Journal of Biomechanics 159 (2023) 111792

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Analysis of upper limb propulsion in young swimmers in front-crawl through Statistical Parametric Mapping

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ARTICLE INFO

Keywords:
Swimming
Technique
Propulsion
Training
Performance

ABSTRACT

This study aimed to: (i) verify the within-subject effect of the dominant and non-dominant upper limb propulsion during consecutive arm-pulls through discrete (average) and continuous analysis (SPM), and; (ii) compare young swimmers' propulsion between both upper limbs through discrete (average) and continuous analysis (Statistical Parametric Mapping – SPM). The sample consisted of 17 young male swimmers (age = 16.02 ± 0.61-years) who regularly participate in national and international level competitions. A set of kinematic and propulsion variables were measured during a 25-m maximal trial in front-crawl. Statistical analysis of propulsion was performed using discrete variables and through SPM. Swimming velocity showed a significant decrease over time. A significant interaction between the "time" (consecutive arm-pulls) and "side" (dominant vs. non-dominant) effects was observed in both statistical analyzes. Only the dominant upper limb demonstrated a significant "time" effect with a significant difference ($p < 0.05$) between the first and third arm-pulls. SPM indicated that the "time" effect was observed between the ~ 34% and ~ 42% of the arm-pull. The differences between the first and third arm-pull were verified between the ~ 32% and ~ 43% of the arm-pull. A non-significant "side" effect was verified in both analyzes. Therefore, SPM analysis provided more sensitive and accurate outputs than discrete analysis. This will allow coaches to design specific training drills focused on specific moments of the arm-pull.

1. Introduction

Swimming velocity is characterized by a periodically accelerated motion relying on the net balance between propulsive and drag forces (Barbosa et al., 2010). Thus, swimmers who can generate greater levels of propulsion and reduce drag are more likely to perform better. The literature presents solid evidence about experimental research on the drag of swimmers performing front-crawl (Barbosa et al., 2014; Kjendlie and Stallman, 2008). On the other hand, less is known about the propulsion of swimmers measured directly by experimental methods (Santos et al., 2021).

In the front-crawl sprint, it has been experimentally found that greater propulsion leads to faster swimming velocities (Koga et al., 2020; Morais et al., 2020a). During front-crawl all-out trials or sprint events, swimmers tend to slow down over time (Morais et al., 2022). However, there is little evidence about changes in propulsion over time during maximal trials (Morais et al., 2020a). Nonetheless, it was reported that better front-crawl performances were related to fewer imbalances between the two upper limbs (Borges dos Santos et al., 2013). However, the literature still lacks evidence on this topic, especially with propulsion being directly measured.

Swimming research is mainly based on discrete variables considering average values during the stroke cycle (Morais et al., 2018; Oliveira et al., 2021). However, front crawl presents key moments during the arm-pull (i.e., underwater phase) (Morais et al., 2020b). Thus, there may be differences in these specific moments of the arm-pull that are not reflected in the analysis of average values. On the other hand, continuous analysis has proven to have a significant advantage of maintaining time-series data integrity and sensitivity, allowing the understanding of what happens during the total time-series (Preatoni et al., 2013). 1D

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https://doi.org/10.1016/j.jbiomech.2023.111792
Accepted 4 September 2023

Statistical Parametric Mapping (SPM) procedures can be employed to maintain time-series data integrity and sensitivity, allowing the understanding of what happens during the total time-series (Pataky, 2010). This approach is increasingly being used in sport science, contributing to a more detailed analysis of movement in specific performance settings (Bertozzi et al., 2022; Warmenhoven et al., 2018). On the other hand, few studies have explored continuous analysis in swimming (Gourgoulis and Nikodelis, 2022; Ruiz-Navarro et al., 2021).

Therefore, this study aimed to: (i) verify the within-subject effect of the dominant and non-dominant upper limb propulsion through discrete (average) and continuous analysis (SPM), and; (ii) compare young swimmers' propulsion between the two upper limbs through discrete (average) and continuous analysis (SPM).

2. Methods

2.1. Participants

Participants were 17 young male swimmers (age = 16.02 ± 0.61 years, body mass = 68.18 ± 5.67 kg, height = 175.47 ± 4.76 cm, arm span = 180.50 ± 7.74 cm, FINA points = 560.76 ± 51.56 at the 100-m freestyle event in short-course meter) who regularly participate in national and international level competitions. The sample included age-group national record holders (Tier 3; McKay et al., 2021). At the time of data collection, these swimmers were part of a national swimming team and only freestyle sprinters were recruited. They attended six to nine training sessions per week. Parents or guardians, as well as swimmers, provided informed consent. All procedures were in accordance with the Declaration of Helsinki regarding human research, and the Polytechnic Ethics Board approved the research design (N. 72/2022).

2.2. Research design

After a standardized 1,000-m warm-up for sprint events, swimmers were instructed to perform three all-out 25-m trials in front-crawl (with a push-off start) with 20 min of recovery between them. They were advised to perform non-breathing stroke cycles during the 11th and the 24th-meter marks to avoid disruptions/changes in stroke coordination or technique. The fastest trial was used for further analysis. Three consecutive stroke cycles between the 11th and the 24th-meter marks were analyzed. For data related to swimming kinematics, please refer to the supplementary file.

2.3. Propulsion

Propulsion was acquired simultaneously with kinematic data with a pressure sensor system ($f = 100$ Hz) (Swimming Technology Research, USA). This system is based on sensors that estimate the in-water pressure. The sensors were placed between the third and fourth metacarpals to measure the pressure differential between the palmar and dorsal surfaces. This location is considered a good approximation for the point of application of the propulsive force vector on the hand (Gourgoulis et al., 2013). The pressure sensor data were transferred to the Aquanex software (Aquanex v. 4.2 C1211, Richmond, USA) by an A/D converter. Afterward, time-force series were imported into a signal processing software (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, USA). Signals were again handled using a Butterworth 4th order low-pass filter (cut-off: 5 Hz). Each arm-pull was defined as the time spent between the entry and exit of the hand. For the dominant ($F_{mean\_dominant}$, in N) and non-dominant ($F_{mean\_non\text{-}dominant}$, in N) arm-pull, the mean propulsion was calculated.

2.4. Statistical analysis

Based on discrete variables, a two-way repeated measures ANOVA was used ($\alpha = 0.05$). Thus, two within-factors were considered: (i) "time": intra-cyclic changes in propulsion over time, and; (ii) "side": comparison between the dominant and non-dominant upper limbs. When suitable, Bonferroni post-hoc test was used to verify significant differences between pairwise. For the ANOVA effect size index, the eta square (η^2) was computed and interpreted as: (i) without effect if $0 < \eta^2 < 0.04$; (ii) minimum if $0.04 < \eta^2 < 0.25$; (iii) moderate if $0.25 < \eta^2 < 0.64$ and; (iv) strong if $\eta^2 > 0.64$ (Ferguson, 2009). Cohen's d was used to estimate the standardized effect sizes between pairwise and was deemed as: (i) trivial if $0 \leq d < 0.20$; (ii) small if $0.20 \leq d < 0.60$; (iii) moderate if $0.60 \leq d < 1.20$; (iv) large if $1.20 \leq d < 2.00$; (v) very large if $2.00 \leq d < 4.00$; (vi) nearly distinct if $d \geq 4.00$ (Hopkins, 2019).

Based on continuous variables, a two-way repeated measures SPM ANOVA (with Bonferroni post-hoc correction) was used (Pataky, 2010). Two within-factors were again considered: (i) "time": intra-cyclic changes in propulsion over time, and; (ii) "side": comparison between the dominant and non-dominant upper limbs. Prior to this analysis, each arm-pull was normalized to its duration on a R routine (Team, 2017). SPM analyses were implemented using the open-source spm1d code on Python (v.M0.1, https://www.spm1d.org).

3. Results

Regarding propulsion, there was a statistically significant interaction between the two factors ("time" and "side") ($p = 0.025$) (Table 1). When analyzing the interaction, the results revealed a non-significant simple main effect of the "time" factor for the non-dominant upper limb ($p = 0.805$). On the contrary, a statistically significant simple main effect was observed for the dominant upper limb ($p = 0.005$). Post-hoc analysis with Bonferroni correction produced a statistically significant difference only between the 1st and 3rd arm-pulls ($p = 0.004$). Regarding the simple main effect of the "side" factor, a non-significance effect was observed at all levels (i.e., 1st, 2nd, and 3rd arm-pull) of the "time" factor ($p > 0.05$).

Fig. 1 shows the two-way repeated measures SPM ANOVA. There was a significant interaction ($F = 7.37$; $p = 0.012$) between the two factors (i.e., "time" and "side") between the ~ 34% and ~ 42% of the arm-pull (Panel A). When analyzing the interaction, the results revealed a non-significant simple main effect of the "time" factor for the non-dominant upper limb (Panel B). On the contrary, a statistically significant simple main effect ($F = 7.35$; $p = 0.0006$) was observed for the dominant upper limb between ~ 32% and ~ 43% of the arm-pull (Panel C).

Fig. 2 shows the post-hoc analysis with Bonferroni correction for the dominant upper limb. This produced a statistically significant difference only between the 1st and 3rd arm-pull ($t = 3.92$; $p = 0.0003$) between the ~ 32% and ~ 43% of the arm-pull (Panel C). Between the 1st and the 2nd (Panel A) and between the 2nd and the 3rd arm-pull (Panel B), no statistically significant differences were found. Regarding the simple main effect of the "side" factor (Figs. 1-S1), non-significant effects were observed at all levels of the "time" factor.

4. Discussion

This study aimed to compare the propulsion of the upper limbs analyzed through discrete (average) and continuous analysis (SPM). Both discrete and continuous analysis produced a statistically significant interaction between the two factors (i.e., "time" and "side"). In both analyses, a statistically significant simple main effect ("time") was observed only for the dominant upper limb. Post-hoc analysis correction produced a statistically significant difference only between the 1st and 3rd arm-pulls. Notwithstanding, SPM allowed for a more detailed analysis, pointing out where, within the arm-pull, an effect was observed (between the ~ 32% and ~ 43% of the arm-pull). Moreover, both discrete and SPM analyses showed a non-significant "side" effect at all levels of the "time" factor.

As with swimming velocity (in maximal or sub-maximal trials),

Table 1
Descriptive data (mean ± one standard deviation – 1SD) of the propulsion by arm-pull. The two-way repeated measures ANOVA based on discrete variables is also presented.

	Mean ± 1SD 1st arm-pull	 2nd arm-pull	 3rd arm-pull	Time factor F-ratio (p)	 dg	 η^2	 Pairwise comparison [descriptor]	Time X Side interaction F-ratio (p)	 dg	 η^2
$F_{mean\_dominant}$ [N]^{a*}	37.48 ± 5.36	35.44 ± 5.18	34.15 ± 5.84	7.73 (0.005)	2,15	0.06	d = 0.57 [small]	4.16 (0.025)	2,32	0.09
$F_{mean\_non\text{-}dominant}$ [N]	35.73 ± 4.90	35.27 ± 5.37	35.63 ± 4.99	0.22 (0.805)	2,15	0.00				

$F_{mean\_dominant}$ - mean propulsion of the dominant upper-limb; $F_{mean\_non\text{-}dominant}$ – mean propulsion of the non-dominant upper-limb; p – significance value; η^2 – eta squared (effect size index); dg – degree of freedom; d – Cohen's effect size, the descriptor within brackets indicates the qualitative magnitude of the effect. superscripts: a – significant time factor; * – significant differences ($p < 0.05$) between the 1st and the 3rd arm-pull.

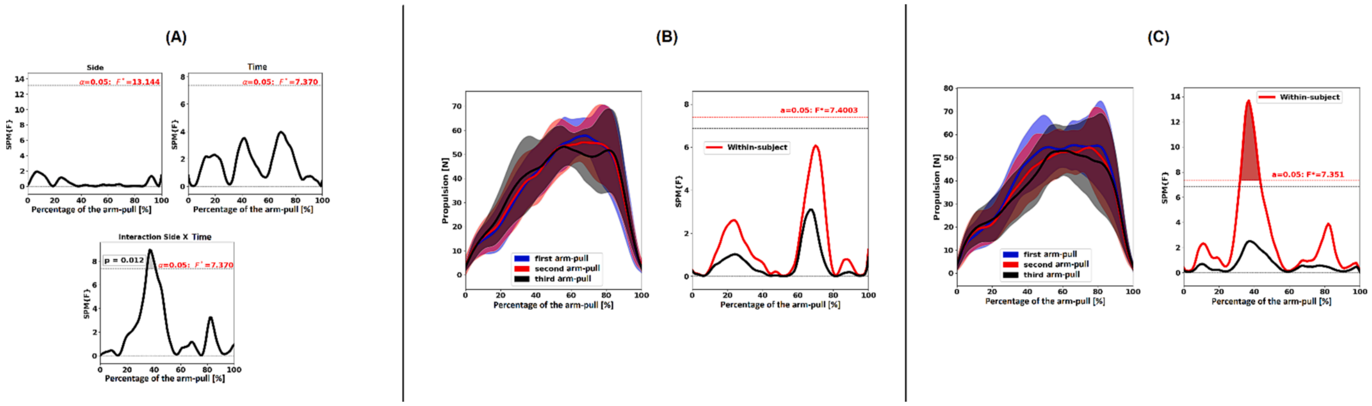

Fig. 1. Analysis of propulsion-time series by SPM through three consecutive arm-pulls. Panel (A) – "time" factor, "side" factor, and respective "time" X "side" interaction. Panel (B) – within-subject effect for the "time" factor of the non-dominant upper-limb. Panel (C) – within-subject effect for the "time" factor of the dominant upper-limb. SPM {F} – variance statistic for Statistical Parametric Mapping. Grey area (Panel A) and red area (Panel C) and indicate significant differences. Dash lines represent the 95% confidence intervals (95CI). In panels (B) and (C), the black solid line in the right charts refers to the ANOVA's between-subject factor (non-significant in both).

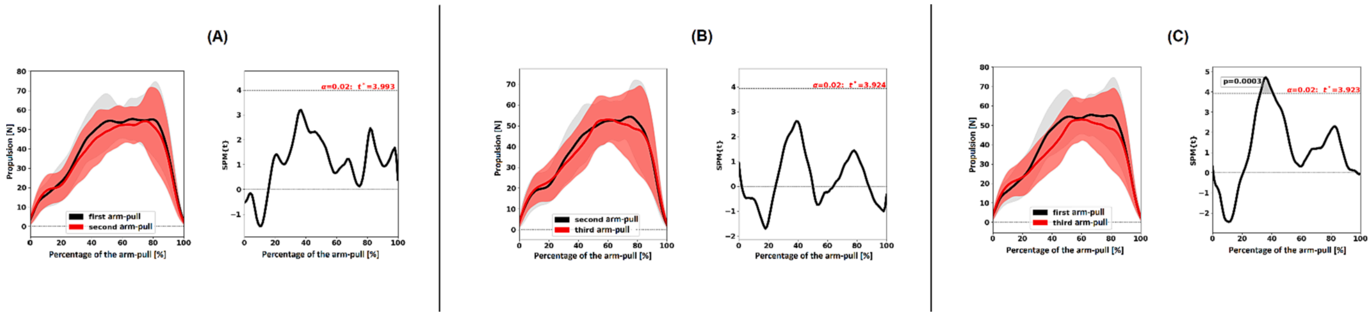

Fig. 2. Post-hoc comparison of the dominant upper limb for the "time" factor. Panel (A) – Post-hoc comparison between the first and second arm-pull of the dominant upper limb. Panel (B) – Post-hoc comparison between the second and third arm-pull of the dominant upper limb. Panel (C) – Post-hoc comparison between the first and third arm-pull of the dominant upper limb. SPM {t} – post-hoc statistic for Statistical Parametric Mapping. Dash lines represent the 95% confidence intervals (95CI).

propulsion outputs are observed by discrete values based on the average of a given trial (Koga et al., 2020; Oliveira et al., 2021). Therefore, researchers report the average of several arm-pulls. Thus, the literature lacks evidence on a hypothetical change over time that propulsion could have and, consequently, affect swimming velocity. As far as is known, only one study reported these differences in propulsion (in both upper limbs independently) (Morais et al., 2020a). The discrete and SPM analyses of the current study observed significant differences in the dominant upper limb, but not in the non-dominant. As SPM allows a more sensitive analysis, it was possible to detect and point out at which moments of the arm-pull these differences occurred.

For the dominant upper limb, SPM produced significant differences in the transition between the final phase of the downsweep and the beginning of the insweep (between ~ 32% and ~ 43% of the arm-pull). These differences may be related to muscle activation (Martens et al., 2015). At maximal trials, swimmers may experience a rapid decrease in muscle force production, which leads to a decrease in propulsion. During the pull phase (where differences in the dominant upper limb were observed), the biceps brachii and pectoralis major were the most activated muscles (Figueiredo et al., 2013). Thus, muscle recruitment (to generate in-water force) may be responsible for the aforementioned difference in the dominant upper limb. Hand kinematics may also play a key role in decreasing propulsion. It was found that changes in stroke kinematics led to different angles of attack (although not significantly different) and significantly different propulsion outputs (Koga et al., 2020).

Regarding the comparison of the propulsion outputs between the upper limbs, both analyses revealed a non-significant imbalance. It has been suggested that front-crawl sprint decreased the imbalance between the upper limbs, which would lead to faster swimming (Borges dos Santos et al., 2013). Moreover, it can be argued that sprinters can produce similar propulsion in both upper limbs. Because these swimming events take such a short amount of time, swimmers are able to maintain similar propulsion outputs in both upper limbs. Notwithstanding, the literature shows conflicting findings on this topic (Bishop et al., 2018). E.g., Borges dos Santos et al. (2013) showed that the fastest swimmers had fewer imbalances in tethered swim. On the other hand, it was shown that similar age-group swimmers tend to present significant imbalances between the upper limbs measured by independent sensors (Bartolomeu et al., 2021; Morais et al., 2020a). Based on these mixed findings, more information is needed on the effect of inter-limb imbalance on sprint swimming.

Overall, it can be highlighted that SPM analysis provides more accurate and insightful information than classical statistics based on discrete variables. SPM can be considered an adequate and sensitive method to detect differences in time-series signals that have similar patterns but different amplitudes as it occurs in swimming arm-pulls. Therefore, SPM makes it possible to identify at which moments between and within the arm-pull these differences were observed. This allows coaches to design more specific swimming drills to overcome these differences. A non-significant imbalance was observed between the upper limbs through both statistical approaches. As a main limitation, it can be considered that these findings are only valid for male swimmers in this age-group in maximum front-crawl swimming. Future studies should aim to understand this phenomenon in female swimmers and in other age-groups, swimming strokes, and distances. Moreover, more arm-pulls within the same trial should also be considered for analysis.

5. Conclusion

Both the discrete analysis and the SPM revealed a significant interaction between the two factors (i.e., “time” and “side”), but only SPM allowed identifying the specific moments of the arm-pull where these differences were observed.

CRediT authorship contribution statement

Jorge E Morais: Methodology, Conceptualization, Writing - original draft, Writing - review & editing. **Tiago M Barbosa:** Conceptualization, Supervision, Writing - review & editing. **Tiago Lopes:** Data curation, Writing - review & editing. **Vassilios Gourgoulis:** Software, Formal analysis, Writing - review & editing. **Thomas Nikodelis:** Software, Formal analysis, Writing - review & editing. **Daniel A Marinho:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

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.

Acknowledgments

This work is supported by national funds (FCT - Portuguese Foundation for Science and Technology) under the project UIDB/DTP/04045/2020.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2023.111792.

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