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IMU-BASED CLUSTERING OF INTRA AND INTER-CYCLIC VARIABILITY TO EXTRACT TECHNICAL ABILITIES DURING FRONT CRAWL SPRINT

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The aim of this study was to cluster swimming intra- and inter-cyclic variability to identify effect of technical skills profiles on performance. 91 trained to world-class swimmers performed 25m front crawl sprints with an Inertial Measurement Unit (IMU) on the sacrum. Data were clustered based on stroke pattern and dispersion around it. Technical and performance profiles of each cluster were respectively determined based on mean cluster curves with credibility regions and discrete parameter, and swimming speed. Results showed that combining high levels of both kinds of variability are associated with sprint performance. Coaches should target the development of a jerky and unsteady stroke pattern for sprinters along with huge longitudinal and anteroposterior acceleration variations while reducing body roll.

Keywords: swimming variability, clustering, IMU, sprint swimming, technical skills

INTRODUCTION

The analysis of movement variability, corresponding to the repetitions of close but not same movement patterns, is of major interest to understand elite swimmer's performance through the assessment of the biomechanical variability of technique. It is defined as the degree to which motor patterns vary within and between cycles. It is inherent to technique and can occur within a single stroke cycle (i.e. intra-cycle variability), or across multiple stroke cycles (i.e. inter-cycle variability) (Fernandes et al, 2022a). Such variability can affect the swimming speed and provide insights regarding underlying regulations of stroke. Then, monitoring intra and inter-cyclic variability during swimming is a challenge for technical skills assessment.

Research on swimming movement variability commonly focused on intra-cycle aspects and its relations with performance, by investigating intra-cyclic velocity variations (IVV). However, contradictory findings were emphasized since negative, positive or null correlations between IVV and velocity were observed and can reflect different coordination and technical adaptations (Fernandes et al., 2023). Then, inconsistency of literature leads to a crucial lack of knowledge regarding regulation of intra-cyclic variability supporting technical skills to be explained. Thus, considering other variables to assess biomechanical variability may provide valuable information to understand swimming technical skills. Acceleration may be of great interest because it provides a more direct investigation of the propulsion (Buchner & Reischle, 2002). Indeed, previous literature emphasized that acceleration pattern analysis links stroke mechanics and technique with swimming performance and expertise (Engel et al., 2022). Analysis of swimming biomechanical variability usually regards strokes in isolation from adjacent cycles. However, considering both intra and inter-cycle kinematical variations is of utmost importance, especially because the variation structure and not only its magnitude is valuable to support a more complete performance characterization (Fernandes et al., 2022b). Inter-cyclic variability is an indicator of motor pattern dispersion. Whereas the traditional approaches consider variability as noise, it may also contain information about motor organization and reflect functional regulations to optimize performance (Preatoni et al., 2013).

Data supporting variability analyses in swimming has been collected using a variety of devices (Fernandes et al., 2023). Among them, IMU are relevant for on-board technical assessment in swimming, therefore, previous literature using such sensors showed their relevance to monitor intra-cyclic patterns related to technical skills (Ganzevles et al., 2019). IMU provide multivariate functional data allowing continuous measures of variability. However, numerous studies in swimming were restricted to computing discrete features that led to limited data-driven insights regarding biomechanical variability. Then, there is a need to take into account the functional nature of IMU data through appropriate methodology. To do so, Functional Data Analysis (FDA) allows clustering of functional data by grouping similar curve patterns to identify technique and performance profiles. Then, literature demonstrated the usefulness of FDA for motion pattern analysis on cyclic sport, especially because it can outpace traditional empirical analysis (Helwig et al., 2016). Then, FDA may be a powerful approach to cluster variability in swimming based on IMU data, allowing to link these data-driven kinematical profiles to technical skills and performance.

The aim of this study was to cluster intra- and inter-cyclic kinematical variability considering the functional nature of 3D IMU data during sprint front-crawl swimming to identify incidence of technical skills profiles on performance.

METHODS

91 swimmers ranging from trained to world-class performed a maximal 25m front crawl with an IMU (Xsens DOT, Xsens Technologies B.V, Enschede, The Netherlands) sampled at 60 Hz on the sacrum. Full scale set at 16 g and 1000 deg/s were respectively used for the accelerometer and gyroscope. All participants signed an informed consent form in agreement with the French Ethical Committee (approval obtained under reference 2021-A00250-41).

Raw data were filtered and downsampled to match the model of Delhaye et al., 2022 allowing to extract the front crawl frames and to compute the swimming speed. 1s window before and after the first and last front crawl frame were removed. Curve alignment of swimmer's time serie was performed by adjusting the signal starting point at the frame corresponding to the first cycle beginning according to the detection of zero-crossing in medio-lateral acceleration of Ganzevles et al., 2019. Data were time normalized based on these zero-crossing events. Furthermore, the double partition model of Bouvet et al., (2023) was used. It allows the swimming technical skills to be clustered by a multivariate functional decomposition of both IMU signals and residuals into Fourier basis. Thus, the model considers both the information related to the swimming pattern and its dispersion. It results in two partitions of intra and inter-cyclic variability clusters. Clustering visualization was performed by computing the mean cluster curves (i.e. intra-cyclic) as well as credibility region (i.e. inter-cyclic).

Statistical analyses were conducted using RStudio (Version 4.2.2, RStudio, Inc., Boston, MA, USA). The level of significance was set at $p < 0.05$. Technical profile was determined regarding clustering visualization and computation of biomechanical parameters of literature on each axis. Standard deviation (SD) of clusters mean curves and credibility region was calculated as a reflection of variation magnitude. Performance profile was determined using a one-way analysis of variance (ANOVA) between swimming speed and the cross-partition (i.e. gathering clusters of the double partition model). Post-hoc tests were conducted with Tukey test and Bonferroni correction. The magnitude of differences was interpreted by effect size using eta-squared (η^2) for ANOVA or Cohen's d (d) for Tukey test with threshold values of 0.2, 0.5 and 0.8 defining trivial, small, medium and large effects respectively (Cohen, 2013).

RESULTS

Technical profiles

Mean cluster curves and credibility regions for the accelerometric and gyroscopic dimensions are presented on Figure 1 and Figure 2. It showed two clusters of specific stroke patterns related to intra-cyclic variability and discriminated by (1) higher signal amplitude and/or number of peaks in longitudinal and anteroposterior acceleration as well as in mediolateral angular velocity, (2) lower signal amplitude in mediolateral acceleration and longitudinal rotation. Then, they were named as the *jerky* and the *smoothy* cluster respectively. These functional findings are in line with SD computation presented on Table 1. Three clusters of pattern dispersion, ordered according to the magnitude of inter-cyclic variability, were observed. These clusters were interpreted as *low* (LR), *moderate* (MR), and *high* (HR) *repeatability*. Indeed, both credibility regions and SD were higher as clusters moved closer to LR.

Performance profiles

There was a medium significant effect of cross-partition clusters on swimming speed ($F(4.86)=34.6$, $p<0.001$, $\eta^2=0.62$, see Figure 3). All the *smoothy* clusters had a significantly lower speed than the *jerky*. Among the *smoothy* clusters, all kinds of inter-cyclic variability clusters displayed non-significant speed differences. The *jerky+low repeatability* (1.86 ± 0.12 m/s) and the *jerky+moderate repeatability* (1.81 ± 0.13 m/s) were the fastest clusters since all pairwise comparisons were significant except between them ($p=0.96$).

DISCUSSION

This work relies on a data-driven approach and a large database including heterogeneity of performance ranging from trained to world-class sprinters. Specific profiles of swimming technique variability were identified based on respectively two and three clusters of intra and inter-cyclic regulation and analyzed regarding swimming speed.

The *jerky* clusters is composed of more explosive and irregular stroke patterns including higher acceleration variations on propulsive axes. It might explain their higher swimming speed (Ganzevles et al., 2019) as greater intra-cycle acceleration and decelerations could be converted into higher speed with appropriate technical skills to feel the water (Leblanc et al., 2007). However, high intra-cyclic variability implies stroke smoothness degradation associated with lower stroke efficiency (Fernandes et al., 2023). *Jerky* clusters display also reduced body roll that might refer to more core stability and better body alignment. This higher steadiness especially occurs during the propelling phases of the cycle. It's in line with literature as reducing body roll is expected from sprinters to allow stroke rate increase by reduction of cycle duration (Gonjo et al., 2021) and a possible more continuous inter-limb coordination (Seifert et al., 2010). Then, these specific regulations of intra-cyclic variability enable the *jerky* swimmers to swim effortlessly while maintaining a high velocity per stroke (Engel et al., 2022).

The *jerky+low/moderate repeatability* are the fastest biomechanical strategies for front crawl sprint swimming indicating that lower repeatability of swimming pattern is associated with better performance. These two clusters are both composed of more than 70% by national or international swimmers. It indicates the discriminative aspect of high levels of both intra and inter-cyclic variability for sprint task. These findings are in line with those of Fernandes et al., 2022a demonstrating that variability characterizes the sprint swimming. Then, a jerky and unsteady swimming style could refer to a proficient functional regulation of motor pattern

leading to efficient outcomes (Seifert et al., 2016). Technical skills might be driven by the management of intra and inter-cyclic stroke variability, in order to align stroke pattern and its associated dispersion according to the task requirements.

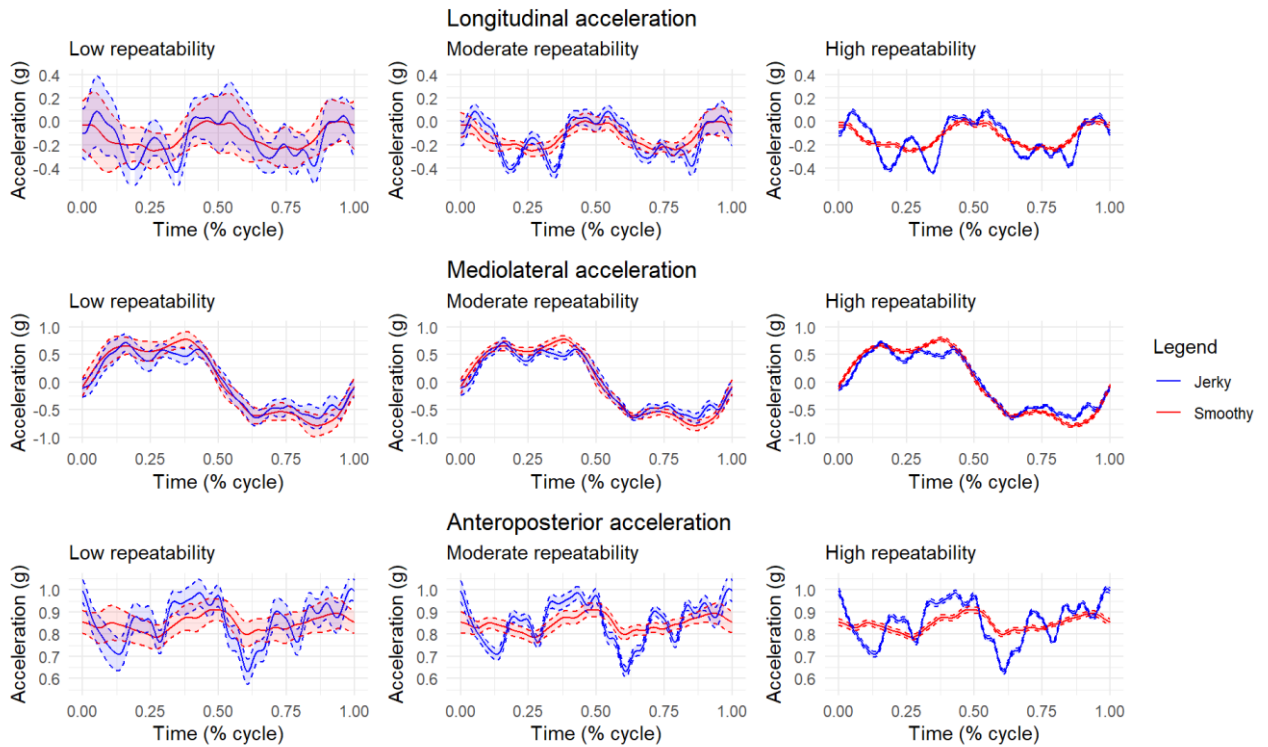


Figure 1. Intra-cyclic (jerky and smoothy stroke patterns) and inter-cyclic clustering (low, moderate and high repeatability credibility regions) of 3D accelerations

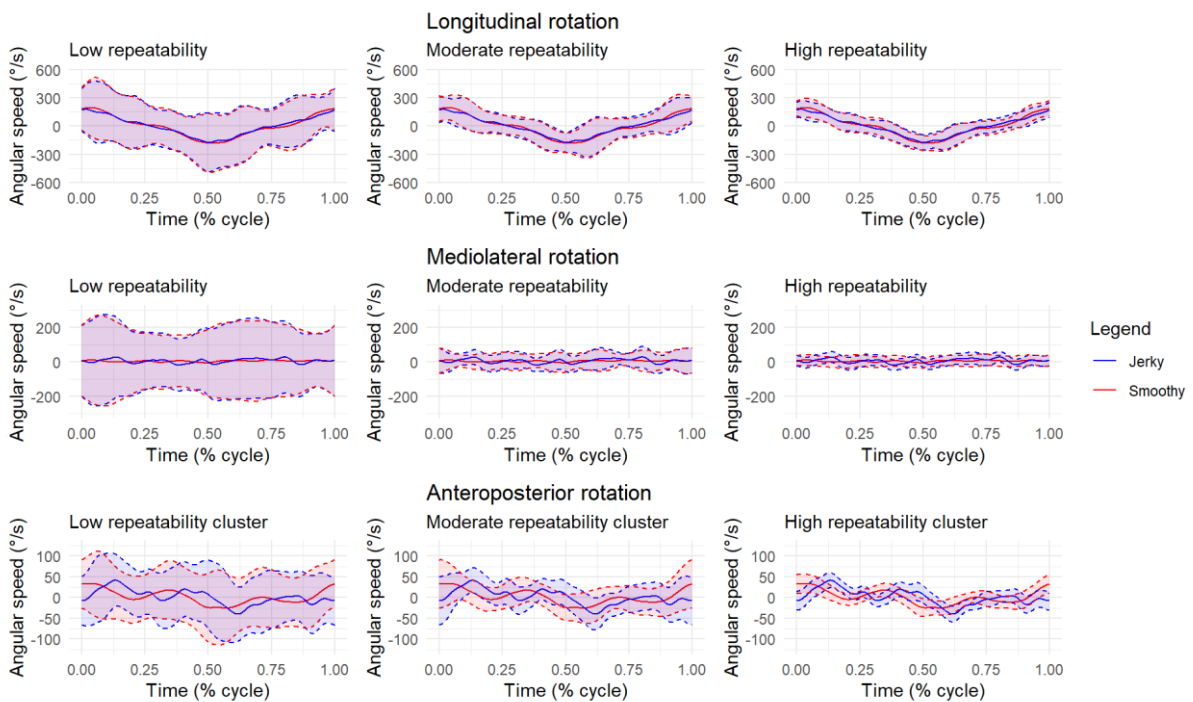


Figure 2. Intra-cyclic (jerky and smoothy stroke patterns) and inter-cyclic clustering (low, moderate and high repeatability credibility regions) of 3D angular velocities

	Cluster	Acceleration ($g \times 10^{-2}$)			Angular velocity (deg/s)		
		Longitudinal	Mediolateral	Anteroposterior	Longitudinal	Mediolateral	Anteroposterior
Standard deviation	<i>Jerky</i>	15.4	47.7	9.12	101	11.9	18.1
	<i>Smoothy</i>	8.84	56.3	3.28	113	4.23	16.7
	<i>LR</i>	2.39	1.32	0.39	426	334	87.0
	<i>MR</i>	1.10	1.14	0.36	284	96.8	81.0
	<i>HR</i>	0.15	0.38	0.07	117	21.3	28.1

Table 1. Discrete features computed on the mean curves and the credibility regions. *LR*: low repeatability. *MR*: moderate repeatability. *HR*: high repeatability

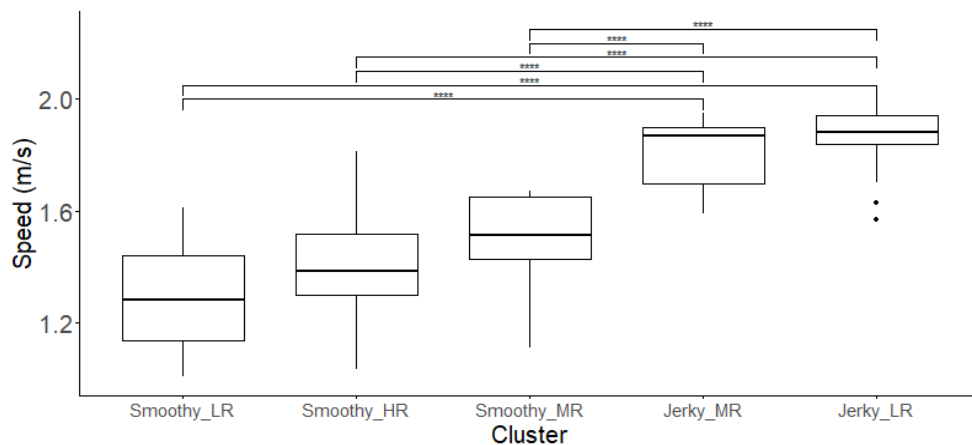


Figure 3. Swimming speed according to the cross-partitions clusters

Sprint swimming involves large constraints on motricity through the requirement of maximal propulsive forces achieved by high power output (Gatta et al., 2018). It requires kinematical variations at the expense of the swimming economy (Ganzevles et al., 2019) and then can explain why the *jerky+low/moderate repeatability* clusters are the better strategies for this task since it induces higher peak speeds with similar minimum speeds (Leblanc et al., 2007).

CONCLUSION

This work provides the first data-driven tool to perform technical evaluation and classification of swimmers based on clustering of intra and inter-cyclic kinematics. Then, it provides a novel non-invasive and automatic method for variability determination in swimming using embedded sensors as it is a hot topic in literature (Fernandes et al., 2023).

The findings of this study can daily assist coaches eye's to profile their swimmers while providing benchmarks to aim at the development of a jerky and unsteady stroke patterns for their sprinters. Then, practical advice used to teach it should target explosive swimming style

(i.e. huge longitudinal and anteroposterior accelerations) with a high level of core stability and body alignment (i.e. reduce body roll) to focus on sustaining the highest possible speed.

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