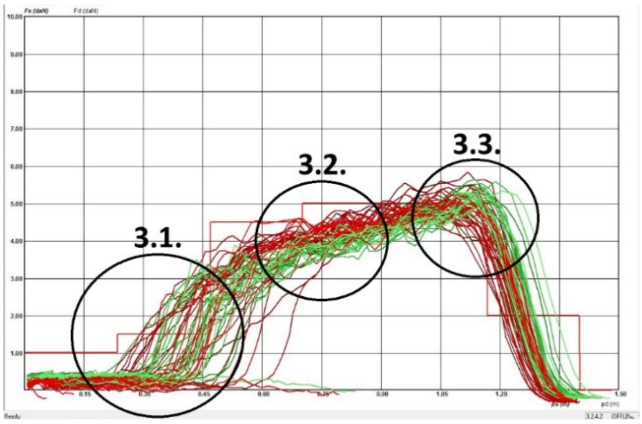

Figure 3. Force based on position T1-E3

3.2 Second training day (T2)

The same exercises were repeated under identical load conditions (1.5 daN to 5.5 daN force profile) to assess adaptation across sessions.

E1 (0 m/s, 15% braking). Figure 4 highlights an uncontrolled application of excessive force with the left arm during the catch (1.1), suggesting an error analogous to water "splashing." Improvement was observed in the traction phase (1.2), where asymmetry diminished compared to the previous day. In the push phase (1.3), dominance shifted to the right arm, which generated an explosive peak of 6 daN, surpassing the modeled threshold.

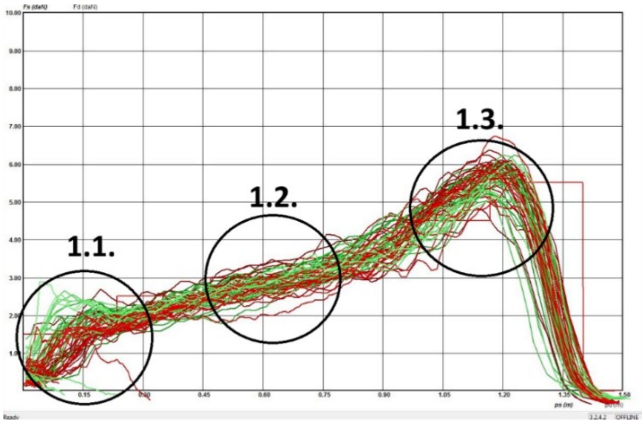

Figure 4. Force based on position T2-E1

E2 (0.5 m/s, 15% braking). At this speed (Figure 5), the athlete demonstrated reduced asymmetry in the initial catch phase (2.1) relative to both the earlier exercise and the previous day's session. Although right-arm dominance persisted during the final phase (2.3), overall interlimb control showed improvement.

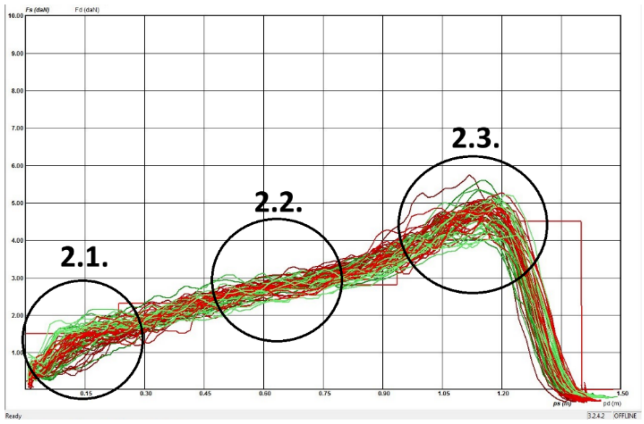

Figure 5. Force based on position T2-E2

E3 (1.2 m/s, 15% braking). At elevated velocity (Figure 6), variability in catch (3.1) and traction (3.2) phases remained evident. Right-arm dominance persisted, but with an important distinction: the athlete exhibited active attempts to modulate force. The push phase (3.3) again showed clear right-arm superiority, contrasting with the left-arm dominance observed under the same condition on the first day.

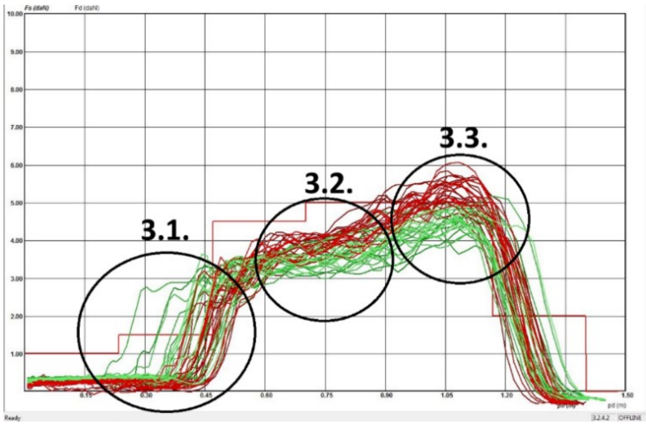

Figure 6. Force based on position T2-E3

Overall, the results indicate that upper-limb control asymmetries in the backstroke stroke cycle are highly sensitive to execution speed. At lower velocities, dominance of the left arm was consistently observed during the catch and traction phases, while both arms converged toward similar force output in the push phase. As velocity increased, however, control variability became more pronounced, with a shift in dominance toward the right arm and signs of reduced neuromotor control, particularly during the initial phases of movement. Importantly, between the two training sessions, progressive improvements in interlimb coordination were noted, reflected in a reduction of asymmetry and greater force balance, although variability persisted under high-speed conditions. These findings suggest that systematic exposure to progressive velocity demands, combined with real-time feedback, can promote adjustments in movement execution and a gradual reduction of functional asymmetries.

4 Discussions

The findings of this study indicate that upper-limb asymmetries in backstroke swimming are closely influenced by execution speed, with clear variations across stroke phases. At lower speeds, the left arm consistently showed greater control in the catch and traction phases, whereas higher speeds increased variability and shifted dominance to the right arm. These asymmetries, although evident, diminished across training sessions, suggesting that repeated exposure to simulator-based feedback promoted more symmetrical coordination.

From a motor control perspective, these results align with established principles such as Fitts's (1954) speed–accuracy trade-off, which highlights the difficulty of maintaining precision at higher velocities. Similarly, Bernstein's (1967) *"degrees of freedom"* concept refers to the challenge faced by the central nervous system in coordinating the numerous independent components of the musculoskeletal system during movement. As movement speed increases, control tends to deteriorate because the system must manage more dynamic interactions among these degrees of freedom. The reduction of asymmetries between sessions demonstrates the adaptive capacity of the neuromotor system, reinforcing the value of repetitive, feedback-driven practice in promoting more efficient and balanced execution.

Comparisons with prior studies further contextualize these findings. Morouço identified force imbalances in the majority of elite freestyle swimmers (Morouço, 2018), while Seifert emphasized the influence of lateralized breathing on stroke asymmetry (Seifert, 2004). By examining phase-specific variations and their dependence on velocity, the present work extends this literature, underlining the need to consider speed as a decisive factor in evaluating motor coordination.

The practical implications for training are significant. The *C.S.N. Simulator* proved effective in reproducing water-like resistance while delivering real-time visual feedback, enabling the athlete to identify and correct asymmetries across repetitions. Such controlled conditions may reveal hidden imbalances that are difficult to detect in water, allowing coaches to intervene more precisely. Reducing asymmetries not only enhances performance efficiency but also contributes to injury prevention, as persistent imbalances have been linked to overuse injuries in swimmers (Bishop, 2018).

Certain limitations should be acknowledged. The study involved a single elite swimmer, which limits generalization, and the intervention period was short, preventing assessment of long-term adaptations. Furthermore, although the simulator reproduces resistance patterns realistically, it cannot fully replicate the complex hydrodynamics of actual swimming conditions.

Future studies should therefore examine larger groups of swimmers across performance levels and adopt longitudinal designs to assess whether simulator-based improvements transfer to in-water performance. Integrating simulator analyses with biomechanical assessments in real swimming environments would strengthen the ecological validity of the findings and further clarify the link between psycho-neuro-motor control and competitive outcomes.

In summary, this study demonstrates that upper-limb asymmetries in backstroke swimming are dynamic and speed-dependent, with the potential for correction through targeted simulator-based training. The *C.S.N. Simulator* proved to be a valuable tool for both diagnosis and intervention, supporting enhanced coordination, performance efficiency, and potentially reduced injury risk in elite swimmers.

5 Conclusions

The present study demonstrates that upper-limb control asymmetries in backstroke swimming are dynamic and highly dependent on execution speed. At lower velocities, the left arm exhibited dominance during the catch and traction phases, while higher speeds introduced greater variability and a shift toward right-arm dominance, particularly during the push phase. Progressive improvements in interlimb coordination across training sessions indicate that repeated exposure to simulator-based practice, combined with real-time feedback, can facilitate more symmetrical movement patterns and refined neuromotor control.

These findings emphasize the importance of considering speed-dependent asymmetries when designing training programs for elite swimmers. Simulator-based interventions, such as those using the *C.S.N. Simulator*, provide a controlled environment to detect and correct hidden asymmetries, promoting efficiency, performance enhancement, and potentially reducing injury risk.

Finally, the study underscores the need for future research involving larger cohorts and longitudinal designs to confirm the transfer of simulator-based improvements to in-water performance. Integrating biomechanical assessments in natural swimming conditions will further clarify the relationship between psycho-neuro-motor adaptations and competitive outcomes, contributing to the optimization of elite backstroke training methodologies.

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