

Developing sprinters: how can we swim, cycle and run faster?

Edited by

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Developing sprinters: how can we swim, cycle and run faster?

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Editorial: Developing sprinters: how can we swim, cycle, and run faster?

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swimming, track and field, athletics, biomechanics, physiology, performance

Editorial on the Research Topic

Developing sprinters: how can we swim, cycle and run faster?

Swimming, cycling, and track and field are among the most-watched sports in the Olympic Games. Despite the complex interaction between aerobic and anaerobic energy supply, sprint performances in these three sports heavily rely on rapid energy production from anaerobic metabolism. Although event durations and intensities may be similar between sports, the training regimens of swimmers, cyclists, and track and field athletes differ considerably and provide the opportunity for cross-disciplinary learning. Therefore, this research topic aimed to gather insights into the determinants of sprint performances across these sports to develop faster athletes.

Because water does not provide sufficient resistance for substantial strength gains from sport-specific movements, swimmers typically perform several dry-land strength training sessions per week to provide an overload stimulus to the neuro-muscular system (1). In this regard, [Venâncio et al.](#) explored the evolution of research on strength training in swimmers. Their review reveals an exponential increase in research interest, particularly since 2010. Moreover, strength training has been predominantly related to sprint events in the swimming literature. This growing body of evidence encompasses a wide range of countries, highlighting the importance of incorporating strength training into swimmers' programs while respecting each athlete's unique characteristics and the specific demands of their events.

Resisted and assisted sprints are often used to enhance speed and acceleration capabilities (2). Following advancements in motorized resistance devices (MRD), [Eriksrud and Westheim](#) assessed intrasession and test-retest reliability of assisted running sprint outcomes. They reported high to extremely high intra-class correlations and, generally, good coefficients of variation for both test-retest and intrasession reliability, hence supporting the use of MRD for training and evaluation. In addition, [Jiménez-Reyes et al.](#) investigated the impact of varying overload conditions on the mechanical determinants of runners' performance during sprint acceleration. Their results indicated that heavy loads mainly affect the early acceleration phase, while light

loads provide a broader range of mechanical stimulation. These findings can guide load selection, thereby improving effectiveness and specificity of resistance- and assistance-based sprint training.

MRD has also facilitated the assessment of in-water swimmers' physical capabilities through the load-velocity (LV) profile (3). Sengoku et al. examined the usefulness of LV profiling by investigating the relationship between maximal lactate accumulation rate ($\dot{c}La_{max}$) and sprint performance parameters. The $\dot{c}La_{max}$ was associated with the theoretical maximal load that a swimmer can pull during front crawl swimming and 50 m front-crawl performance, particularly during the initial meters of the event. These results highlight the contribution of higher glycolytic power to faster performance at the start of a sprint race. As most studies have used cross-sectional designs (4, 5), Keating et al. investigated LV profiling and competition performance in national- and international-level swimmers over 15 months. Although fluctuations were observed across the evaluated period, no differences emerged relative to the baseline measurements. However, differences were observed between performance levels, with international-level swimmers showing greater stability than national-level swimmers. These findings support LV profiling as a valuable tool for swimmers' monitoring over time, contributing to more effective training prescription.

The inflammatory response to exercise, which is influenced by myokine release and modulated by fat-free mass, biological maturation, and dietary inflammatory index, may be considered when manipulating training loads (6). Almeida-Neto et al. investigated the effect of these factors on myokine release following repeated sprint training. The results showed that athletes with higher fat-free mass or greater maturity evidenced smaller inflammatory variations, hence showing potential for faster recovery between high-intensity sessions. Moreover, diets with lower inflammatory potential were linked to more efficient immune responses, thus highlighting the importance of nutrition to reduce exercise-induced immune stress, improve recovery, and enhance performance.

Given the comparable competition formats in swimming and track running competitions (7, 8), Born et al. compared performance progression and variety in race distances of comparable lengths (timewise) between swimmers and runners. Sprint swimmers exhibited a wider variety of race distances than runners. However, distance variety was not a fixed continuum, but rather an evolving process throughout the female athletes' careers (Born et al.). While swimmers generally exhibited greater variety than track runners, progressive specialization with advancing age increased the likelihood of achieving international-class swimming performance. Taken together, both studies suggest that sprint swimmers may benefit from earlier and more pronounced specialization to maximize their physiological potential.

Additionally, stroke specialization appears to be an important performance contributor to the technical adjustments. As such (9), Yamakawa et al. examined the effects of different breathing patterns on muscle activity and coordination in butterfly sprint swimming. Although breathing every compared to every second

stroke did not affect swimming speed, it altered muscle synergies, leading to an earlier onset of muscle activity. These findings highlight the need for race pace-specific training, implementation of the specific breathing patterns, and neuromuscular preparation during dry-land training for the improvement of specific muscle synergies.

As pacing is another key factor for sprint performance (10), Yoshimoto et al. investigated the relationship between 200 m running performance and pace distribution. World-class athletes typically run relatively slower in the first half. Similarly, a within-subject analysis showed that a faster second-half speed was linked to better overall performance time. As such, moderating early acceleration and maintaining speed later in the race may enhance the overall race outcome in 200 m sprint running.

In conclusion, this special issue offers valuable, state-of-the-art insights into the development of human sprint performances. Through comparisons across multiple sports, it presents evidence that can inform and enhance coaching and training methodologies. Specifically, the findings highlight the importance of strength training and provide guidance for optimal load adjustments of resisted sprinting, reliability of assisted sprints, and the use of MRD for longitudinal assessment of physical capacities. The findings also show the individual response to repeated sprints, underscoring the need for personalized programming in sprint training. As swimmers may benefit from greater specialization than track runners, sprint training should be designed to target the specific technical and pacing demands of the competition. Finally, we would like to thank the authors and reviewers for their support and efforts with this research topic.

Author contributions

JR-N: Writing – review & editing, Writing – original draft. DB: Writing – original draft, Writing – review & editing. MG-C: Writing – original draft, Writing – review & editing. D-PB: Writing – original draft, Writing – review & editing.

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Sprinting to the top: comparing quality of distance variety and specialization between swimmers and runners

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Objectives: To compare performance progression and variety in race distances of comparable lengths (timewise) between pool swimming and track running. Quality of within-sport variety was determined as the performance differences between individual athletes' main and secondary race distances across (top-) elite and (highly-) trained swimmers and runners.

Methods: A total of 3,827,947 race times were used to calculate performance points (race times relative to the world record) for freestyle swimmers ($n = 12,588$ males and $n = 7,561$ females) and track runners ($n = 9,230$ males and $n = 5,841$ females). Athletes were ranked based on their personal best at peak performance age, then annual best times were retrospectively traced throughout adolescence.

Results: Performance of world-class swimmers differentiates at an earlier age from their lower ranked peers (15–16 vs. 17–20 year age categories, $P < 0.05$), but also plateaus earlier towards senior age compared to runners (19–20 vs. 23+ year age category, $P < 0.05$), respectively. Performance development of swimmers shows a logarithmic pattern, while runners develop linearly. While swimmers compete in more secondary race distances (larger within-sport variety), runners specialize in either sprint, middle- or long-distance early in their career and compete in only 2, 4 or 3 other race distances, respectively. In both sports, sprinters specialize the most ($P < 0.05$). Distance-variety of middle-distance swimmers covers more longer rather than sprint race distances. Therefore, at peak performance age, (top-) elite female 200 m swimmers show significantly slower sprint performances, i.e., 50 m ($P < 0.001$) and 100 m ($P < 0.001$), but not long-distance performances, i.e., 800 m ($P = 0.99$) and 1,500 m ($P = 0.99$). In contrast, (top-) elite female 800 m middle-distance runners show significantly slower performances in all their secondary race distances ($P < 0.001$). (Top-) elite female athletes specialize more than (highly-) trained athletes in both sports ($P < 0.05$).

Conclusions: The comparison to track running and lower ranked swimmers, the early performance plateau towards senior age, and the maintenance of a large within-sport distance variety indicates that (top-) elite sprint swimmers benefit from greater within-sport specialization.

KEYWORDS

competition, elite athlete, talent, competitive swimming, diversification, long-term athlete development, sampling

Introduction

Specializing late and maintaining a large variety of sport disciplines supposedly increase the chances of top performances at elite age, limit burnout risk and reduce injury incidences (1–3). However, evidence is limited to review articles and only a low number of original investigations (4). Additionally, many findings originate from game sports (5), which profit from skill transfer between disciplines, i.e., tactical positioning and decision-making (6), and limit their implications for cgs- (centimeter-gram-second) and individual sports. Furthermore, accuracy of retrospective questionnaires on sport participation during junior age are limited to the participants’ accurate memory and only assess quantity of sport variety (3, 7, 8). Assessment of the quality of within-sport variety, i.e., performance differences between the athletes’ main and secondary events, may further improve knowledge of specialization and variety during long-term athlete development (LTAD).

The quality of within-sport variety can be assessed by comparing performance over various race distances. Swimming conditions are standardized during competitions, i.e., specified water temperature, limited current, exact pool length and wave breaking lane ropes (9). This allows the comparison of race results from various venues and championships to analyze variety in race distances and throughout an athlete’s entire swimming career. As such, previous studies found that swimmers typically enter the sport early and, on average, accumulate 8 years of competition participation before reaching (top-) elite level (10, 11), but maintain a larger skill variety within their sport (12). Competing in more than one swimming stroke and race distance as a child may indeed improve success and medal chances at adult age, particularly for freestyle events, which provide up to six race distances from 50 m to 1,500 m (13, 14).

However, large within-sport variety may also limit performance progression, as the ever-evolving landscape of swimming and continuously improving world records (15–17) require new training and development strategies to meet the distance-specific biomechanical and physiological requirements (18, 19). Sprint swimmers in particular may benefit a more intense, race-pace specific, and less voluminous training approach to optimally transfer high stroke frequencies into propulsion, develop neuro-muscular abilities, explosivity, speed and power for start and turn performances (20–23). Compared to the over-distance oriented approach in swimming, track runners typically follow training regimes that are characterized by more under-distance training: fewer hours per week with higher training intensities (24–27). This approach may be used to reduce overuse injuries, e.g., fatigue fractures, which are associated with impact forces and high volumes of running (28). Furthermore, the majority of disciplines in track-and-field involve explosive movement patterns, which typically require under-distance oriented training regimes with higher exercise intensities (25, 27, 29).

Additionally, track runners do not maintain the same within-sport variety as swimmers, but instead specialize in either sprint-, middle- and long-distance races (12, 27, 30). Despite their very different approaches to training, pool swimming and track running share common race lengths in competition (timewise, Table 1) as

TABLE 1 World record times [mm:ss.00] of long-course (50 m pool length) freestyle swimming and outdoor (400 m track length) track running events (31, 32).

Pool swimming			Track running		
	Women	Men		Women	Men
Sprint					
50 m	00:23.61	00:20.91	200 m	00:21.34	00:19.19
100 m	00:51.71	00:46.80	400 m	00:47.60	00:43.03
Middle-distance					
200 m	01:52.85	01:42.00	800 m	01:53.28	01:40.91
400 m	03:55.38	03:40.07	1,500 m	03:49.11	03:26.00
Long-distance					
800 m	08:04.79	07:32.12	3,000 m	08:06.11	07:20.67
1,500 m	15:20.48	14:31.02	5,000 m	14:00.21	12:35.36

well as common physiological and metabolic demands for sprint, middle- and long-distance events (33–37). Therefore, comparing LTAD and evolution of within-sport distance variety between track runners and pool swimmers may provide new insights into training and development strategies, particularly for the neuro-muscular adaptations of sprint swimmers.

The aim of the present study was to compare performance progression and variety in race distances of comparable lengths (timewise) between pool swimming and track running. Quality of within-sport variety was assessed between the athletes’ main and secondary race distances as well as between various performance levels. Track runners were expected to show lower variety and higher specialization on and around their main race distances.

Methods

Subjects

A total of 3,827,947 race times of freestyle pool swimmers ($n = 12,588$ males and $n = 7,561$ females) and track runners ($n = 9,230$ males and $n = 5,841$ females) representing 213 countries were obtained from the official databases of the European Aquatics (38) and World Athletics associations (39) and used for the present study. The data set of the male swimmers has previously been used as part of another study (12), however, to provide a comprehensive data set and comparison to the male runners’ race data, two additional years (2022 and 2023) and another performance level (regional-class swimmers) have been added since the mentioned publication. Additionally, we have further developed the statistical model from repeated measure analysis of variance (ANOVA) to linear mixed model analysis (LMM). As only publicly available data are included and were analyzed anonymously, explicit written consent from the athletes was not required. The study protocol received prior approval from the institutional review board of the Swiss Federal Institute of Sport Magglingen (Reg.-Nr. 222_LSP_Born_03_2024) and adheres to the ethical standards outlined in the Declaration of Helsinki by the World Medical Association regarding research with human subjects.

Data collection

To compare performance progression and variety in race distances of comparable lengths (timewise, refer to [Table 1](#)) and to determine factors leading to world-class performances at peak performance age in swimming and track running regarding performance progression and quality of within-sport distance variety, only swimmers and runners still competing at peak performance age were included in the present study. Hence, all swimmers and track runners at peak performance age were extracted from the 2023 to 2016 databases and ranked based on their personal best in each particular race distance at peak performance age. Then, each individual athlete's annual best times for all race distances were retrospectively extracted until early junior age (13–14 year age category), i.e., also including the 2015–2006 databases.

Although, individual athletes may perform at the highest international level at a younger age, previous literature has shown that, on average, swimmers and track runners reach their peak performance aged 23–30 years ([40](#), [41](#)). Additionally, the recently introduced U23 European swimming championships, which is intended as a transition phase between international junior and senior championships ([42](#)), further supports the 23 year cut-off age that distinguishes between developing and peak performing swimmers and runners. Consistent with the Olympic events, which high-performance swimmers and runners aim for, only long-course swimming races (50 m pool length) and outdoor running races (400 m track) were considered for the present study. Freestyle provides the largest range in swimming race distances at Olympic swimming competitions (50 m to 1,500 m) and, therefore, provides a reasonable data base for the comparison with track running. Hence, only freestyle swimming races are included in the present study.

Data analysis

All race times were converted to performance points according to the official method of the world governing body in swimming. The point system expresses race times relative to the current world record (which equals 1,000 points) and allows the comparison of performances across various race distances ([9](#)), and thus, the comparison between sports. With swimming as the main point of interest for the present study, the swimming-specific point system was used for both sports to cluster swimmers and runners into different performance levels. Those performance levels were based on previous recommendations ([43](#)) and each individual athlete's personal best at peak performance age: world-class finalists (>850 performance points), international-class (850–750 performance points), national-class (750–650 performance points) and regional-class (650–550 performance points). Athletes with fewer than 550 performance points were excluded from the data analysis.

Quality of within-sport variety was then compared across six race distances (refer to [Table 1](#)) for both swimmers and runners. Performances of the athletes' main race distance (the particular race distance on which the ranking at peak performance age was based) were compared with their individual performances in the

other (secondary) race distances. For the sake of clarity and to make the data tsunami of the present study more accessible for the reader, only two performance groups were used to assess the quality of variety and comparison between the athletes' main and secondary race distances: (top-) elite (1,000–750) and (highly-) trained (750–550 performance points) swimmers and runners ([44](#)). To assess longitudinal development, annual best times were averaged over two years and compared across the 13–14, 15–16, 17–18, 19–20, 21–22 and 23–30 year age categories.

The “pandas” library (version 1.5.1, pandas-dev/pandas, Zenodo, Genève, Switzerland) in Python (version 3.9.7, Python Software Foundation, Beaverton, USA) was used to compute performance points, establish rankings at peak performance age, and extract annual best times retrospectively for all included swimmers and runners. The subsequent data processing was carried out with Microsoft Excel (version 2209, Microsoft Corporation, Redmond, WA, USA). As part of the present interdisciplinary study, the data collection and analysis were led by an experienced data scientist, holding a master's degree and PhD. Scripts and procedures were validated by the other scientists involved in the project.

Statistical analysis

All data are presented as mean $\pm$ standard deviation and were analyzed with the Jamovi software package version 2.3.28.0 (Jamovi Project 2022, retrieved from <https://www.jamovi.org>). A diagonal straight line in the Q-Q plot and a Gaussian distribution in the histogram confirmed normally distributed standardized residuals ([45](#)). Non-normally distributed data were subjected to logarithmic transformation. Linear mixed model (LMM) analysis was used to compare performance levels (850 vs. 750 vs. 650 vs. 550 or international vs. national) across the age categories (13–14 vs. 15–16 vs. 17–18 vs. 19–20 vs. 21–22 vs. 23+) as fixed factors and athletes' performance points for the particular age category as dependent variable. Subject was added as the random factor to account for missing values in the time series. Fixed intercepts and restricted maximum likelihood (REML) were employed. Bonferroni's correction was used to correct *post hoc* tests for multiple pairwise comparisons. An alpha error of 0.05 determined significant differences. Since maturational growth rates are different between sexes, all analyses were conducted separately for men and women ([46](#)).

Results

Performance progression

Performance progression of pool swimmers shows a logarithmic pattern: a steeper incline during the younger age categories and a flattening off towards peak performance age. In contrast, track runners show a linear development pattern ([Figure 1](#)). The earlier performance plateau in swimmers occurs between 17 and 22 years of age, while runners typically progress until the 23+ age category ($P < 0.05$, refer to [Figure 1](#) and [Table 2](#)). While performance

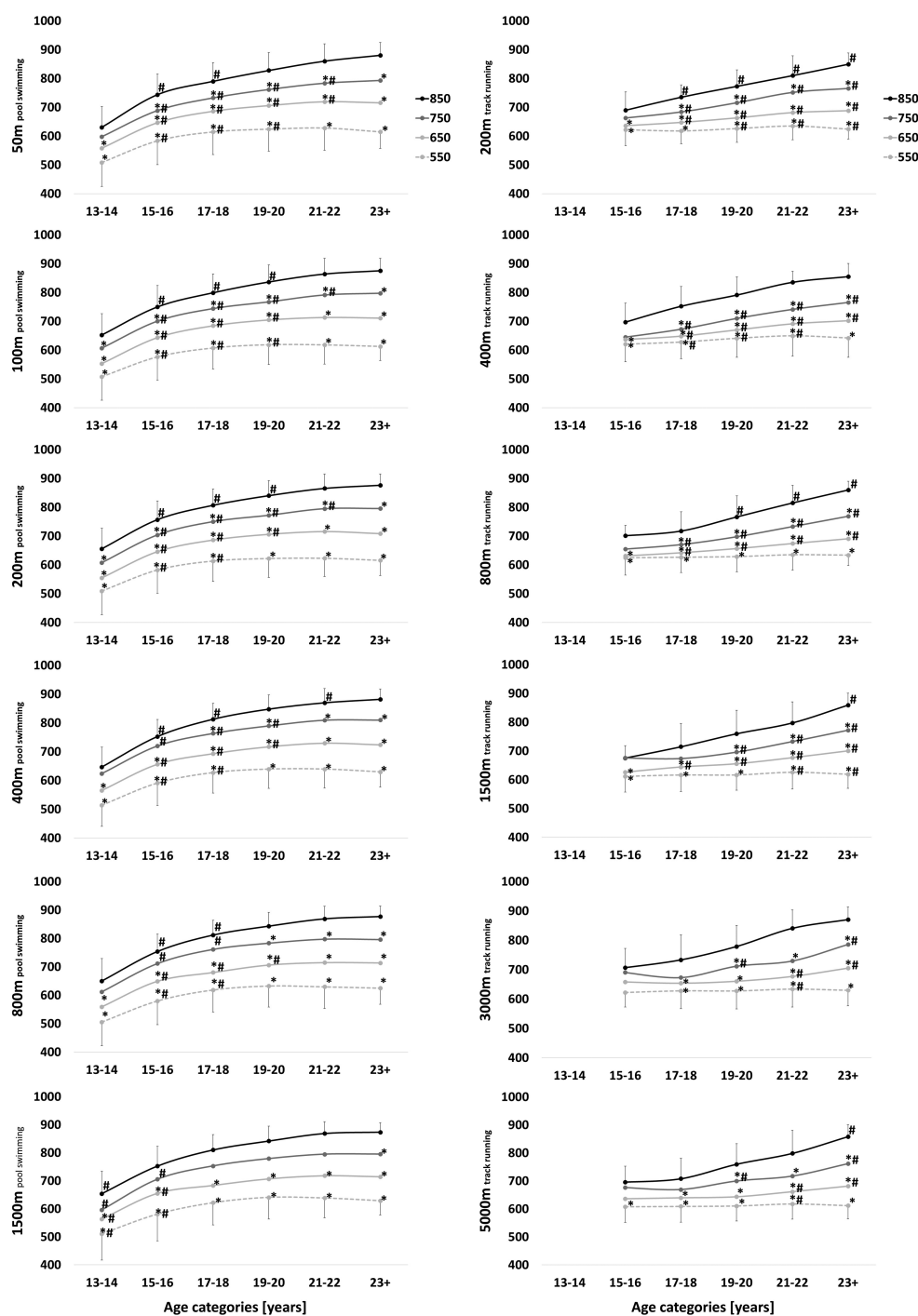


FIGURE 1

Progression of performance points [a.u.] over the age categories [years] of world-class finalists (850), international- (750), national- (650) and regional-class (550) female pool swimmers and track runners. Athletes were ranked based on their personal best at peak performance age in the particular race distance. Annual best times across the age categories were retrospectively extracted across all race distances and compared between performance levels and age categories with linear mixed model analysis. Significant differences are indicated compared to world-class finalists (*) and the previous age category (#).

plateaus earlier in long-distance compared to sprint- and middle-distance swimmers, this is not the case for runners. However, performance of both female regional-class swimmers and runners declined towards the 23+ age category. In male regional-class athletes, this performance decline towards the 23+ age category is

particularly evident in sprint swimmers, i.e., 50 m ($P < 0.001$) and 100 m ($P = 0.007$), as well as sprint, middle- and long-distance runners, i.e., 200 m ($P < 0.001$), 400 m ($P = 0.012$), 1,500 m ($P < 0.001$) and 5,000 m ($P < 0.001$). Furthermore, female swimmers' performances differentiate between the performance

TABLE 2 Progression of performance points [a.u.] over the various age categories [years] of world-class finalists (850), international- (750), national- (650) and regional-class (550) *male pool swimmers and track runners*.

Performance level		Age categories [years]						Linear mixed model analysis		
		13–14	15–16	17–18	19–20	21–22	23+			
Pool swimmers										
50 m	850	512 ± 107	643 ± 92 [#]	753 ± 81 [#]	821 ± 65 [#]	871 ± 54 [#]	881 ± 34	$R_c^2 = 0.83$ ICC = 0.54	(a) $F_{[5 13965]} = 1,949$ (b) $F_{[3 4203]} = 650$ (c) $F_{[15 14010]} = 31$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750	472 ± 78	632 ± 82 [#]	727 ± 73 [#]	773 ± 66 [#]	802 ± 57 ^{*,#}	810 ± 46 [*]			
	650	452 ± 85 [*]	591 ± 81 ^{*,#}	674 ± 74 ^{*,#}	708 ± 69 ^{*,#}	724 ± 73 ^{*,#}	721 ± 56 [*]			
	550	415 ± 87 [*]	542 ± 88 ^{*,#}	613 ± 81 ^{*,#}	637 ± 80 ^{*,#}	646 ± 78 ^{*,#}	627 ± 62 ^{*,#}			
100 m	850	510 ± 78	667 ± 78 [#]	768 ± 69 [#]	821 ± 57 [#]	858 ± 50 [#]	869 ± 33	$R_c^2 = 0.85$ ICC = 0.48	(a) $F_{[5 15667]} = 6,037$ (b) $F_{[3 4530]} = 1,520$ (c) $F_{[15 15721]} = 27$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750	478 ± 84 [*]	627 ± 80 ^{*,#}	717 ± 66 ^{*,#}	760 ± 60 ^{*,#}	781 ± 55 ^{*,#}	785 ± 41 [*]			
	650	443 ± 83 [*]	584 ± 82 ^{*,#}	661 ± 75 ^{*,#}	691 ± 69 ^{*,#}	704 ± 65 ^{*,#}	699 ± 50 [*]			
	550	400 ± 80 [*]	520 ± 84 ^{*,#}	589 ± 76 ^{*,#}	611 ± 72 ^{*,#}	616 ± 70 [*]	603 ± 49 ^{*,#}			
200 m	850	534 ± 89	697 ± 76 [#]	795 ± 68 [#]	846 ± 60 [#]	879 ± 47	882 ± 34	$R_c^2 = 0.84$ ICC = 0.45	(a) $F_{[5 9303]} = 3,366$ (b) $F_{[3 2448]} = 803$ (c) $F_{[15 9324]} = 10$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750	493 ± 79 [*]	659 ± 75 ^{*,#}	754 ± 63 ^{*,#}	796 ± 55 ^{*,#}	816 ± 55 ^{*,#}	811 ± 50 [*]			
	650	471 ± 85 [*]	616 ± 78 ^{*,#}	695 ± 70 ^{*,#}	727 ± 64 ^{*,#}	740 ± 63 ^{*,#}	732 ± 55 [*]			
	550	423 ± 83 [*]	550 ± 81 ^{*,#}	623 ± 71 ^{*,#}	646 ± 69 ^{*,#}	655 ± 69 [*]	643 ± 60 [*]			
400 m	850	522 ± 88	701 ± 66 [#]	800 ± 59 [#]	852 ± 53 [#]	882 ± 45	879 ± 40	$R_c^2 = 0.85$ ICC = 0.48	(a) $F_{[5 5591]} = 3,358$ (b) $F_{[3 1434]} = 568$ (c) $F_{[15 5599]} = 9$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750	493 ± 89	662 ± 82 ^{*,#}	753 ± 67 ^{*,#}	792 ± 59 ^{*,#}	806 ± 52 [*]	797 ± 46 [*]			
	650	453 ± 80 [*]	604 ± 77 ^{*,#}	682 ± 67 ^{*,#}	712 ± 66 ^{*,#}	723 ± 64 [*]	712 ± 54 [*]			
	550	428 ± 91 [*]	545 ± 84 ^{*,#}	615 ± 77 ^{*,#}	632 ± 74 ^{*,#}	640 ± 71 [*]	625 ± 59 [*]			
800 m	850	504 ± 87	708 ± 73 [#]	817 ± 57 [#]	860 ± 66	897 ± 47	902 ± 39	$R_c^2 = 0.86$ ICC = 0.51	(a) $F_{[5 2993]} = 1,999$ (b) $F_{[3 766]} = 245$ (c) $F_{[15 3001]} = 8$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750	511 ± 88	671 ± 82 [#]	764 ± 67 ^{*,#}	809 ± 56 [#]	826 ± 52 [*]	818 ± 44 [*]			
	650	459 ± 80 [*]	619 ± 76 ^{*,#}	700 ± 69 ^{*,#}	734 ± 68 ^{*,#}	746 ± 65 [*]	733 ± 54 [*]			
	550	440 ± 89 [*]	565 ± 87 ^{*,#}	636 ± 85 ^{*,#}	656 ± 83 ^{*,#}	669 ± 74 [*]	646 ± 60 [*]			
1,500 m	850	502 ± 91	709 ± 77 [#]	802 ± 69 [#]	855 ± 59 [#]	883 ± 50	883 ± 43	$R_c^2 = 0.86$ ICC = 0.50	(a) $F_{[5 2448]} = 1,891$ (b) $F_{[3 648]} = 246$ (c) $F_{[15 2450]} = 8$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750	486 ± 88	652 ± 87 ^{*,#}	746 ± 66 ^{*,#}	791 ± 57 ^{*,#}	805 ± 51 [*]	797 ± 41 [*]			
	650	454 ± 74 [*]	607 ± 74 ^{*,#}	684 ± 71 ^{*,#}	711 ± 67 ^{*,#}	719 ± 64 [*]	710 ± 50 [*]			
	550	430 ± 88 [*]	559 ± 81 ^{*,#}	620 ± 78 ^{*,#}	634 ± 79 [*]	647 ± 76 [*]	627 ± 56 [*]			
Track runners										
200 m	850		687 ± 49	756 ± 47 [#]	800 ± 44 [#]	837 ± 48 [#]	854 ± 39	$R_c^2 = 0.75$ ICC = 0.57	(a) $F_{[4 5680]} = 352$ (b) $F_{[3 5486]} = 330$ (c) $F_{[12 5767]} = 74$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750		690 ± 34	714 ± 44 ^{*,#}	743 ± 49 ^{*,#}	767 ± 51 ^{*,#}	779 ± 40 ^{*,#}			
	650		684 ± 38	694 ± 42 ^{*,#}	705 ± 46 ^{*,#}	714 ± 48 ^{*,#}	707 ± 41 [*]			
	550		668 ± 18	676 ± 33 [*]	684 ± 36 [*]	687 ± 40 [*]	660 ± 32 ^{*,#}			
400 m	850		698 ± 55	762 ± 51 [#]	800 ± 56 [#]	835 ± 53 [#]	857 ± 42 [#]	$R_c^2 = 0.75$ ICC = 0.60	(a) $F_{[4 5116]} = 254$ (b) $F_{[3 5030]} = 213$ (c) $F_{[12 5132]} = 45$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750		697 ± 36	721 ± 46 ^{*,#}	750 ± 48 ^{*,#}	768 ± 50 ^{*,#}	777 ± 37 ^{*,#}			
	650		680 ± 33	696 ± 41 ^{*,#}	710 ± 47 ^{*,#}	721 ± 51 ^{*,#}	711 ± 47 ^{*,#}			
	550		690 ± 43	698 ± 47 [*]	698 ± 43 [*]	704 ± 49 [*]	680 ± 50 ^{*,#}			
800 m	850		746 ± 52	770 ± 62 [#]	811 ± 58 [#]	845 ± 51 [#]	863 ± 38 [#]	$R_c^2 = 0.73$ ICC = 0.49	(a) $F_{[4 3987]} = 466$ (b) $F_{[3 4693]} = 327$ (c) $F_{[12 4027]} = 58$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750		714 ± 47	731 ± 44 ^{*,#}	753 ± 47 ^{*,#}	774 ± 46 ^{*,#}	783 ± 38 ^{*,#}			
	650		695 ± 27	709 ± 36 [*]	720 ± 39 ^{*,#}	727 ± 40 ^{*,#}	719 ± 32 [*]			
	550									
1,500 m	850		750 ± 47	758 ± 54	796 ± 60 [#]	833 ± 53 [#]	860 ± 37 [#]	$R_c^2 = 0.75$ ICC = 0.58	(a) $F_{[4 4507]} = 127$ (b) $F_{[3 5717]} = 230$ (c) $F_{[12 4429]} = 56$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750		719 ± 51	721 ± 44 [*]	744 ± 49 ^{*,#}	765 ± 50 ^{*,#}	780 ± 40 ^{*,#}			
	650		709 ± 39 [*]	706 ± 44 [*]	713 ± 47 ^{*,#}	721 ± 46 ^{*,#}	715 ± 42 [*]			
	550			693 ± 33 [*]	703 ± 37 [*]	704 ± 46 [*]	660 ± 38 ^{*,#}			
3,000 m	850			785 ± 87	808 ± 82 [#]	838 ± 66 [#]	866 ± 42 [#]	$R_c^2 = 0.79$ ICC = 0.64	(a) $F_{[4 1642]} = 103$ (b) $F_{[3 2585]} = 76$ (c) $F_{[12 1653]} = 18$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750		723 ± 70	716 ± 51 [*]	743 ± 60 ^{*,#}	767 ± 55 ^{*,#}	787 ± 42 ^{*,#}			
	650		719 ± 74	706 ± 46 [*]	707 ± 50 ^{*,#}	713 ± 52 ^{*,#}	712 ± 47 [*]			
	550		679 ± 70	708 ± 52 [*]	697 ± 46 [*]	700 ± 48 [*]	674 ± 42 [*]			
5,000 m	850		792 ± 34	804 ± 72	821 ± 74 [#]	840 ± 62	856 ± 44 [#]	$R_c^2 = 0.75$ ICC = 0.58	(a) $F_{[4 2688]} = 84$ (b) $F_{[3 4215]} = 166$ (c) $F_{[12 2728]} = 23$	$P < 0.001$ $P < 0.001$ $P < 0.001$
	750		752 ± 52	734 ± 57 [*]	743 ± 60 ^{*,#}	760 ± 56 ^{*,#}	780 ± 42 ^{*,#}			
	650		688 ± 42 [*]	695 ± 42 [*]	706 ± 47 ^{*,#}	715 ± 47 ^{*,#}	709 ± 41 [*]			
	550		689 ± 66 [*]	698 ± 34 [*]	694 ± 47 [*]	694 ± 47 [*]	667 ± 43 ^{*,#}			

Athletes were ranked based on their personal best at peak performance age in the particular race distance. Annual best times across the age categories were retrospectively extracted across all race distances.

R_c^2 , R -squared conditional; ICC, intra-class correlation coefficient.

Linear mixed model analysis:

a) Main effect: age category (13–14 vs. 15–16 vs. 17–18 vs. 19–20 vs. 21–22 vs. 23+).

b) Main effect: performance level (850 vs. 750 vs. 650 vs. 550).

c) Interaction effect: age category x performance level.

Bonferroni *post hoc* comparison:

*significant difference to the 850 performance level (world-class finalists).

#significant difference to the previous age category.

levels at a younger age compared to female track runners. Specifically, female world-class finalists start showing significantly faster race times compared to international-class athletes at a younger age in swimming compared to running ($P < 0.05$). Similar differences in differentiation between the two sports can also be seen in male athletes (Table 2).

Quality of within-sport distance variety

While swimmers typically compete across all race distances, runners specialize in either sprint, middle- or long-distance early in their career and compete in only two, four or three other race distances, respectively. In both sports, sprinters specialize more than middle- and long-distance athletes. As such, (top-) elite female 50 m swimmers show significantly slower performances in their 200 m ($P < 0.001$), 400 m ($P < 0.001$), 800 m ($P < 0.001$) and 1,500 m races ($P = 0.029$) at peak performance age, while (top-) elite female 200 m sprint runners do not even compete over race distances of more than 800 m. (Top-) elite female 800 m and 1,500 m swimmers show significantly slower performances in their 50 m ($P < 0.001$), 100 m ($P < 0.001$) and 200 m ($P < 0.001$) races at peak performance age. The variety of middle-distance swimmers covers more long- rather than sprint race distances. As such, at peak performance age, (top-) elite female 200 m swimmers show significantly slower sprint performances, i.e., 50 m ($P < 0.001$) and 100 m ($P < 0.001$), but not long-distance performances, i.e., 800 m ($P = 0.99$) and 1,500 m ($P = 0.99$) (23+ age category). Runners are more specialized, as (top-) elite female 800 m middle-distance runners show significantly slower performances in all their secondary race distances, i.e., 200 m, 400 m, 1,500 m, 3,000 m (all $P < 0.001$; Figures 2, 3).

(Top-) elite female athletes specialize more than (highly-) trained female athletes in both sports. While (top-) elite swimmers still compete across all six race distances at peak performance age (23+ age category), they show more significantly slower secondary race distances compared to their main race distance than (highly-) trained swimmers ($P < 0.05$). Specifically, (top-) elite female 100 m swimmers show significantly slower 50 m ($P = 0.002$), 200 m ($P = 0.008$), 400 m ($P < 0.001$) and 800 m ($P < 0.001$) race times, while (highly-) trained female 100 m swimmers only show significantly slower 50 m ($P < 0.001$) and 400 m ($P < 0.001$) race times at peak performance age. The same effect of greater specialization in higher ranked athletes is apparent in male swimmers. (Top-) elite female runners generally compete in a lower number of secondary race distances compared to (highly-) trained runners. For instance, (top-) elite female 400 m runners also compete in 200 m and 800 m races, while (highly-) trained 400 m runners compete in 200 m–1,500 m races. (Top-) elite female 5,000 m runners compete over all race distances from 800 m to 5,000 m, while (highly-) trained 5,000 m runners compete over all race distances from 400 m to 5,000 m. Male runners showed the opposite trend, with (top-) elite 800 m, 1,500 m and 5,000 m runners competing in more secondary race distances than (highly-) trained runners (Tables 3, 4).

Discussion

The main findings of the present study are that swimmers' performances differentiate between world-class athletes and their lower ranked peers at an earlier age compared to that of runners. Due to the logarithmic development pattern, performance of swimmers plateaus earlier towards senior age compared to that of runners, which show a linear development pattern. Swimmers also show a greater within-sport distance variety and compete across all six race distances, whereas runners focus on only three to five race distances. While sprinters specialize most in both sports, within-sport variety of middle-distance swimmers covers more long-distance races rather than sprints. Additionally, (top-) elite swimmers specialize more than (highly-) trained swimmers.

Performance development

Swimmers show a larger within-sport variety and compete in more events alongside their main race distance than runners, who specialize more and compete in fewer secondary race distances. As swimming technique is a dominant key performance indicator and important contributing factor to swimming performance, swimmers are able to compete over a greater variety of race distances within their specific swimming stroke than runners (14). The large contribution of swimming technique may also explain the logarithmic development pattern. Quick learning experience of technical elements may add to the physical development and allow for the steep performance curve at young age, which has also previously been shown in backstroke swimmers (47). In contrast, track runners primarily rely on physical fitness, and thus, develop linearly with later differentiation between performance levels (27, 29). The present findings are also supported by previous sprint data of track runners, which showed a similar linear development pattern after 10 years of age (48).

Neuro-muscular aspects of sprint swimming

The present study shows that sprint swimmers specialize more than middle- and long-distance swimmers. Additionally, specialization affects performance level, as (top-) elite show earlier and greater specialization compared to (highly-) trained sprint swimmers. This higher degree in specialization may be due to the specific technical, metabolic and neuro-muscular demands that are required for world-class success (18, 19, 49). The neuro-muscular abilities have gained particular importance over the last decade, as they enhance in-water force production (50, 51) as well as start and turn performances, which have been shown to be distinguishing factors for swim races (52–55). As such, the push-off from a solid base during starts and turns allows swimmers to translate their full capacity of maximal strength and power into propulsion (20, 56). Therefore, the early introduction to dry-land training and strength-and-conditioning regimes is particularly important for sprint swimmers (21, 57) and may explain the earlier and higher degree

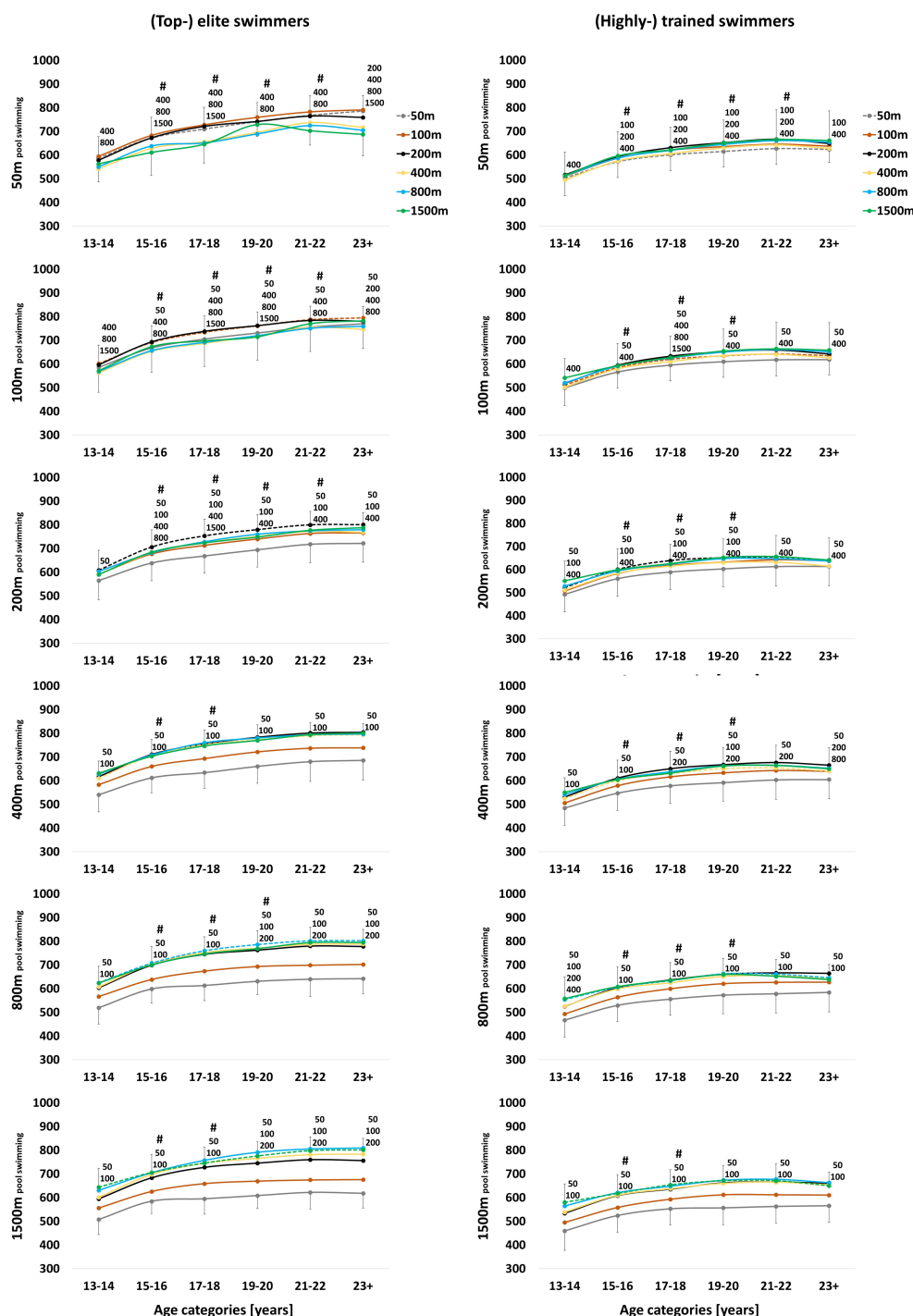


FIGURE 2

Progression of performance points [a.u.] of (top-) elite (1,000–750 performance points) and (highly-) trained *female freestyle pool swimmers* (750–550 performance points) across the various age categories [years]. Annual best times of the main race distance (dotted lines) were retrospectively extracted and compared to the individual swimmers' annual best times of their secondary race distances using linear mixed model analysis, with 50, 100, 200, 400, 800 and 1500 indicating the significant difference to the specific secondary race distance. For the sake of clarity, significant differences to the previous age category (#) are only indicated for the main race distance.

of specialization in (top-) elite compared to (highly-) trained sprint swimmers. Furthermore, the scientific literature supports the early introduction of children and adolescents to strength training and shows that both sexes gain substantial strength even before puberty

(58, 59). Additionally, establishing a solid technical foundation in regard to dry-land exercises and barbell lifting techniques during early stages of their swimming careers prepares sprinters for heavy lifts and minimizes injury risk at late junior and senior age (59, 60).

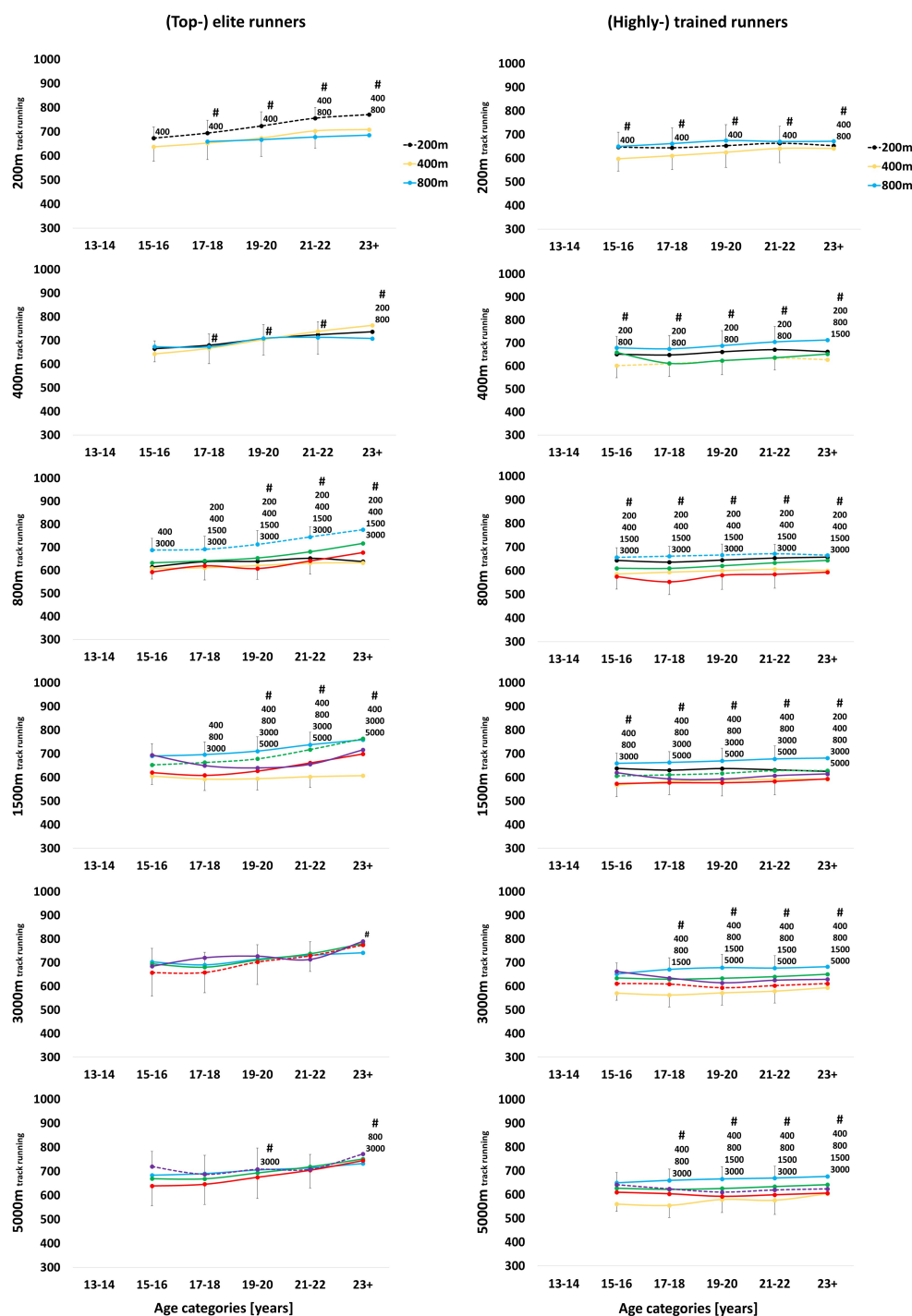


FIGURE 3

Progression of performance points [a.u.] of (top-) elite (1,000-750 performance points) and (highly-) trained *female track runners* (750-550 performance points) across the various age categories [years]. Annual best times of the main race distance (dotted lines) were retrospectively extracted and compared to the individual runners' annual best times of their secondary race distances using linear mixed model analysis, with ²⁰⁰, ⁴⁰⁰, ⁸⁰⁰, ¹⁵⁰⁰, ³⁰⁰⁰ and ⁵⁰⁰⁰ indicating significant differences to specific secondary race distances. For the sake of clarity, significant differences to the previous age category (#) are only indicated for the main race distance.

Technical elements

In addition to the physiological and neuro-muscular specificities of sprint races, technical elements should be considered when discussing differences in specialization pattern.

Swimming is traditionally considered an endurance sport, which requires high training volumes to maximize aerobic capacity and ingrained movement patterns specific to swimming technique (26). The relatively low density of water requires a progressively increasing hand velocity during the arm stroke,

TABLE 3 Progression of performance points [a.u.] of (top-) elite (1,000-750 performance points) and (highly-) trained male freestyle pool swimmers (750-550 performance points) across the various age categories [years].

Main and secondary race distances		Age categories [years]					Linear mixed model analysis		
		13–14	15–16	17–18	19–20	21–22			
(Top-) elite pool swimmers									
50 m	437 ± 80	590 ± 76 ^b	682 ± 70 ^b	730 ± 60 ^b	765 ± 55 ^b	781 ± 43	R _c ² = 0.79 ICC = 0.40	(a) F _[5 6763] = 1235 (b) F _[5 6756] = 243 (c) F _[25 6718] = 15	P < 0.001 P < 0.001 P < 0.001
100 m	468 ± 83 ^a	630 ± 83 ^a	725 ± 74 ^a	777 ± 67 ^a	804 ± 72 ^a	810 ± 72 ^a			
200 m	444 ± 82	589 ± 91	668 ± 89 ^a	707 ± 90 ^a	731 ± 96 ^a	736 ± 96 ^a			
400 m	458 ± 80	585 ± 95	652 ± 102 ^a	699 ± 114 ^a	719 ± 126 ^a	732 ± 106 ^a			
800 m	465 ± 69	546 ± 81 ^a	611 ± 110 ^a	649 ± 114 ^a	687 ± 130 ^a	681 ± 137 ^a			
1,500 m	493 ± 67 ^a	572 ± 89 ^a	631 ± 102 ^a	659 ± 125 ^a	650 ± 112 ^a	646 ± 149 ^a			
50 m	428 ± 77 ^a	570 ± 73 ^a	654 ± 69 ^a	697 ± 65 ^a	724 ± 65 ^a	733 ± 60 ^a	R _c ² = 0.76 ICC = 0.38	(a) F _[5 16118] = 4369 (b) F _[5 16104] = 353 (c) F _[25 15991] = 18	P < 0.001 P < 0.001 P < 0.001
100 m	468 ± 81	623 ± 78 ^b	715 ± 67 ^b	763 ± 59 ^b	790 ± 60 ^b	797 ± 48			
200 m	457 ± 85 ^a	600 ± 88 ^a	686 ± 81 ^a	727 ± 80 ^a	747 ± 84 ^a	746 ± 82 ^a			
400 m	479 ± 88	613 ± 96	687 ± 102 ^a	737 ± 100 ^a	766 ± 103 ^a	763 ± 98 ^a			
800 m	472 ± 81	581 ± 86 ^a	645 ± 99 ^a	697 ± 99 ^a	731 ± 97 ^a	723 ± 107 ^a			
1,500 m	509 ± 81 ^a	612 ± 89 ^a	674 ± 93 ^a	732 ± 98 ^a	737 ± 104 ^a	728 ± 106 ^a			
50 m	415 ± 74 ^a	561 ± 71 ^a	633 ± 73 ^a	668 ± 71 ^a	697 ± 73 ^a	703 ± 73 ^a	R _c ² = 0.78 ICC = 0.33	(a) F _[5 11439] = 5210 (b) F _[5 11433] = 696 (c) F _[25 11359] = 7	P < 0.001 P < 0.001 P < 0.001
100 m	463 ± 77	624 ± 73	713 ± 68	758 ± 64	785 ± 69	789 ± 66			
200 m	470 ± 79	629 ± 75 ^b	722 ± 65 ^b	766 ± 57 ^b	791 ± 54 ^b	791 ± 45			
400 m	501 ± 85 ^a	657 ± 83 ^a	747 ± 77 ^a	790 ± 69 ^a	810 ± 75	800 ± 74			
800 m	491 ± 79 ^a	621 ± 79	710 ± 76	746 ± 84	777 ± 80	773 ± 85			
1,500 m	524 ± 81 ^a	657 ± 80 ^a	730 ± 80	777 ± 87	799 ± 83	796 ± 88			
50 m	385 ± 73 ^a	522 ± 75 ^a	588 ± 72 ^a	622 ± 68 ^a	642 ± 76 ^a	647 ± 78 ^a	R _c ² = 0.81 ICC = 0.39	(a) F _[5 11231] = 5716 (b) F _[5 11207] = 1574 (c) F _[25 11165] = 4	P < 0.001 P < 0.001 P < 0.001
100 m	441 ± 79 ^a	591 ± 77 ^a	671 ± 74 ^a	713 ± 71 ^a	734 ± 76 ^a	735 ± 81 ^a			
200 m	462 ± 80 ^a	615 ± 75 ^a	704 ± 67 ^a	745 ± 64 ^a	765 ± 67 ^a	764 ± 65 ^a			
400 m	506 ± 88	661 ± 81 ^b	755 ± 67 ^b	795 ± 62 ^b	812 ± 60	803 ± 54			
800 m	496 ± 83	636 ± 79 ^a	725 ± 71 ^a	762 ± 69 ^a	780 ± 65 ^a	776 ± 69 ^a			
1,500 m	531 ± 91 [*]	671 ± 78	749 ± 75	793 ± 71	805 ± 70	801 ± 70			
50 m	366 ± 58 ^a	495 ± 72 ^a	559 ± 61 ^a	594 ± 61 ^a	610 ± 70 ^a	607 ± 76 ^a	R _c ² = 0.86 ICC = 0.44	(a) F _[5 5925] = 3645 (b) F _[5 5912] = 1700 (c) F _[25 5901] = 2	P < 0.001 P < 0.001 P = 0.011
100 m	430 ± 72 ^a	574 ± 74 ^a	643 ± 74 ^a	688 ± 65 ^a	698 ± 73 ^a	702 ± 78 ^a			
200 m	461 ± 74 ^a	607 ± 74 ^a	691 ± 68 ^a	729 ± 62 ^a	749 ± 69 ^a	748 ± 69 ^a			
400 m	513 ± 78	667 ± 78	759 ± 66	802 ± 61	821 ± 60	813 ± 59			
800 m	505 ± 73	649 ± 77 ^b	741 ± 67 ^b	782 ± 61 ^b	800 ± 56	801 ± 49			
1,500 m	542 ± 83 ^a	684 ± 76 ^a	766 ± 72 ^a	808 ± 67 ^a	824 ± 61 ^a	821 ± 56 ^a			
50 m	351 ± 55 ^a	481 ± 75 ^a	545 ± 62 ^a	577 ± 61 ^a	596 ± 72 ^a	593 ± 75 ^a	R _c ² = 0.88 ICC = 0.48	(a) F _[5 5476] = 3609 (b) F _[5 5462] = 1787 (c) F _[25 5454] = 2	P < 0.001 P < 0.001 P = 0.017
100 m	409 ± 67 ^a	556 ± 76 ^a	626 ± 73 ^a	670 ± 63 ^a	678 ± 73 ^a	676 ± 71 ^a			
200 m	442 ± 72 ^a	591 ± 77 ^a	673 ± 67 ^a	712 ± 61 ^a	726 ± 68 ^a	727 ± 67 ^a			
400 m	498 ± 79 ^a	654 ± 85 ^a	748 ± 69	791 ± 64	809 ± 62	798 ± 62			
800 m	495 ± 72 ^a	644 ± 77 ^a	733 ± 70 ^a	777 ± 63 ^a	794 ± 59 ^a	790 ± 55 ^a			
1,500 m	530 ± 87	679 ± 78 ^b	761 ± 74 ^b	807 ± 66 ^b	823 ± 60	818 ± 53			
(Highly-) trained pool swimmers									
50 m	385 ± 76	504 ± 72 ^b	577 ± 66 ^b	608 ± 65 ^b	625 ± 66 ^b	626 ± 55	R _c ² = 0.73 ICC = 0.51	(a) F _[5 43650] = 8034 (b) F _[5 43614] = 462 (c) F _[25 43393] = 33	P < 0.001 P < 0.001 P < 0.001
100 m	412 ± 85 ^a	546 ± 84 ^a	625 ± 77 ^a	658 ± 75 ^a	675 ± 76 ^a	667 ± 78 ^a			
200 m	408 ± 87 ^a	530 ± 89 ^a	601 ± 92 ^a	634 ± 95	649 ± 97	636 ± 102 ^a			
400 m	431 ± 92 ^a	549 ± 100 ^a	615 ± 108 ^a	648 ± 116	673 ± 117 ^a	650 ± 128			
800 m	431 ± 84 ^a	530 ± 90	593 ± 102	622 ± 111 ^a	651 ± 115 ^a	628 ± 132 ^a			
1,500 m	465 ± 89 ^a	560 ± 96 ^a	624 ± 103 ^a	654 ± 113	687 ± 107	650 ± 134			
50 m	371 ± 73 ^a	486 ± 71 ^a	553 ± 66 ^a	585 ± 64 ^a	601 ± 67 ^a	599 ± 62 ^a	R _c ² = 0.75 ICC = 0.51	(a) F _[5 44467] = 11189 (b) F _[5 44381] = 620 (c) F _[25 44160] = 40	P < 0.001 P < 0.001 P < 0.001
100 m	399 ± 81	528 ± 80 ^b	605 ± 71 ^b	635 ± 67 ^b	647 ± 68 ^b	638 ± 58			
200 m	400 ± 82	520 ± 86 ^a	590 ± 84 ^a	617 ± 86 ^a	627 ± 85 ^a	608 ± 87 ^a			
400 m	424 ± 86 ^a	544 ± 96	610 ± 102	636 ± 109 ^a	656 ± 110 ^a	633 ± 119 ^a			
800 m	429 ± 75 ^a	533 ± 90 ^a	596 ± 101 ^a	627 ± 108 ^a	651 ± 115 ^a	622 ± 128 ^a			
1,500 m	459 ± 82 ^a	561 ± 95 ^a	627 ± 101	657 ± 108	683 ± 110	648 ± 133 ^a			
50 m	378 ± 74 ^a	493 ± 72 ^a	561 ± 71 ^a	597 ± 71 ^a	614 ± 78 ^a	617 ± 78 ^a	R _c ² = 0.75 ICC = 0.49	(a) F _[5 30198] = 9397 (b) F _[5 30128] = 936 (c) F _[25 29984] = 33	P < 0.001 P < 0.001 P < 0.001
100 m	415 ± 82	546 ± 79	623 ± 72	657 ± 71	674 ± 76 ^a	672 ± 73 ^a			
200 m	419 ± 82	548 ± 80 ^b	621 ± 75 ^b	651 ± 71 ^b	659 ± 68	642 ± 59 ^b			
400 m	452 ± 88 ^a	576 ± 87 ^a	641 ± 88 ^a	669 ± 89 ^a	681 ± 86 ^a	657 ± 88 ^a			
800 m	450 ± 78 ^a	557 ± 85	619 ± 91	654 ± 91	667 ± 94	646 ± 101			
1,500 m	481 ± 83 ^a	586 ± 87 ^a	648 ± 92 ^a	682 ± 95 ^a	696 ± 95 ^a	678 ± 107 ^a			

(Continued)

TABLE 3 Continued

Main and secondary race distances	Age categories [years]						Linear mixed model analysis		
	13–14	15–16	17–18	19–20	21–22	23+			
50 m	360 ± 71 ^a	471 ± 74 ^a	533 ± 74 ^a	567 ± 74 ^a	581 ± 80 ^a	585 ± 78 ^a	$R^2_c = 0.78$ ICC = 0.54	(a) $F_{[5 16467]} = 6032$ (b) $F_{[5 16412]} = 978$ (c) $F_{[25 16370]} = 25$	$P < 0.001$ $P < 0.001$ $P < 0.001$
100 m	401 ± 80 ^a	527 ± 79 ^a	597 ± 77 ^a	630 ± 77 ^a	648 ± 83 ^a	646 ± 81			
200 m	413 ± 78 ^a	539 ± 79 ^a	610 ± 75 ^a	638 ± 75 ^a	651 ± 74 ^a	639 ± 71			
400 m	449 ± 81	571 ± 84^b	639 ± 83^b	665 ± 78^b	669 ± 78	643 ± 61^b			
800 m	448 ± 71	552 ± 79 ^a	614 ± 84 ^a	642 ± 81 ^a	644 ± 81 ^a	622 ± 72 ^a			
1500 m	477 ± 76 ^a	582 ± 80	640 ± 85	668 ± 82	670 ± 85	649 ± 80			
50 m	357 ± 75 ^a	474 ± 80 ^a	530 ± 79 ^a	563 ± 76 ^a	586 ± 80 ^a	582 ± 80 ^a	$R^2_c = 0.80$ ICC = 0.54	(a) $F_{[5 9986]} = 4146$ (b) $F_{[5 9952]} = 918$ (c) $F_{[25 9939]} = 11$	$P < 0.001$ $P < 0.001$ $P < 0.001$
100 m	400 ± 80 ^a	528 ± 83 ^a	593 ± 82 ^a	628 ± 79 ^a	653 ± 84 ^a	644 ± 84			
200 m	417 ± 81 ^a	549 ± 79 ^a	618 ± 78 ^a	646 ± 81	665 ± 79	652 ± 76			
400 m	453 ± 81	586 ± 82 ^a	657 ± 85 ^a	685 ± 83 ^a	698 ± 78 ^a	666 ± 73 ^a			
800 m	452 ± 73	570 ± 71	633 ± 80	661 ± 79	670 ± 73	644 ± 60			
1,500 m	479 ± 81 ^a	597 ± 75 ^a	656 ± 82 ^a	688 ± 79 ^a	693 ± 75 ^a	668 ± 69 ^a			
50 m	353 ± 69 ^a	468 ± 73 ^a	520 ± 77 ^a	550 ± 77 ^a	565 ± 79 ^a	563 ± 75 ^a	$R^2_c = 0.80$ ICC = 0.55	(a) $F_{[5 7478]} = 2855$ (b) $F_{[5 7451]} = 701$ (c) $F_{[25 7442]} = 8$	$P < 0.001$ $P < 0.001$ $P < 0.001$
100 m	396 ± 79 ^a	523 ± 75 ^a	584 ± 77 ^a	614 ± 78 ^a	631 ± 83 ^a	624 ± 79 ^a			
200 m	416 ± 76 ^a	540 ± 75 ^a	604 ± 77 ^a	626 ± 80 ^a	645 ± 81 ^a	633 ± 75 ^a			
400 m	447 ± 78 ^a	578 ± 79	642 ± 82	666 ± 79	674 ± 79	650 ± 73			
800 m	449 ± 71 ^a	564 ± 70 ^a	622 ± 81	641 ± 79 ^a	650 ± 72	626 ± 64 ^a			
1,500 m	477 ± 80	589 ± 74^b	641 ± 81^b	663 ± 78^b	669 ± 74	647 ± 59^b			

Annual best times of the main race distance (dotted lines) were retrospectively extracted and compared to the individual swimmers' annual best times of their secondary race distances. For the sake of clarity, significant differences to the previous age category are only indicated for the main race distance.

R^2_c , R-squared conditional; ICC, intra-class correlation coefficient.

Bold indicates main race distances.

Linear mixed model analysis:

a) Main effect: age category (13–14 vs. 15–16 vs. 17–18 vs. 19–20 vs. 21–22 vs. 23+).

b) Main effect: race distance (50 m vs. 100 m vs. 200 m vs. 400 m vs. 800 m vs. 1500 m).

c) Interaction effect: age category × performance level.

Bonferroni *post-hoc* comparison:

^aSignificant difference to the main race distance.

^bSignificant difference to previous age category.

with minimal adjustments affecting optimal usage of the hydrodynamic lift, to allow for effective water-based movement (61, 62). Based on the fact that swimming involves different conversion of metabolic to mechanical power than land-based movement patterns, i.e., running (19), large training volumes are commonly prescribed to maximize the technical learning experience (23, 26). This aerobic culture of the sport may provide good development opportunities for middle-distance swimmers, whose distance variety covers more long-distance rather than sprint race. However, the higher velocities during sprint races require a higher cadence, which swimmers must translate into propulsion without losing traction, control of the water resistance and hydrodynamic lift during the in-water phase of the arm stroke (63–65). Additionally, the high cadence of sprint swimming does not allow for a completely relaxed arm and strict high elbow position during the overwater phase of the arm stroke. Instead, sprinter swing their arm forward with a more extended elbow and show fewer intra-cyclic gliding phases compared to middle- and long-distance swimmers (66, 67). This sprint-specific swimming technique, e.g., underwater hand trajectories, arm stroke, shoulder and hip roll at a high cadence (65, 68), are unlikely to develop during long-slow distance training. Instead, aerobic sessions should only be used

to provide sufficient ability to recovery and to improve resilience to maximize volume of velocity-specific sets, i.e., 15–25 m bouts at and above race-pace (24, 69).

Aerobic aspects and over-distance training

Throughout the development process, junior swimmers are typically developed from longer to shorter race distances, due to the over-distance oriented training approach (26, 70). In contrast, track sprinters (runners) aim for shorter sprints at younger ages and progress to longer race distances throughout adolescence in many countries, i.e., 60 m (U14), 80 m (U16) and 100 m [U18 and older (71, 72)]. While maximal sprint velocity and basic speed abilities can be developed from an early age in an athlete's career, insights from other endurance sports show that the aerobic capacity develops over consecutive years of training and that resilience for longer race distances increases with ages (73–75). Due to the technical challenge of translating a high stroke rate into propulsion (63–65), sprint swimmers in particular may benefit from an early focus on sprint speed, while their aerobic capacity could develop over the years of training (73, 75).

TABLE 4 Progression of performance points [a.u.] of (top-) elite (1,000-750 performance points) and (highly-) trained male track runners (750-550 performance points) across the various age categories [years].

Main and secondary race distances	Age categories [years]						Linear mixed model analysis		
	13–14	15–16	17–18	19–20	21–22	23+			
(Top-) elite track runners									
200 m		686 ± 36	713 ± 47 ^b	738 ± 50 ^b	761 ± 52 ^b	776 ± 41 ^b	R _c ² = 0.51 ICC = 0.39	(a) F _[4 2660] = 11	P < 0.001
400 m		708 ± 43	730 ± 47	743 ± 60	772 ± 64	763 ± 67 ^a		(b) F _[2 2720] = 7	P = 0.001
800 m				710 ± 20	715 ± 40	722 ± 23		(c) F _[8 2636] = 6	P < 0.001
200 m		671 ± 29 ^a	696 ± 43 ^a	716 ± 48 ^a	728 ± 51 ^a	730 ± 49 ^a	R _c ² = 0.62 ICC = 0.46	(a) F _[4 3337] = 127	P < 0.001
400 m		705 ± 41	731 ± 49 ^b	756 ± 52 ^b	774 ± 54 ^b	782 ± 43		(b) F _[2 3406] = 211	P < 0.001
800 m		707 ± 25	730 ± 49	752 ± 51	776 ± 60	776 ± 67		(c) F _[8 3300] = 2	P = 0.115
200 m		653 ± 16 ^a	671 ± 21 ^a	679 ± 42 ^a	673 ± 42 ^a	687 ± 41 ^a	R _c ² = 0.67 ICC = 0.49	(a) F _[4 4699] = 79	P < 0.001
400 m		665 ± 28 ^a	687 ± 38 ^a	698 ± 43 ^a	704 ± 49 ^a	700 ± 48 ^a		(b) F _[4 4753] = 258	P < 0.001
800 m		737 ± 39	743 ± 48	764 ± 49 ^b	782 ± 50 ^b	788 ± 45		(c) F _[16 4669] = 6	P < 0.001
1,500 m		740 ± 55	726 ± 44 ^a	740 ± 52 ^a	758 ± 57 ^a	760 ± 60 ^a	R _c ² = 0.65 ICC = 0.52	(a) F _[4 4372] = 111	P < 0.001
3,000 m			666 ± 54 ^a	691 ± 54 ^a	702 ± 52 ^a	725 ± 56 ^a		(b) F _[3 4410] = 117	P < 0.001
400 m		681 ± 33	678 ± 32 ^a	686 ± 40 ^a	686 ± 37 ^a	680 ± 35 ^a		(c) F _[12 4335] = 12	P < 0.001
800 m		737 ± 43	734 ± 42	752 ± 49	767 ± 52	769 ± 53 ^a	R _c ² = 0.69 ICC = 0.62	(a) F _[4 1295] = 112	P < 0.001
1,500 m		725 ± 55	727 ± 44	744 ± 49 ^b	764 ± 52 ^b	781 ± 44 ^b		(b) F _[2 1273] = 10	P < 0.001
3,000 m		689 ± 29	670 ± 41 ^a	696 ± 52 ^a	716 ± 58 ^a	741 ± 59 ^a		(c) F _[8 1276] = 9	P < 0.001
800 m			733 ± 33 ^a	745 ± 44	757 ± 51	759 ± 45 ^a	R _c ² = 0.65 ICC = 0.60	(a) F _[4 2017] = 99	P < 0.001
1,500 m		770 ± 79	731 ± 49 ^a	754 ± 55 ^a	772 ± 58 ^a	786 ± 52		(b) F _[3 2019] = 2	P = 0.081
3,000 m		732 ± 77	703 ± 71	729 ± 75 ^b	749 ± 74 ^b	781 ± 47 ^b		(c) F _[12 1994] = 3	P < 0.001
800 m			742 ± 43	741 ± 47	760 ± 48	765 ± 51	R _c ² = 0.65 ICC = 0.60	(a) F _[4 2017] = 99	P < 0.001
1,500 m		767 ± 36	747 ± 54	754 ± 57	770 ± 55	778 ± 54		(b) F _[3 2019] = 2	P = 0.081
3,000 m		768 ± 63	718 ± 72	741 ± 82	758 ± 73	779 ± 56		(c) F _[12 1994] = 3	P < 0.001
5,000 m		771 ± 26	748 ± 75	737 ± 73	748 ± 65 ^b	779 ± 46 ^b			
(Highly-) trained track runners									
200 m		672 ± 33	678 ± 36 ^b	686 ± 39 ^b	692 ± 41 ^b	681 ± 33 ^b	R _c ² = 0.53 ICC = 0.45	(a) F _[4 6578] = 20	P < 0.001
400 m		686 ± 35	699 ± 43 ^a	711 ± 46 ^a	721 ± 49 ^a	717 ± 47 ^a		(b) F _[2 6746] = 152	P < 0.001
800 m		731 ± 21	713 ± 22	721 ± 39 ^a	731 ± 39 ^a	736 ± 41 ^a		(c) F _[8 6536] = 8	P < 0.001
200 m		662 ± 33	676 ± 40 ^a	684 ± 43 ^a	690 ± 47 ^a	684 ± 45 ^a	R _c ² = 0.59 ICC = 0.41	(a) F _[4 6171] = 102	P < 0.001
400 m		676 ± 29	686 ± 37 ^b	695 ± 37 ^b	703 ± 40 ^b	687 ± 31 ^b		(b) F _[2 6393] = 264	P < 0.001
800 m		720 ± 23	730 ± 34 ^a	749 ± 45 ^a	762 ± 52 ^a	765 ± 50 ^a		(c) F _[8 6059] = 23	P < 0.001
400 m		669 ± 26 ^a	682 ± 45 ^a	690 ± 45 ^a	692 ± 51 ^a	691 ± 46 ^a	R _c ² = 0.44 ICC = 0.37	(a) F _[4 3353] = 27	P < 0.001
800 m		708 ± 19	715 ± 31	723 ± 36 ^b	726 ± 35	712 ± 23 ^b		(b) F _[2 3393] = 68	P < 0.001
1,500 m		682 ± 23	701 ± 31 ^a	712 ± 32 ^a	720 ± 38 ^a	715 ± 42		(c) F _[8 3246] = 9	P < 0.001
800 m		719 ± 21	719 ± 37 ^a	729 ± 41 ^a	735 ± 43 ^a	735 ± 44 ^a	R _c ² = 0.54 ICC = 0.43	(a) F _[4 4572] = 46	P < 0.001
1,500 m		732 ± 35	703 ± 37	708 ± 36 ^b	715 ± 34 ^b	694 ± 32 ^b		(b) F _[2 4571] = 84	P < 0.001
3,000 m		659 ± 29	663 ± 32 ^a	668 ± 38 ^a	680 ± 44 ^a	682 ± 43 ^a		(c) F _[8 4368] = 18	P < 0.001
800 m			718 ± 37 ^a	723 ± 36 ^a	733 ± 38 ^a	727 ± 38 ^a	R _c ² = 0.59 ICC = 0.47	(a) F _[4 2344] = 31	P < 0.001
1,500 m		697 ± 34	712 ± 35 ^a	717 ± 42 ^a	722 ± 43 ^a	718 ± 43 ^a		(b) F _[2 2247] = 35	P < 0.001
3,000 m		687 ± 69	669 ± 42	668 ± 33	677 ± 39 ^b	673 ± 32		(c) F _[8 2260] = 1	P < 0.479
1,500 m		674 ± 30	706 ± 29 ^a	716 ± 36 ^a	724 ± 41 ^a	720 ± 42 ^a	R _c ² = 0.60 ICC = 0.50	(a) F _[4 4270] = 72	P < 0.001
3,000 m		673 ± 39	667 ± 33	674 ± 37	681 ± 41	687 ± 41 ^a		(b) F _[2 4077] = 35	P < 0.001
5,000 m		709 ± 80	677 ± 43	677 ± 47	686 ± 44 ^b	675 ± 38		(c) F _[8 4088] = 6	P < 0.001

Annual best times of the main race distance (dotted lines) were retrospectively extracted and compared to the individual swimmers' annual best times of their secondary race distances. For the sake of clarity, significant differences to the previous age category are only indicated for the main race distance.

R_c^2 , R-squared conditional; ICC, intra-class correlation coefficient.

Bold indicates main race distances.

Linear mixed model analysis:

a) Main effect: age category (13–14 vs. 15–16 vs. 17–18 vs. 19–20 vs. 21–22 vs. 23+).

b) Main effect: race distance (200 m vs. 400 m vs. 800 m vs. 1,500 m vs. 3,000 m vs. 5,000 m).

c) Interaction effect: age category $\times$ performance level.

Bonferroni *post-hoc* comparison:

^aSignificant difference to the main race distance.

^bSignificant difference to previous age category.

Other disciplines in the sport

Training regimes are also affected by the other disciplines in the sport. Since most track and field disciplines rely on explosive strength, i.e., jumping, throwing and sprinting, the general athletic education is more oriented towards strength, speed and power. In contrast, with race times of more than one minute, the majority of swimming events rely mostly on aerobic energy contribution (33, 34), which explains the over-distance oriented training approaches (26). However, with the increasing importance of the acyclic elements, i.e., start and turn (52, 53, 55), placing more focus on dry-land training strategies from an early stage in swimming careers may help develop specific key performance indicators (21, 57). Future research should determine optimal ratios between dry-land and specific pool-based training, as well as volume and intensity during in-water sessions (21, 57, 76). This is also important in regard to the earlier performance plateaus evident in swimmers compared to runners, which indicates that key performance indicators related to swimming-specific physical fitness have not yet reached their full potential. Earlier and greater specialization on specific race distances and further development of strength and conditioning regimes may improve swimming performances and even world records in the future.

Study limitations

The present study is based on race results that only allow retrospective analyses of performance pattern. By clustering performance groups, i.e., world-class finalists, international-, national- and regional-class athletes, in two sports, we aimed to discover the most promising development strategies, draw parallels and highlight differences between swimming and running. However, although development strategies of world-class athletes may have worked well in the past, they may not be the ideal for the future. Thus, the results of the present study can only provide a starting point for the development of new training strategies.

Infrastructural aspects need to be considered as well and may affect the development of optimal swimming technique (77). Compared to track runners, who have large track-and-field grounds and the option to complete aerobic sets, i.e., long-slow distance training, outside the running track, swimming pools are less spacious training facilities. In some countries, swimming clubs and teams have to share pools with the public and lane use is limited. Particularly at junior age, before swimmers train in national training centers (24, 70), sprint talents cannot be placed in a separate training group—due to infrastructure constraints—and often train in the same lane as middle-distance and long-distance swimmers. Hence, the volume-oriented programs do not allow for optimal training differentiation and development of sprint abilities. Even with knowledge of optimal development strategies, infrastructural aspects need to be considered and will

affect knowledge transfer into the daily training and competition routine of coaches and athletes.

Conclusion

Although, sprinters specialize more than middle- and long-distance swimmers, as do (top-) elite compared to (highly-) trained swimmers, the comparison to similar race distances (timewise) in track running indicates that swimmers have a larger within-sport distance variety compared to runners. The early performance plateau towards senior age, the large within-sport distance-variety and high reliance of key performance indicators on technical elements indicate that swimmers may not yet use their full physiological potential.

Since the majority of events favors aerobic and over-distance training, the landscape of competitive swimming does not provide an optimal environment for the development of sprint swimmers. The comparison with track running indicates that sprint swimmers may require an even earlier and higher degree of specialization with more attention to explosivity-oriented training regimes and frequent race-pace specific training sessions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by institutional review board of the Swiss Federal Institute of Sport Magglingen (Reg.-Nr. 222_LSP_Born_03_2024). The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee waived the requirement of written informed consent for participation as only publicly available data are included and were analyzed anonymously. Explicit written consent from the athletes was not required.

Author contributions

D-PB: Conceptualization, Data curation, Formal Analysis, Investigation, Funding acquisition, Visualization, Writing – original draft. MR: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Visualization, Writing – original draft. JL: Conceptualization, Data curation, Formal Analysis, Writing – review & editing. DZ: Data curation, Writing – review & editing. AF: Conceptualization, Data curation, Investigation, Writing – review & editing. JR-N:

Conceptualization, Data curation, Formal Analysis, Investigation, Visualization, Writing – original draft.

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The relationship between maximal lactate accumulation rate and sprint performance parameters in male competitive swimmers

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This study aimed to examine the relationship between the maximal lactate accumulation rate ($\dot{c}La_{max}$) and sprint performance parameters in male competitive swimmers. Seventeen male competitive swimmers volunteered to perform a 20 m maximal front crawl sprint without pushing off the wall from a floating position. $\dot{c}La_{max}$ was determined by the 20-m sprint time and blood lactate measured before and after the 20 m sprint. For the sprint performance parameter, a 50 m time trial with the front crawl swimming stroke was conducted, and the times taken from 0 to 15 m, 15–25 m, 25–35 m, and 35–45 m were analyzed. A semi-tethered swimming test was conducted to investigate the load-velocity profile of each swimmer. From the load-velocity profile, theoretical maximal velocity (V_0), maximal load (L_0) and relative maximal load (rL_0) were examined. The slope of the load-velocity profile was also determined. According to the results, $\dot{c}La_{max}$ correlated with 50 m front crawl performance ($r = -.546$, $p < .05$). Moreover, a higher $\dot{c}La_{max}$ was related to faster 0–35 m section time. Furthermore, $\dot{c}La_{max}$ correlated with L_0 ($r = .837$, $p < .01$), rL_0 ($r = .820$, $p < .01$), and load-velocity slope ($r = .804$, $p < .01$). $\dot{c}La_{max}$ is a good indicator of 50 m front crawl performance in male swimmers, and higher glycolytic power contributes to the faster time at the beginning of the sprint race. $\dot{c}La_{max}$ could also evaluate the ability of a swimmer to apply force to the water during high-intensity swimming.

KEYWORDS

anaerobic capacity, glycolytic power, blood lactate, load-velocity profile, front crawl swimming

1 Introduction

Competitive swimming events include different distances, from 50 m to 1,500 m. The energy required to swim these distances is supplied by the aerobic and anaerobic systems; the relative contributions of each energy system vary depending on the duration of each race (1). Therefore, improvements in both energy systems are essential to enhance swimming performance, and effective monitoring is key to assessing the impact of training and achieving successful performance (2).

Several reliable parameters are available to monitor aerobic capacity in swimmers, including lactate threshold (3, 4), onset of blood lactate accumulation (5), and critical velocity (4, 6). Measurement of maximal accumulated oxygen uptake (MAOD) is widely used to assess anaerobic capacity in sports and is also used in swimming (7–9). However, MAOD is a time-consuming procedure to measure, and it may not be a fully defensible method to determine anaerobic capacity (10). Therefore, alternative practical methods and indices have been explored (11, 12).

The maximal lactate accumulation rate ($\dot{c}La_{max}$) is also an index to access anaerobic capacity. $\dot{c}La_{max}$ is calculated by dividing the maximum difference in blood lactate (Bla) before and after a maximal sprint by the sprint time, which is reportedly a parameter to evaluate the athlete's glycolytic power (13). Due to its applicability in the training setting, $\dot{c}La_{max}$ regained popularity and was investigated recently in cycling (14, 15), running (16), and rowing exercises (17). In addition, Quittmann et al. (16) investigated $\dot{c}La_{max}$ during 100 m sprint running and reported that $\dot{c}La_{max}$ was significantly correlated with sprint performance parameters, suggesting that it can be used as a sport-specific field test. $\dot{c}La_{max}$ reportedly differs between handcycling and cycling (15) or cycling and running (18) even when investigated in the same individual, so it has been suggested that $\dot{c}La_{max}$ is an extremity and movement-specific parameter.

$\dot{c}La_{max}$ has also been investigated in swimming (19). Sperlich et al. (20) reported that $\dot{c}La_{max}$ increases with high intensity interval training and decreases with high volume training, and that $\dot{c}La_{max}$ is sensitive to detecting the change of anaerobic capacity in swimmers. Studies on the relationship between $\dot{c}La_{max}$ and sprint performance in swimming have yet to reach consensus. Mavroudi et al. (21) reported a significant correlation between 50 m sprint performance and $\dot{c}La_{max}$ which was investigated at that sprint. On the other hand, Kellar and Wahl (22) reported no significant correlation between $\dot{c}La_{max}$ assessed by a 20-s sprint test and the average velocity of a 50 m official race. Thus, it is still being determined whether $\dot{c}La_{max}$ is a genuinely valid measure that can assess anaerobic capacity in swimmers.

Mechanical power is one of the factors that determines maximal swimming velocity (23). Even a semi-tethered swimming test cannot evaluate pure propulsive power, Gonjo et al. (24) reported that the index of the load-velocity profile investigated by semi-tethered swimming can be used to evaluate sprint swimming performance. Their findings revealed that theoretical maximal velocity (V_0), maximal load (L_0), and load-velocity slope were significantly correlated with the mean velocity of a 50 m front crawl trial. Given the potential of these indices as indicators of sprinting ability, understanding the relationship between $\dot{c}La_{max}$ and these parameters could shed light on whether pure physiological capacity is related to sprinting ability in swimming. If glycolytic power is indeed related to sprint performance parameters, this approach would allow for a more comprehensive understanding of sprint swimming performance, combining both mechanical and physiological aspects.

The purpose of the present study was to investigate the relationship between $\dot{c}La_{max}$ and parameters related to sprint

performance in male competitive swimmers. The primary hypothesis of this study was that $\dot{c}La_{max}$ negatively correlates with 50 m race time. Secondly, we hypothesized that $\dot{c}La_{max}$ positively correlates with parameters related to sprint performance (such as V_0 and L_0) estimated by the load-velocity profile. By addressing these research objectives, we provide valuable insights into the use of $\dot{c}La_{max}$ as an index of anaerobic capacity in competitive swimming.

2 Materials and methods

2.1 Participants

Seventeen well-trained male competitive swimmers participated in this study. The personal characteristics of the swimmers are shown in Table 1. Four swimmers specialized in short-distance front crawl, five in middle-distance front crawl, five in butterfly, two in backstroke, and one in individual medley. All swimmers (who were from the same university swimming team) had engaged in competitive swimming for over 6 years and competed at national-level championships. The World Aquatics point scoring of the swimmers' personal best records of their major event was 751.8 ± 68.1 point. The participants were made fully aware of the risks, benefits, and stress factors of the study and gave their written consent to participate. In addition, the participants were instructed to refrain from caffeine intake within 12 h, and water was only allowed within 2 h of testing. This study received the formal approval of the Research Ethics Committee of the authors' institution (No. 024-23) in compliance with the Declaration of Helsinki.

2.2 Experimental procedure

All experiments were scheduled during the general and preparation period of the training season (2) and conducted in an indoor 50 m pool. Participants were instructed to conduct a self-selected warm-up mimicking their competition routine. This was followed by 5 min of passive rest while seated. The duration of the rest period was in accordance with previous research (15, 17, 18). After the passive rest, the participants performed a 20 m all-out front crawl sprint swim without pushing off the wall to evaluate $\dot{c}La_{max}$. In this trial, the participants were instructed to accelerate as fast as possible from a floating position at the 5 m point until they passed the 25 m point. Thereafter, a 50 m time trial and semi-tethered swimming test with a front crawl were conducted to investigate the sprint performance parameters. All experiments were separately conducted with minimum interval of 16 h and performed within one week.

2.3 $\dot{c}La_{max}$ investigation

Olbrecht (19) recommends that $\dot{c}La_{max}$ should be obtained and measured during a maximal sprint exercise of 10–15 s. In

TABLE 1 Participants' physical characteristics, major swimming style and performance level. The World Aquatics point scoring of the swimmers' personal best records of their major event is demonstrated.

Subject	Body height	Body mass	Age	Major swimming style	World aquatics point
	(cm)	(kg)	(yrs)		
A	178.0	85.0	24	Butterfly	840
B	175.0	69.0	22	Front crawl (Short)	632
C	176.0	78.0	21	Backstroke	843
D	175.0	72.0	21	Front crawl (Short)	791
E	169.0	73.0	20	Butterfly	737
F	170.0	67.0	21	Butterfly	720
G	178.0	77.0	19	Front crawl (Short)	787
H	172.0	67.0	19	Front crawl (Short)	655
I	172.0	70.0	18	Butterfly	727
J	178.0	74.0	19	Backstroke	739
K	165.0	64.0	22	Front crawl (Middle)	601
L	170.0	69.0	20	Front crawl (Middle)	789
M	173.0	71.0	19	Front crawl (Middle)	776
N	177.0	73.0	19	Front crawl (Middle)	785
O	173.0	67.0	19	Front crawl (Middle)	797
P	175.0	69.0	18	Butterfly	787
Q	170.0	70.0	18	Individual Medley	775
Ave	173.3	71.5	19.9		751.8
SD	3.7	5.0	1.7		68.1

swimming, Mavroudi et al. (21) reported that $\dot{c}La_{\max}$ values obtained in a 25 m all-out swim were significantly higher than those obtained in 35 m and 50 m all-out swims, shorter duration is appropriate for investigating $\dot{c}La_{\max}$. Instead of a 25 m all-out swim, we adopted a 20 m sprint swim of front crawl starting from a floating position at the 5 m mark. As it is reported that $\dot{c}La_{\max}$ is a limb and movement specific parameter (15, 18), this procedure eliminates the movement of the block start or wall push and the underwater phase and make it possible to execute the sprint exercise with front crawl swimming movement only. Our preliminary investigation confirmed that the duration of this swim sprint can last approximately 11 s, which falls within the range recommended by Olbrecht (19). $\dot{c}La_{\max}$ was determined using Equation 1 (13, 19, 25):

$$\dot{c}La_{\max} = (La_{\max} - La_{\text{pre}}) / (t_{\text{sprint}} - t_{\text{alac}}) \quad (1)$$

where $La_{\max}$ is the highest Bla after the 20 m sprint, La_{pre} is the Bla measured during the passive rest before the sprint, t_{sprint} is the time to complete the 20 m sprint, and t_{alac} is the estimated time when energy is delivered by the alactic system.

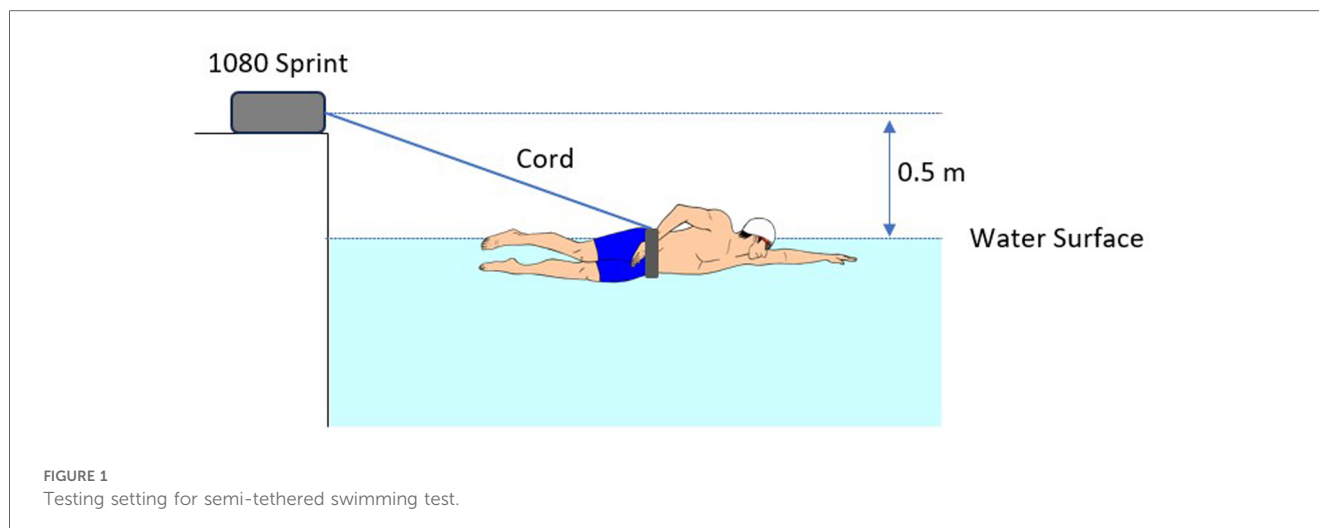
Bla was measured using a portable analyzer (Lactate Pro2, LT-1730, Arkray, Kyoto, Japan). Considering the reliability and accuracy of the measurement device (26), each Bla was examined using two analyzers, and then the average value was used for analysis. Immediately after completing the 20 m sprint swim, participants were seated on the pool deck. An examiner started a stopwatch at the moment swimmer completed the 20 m sprint. Blood was sampled from the fingertips at precise one-minute intervals. The sampling and measurement process continued until the mean Bla value was lower than the previous measurement, indicating that the peak had been reached and

passed. The timing of the blood sampling was consistent for all participants, ensuring standardized data collection across the study. The highest value was taken as $La_{\max}$, and the time to reach $La_{\max}$ after the sprint ($tLa_{\max}$) was also examined. Two digital cameras (GC-IJ20B; Sports Sensing, Fukuoka, Japan) were set at 5 m and 25 m points to capture the timing of the passage of an LED marker attached to the participant's head through 5 m and 25 m marks of the pool. Their passing times and t_{sprint} were analyzed using 2-D motion analysis software (Frame Dias V, Q'sfix, Tokyo, Japan). Camera synchronization was achieved through an LED system (LED synchronizer, Q'sfix). t_{alac} is the period at the beginning of exercise for which no lactate production is assumed. In cycling exercise, t_{alac} can be determined as the time when power output decreased by 3.5% from peak power output directly measured during the maximal sprint (27, 28). However, as it is difficult to measure the power output during swimming exercise, a fixed standard value of 3 s was used for t_{alac} in this study according to previous research (13, 29). Eleven participants were retested with the same procedure within 4 days to confirm the reliability of the measurement data.

2.4 Sprint performance parameters

2.4.1 50 m maximal trial

The 50 m time trial required participants to swim front crawl with maximum effort for the sprint performance parameter. After a self-selected warm-up on land and in water, the trial was performed starting from the starting block. The maximal trial was conducted by each swimmer at the center lane of the pool to avoid pacing strategies. The 50 m time trial was recorded by panning one digital video camera (60 fps, GC-IJ20B; Sports



Sensing) from the second floor of the indoor pool. The timing when the swimmer's head passed the 15, 25, 35, and 45 m point, which was marked on both side of the lane ropes, and the timing swimmer's hand touched the wall after the starting signal was investigated by feeding the video recording frame by frame at a frame rate of 60 fps. This procedure was repeated three times by the same researcher, and the total time to complete 50 m swim (t_{50}) and the section time of 0–15 m, 15–25 m, 25–35 m, and 35–45 m distances were analyzed.

2.4.2 Load-velocity profile

To obtain the load-velocity profile of each participant, a semi-tethered swimming test was performed using a portable robotic resistance device “1080 sprint” (1080 Motion, Lidingö, Sweden). The device was positioned 0.5 m above the water surface on the starting side of the pool (Figure 1). Participants were instructed to wear a swim belt for resisted sprint training around their pelvis (Long Belt Slider S11875, StrechCordz, Bloomington, IL, USA), which was connected to the cord of the resistance device. Each sprint began with a push-off start in the water, and the participants were instructed to start swimming before reaching the 5 m mark. After the warm-up, participants had to perform five 25 m front crawl sprints with maximal effort. There was a rest interval of more than 6 min between each sprint. The instantaneous time-swim velocity data were collected at 333 Hz. The mean velocity during the three stroke cycles between 10 and 20 m section was analyzed using the 1080 sprint software. The velocity measurement cord was not aligned with the swimming direction because the measurement device was placed 0.5 m above the water surface. As a result, the measured velocity was adjusted to the horizontal velocity based on Gonjo et al. (30).

The load-velocity profile of the sprint swim was calculated. The added loads for each sprint were 1, 3, 5, 7, and 9 kg (investigated in ascending order). Olstad et al. (31) reported that 9 kg load imposed more than a 50% velocity reduction compared to a 1 kg load trial in swimmers. This aligns with the suggestion by Cross et al. (32) that a 50% velocity decrease is appropriate for multiple trial sprint

testing with external loads. Based on these findings, Gonjo et al. (24) proposed that an absolute load with a maximum of 9 kg is adequate for a semi-tethered swimming test. While Olstad et al. (31) indicated that using five trials (i.e., 1, 3, 5, 7, and 9 kg) in semi-tethered front crawl swimming does not significantly change the outcomes of load-velocity profiling compared to three trials (1, 5, and 9 kg), we opted the five-load protocol to obtain a more precise load-velocity relationship. By examining the linear regression line of the five load-velocity plots (33), the theoretical maximal velocity (V_0) and maximal load (L_0) were investigated. L_0 was also expressed as a percentage of body weight (rL_0). The slope of the load-velocity relationship was also determined (31). The load-velocity slope indicates the resistive force and is reportedly correlated with active drag in front crawl swimming. A steeper slope indicates lower active drag (34). Figure 2 shows an example of the load-velocity profile measured for the sprint performance parameters.

2.5 Statistical analysis

All data are reported as mean $\pm$ SD and 95% confidence intervals was calculated. Normal distribution of variables was assessed using the Shapiro–Wilk test. The reliability of $\dot{c}La_{\max}$ (measured twice in 11 swimmers) was analyzed using the intra-class correlation coefficient (ICC). ICC was classified as “excellent” ($ICC \geq 0.90$), “good” ($0.90 > ICC \geq 0.75$), “moderate” ($0.75 > ICC \geq 0.50$), or “poor” ($ICC < 0.50$) (35). The relationships between $\dot{c}La_{\max}$ and sprint performance parameters were investigated using Pearson's correlation coefficient for normally distributed data and Spearman's rank correlation coefficient for non-normally distributed data. Correlation threshold values of 0.1, 0.3, 0.5, 0.7, and 0.9 were interpreted as small, moderate, large, very large, and extremely large correlations, respectively (36). The power of the correlation test was also computed. The analysis was performed with SPSS

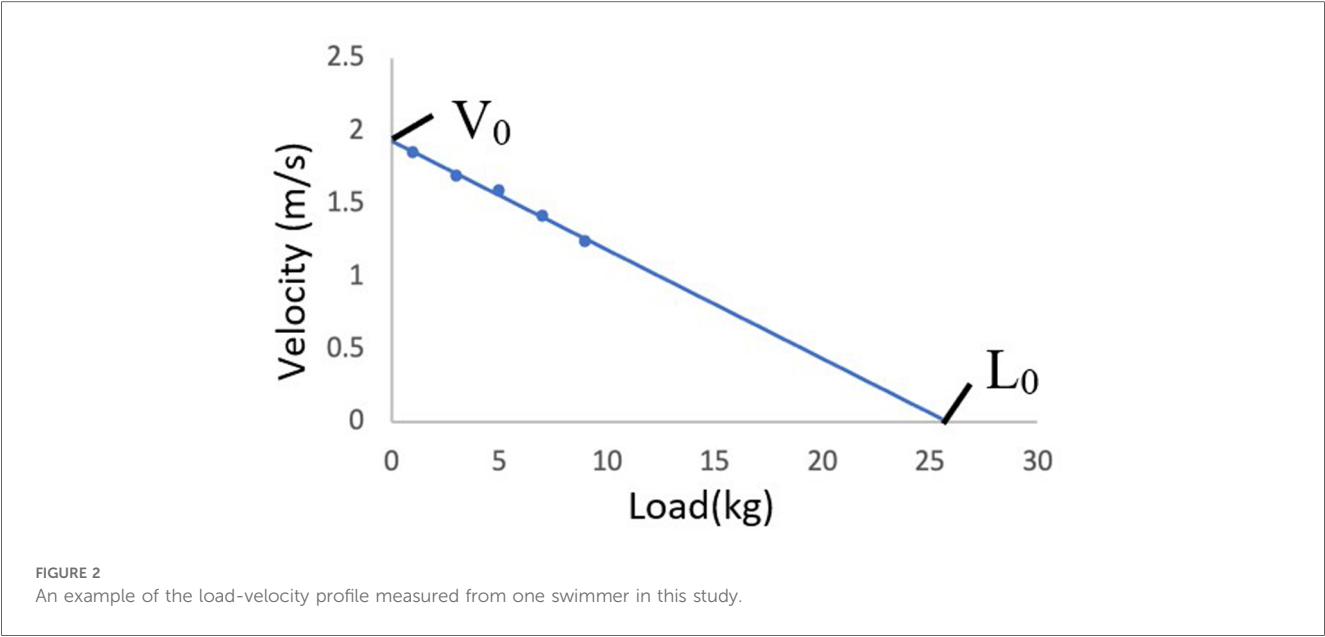


TABLE 2 $\dot{c}La_{max}$ and its correlation with measured parameters.

			Mean $\pm$ SD	95% confidence interval	Correlation between $\dot{c}La_{max}$	Power of correlation
$\dot{c}La_{max}$		(mmol/L/s)	0.63 ± 0.14	$0.56 \sim 0.70$		
50 m time trail	0–15 m	(s)	5.93 ± 0.27	$5.80 \sim 6.05$	-.627**	.817
	15–25 m	(s)	5.18 ± 0.18	$5.10 \sim 5.26$	-.618**	.796
	25–35 m	(s)	5.31 ± 0.16	$5.24 \sim 5.39$	-.604*	.771
	35–45 m	(s)	5.41 ± 0.14	$5.34 \sim 5.48$	-.465	.490
	total time	(s)	24.58 ± 0.73	$24.23 \sim 24.93$	-.546*	.657
Load-velocity profile	V_0	(m/s)	1.81 ± 0.09	$1.77 \sim 1.86$	.224	.139
	L_0	(kg)	18.56 ± 3.83	$16.74 \sim 20.38$	.837**	.996
	rL_0	(%)	25.94 ± 4.79	$23.66 \sim 28.21$	.820**	.993
	slope	(-m/s/kg)	-0.10 ± 0.02	$-0.11 \sim -0.09$	.804**	.989

* $p < .05$, ** $p < .01$.

software (version 29, IBM, Tokyo, Japan), and the statistical significance level was set at 5%.

3 Results

The measured parameters are shown in Table 2. The average time of the 20 m sprint for the $\dot{c}La_{max}$ measurement was 11.5 ± 0.4 s, La_{pre} was 1.6 ± 0.4 mmol/L, La_{max} was 6.8 ± 1.2 mmol/L, tLa_{max} was 1.8 ± 0.8 min, and $\dot{c}La_{max}$ was 0.63 ± 0.14 mmol/L/s. ICC of the twice-measured $\dot{c}La_{max}$ was 0.913 (95% confidence interval: 0.724–0.976, $p < .01$). $\dot{c}La_{max}$ showed significant correlation with $t50$ ($r = -.546$, $p < .05$) and the section time of 0–15 m ($r = -.627$, $p < .01$), 15–25 m ($r = -.618$, $p < .01$), 25–35 m ($r = -.604$, $p < .05$) of the trial. L_0 ($r = .837$, $p < .01$), rL_0 ($r = .820$, $p < .01$), and the slope ($r = .804$, $p < .01$) obtained from the load-velocity profile also significantly correlated with $\dot{c}La_{max}$.

4 Discussion

The present study explored the relationship between $\dot{c}La_{max}$ and factors associated with sprint performance in male competitive swimmers. The main findings of this study were that $\dot{c}La_{max}$ is significantly correlated with 50 m front crawl performance in male swimmers and that a higher glycolytic power contributes to a faster time at the beginning of the sprint race. We were also able to clarify that $\dot{c}La_{max}$ is significantly related to the theoretical maximal load a swimmer can pull with front crawl swimming.

The time taken for the 20 m sprint to measure $\dot{c}La_{max}$ was 11.5 ± 0.4 s, which falls within the recommended range of 10–15 s for this parameter (19). In a study by Langley et al. (37), it was found that the 10-s sprint duration produced the highest $\dot{c}La_{max}$ value when compared to the 15-s and 30-s sprints in cycling tests. Mavroudi et al. (21) also reported higher $\dot{c}La_{max}$ values when investigating shorter sprints in swimming. Additionally, Quittmann et al. (16)

suggested that investigating $\dot{c}La_{max}$ based on a fixed distance instead of a fixed duration protocol may be more appropriate in field-based settings if the duration variation is minimal. Overall, the 20 m sprint utilized in this study was appropriate and applicable for assessing a swimmer's highest glycolytic power. The $\dot{c}La_{max}$ value calculated in this study was 0.63 ± 0.14 mmol/L/s, which is similar to the values reported by Sperlich et al. (20) and Mavroudi et al. (21) of 0.64 ± 0.29 and 0.75 ± 0.18 mmol/L/s, respectively. However, in research with young female swimmers, Kellar and Wahl (22) found a lower value of 0.38 ± 0.11 mmol/L/s in their research with young female swimmers. It is worth noting that although $\dot{c}La_{max}$ was assessed using different methods in these studies, it seems that the value is lower in females compared to males, possibly due to differences in muscle mass (38), which could affect lactate production during exercise (39). Generally, female swimmers tend to have longer completion times for a 20 m sprint compared to male swimmers. Additionally, if lactate production is lower in females, $\dot{c}La_{max}$ values will tend to be lower due to the formula used to calculate this parameter (Equation 1). These factors suggest that the relationship between $\dot{c}La_{max}$ and performance may be gender-specific.

The reliability of the $\dot{c}La_{max}$ was "excellent" when measured twice within 4 days (ICC = 0.913). This ICC value was slightly higher than those reported in previous investigations on cycling [ICC = 0.904, (40)], running [ICC = 0.907, (16)], and rowing [ICC = 0.85, (17)]. The accuracy and reliability of the Bla measurement device used in this study were evaluated as good according to the methods of Bonaventura et al. (26). It is worth noting that given the small volume of sampled blood (0.3 μ l), we took the average Bla value assessed by the two devices to ensure a stable value. The measurement procedure used in this study clarified that $\dot{c}La_{max}$ could be investigated with high reliability.

Mavroudi et al. (21) studied eight male and four female swimmers and found that a 50 m sprint trial significantly correlated with $\dot{c}La_{max}$ measured during that swim; however, this result may be affected by including both genders. In the present study of male-only measurements and a 20 m sprint, we also found a significant correlation between $\dot{c}La_{max}$ and t50. On the other hand, Kellar and Wahl (22) investigated the relationship between $\dot{c}La_{max}$ and 50 m swim race performance but found no significant relationship. The differences in the measurement protocol may cause different results. Kellar and Wahl (22) investigated $\dot{c}La_{max}$ from a 20-s sprint test in which the duration is longer than the highest value reportedly observed. The sprint duration should be shorter to assess $\dot{c}La_{max}$ related to 50 m performance. Moreover, our measurement setting was defined by the fact that the short sprint was executed from a floating position. This execution eliminates the movement of the block start or wall push and the underwater phase, which is completely different from the regular swimming motion. Thus, this indicated that accurately assessing $\dot{c}La_{max}$ could be achieved by excluding factors other than swimming motion, allowing for the practical evaluation of glycolytic power during swimming. As a result, a 20 m sprint swim solely relying on the swimming motion is an effective way to measure $\dot{c}La_{max}$, making it an important parameter to monitor during training.

When examining the relationship between $\dot{c}La_{max}$ and each section time of the 50 m trial, large correlations were observed at the

0–15 m, 15–25 m, and 25–35 m section times. The contribution ratio of aerobic and anaerobic metabolism is reportedly 30:70 in a 50 m race (1). Therefore, a higher glycolytic power is related to a faster time up to 35 m of the race, while aerobic capacity may be related to the later performance. Therefore, the present study confirmed that $\dot{c}La_{max}$ is a good performance indicator in the first half of a 50 m front crawl swim, suggesting that glycolytic power is crucial for 50 m sprint performance, and swimmers aiming to start fast in a 50 m race should focus on improving $\dot{c}La_{max}$. Research has shown varied effects of different training modalities on $\dot{c}La_{max}$. Sperlich et al. (20) reported an increase in $\dot{c}La_{max}$ following high-intensity interval training in junior swimmers. Similarly, Nitzsche et al. (41) observed an increase in $\dot{c}La_{max}$ with resistance training in male strength-trained volunteers. However, contrasting results were found by Hommel et al. (14), who reported a decrease in $\dot{c}La_{max}$ after a six-week sprint interval cycling training program. These conflicting findings underscore the need for further research on training interventions specifically aimed at improving glycolytic power in swimmers.

$\dot{c}La_{max}$ correlated with L_0 and rL_0 , indicating the connection between glycolytic power and the ability to exert force in the water. As Maglischo (2) highlighted, the limiting factors of a 50 m race performance are the stroke technique, the rate of anaerobic metabolism, and the amount of creatine phosphate in the working muscle fibers of a swimmer. Therefore, $\dot{c}La_{max}$ could evaluate the first two factors, making it a valuable parameter for monitoring the swimmer's sprint performance capacity throughout the training season. Coaches and athletes can use $\dot{c}La_{max}$ and aerobic capacity parameter to plan and prescribe training for performance improvement and to avoid nonfunctional overreaching (19, 29). Our study also proposed a practical procedure to evaluate $\dot{c}La_{max}$ in swimming.

A very large correlation was found between $\dot{c}La_{max}$ and L_0 , rL_0 , and the slope calculated from the load-velocity profile. L_0 represents the theoretical maximal load that swimmers can exert on the water (31). As active drag is approximately proportional to the cube of swimming velocity (42), swimmers need to overcome a large amount of drag during high-velocity swimming. Consequently, a high L_0 is one of the essential abilities for sprinters. rL_0 correlates significantly with 50 m front crawl performance (24). Therefore, the present results indicate that the pure capacity to produce power at a higher rate is related to the higher capacity to apply force to the water, which could be crucial for achieving high sprinting performance. Moreover, the significant correlation between $\dot{c}La_{max}$ and the load-velocity slope may be affected by the significant relationship between $\dot{c}La_{max}$ and L_0 . Based on our findings, V_0 did not correlate with $\dot{c}La_{max}$. As V_0 represents the theoretical maximal velocity, it may be closely associated with the contribution of the alactic energy system. Furthermore, Gonjo et al. (24) suggested that V_0 should not be used to predict the absolute free-swimming speed during a race due to the observed systematic bias between the average swimming velocity of the 50 m front crawl trial and V_0 , which may have affected our results.

Beyond evaluating an athlete's glycolytic power, $\dot{c}La_{max}$ has potential applications in predicting individual pacing strategies. Quittmann et al. (43) suggested that this parameter

could be used to predict pacing strategies in 5,000 m running, a concept that may be applicable to sprint swimming races. Swimmers with high $\dot{c}La_{max}$ values are likely to start races quickly and apply greater force to the water. For these athletes, coaches should focus on strategies that allow for a fast start while minimizing effort, to prevent fatigue at the end of the race. Conversely, swimmers with lower $\dot{c}La_{max}$ values should avoid an intense burst immediately after the breakout. Instead, they should focus on gradually increasing their effort towards the end of the race. By tailoring race strategies to individual $\dot{c}La_{max}$ profiles, coaches and swimmers can optimize performance and energy distribution throughout the race. Comparing the relationship between $\dot{c}La_{max}$ and race performance across multiple competitions may provide valuable insights into whether success or failure in a race is primarily due to physiological or technical factors. This approach could help coaches and athletes differentiate between improvements in anaerobic capacity and enhancements in swimming technique or race strategy. Furthermore, Morais et al. (44) reported that swimmer with faster critical speed was more likely to perform better in middle- or long-distance events than in sprints. By examining critical speed together, it may provide more detailed information to coaches and swimmers including evaluation of aerobic capacity. Longitudinal studies are warranted to fully clarify the practical applicability of $\dot{c}La_{max}$ in real-world competitive settings. Such research could reveal how this parameter changes over time with training and how these changes correlate with performance improvements. Additionally, it could help establish $\dot{c}La_{max}$ as a reliable tool for long-term athlete monitoring and performance prediction.

A limitation of the present study is that a constant value of 3 s was used for t_{alac} to calculate $\dot{c}La_{max}$. Yang et al. (45) reported that insights into the inter-individual differences in energy and glycolytic metabolism would be altered by using different t_{alac} values. An alternative procedure to assess t_{alac} is being explored (46). The actual time of t_{alac} likely varies among participants, which may influence the precision of $\dot{c}La_{max}$ calculations. If novel approaches to measure power output during swimming can be developed, it would enable a more accurate evaluation of $\dot{c}La_{max}$. Such advancements in measurement techniques could potentially affect the results of the present study and provide more precise insights into the relationship between $\dot{c}La_{max}$ and swimming performance. However, it still seems complicated to establish a rational method to assess t_{alac} during swimming exercise; using a constant value may remain a practical procedure to investigate $\dot{c}La_{max}$ in this sport. Second, Affonso et al. (47) reported an extremely high Bla level of 12.1–17.4 mmol/L after a 5-s short sprint in an elite front crawl swimmer (World Aquatics point = 985). The high $\dot{c}La_{max}$ in this swimmer suggests that higher glycolytic power may be essential for achieving high sprint performance. However, it should be noted that this relationship may have been observed due to the swimmers having identical mechanical efficiencies. Toussaint (48) examined the propelling efficiency of well-trained competitive swimmers and triathletes, reporting values of $61 \pm 6\%$ for swimmers and

$44 \pm 3\%$ for triathletes. This suggests that, even if two swimmers exert the same glycolytic power, a swimmer with lower mechanical efficiency will be slower. It is essential to consider the implications of our study when applied to swimmers at different performance levels. Several methods exist for investigating propulsive efficiency during sprint swimming, including the MAD (Measuring Active Drag) system (48) and pressure distribution analysis (49). By combining these propulsive efficiency evaluations with $\dot{c}La_{max}$ assessments, it would be possible to develop a more comprehensive profile of a swimmer's characteristics. This integrated approach could provide valuable information for planning future training strategies. Specifically, it would allow coaches and athletes to determine whether to focus on improving stroke mechanics or enhancing anaerobic power, based on individual strengths and weaknesses identified through these complementary assessments. Such a multifaceted evaluation strategy could lead to more targeted and effective training interventions, potentially optimizing performance improvements in sprint swimming.

5 Conclusion

The testing procedure of $\dot{c}La_{max}$ used in the present study was found to be suitable for training settings and to have high reliability. The study clarified that $\dot{c}La_{max}$ is a parameter associated with the 50 m front crawl performance in male swimmers, and a higher glycolytic power leads to faster times at the beginning of a sprint race. It also indicated that $\dot{c}La_{max}$ can assess a swimmer's ability to apply force to the water during high-intensity swimming. Therefore, $\dot{c}La_{max}$ is a good indicator of front crawl sprint performance for well-trained male swimmers.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Human Subjects Committee of the University of Tsukuba. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

YS: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – original draft, Writing – review & editing, Data curation. AS: Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

JK: Formal Analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. KH: Formal Analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. YN: Formal Analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. TT: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. NH: Conceptualization, Resources, Writing – original draft, Writing – review & editing. AN: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. Formal Analysis. MI: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Quantity of within-sport distance variety – what can pool swimmers and track runners learn from each other?

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Objective: To determine the relationship between success at peak performance age and *quantity of within-sport distance variety* and compare the *dose-time-effect* between swimming and track running by determining probability of becoming an international-class female athlete based on the number of different race distances the athletes compete in each year throughout their development process.

Methods: Race times of female Tier 2 to Tier 5 freestyle pool swimmers ($n = 2,778$) and track runners ($n = 9,945$) were included in the present study. All athletes were ranked according to their personal best at peak performance age. Subsequently, number of different race distances during each year were retrospectively extracted from peak performance to early junior age. Personal best performance points at peak performance age were correlated with the number of different race distances across the various age categories. Poisson distribution determined the dose-time-effect of becoming an international-class athlete based on the number of different swimming strokes.

Results: At peak performance age, correlation analysis showed a larger within-sport distance variety for higher ranked athletes, particularly for track runners ($r \leq 0.35$, $P < 0.001$). Despite reaching statistical significance, the effects were small to moderate. While swimmers showed a generally larger within-sport distance variety than track runners, Poisson distribution revealed a dose-time-effect for the probability of becoming an international-class swimmer. Sprint and middle-distance swimmers benefit from competing in three race distances during junior age and a transition to two race distances at 17–18, 18–19, 20–21 and 25–26 years of age for 50 m, 100 m, 200 m and 400 m races, respectively. Long-distance swimmers should maintain three different race distances throughout peak performance age. Probability analysis showed a consistent benefit of competing in one or two race distances for 100 m, 200 m, 400 m and 800 m track runners.

Conclusion: Within-sport distance variety is not a continuum but an ever-evolving process throughout the athletes' careers. While swimmers generally show larger variety than track runners, the progressive specialization towards peak performance age improves success chances to become an international-class swimmer.

KEYWORDS

adolescence, competition, diversification, elite athlete, long-term athlete development, sampling, talent

Introduction

Sport specialization is a heavily discussed topic among talent development experts: as such, some previous studies showed the benefits of sport variety during junior age for success at adult age (1–3). Other studies, however, found that specialization and performance level during junior age are related to adult success (4, 5). These conflicting findings may result from different methodological approaches evaluating involvement in different sports: *between-sport* variety (1–3), or involvement in different disciplines of a particular sport: *within-sport* variety (4, 5). Moreover, sport variety may not be a fixed variable, but rather an evolving factor throughout the development process of young talents. A previous study assessed within-sport variety regarding the involvement in different swimming strokes and showed a dose-time-effect for the probability of becoming an international-class swimmer. As such, a larger within-sport variety during early junior age and successive specialization in fewer swimming strokes were most beneficial for adult age success (6). However, the mentioned study only assessed involvement in different swimming strokes across the various 200 m events and warrants further investigations into the dose-time-effect of involvement in various race distances, i.e., sprint, middle- and long-distance events.

A recent study compared development of performances and race times of athletes' main and secondary events (*quality of variety*) in swimming and track running (7). These two sports have comparable conditions during competitions: (1) standardized distances on a flat course with limited environmental effects and electronic time measurements (8, 9), (2) time-wise equal race lengths (10, 11) and (3) similar physiological and metabolic demands (12–16). Despite these similarities, training regimes are substantially different between the two sports. Track runners emphasize under-distance and high-intensity training (17–19), while swimmers typically rely on long aerobic sets and over-distance training (20–22). Since *quantity of variety* has never been investigated in, nor compared between swimming and track running, determining the dose-time-effect of the number of different race distances the athletes compete in each year may provide deeper insights into the topic of variety and new inputs for prevailing training and development strategies.

Since female study participants are traditionally underrepresented in sport science articles (23), recent editorials and changes in journal policies demand more studies with particular attention to female athletes (24–26). This is particularly justified in swimming, since the considerably different anthropometrics and biological maturation of female compared to male athletes affect development of swimming performance (27, 28) and long-term athlete development programs (29). Due to a lower center of mass, slightly higher and better distributed body fat content even before puberty, and a more hydrodynamic body shape, female swimmers experience a lower leg sinking torque (30–33). Their greater joint mobility also contributes to swimming performance (34, 35). The more advantageous body composition and improved buoyancy allows female swimmers to focus on the development of key

technical elements related to propulsion, such as hydrodynamic lift, catch of the water at the beginning of the arm stroke, and rotation along the longitudinal axis, at a younger age than males (36–39). Moreover, on average, growth velocity peaks two years earlier in females – specifically by the age of 11.9 ± 1.0 years compared to 14.1 ± 1.1 years in males (40).

As a result, female swimmers perform closer to the world record at a younger age, but also show an earlier performance plateau towards peak performance age (41, 42). Sex-specific analyses are warranted to assess all facets of the complexity of within-sport variety across the various race distances and improve long-term athlete development of female swimmers and track runners. Therefore, the aims of the present study were to (1) determine the relationship between success at peak performance age and *quantity of within-sport distance variety* and (2) compare the *dose-time-effect* between female swimmers and track runners by determining probability of becoming an international-class female athlete based on the number of different race distances the athletes compete in each year. The hypotheses were that higher ranked swimmers show a larger within-sport distance variety, however, with a dose-time-effect that allows for successive specialization towards peak performance age. Due to the over-distance oriented training, swimmers are expected to show a generally larger within-sport distance variety compared to track runners.

Methods

Subjects

Race times from officially licensed competitions with electronic time measurements were provided by the databases of the European swimming (43) and World athletics federations (44). A total of $n = 2,778$ individual female freestyle pool swimmers and $n = 9,945$ individual female track runners were included in the present study. Tier 2 to Tier 5 athletes (45) with >550 performance points at peak performance age (as described in detail later) were included. No explicit written informed consent was required, as only publicly available race times were included and analyzed anonymously. The study was preapproved by the institutional review board of the Swiss Federal Institute of Sport Magglingen (Reg.-Nr. 222_LSP_Born_03_2024) and conducted according to the guidelines of the World medical association for medical studies involving human subjects (Declaration of Helsinki).

Procedure

All athletes, who were still competing at peak performance age, were ranked based on their personal best in the respective race distance. Subsequently, the number of different race distances during each year were retrospectively extracted from peak performance age throughout adolescence until early junior age (13 years of age). Ranking at peak performance age was

considered as the dependent and number of different race distances the athletes competed in each year as the independent variable.

The ranking was based on performance points calculated as the division of the specific event's world record time by an individual swimmer's race time, then to the power of three, and multiplied by one thousand (9). As such, performance points can range from 1,000 (equal to the prevailing world record) to theoretically zero. However, since the present study aimed to find contributing factors to high-performance sports, only athletes reaching >550 performance points as their personal best at peak performance age (regional-class level) were included (46). The point system of the world governing body of swimming was used for both sports, since the study was conducted from the perspective of swimming with the aim of taking insights from land-based sports to further develop aquatic sports.

Only long-course (50 m pool length) freestyle swimming events (50 m, 100 m, 200 m, 400 m, 800 m, 1,500 m) and running events held on 400 m tracks (100 m, 200 m, 400 m, 800 m, 1,500 m, 3,000 m, 5,000 m, 10,000 m) were included. Freestyle was chosen, since this swimming stroke encompasses the widest range of race distances (6 vs. 3 in the other swimming strokes) (9). As such, the number of different race distances ranged from 1 to 6 in swimming and from 1 to 8 in running. To facilitate data interpretation and reduce multiple comparisons for the correlation analysis, the numbers of different race distances were averaged across two-year age categories, i.e., 13–14, 15–16, 17–18, 19–20, 21–22, 23–30 (23+) years of age. Peak performance age was set at 23–30 years of age based on previous research studies (47, 48) and the newly introduced U23 European junior championships, which should help swimmers transition from international junior to adult championships (49).

Data analysis

To rank athletes at peak performance age, race times from the 2016–2023 databases were used. The retrospective tracking of the number of different race distances was conducted also using the 2006–2015 databases. Initial data extraction from the databases, calculation of performance points, establishment of ranking at peak performance age, and retrospective extraction of the number of different race distances per year were conducted in Python (version 3.11.5, Python Software Foundation, Beaverton, USA) using the “pandas” library for data analysis (version 2.2.1, pandas-dev/pandas, Zenodo, Genève, Switzerland). All subsequent data handling, including the calculation of probabilities using Poisson distribution, was conducted with Microsoft Excel 365 (version 2406, Microsoft Corporation, Redmond, WA, USA). The data analysis was coded by an experienced data scientist, holding a master's degree and PhD. The procedures were validated by another independent data analyst and the other scientists involved in the study.

Statistical analysis

The *relationship* between ranking at peak performance age and within-sport distance variety, i.e., number of different race distances the athletes competed in each year, within the various age categories was assessed with Pearson's correlation coefficient (r). Spearman's ρ was calculated if Q-Q plot or Shapiro-Wilk test showed non-normally distributed data. The magnitude of the correlation coefficients were interpreted as follows: trivial (<0.10), small (0.10–0.29), moderate (0.30–0.49), high (0.50–0.69), very high (0.70–0.89) and practically perfect (>0.90) (50, 51). Since the present study evaluates a population rather than a sample, i.e., all swimmers and runners still competing at peak performance age with >550 performance points, a *post-hoc* rather than *a priori* power analysis was conducted with G*Power (version 3.1.9.7). Using the point biserial model for two-tailed correlations, coefficients were used for effect sizes with their corresponding alpha-levels and sample sizes. Underpowered correlations with a statistical power <0.80 were disregarded from the data interpretation, regardless of their effect size or statistical significance (52).

The *dose-time-effect* of within-sport distance variety across the development process from junior to adult age was determined using Poisson distribution for international-class athletes [personal best of >750 performance points at peak performance age (46)]. The Poisson distribution reveals the probability that an independent event occurs, such as becoming an international-class athlete at peak performance age, based on the number of different race distances the athletes competed in each year. The likelihood of an independent event occurring is expressed between 0 and 1 for each point on a constant time scale using the probability mass function. Statistical analyses were conducted with JASP statistical software package (version 0.19, JASP-Team, University of Amsterdam, Amsterdam, The Netherlands). An alpha-level of 0.05 indicated statistical significance.

Results

Table 1 shows the correlation analysis between personal best performance points at peak age (in the respective race distance) and number of different race distances the athletes competed in during the various age categories. Although correlations are highly significant ($P < 0.001$), magnitude of the coefficients are small to moderate. For swimmers, the effects increase towards peak performance age and show that higher ranking is associated with larger variety. Sprint and long-distance swimming events, i.e., 50 m and 1,500 m, showed fewer significant effects. In contrast, runners indicate highly significant effects over all race distances for the 19–20 year and older age categories.

The probabilities of becoming an international-class athlete at peak performance age are indicated in Figures 1, 2. Sprint and middle-distance swimmers benefit from competing in three race distances during junior age with a later transition to two race distances. This transition point occurs at an older age the longer

TABLE 1 Correlation analysis between personal best performance points at peak age (in the respective race distance) and number of different race distances the athletes competed in during the various age categories. The correlation analysis included female world-class finalists, international-, national- and regional-class swimmers or runners (>550 performance points as personal best at peak performance age).

		Age categories [years]					
		13–14	15–16	17–18	19–20	21–22	23+
Swimmers							
50 m	<i>n</i> = 1,875	0.01	0.00	-0.01	0.04	0.05*	0.10***
100 m	<i>n</i> = 1,825	0.04	0.03	0.02	0.04	0.11***	0.10***
200 m	<i>n</i> = 1,333	0.02	0.06*	0.06	0.07*	0.14***	0.14***
400 m	<i>n</i> = 822	0.08	0.08*	0.10**	0.11**	0.20***	0.18***
800 m	<i>n</i> = 518	0.08	0.06	0.14**	0.15**	0.17***	0.10*
1,500 m	<i>n</i> = 275	0.05	0.03	0.09	0.00	0.04	-0.04
Runners							
100 m	<i>n</i> = 3,435		0.18***	0.22***	0.25***	0.26***	0.23***
200 m	<i>n</i> = 4,068		0.21***	0.28***	0.31***	0.35***	0.35***
400 m	<i>n</i> = 2,893		0.11**	0.21***	0.23***	0.26***	0.27***
800 m	<i>n</i> = 2,048		0.08	0.12***	0.22***	0.23***	0.18***
1,500 m	<i>n</i> = 2,581		0.14**	0.12***	0.17***	0.19***	0.29***
3,000 m	<i>n</i> = 1,274		0.22**	0.10*	0.19***	0.18***	0.28***
5,000 m	<i>n</i> = 2,033		0.03	0.09*	0.18***	0.14***	0.22***
10,000 m	<i>n</i> = 1,130				0.15***	0.11**	0.10***

Level of significance: **P* < 0.05, ***P* < 0.01, ****P* < 0.001.
Correlation coefficients with low statistical power (<0.80) are marked with gray color.

the race distances, i.e., 17–18, 18–19, 20–21 and 25–26 years of age for 50 m, 100 m, 200 m and 400 m races, respectively, indicating that long-distance swimmers (800 m and 1,500 m) should maintain three different race distances throughout peak performance age. Low probabilities of becoming an international-class athlete were evident when competing in five to six race distances. Competing in only one race distance showed the second highest probability of becoming an international-class swimmer at 22–23 years of age for 50 m races. The advantage of competing in a single race distance diminishes as the swimming race distances increase. For track runners competing in 100 m, 200 m, 400 m or 800 m, probability analysis showed a consistent benefit of competing in one or two race distances. Long-distance track runners benefit from two race distances with three or a single race distance showing the second highest probabilities of becoming an international-class athlete.

Tables 2, 3 show the most common race distance combinations for all race distances and age categories. At peak performance age, 50 m, 100 m and 200 m swimmers typically compete in all those three race distances (50 m–200 m), the 400 m and 800 m swimmers compete in all available race distances (50 m–1,500 m), and the 1,500 m swimmers in all 200 m and longer races (200 m–1,500 m). Track runners typically compete in the neighboring race distances of their main event. There are few sprinters who also compete in middle-distance races, while 800 m runners commonly also compete in the 400 m distance. In detail, most 400 m runners (47.3%) additionally compete in 100 m and 200 m races but only a few (8.8%) compete in 800 m races, while the most common combination (28.9%) of the 800 m runners also involves 400 m races. Whereas 800 m runners compete in races of no longer than 1,500 m, the 1,500 m

and long-distance runners commonly compete in both middle- and long-distance races.

Discussion

The main findings of the present study are that the higher ranking of Tier 2 to Tier 5 female athletes correlates with a larger within-sport distance variety, especially towards peak performance age. As hypothesized, however, optimal variety for swimmers is not a continuum but an evolving process throughout the athletes' careers. As such, Poisson distribution shows the highest probability of becoming an international-class swimmer when competing in three to four race distances during junior age with a progressive reduction to two to three race distances towards peak performance age. International-class track runners generally show lower distance variety than swimmers. Competing in one to three race distances throughout the career appears most beneficial to become an international-class athlete. Within-sport distance variety is larger for long-distance athletes vs. sprinters for both runners and swimmers.

Correlation analysis revealed a small but significant relationship between a larger within-sport distance variety and success at peak performance age. However, increasing distance variety should not be interpreted as a causal effect that improves success chances, as better athletes may be capable of successfully competing in a larger number of race distances. For instance, at national championships and regional competitions, high-level athletes are important representatives for their home clubs. Due to their overall superior performance level, they typically compete in the relays, although these races do not necessarily cover their favorable or strongest distances. Moreover, the

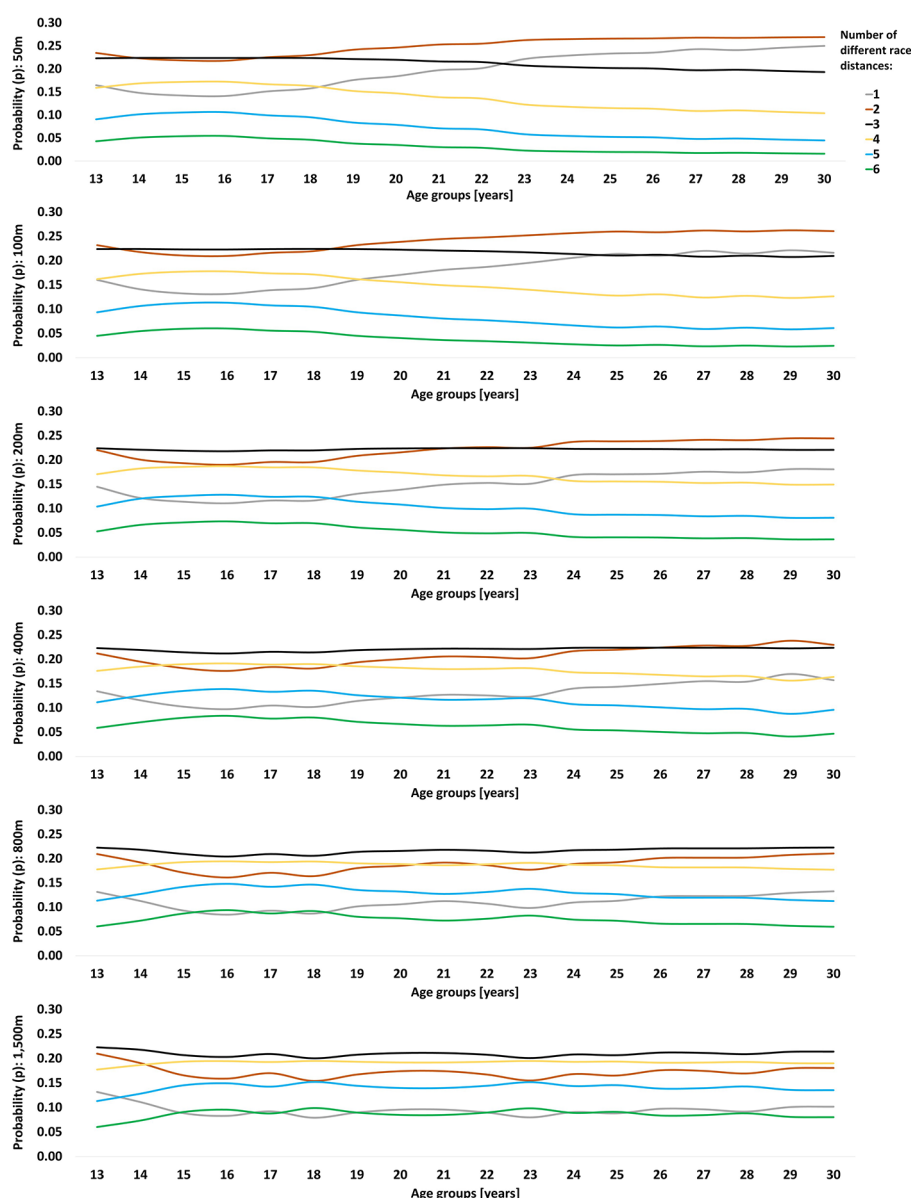


FIGURE 1

Dose-time-effect as probability (p) of becoming an international-class female swimmer based on the number of different race distances per year throughout adolescence until peak performance age. International-class was defined as a personal best of >750 performance points at peak performance age.

present study assessed quantity rather than quality of distance variety [refer to a previous article (7)] and therefore does not distinguish between primary and secondary race distances. Since high-level swimmers commonly use local competitions to compete in multiple secondary events for training purposes and to improve their competition routine (53), this may explain the larger within-sport distance variety in higher ranked athletes.

In both swimming and running, distance variety increases the longer the race distances. After crossing the transition point to mainly aerobic energy production in the 200 m swimming and 800 m running races, this metabolic energy system appears to be used in and adapted to longer race distances too (12, 13, 16, 54).

The high reliance on over-distance training and aerobic sets in swimming particularly favors distance variety across middle- and long-distance races (20, 22). In contrast, the aerobic and anaerobic metabolic energy systems cannot be maximized at the same time and sprint swimmers may benefit from an earlier and larger degree of specialization to further improve performances, according to track sprinters' specialization pattern of 1–2 race distances. Additionally, sprint swimmers show specific stroke mechanics: the high cadence, extended elbow during the overwater movement, and fast hand entry at the beginning of the underwater phase of each arm stroke combined with the higher drag experience at such speeds require more energy

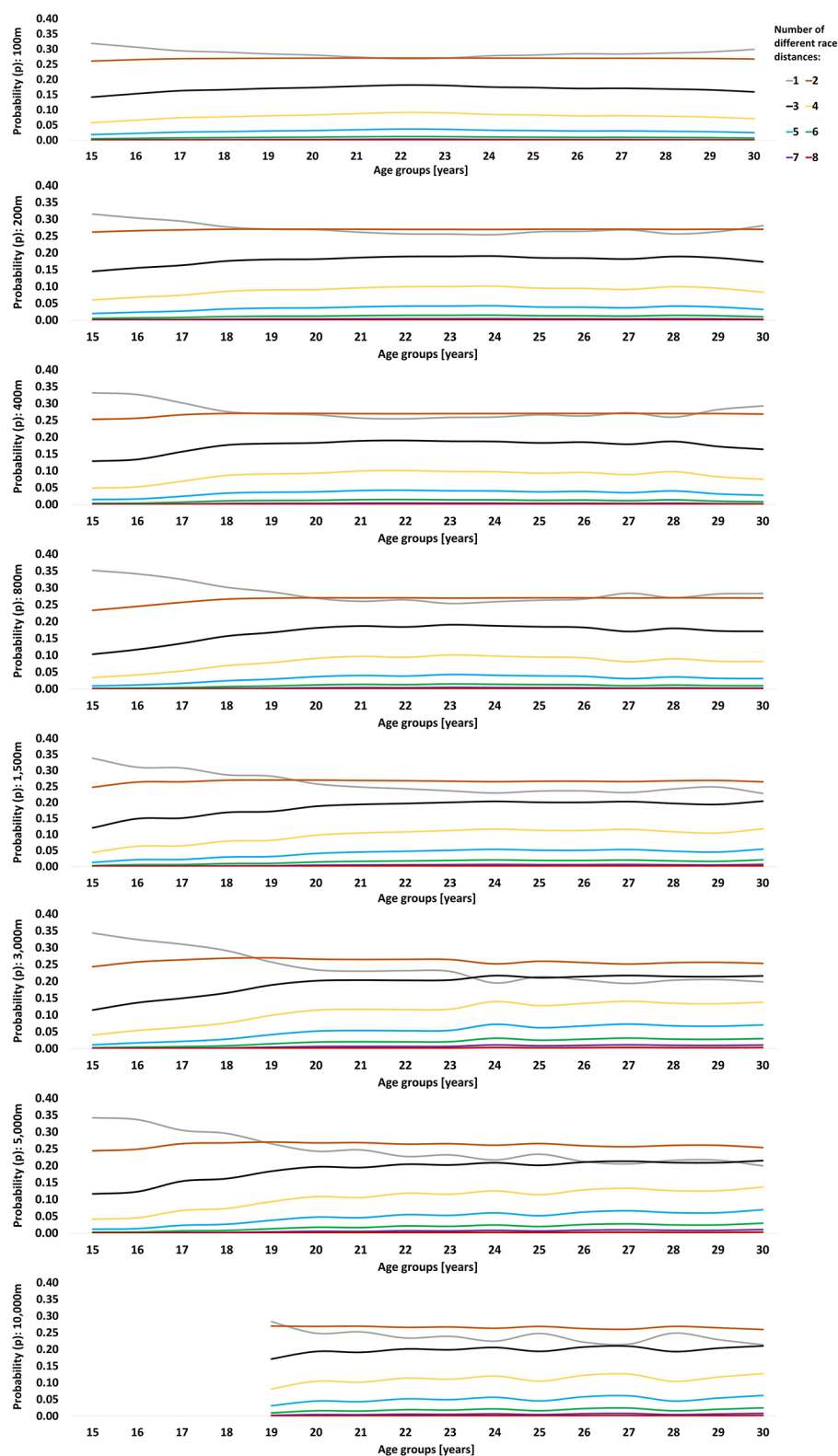


FIGURE 2
Dose-time-effect as probability (p) of becoming an international-class female track runner based on the number of different race distances per year throughout adolescence until peak performance age. International-class was defined as a personal best of >750 performance points at peak performance age.

TABLE 2 The three most common combinations of race distances for 50 m, 100 m, 200 m, 400 m, 800 m and 1,500 m female freestyle swimmers with >750 performance points at peak performance age across the various age categories.

	Age categories [years]					
	13–14	15–16	17–18	19–20	21–22	23+
50 m	27.3% ^[50, 100, 200]	30.8% ^[50, 100, 200]	38.2% ^[50, 100, 200]	44.3% ^[50, 100, 200]	45.9% ^[50, 100, 200]	38.3% ^[50, 100, 200]
	23.8% ^[50, 100, 200, 400, 800]	22.9% ^[50, 100, 200, 400]	25.2% ^[50, 100, 200, 400]	25.7% ^[50, 100]	30.8% ^[50, 100]	34.5% ^[50, 100]
	20.3% ^[50, 100, 200, 400]	20.4% ^[50, 100]	19.3% ^[50, 100]	16.1% ^[50, 100, 200, 400]	11.9% ^[50, 100, 200, 400]	16.2% ^[50, 100, 200, 400]
100 m	26.1% ^[50, 100, 200, 400, 800]	25.0% ^[50, 100, 200]	32.7% ^[50, 100, 200]	37.3% ^[50, 100, 200]	44.3% ^[50, 100, 200]	36.8% ^[50, 100, 200]
	21.6% ^[50, 100, 200]	23.3% ^[50, 100, 200, 400]	27.2% ^[50, 100, 200, 400]	19.6% ^[50, 100, 200, 400]	19.9% ^[50, 100]	24.2% ^[50, 100]
	19.1% ^[50, 100, 200, 400]	20.8% ^[50, 100, 200, 400, 800]	13.7% ^[50, 100, 200, 400, 800]	17.7% ^[50, 100]	15.4% ^[50, 100, 200, 400]	19.6% ^[50, 100, 200, 400]
200 m	27.3% ^[50, 100, 200, 400, 800]	22.5% ^[50, 100, 200, 400, 800]	19.4% ^[50, 100, 200, 400]	21.2% ^[50, 100, 200, 400]	23.8% ^[50, 100, 200]	22.1% ^[50, 100, 200]
	17.2% ^[50, 100, 200]	19.5% ^[50, 100, 200, 400]	18.0% ^[50, 100, 200, 400, 800]	19.8% ^[50, 100, 200]	16.8% ^[50, 100, 200, 400]	21.2% ^[50, 100, 200, 400]
	16.0% ^[50, 100, 200, 400]	18.5% ^[50, 100, 200, 400, 800, 1500]	17.5% ^[50, 100, 200]	13.4% ^[50, 100, 200, 400, 800]	12.4% ^[50, 100, 200, 400, 800]	11.6% ^[50, 100, 200, 400, 800]
400 m	35.4% ^[50, 100, 200, 400, 800]	30.6% ^[50, 100, 200, 400, 800, 1500]	27.3% ^[50, 100, 200, 400, 800, 1500]	15.5% ^[50, 100, 200, 400, 800, 1500]	15.5% ^[200, 400, 800, 1500]	15.8% ^[50, 100, 200, 400, 800, 1500]
	12.0% ^[100, 200, 400, 800]	21.3% ^[50, 100, 200, 400, 800]	17.5% ^[50, 100, 200, 400, 800]	14.5% ^[50, 100, 200, 400, 800]	14.5% ^[50, 100, 200, 400, 800, 1500]	15.4% ^[50, 100, 200, 400]
	11.2% ^[50, 100, 200, 400, 800, 1500]	8.74% ^[50, 100, 200, 400]	12.8% ^[100, 200, 400, 800, 1500]	13.5% ^[100, 200, 400, 800, 1500]	14.0% ^[50, 100, 200, 400, 800]	14.5% ^[50, 100, 200, 400, 800]
800 m	37.9% ^[50, 100, 200, 400, 800]	33.3% ^[50, 100, 200, 400, 800, 1500]	32.3% ^[50, 100, 200, 400, 800, 1500]	21.8% ^[200, 400, 800, 1500]	25.3% ^[200, 400, 800, 1500]	22.6% ^[50, 100, 200, 400, 800, 1500]
	13.7% ^[100, 200, 400, 800]	15.5% ^[50, 100, 200, 400, 800]	19.0% ^[50, 100, 200, 400, 800]	21.1% ^[100, 200, 400, 800, 1500]	16.9% ^[50, 100, 200, 400, 800, 1500]	20.2% ^[200, 400, 800, 1500]
	12.6% ^[50, 100, 200, 400, 800, 1500]	14.8% ^[100, 200, 400, 800, 1500]	16.9% ^[100, 200, 400, 800, 1500]	20.4% ^[50, 100, 200, 400, 800, 1500]	16.1% ^[100, 200, 400, 800, 1500]	14.7% ^[50, 100, 200, 400, 800]
1,500 m	35.7% ^[50, 100, 200, 400, 800, 1500]	50.0% ^[50, 100, 200, 400, 800, 1500]	47.0% ^[50, 100, 200, 400, 800, 1500]	33.3% ^[200, 400, 800, 1500]	38.9% ^[200, 400, 800, 1500]	33.3% ^[200, 400, 800, 1500]
	21.4% ^[100, 200, 400, 800, 1500]	26.9% ^[100, 200, 400, 800, 1500]	29.4% ^[200, 400, 800, 1500]	29.1% ^[100, 200, 400, 800, 1500]	25.9% ^[100, 200, 400, 800, 1500]	32.2% ^[50, 100, 200, 400, 800, 1500]
	21.4% ^[200, 400, 800, 1500]	17.3% ^[200, 400, 800, 1500]	22.0% ^[100, 200, 400, 800, 1500]	26.3% ^[50, 100, 200, 400, 800, 1500]	22.0% ^[50, 100, 200, 400, 800, 1500]	17.7% ^[100, 200, 400, 800, 1500]

Bold values indicate the most common combination of race distances for the particular distance and age category.

and make the sprint-specific stroke mechanics uneconomically to maintain over longer race distances (55–60). To learn transfer this high cadence into propulsion, swimmers may have to accumulate a high amount of race pace specific training throughout their development process, hence sprinters transition from three to two race distances at a younger age than middle- and long distances swimmers, as revealed by the present study (Figure 1).

The present analysis showed that 50 m, 100 m and 200 m swimmers most commonly compete over all these three race distances at peak performance age (Table 2). The 50 m–200 m events provide the opportunity to compete in up to four different swimming strokes (9). As such, previous studies showed that freestyle swimmers commonly also compete in butterfly or backstroke events, allowing for a higher physiological specialization in the shorter events (6). In contrast, the most common combinations of race distances for 400 m and 800 m swimmers involve the full range of 50 m–1,500 m races. As 400 m and 800 m races provide little alternatives to freestyle, swimmers seem to spread their physiological capacity and increase their distance variety in order to maximize medal chances.

Although the present probability analysis revealed that sprinters showed the earliest transition from three to two race distances in swimming, track sprinters show an even earlier and

larger degree of specialization on one to two race distances. The earlier performance plateau of female compared to male sprint swimmers (41) and the insights from track sprinters may motivate female sprint swimmers to focus even earlier on the specific development of their anaerobic energy system in order to maximize performance progression towards peak performance age. While female athletes are traditionally associated with lower trainability in muscular strength and power due to lower levels of testosterone and absolute muscle mass (61, 62), many other anabolic hormones and mechanical stress response induce substantial strength gains after resistance training (63–68). Besides the hypertrophic response, maximal strength gains due to neuro-muscular adaptations contribute significantly to swimming performance (69, 70). Therefore, taking resistance training seriously from an early stage of female swimmers’ careers and developing specific resistance training and periodization protocols will help maximize progression of sprint performances towards peak performance age (71, 72).

Limitations and future directions

The present study is limited to the quantification of variety based on the number of different race distances athletes competed in each year, without considering absolute

TABLE 3 The three most common combinations of race distances for 100 m, 200 m, 400 m, 800 m, 1,500 m, 3,000 m, 5,000 m and 10,000 m female track runners with >750 performance points at peak performance age across the various age categories.

	Age categories [years]				
	15–16	17–18	19–20	21–22	23+
100 m	66.0% ^[100, 200]	72.1% ^[100, 200]	68.7% ^[100, 200]	69.3% ^[100, 200]	60.5% ^[100, 200]
	22.4% ^[100]	14.6% ^[100, 200, 400]	19.9% ^[100, 200, 400]	23.1% ^[100, 200, 400]	33.0% ^[100, 200, 400]
	11.4% ^[100, 200, 400]	13.2% ^[100]	10.9% ^[100]	7.3% ^[100]	6.1% ^[100]
200 m	53.0% ^[100, 200]	56.0% ^[100, 200]	51.5% ^[100, 200]	50.8% ^[100, 200]	45.1% ^[100, 200, 400]
	16.1% ^[200, 400]	21.9% ^[100, 200, 400]	28.1% ^[100, 200, 400]	30.5% ^[100, 200, 400]	41.3% ^[100, 200]
	15.1% ^[100, 200, 400]	14.2% ^[200, 400]	12.0% ^[200, 400]	13.9% ^[200, 400]	9.0% ^[200, 400]
400 m	46.8% ^[400]	34.4% ^[200, 400]	38.1% ^[200, 400]	40.3% ^[100, 200, 400]	47.3% ^[100, 200, 400]
	34.0% ^[200, 400]	30.5% ^[100, 200, 400]	33.6% ^[100, 200, 400]	37.2% ^[200, 400]	28.9% ^[200, 400]
	12.7% ^[100, 200, 400]	22.0% ^[400]	16.1% ^[400]	9.7% ^[400]	8.8% ^[200, 400, 800]
800 m	45.9% ^[800]	29.6% ^[800]	27.9% ^[800, 1500]	32.1% ^[800, 1500]	28.9% ^[400, 800, 1500]
	26.4% ^[400, 800]	29.2% ^[400, 800]	23.1% ^[400, 800]	22.5% ^[400, 800, 1500]	24.6% ^[800, 1500]
	17.2% ^[800, 1500]	15.6% ^[800, 1500]	20.9% ^[400, 800, 1500]	20.5% ^[400, 800]	11.6% ^[400, 800]
1,500 m	31.9% ^[1500]	28.3% ^[800, 1500]	40.3% ^[800, 1500]	49.1% ^[800, 1500]	25.3% ^[800, 1500, 3000, 5000]
	27.6% ^[800, 1500]	20.4% ^[1500]	16.5% ^[400, 800, 1500]	12.5% ^[400, 800, 1500]	24.6% ^[800, 1500]
	14.8% ^[1500, 3000]	18.1% ^[400, 800, 1500]	11.4% ^[1500]	8.7% ^[800, 1500, 3000]	10.3% ^[800, 1500, 3000, 5000, 10,000]
3,000 m	38.8% ^[3000]	22.7% ^[3000]	33.3% ^[1500, 3000, 5000]	22.4% ^[800, 1500, 3000, 5000]	24.3% ^[800, 1500, 3000, 5000]
	27.7% ^[800, 1500, 3000]	20.4% ^[1500, 3000, 5000]	15.0% ^[800, 1500, 3000, 5000]	22.4% ^[1500, 3000, 5000]	20.3% ^[800, 1500, 3000, 5000, 10,000]
	11.1% ^[1500, 3000, 5000]	18.1% ^[800, 1500, 3000]	13.3% ^[1500, 3000, 5000, 10,000]	13.7% ^[3000, 5000, 10,000]	19.5% ^[1500, 3000, 5000, 10,000]
5,000 m	40.0% ^[3000, 5000]	38.8% ^[1500, 3000, 5000]	36.6% ^[1500, 3000, 5000]	18.0% ^[1500, 3000, 5000]	20.5% ^[800, 1500, 3000, 5000, 10,000]
	30.0% ^[1500, 3000, 5000]	38.8% ^[3000, 5000]	15.5% ^[1500, 3000, 5000, 10,000]	15.0% ^[800, 1500, 3000, 5000]	20.0% ^[800, 1500, 3000, 5000]
	20.0% ^[5000]	11.1% ^[5000]	14.4% ^[800, 1500, 3000, 5000]	15.0% ^[3000, 5000, 10,000]	20.0% ^[1500, 3000, 5000, 10,000]
10,000 m			37.0% ^[1500, 3000, 5000, 10,000]	48.2% ^[5000, 10,000]	27.2% ^[1500, 3000, 5000, 10,000]
			29.6% ^[3000, 5000, 10,000]	26.7% ^[3000, 5000, 10,000]	23.9% ^[3000, 5000, 10,000]
			25.9% ^[5000, 10,000]	17.8% ^[1500, 3000, 5000, 10,000]	19.0% ^[5000, 10,000]

Bold values indicate the most common combination of race distances for the particular distance and age category.

performance differences between the various events. As discussed earlier, swimmers may compete in events outside their main race distance for training purposes, to represent their home club, or due to a lack of specific competition and development strategies. Therefore, the results of this study should be interpreted alongside previous research that accounts for performance differences between the main and secondary race distances, which is the quality of variety (7).

It is important to note that the correlation analysis, which associates larger variety with more success at peak performance age, does not indicate a causal effect. Since the correlation analysis involved Tier 2 to Tier 5 (45) swimmers (550–1,000 performance points at peak performance age), the results may be affected by low-level (regional-class) swimmers having not the same professional support and coaching staff like top-elite swimmers, hence a larger variety due to less specific development strategies. Therefore, the results of the probability analysis for international-class swimmers (>750 performance points) should be prioritized, which provides a more sophisticated analysis of the dose-time-effect of specialization throughout the swimmers' careers and showed the advantage of a large distance variety during early junior age but gradual specialization towards peak performance age.

Since the present analysis is limited to retrospective data, it is important to distinguish between descriptive data on the most common race distances in Tables 2, 3, and the probability analyses in Figures 1, 2. As best practice does not always provide

the optimal development pathway for upcoming talents, future strategies should be developed based on a close interaction between practical experience and evidence-based knowledge (73). Therefore, specific training intervention studies are warranted to determine the causal effect of increased variety during junior age on success at peak performance age.

Conclusion

The findings of the present study show that within-sport distance variety is not a continuum but an ever-evolving process throughout the athletes' careers. While swimmers generally show larger variety than track runners, the progressive specialization towards peak performance age improves success chances to become an international-class swimmer. Coaches and swimmers should establish their long-term development strategies based on the transition points at which the number of different race distances should be reduced together with the most commonly combined race distances. While long-distance athletes maintain a larger within-sport distance variety than sprinters, the insights from track running may motivate sprint swimmers to adopt an even earlier and higher degree of specialization for the optimal development of their anaerobic energy system and consequent implementation of resistance training from an early stage of their careers. The present study shows how the comparison between two sports with similar competition formats, but different

training regimes, opens new perspectives and fuels the discussion about optimal long-term athlete development.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Raw data are publicly available at the databases of the European swimming (43) and World athletics federations (44).

Ethics statement

The studies involving humans were approved by institutional review board of the Swiss Federal Institute of Sport Magglingen (Reg.-Nr. 222_LSP_Born_03_2024). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

Author contributions

D-PB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Visualization, Writing – original draft. JL: Conceptualization, Data curation, Formal Analysis, Investigation, Visualization, Writing – review & editing. GB: Conceptualization, Data curation, Formal Analysis, Investigation, Visualization, Writing – review & editing. JR-N: Conceptualization, Data curation, Formal Analysis, Investigation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Understanding sprint phase-specific training stimuli: a cluster analysis approach to overload conditions

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Introduction: This study analyzed the impact of various overload conditions on sprint performance compared to free sprinting, aiming to identify the loading scenarios that most closely replicate the mechanics of unresisted sprints across the full acceleration spectrum. While velocity-based training methods have gained popularity, their applicability is limited to the plateau phase of sprinting.

Methods: To address this limitation, we employed cluster analysis to identify scenarios that best replicate the mechanical characteristics of free sprinting across various overload conditions. Sixteen experienced male sprinters performed sprints under six conditions: unresisted, overspeed (OS) and four overloaded conditions inducing a velocity loss (VL) of 10%, 25%, 50% and 65% using a resistance training device with intelligent drag technology. Ground reaction forces and spatiotemporal parameters were recorded for all steps using a 52-meter force plate system for all sprint conditions.

Results: Cluster analysis revealed four distinct groups aligning with established sprint phases: initial contact, early-acceleration, mid-acceleration, and late-acceleration. Results showed that heavier loads prolonged the mechanical conditions typical of early-acceleration and mid-acceleration phases, potentially enhancing training stimuli for these crucial sprint components of sprint performance. Specifically, VL50 and VL65 loads extended the early-acceleration phase mechanics to steps 7–8, compared to steps 2–4 for lighter loads. Conversely, lighter loads more effectively replicated late-acceleration mechanics, but only after covering substantial distances, typically from the 11- to 29-meter mark onwards.

Discussion: These findings suggest that tailoring overload conditions to specific sprint phases can optimize sprint-specific training and provide coaches with precise strategies for load prescription. These insights offer a more nuanced approach to resistance-based sprint training by accounting for every step across all acceleration phases, rather than focusing solely on the plateau phase, which accounts for only 20–30% of the steps collected during initial contact to peak velocity depending on the analyzed overload condition.

KEYWORDS

resistance-based sprint training, overload conditions, ground reaction forces, dynaspeed, running speed, sprint phases, force plate

1 Introduction

Sprint performance, a crucial component in many sports, heavily depends on the ability to generate propulsive force across a range of speeds. Assessment and modelling of this mechanical capacity often rely on the force-velocity (F-v) relationship, especially in scenarios involving sprint acceleration and other maximal effort movements. Widely validated and frequently used in practice (1–6), the Fv profile provides valuable insights into an individual's ability to generate force under different speed conditions throughout a sprint.

In sprinting, forward acceleration is predominantly influenced by the ground reaction forces (GRFs) generated by the athlete. The interaction between the vertical and horizontal components of these GRFs creates a resultant vector that varies throughout different phases of the sprint. A critical factor in this process is the athlete's "technical ability," often quantified by the ratio of forces (RF). The RF represents the proportion of the step-averaged resultant ground reaction force vector that is directed horizontally (FH) relative to the total applied force (7). The orientation and magnitudes of the force vector, as indicated by the RF, serves as a key mechanical parameter, influencing both the efficiency of acceleration (7, 8) and performance when approaching maximum speed (7, 9). Consequently, a comprehensive understanding of force production and its directional components across varying speed conditions during sprint acceleration is essential for optimizing performance and assessing the kinetic effects of different training protocols.

A significant challenge in training to improve ratio of forces has been determining how to effectively stimulate different phases of a sprint, particularly under varying force-velocity conditions. Among the most prevalent methods for enhancing sprint performance is sprint-specific resisted training, which involves running against varying resistance loads to target specific F-v characteristics (10). Resisted runs are well-known for creating the desired force application context, which is necessary to stimulate specific scenarios during a sprint. In the existing literature, two major context categories have been identified as relevant to the application of anteroposterior force in the context of a standing maximal sprint. These categories are high force-low velocity condition, and low force-high velocity condition, which are observed to occur successively throughout the run.

Historically, the speed of displacement has been a cornerstone for identifying distinct phases of sprinting. More recently, it has also been used as a criterion for prescribing training loads due to its integration of various underlying explanatory variables (8, 11, 12). The velocity-loss approach has gained popularity as an alternative to traditional methods based solely on relative body weight percentages which may not fully account contextual or individual factors -such as variations in friction coefficients or force production capabilities- that can influence the orientation of sprint training stimuli (13–15). The introduction of motorized towing systems (e.g., Muscledab Dynaspeed, 1080 Sprint) has provided coaches with greater control and precision, enabling them to create specific conditions that stimulate athletes and induce sprint-specific overloads, expanding the possibilities beyond traditional loaded sleds, parachutes and elastic bands (3, 16, 17).

It is now recognized that training with specific loads can significantly impact not only the kinetic (force orientation and application) but also kinematic parameters underlying sprint performance. Recent studies have increasingly focused on the effects of sprint resistance training, exploring how different loads affect underlying components such as spatiotemporal kinematics (17, 18), segmental disposition (19, 20), or electromyographic activity (11). However, debate persists over the use of light vs. heavy loads, due in part to the differences between unresisted and resisted sprint conditions, which are not always fully explained (21–23). Much of this research is also based on cross-sectional studies, which often focus on isolated steps within specific sprint phases rather than analysing full acceleration, potentially limiting the understanding of a such a dynamic mechanical context. Additionally, findings from acute overload effects are sometimes interpreted as potential long-term adaptations, though these projections remain unconfirmed under longitudinal studies (20). Although load specificity is a well-established concept in the broader field of resistance training (24–26), its application in sprint training remains underexplored, with limited experimental research offering a step-by-step analysis of kinetic and kinematic changes across different sprint conditions.

Despite these ongoing debates, a primary goal of sprint resistance training is to achieve specificity by manipulating training loads to replicate the kinetic and kinematic conditions of unresisted sprints at various velocities (22, 23, 27, 28). It is well-documented that sprint mechanics remain largely unaffected between free and overloaded conditions when running velocities are similar (29). However, from a practical perspective, this approach only permits accurate characterization of training stimuli during phases where velocity remains constant, such as the plateau phase. Therefore, this study aims to analyze the impact of various loading conditions on sprint performance in comparison to free sprinting. Specifically, the research seeks to identify the loading scenarios that most closely replicate the mechanics of unresisted sprints across the full acceleration spectrum, thereby providing practical guidelines for coaches in selecting appropriate loads for sprint-specific overload training.

2 Material and methods

Sixteen experienced male sprinters competing at state level volunteered to participate (age: 20.5 ± 1.4 years; stature: 1.75 ± 0.06 m; body mass: 68.3 ± 6.4 kg; 100 m personal best, 11.31 ± 0.38 s). Participants were informed about the testing procedures and potential risks, and written consent was obtained prior to the study. They were advised to avoid any fatiguing lower-body activities, including resistance training, sprinting, or high-intensity interval running, for 72 h before testing to ensure they arrived in a non-fatigued state. The study adhered to current ethical guidelines, was approved by the institutional research ethics committee (#11–54), and followed the latest revision of the Declaration of Helsinki.

2.1 Procedure

Two familiarization sessions and one testing session were conducted, spaced by a minimum of two days. Participants, who had extensive experience with resisted and assisted sprint training and had engaged in similar studies, underwent these sessions. The dynaSpeed robotic pulley system (Ergotest Technology AS, Stathelle, Norway), which utilizes a cable mechanism attached to a waist-secured belt, provided resistance and assistance. During the familiarization, the protocol included 50 m sprints with at least five minutes of passive recovery, and 30 m sprints with three minutes of passive recovery. Each session also involved five 20 m resisted sprints with variable pulling resistance and two 50 m assisted sprints with 5 kg of pulling assistance, facilitating adaptation to the robotic pulley system prior to the main testing session.

The main testing session, dedicated to data collection, was conducted on a 110 m long indoor athletic track outfitted with a force platform system for 52 m. This system, consisting of 54 units (models TF-90100, TF-3055, TF-32120, Tec Gihan, Uji, Japan), operated at a sampling frequency of 1,000 Hz. The protocol involved initial sprints of 50 m unresisted, followed by two 30-m sprints with active resistance at 10%, 25%, 50%, and 65% velocity loss, provided by dynaSpeed (Ergotest Technology AS). These velocity losses were calculated based on a linear regression analysis of sprints with different resisted loads after the first familiarization session and tested in the second session. Overspeed condition (OS) was evaluated using the same methodology, ensuring a 5% increase in top-speed. These sprints were either completed over the designated distance or continued until the plateau phase stabilized, defined in this study as the portion of the sprint where velocity ranged between 90%–100% of each participant's top speed. The order of resistance levels administered randomly. Warm-ups were self-selected and tailored by the participants (ranging from 35 to 50 min), who leveraged their experience to optimize performance and minimize injury risk. This standardized routine included 5 min of low-intensity jogging, followed by upper and lower limb dynamic stretches, progressing to sprint drills (e.g., high knee runs, skips, bounds), and concluding with three progressive sprints building to 95% of maximum effort. A minimum of five minutes of passive recovery was mandated between sprints. Sprint trials commenced from a three-point start. Participants wore their personal spiked racing shoes and maintained consistent attire across all trials.

2.2 Data analysis

Captured kinetic data at a sampling rate of 1,000 Hz. Data integrity was ensured by processing the raw outputs through a digital 50 Hz low-pass, fourth-order Butterworth filter. Spatiotemporal variables and GRFs at every step were calculated in reference to previous studies (30, 31), using the following procedures. Step-to-step contact and flight times were determined using a 20 N threshold for vertical GRFs to identify when the foot made or left ground contact. Step duration was the time between two consecutive foot strikes, and step frequency was calculated as its inverse. Foot placement corresponded to the center of pressure (CoP) at the midpoint of the contact phase. Step length was

measured as the anteroposterior distance between CoP positions of consecutive steps. Running speed was determined by multiplying step length by step frequency. Additionally, mean anteroposterior and vertical forces during the contact phase were assessed for each step. RF was calculated by dividing the FH by the total force applied during each step. Finally, effective vertical mean force and impulse were calculated by subtracting body mass from the vertical force and integrating over the contact phase duration (32, 33). All GRFs and impulse variables were divided by body mass. Relative values were expressed as a percentage of the maximum value observed during the free sprint condition, calculated using the formula: $(\text{value under load} / \text{maximum value without load}) \times 100$. For instance, if the step length under load is 1.8 m and the maximum step length during unresisted sprint is 2 m, the resulting relative value would be 90%.

2.3 Statistical analysis

2.3.1 Cluster analysis

K-means clustering was applied to every step to classify the dataset into distinct groups based on five key biomechanical variables: ratio of force, relative mean horizontal force, relative mean vertical force, relative contact time, and relative step length. Prior to clustering, variables were standardized using z-scores to ensure equal contribution and prevent any single variable from disproportionately influencing cluster formation. The optimal number of clusters was determined using the elbow method, which involved identifying the point where the reduction in within-cluster sum of squares began to plateau. Silhouette analysis was then used to confirm the cohesiveness and separation of the clusters. To further validate cluster stability and reliability, we performed cross-validation by randomly selecting two subsets of approximately 800 steps each (representing around 30% of the entire dataset). Each subset was analyzed independently, using the same clustering procedures. These additional analyses yielded the same optimal number of clusters, supporting the robustness of the clustering approach applied to the full dataset.

2.3.2 Inter-cluster statistical comparisons

Once non-normality of the data was confirmed through Levene's test for each analyzed variable ($p < .001$), a series of Kruskal-Wallis tests were conducted to assess differences in selected biomechanical parameters across four clusters. Each test was followed by Dunn's post-hoc pairwise comparisons to identify specific inter-cluster differences, with significance set at $p < 0.05$. Descriptive statistics were calculated as group-averaged minimum and maximum values of key biomechanical variables across different loading conditions within each cluster.

3 Results

3.1 Cluster identification

A four-cluster solution was chosen based on a balance between fit statistics and interpretability. The overall fit statistics for the

clustering solution were as follows: the coefficient of determination (R^2) was 0.888, the Akaike Information Criterion (AIC) was 962.190, and the Bayesian Information Criterion (BIC) was 1070.360. The average silhouette score, which measures the cohesion and separation of clusters, was 0.540, indicating reasonably well-structured data.

3.2 Cluster characteristics

The cluster sizes ranged from 109 to 771 steps, with Cluster 4 having the largest group (771) and Cluster 1 the smallest (109). The proportion of within-cluster heterogeneity explained varied across clusters, with Cluster 2 explaining the most heterogeneity (35.3%) and Cluster 4 the least (15.9%). The within-cluster sum of squares, a measure of cluster compactness, showed that Cluster 1 had

the highest value (325.423), while Cluster 4 had the lowest (146.556). The silhouette scores for individual clusters ranged from 0.467 (Cluster 2) to 0.635 (Cluster 4), suggesting that Cluster 4 had the best separation from other clusters (see Table 1). Visual representation for identified clusters can be observed in Figure 1.

3.3 Differences across clusters

The Kruskal-Wallis test revealed significant differences between the clusters for each performance-related parameter analyzed. Post-hoc analysis further indicated that the clusters differed significantly from one another, with the exception of relative horizontal force, where no significant difference was observed between clusters 4 and 1 ($p > 0.05$). A detailed breakdown of these findings is provided in Table 2.

TABLE 1 Cluster information.

Cluster	Associated phase	Size	Explained proportion within-cluster heterogeneity	Within sum of squares	Silhouette score
1	Initial contact	109	0.159	146.556	0.635
2	Early-acceleration	763	0.353	325.423	0.551
3	Mid-acceleration	716	0.271	249.558	0.467
4	Late-acceleration	771	0.218	200.652	0.596

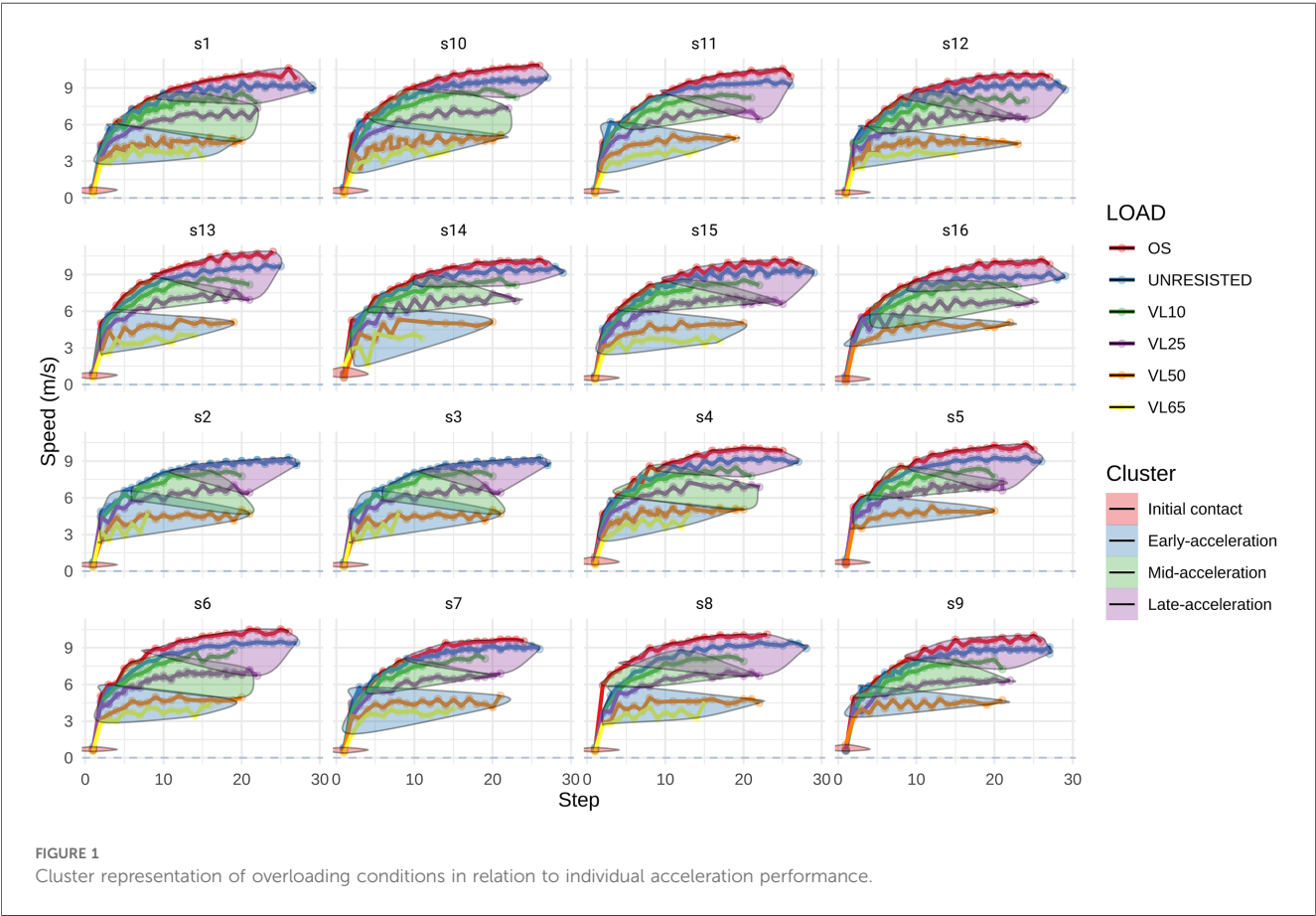


TABLE 2 Differences across clusters for biomechanical parameters.

	Kruskal-Wallis	Cluster differences
Ratio of forces (%)	$\chi^2 (3, N = 1,650) = 1,466.748$, $p < .001$	1 > 2 > 3 > 4
Relative horizontal force (%)	$\chi^2 (3, N = 1,650) = 1,413.08$, $p < .001$	1; 2 > 3 > 4
Relative vertical force (%)	$\chi^2 (3, N = 1,650) = 1,440.686$, $p < .001$	1 > 2 > 3 > 4
Relative CONTACT Time (%)	$\chi^2 (3, N = 1,650) = 1,294.251$, $p < .001$	1 > 2 > 3 > 4
Relative step length (%)	$\chi^2 (3, N = 1,650) = 1,467.299$, $p < .001$	1 > 2 > 3 > 4

3.4 Step characteristics per cluster

Table 3 presents the minimum and maximum values of key biomechanical variables across different loading conditions within distinct clusters. Visual representation of these ranges is shown in Figure 2.

4 Discussion

This research explores the impact of varying overload conditions on the mechanical determinants of athletic performance during sprint acceleration. The findings suggest that these mechanical determinants may align with the distinct phases of sprinting documented in existing literature. Overload conditions, whether involving heavy or light loads, seem to recreate specific mechanical contexts. Heavy loads tend to produce more targeted stimuli, primarily affecting specific sprint phases due to rapid speed stabilization under exclusively high-force low-speed scenarios, whereas light loads seem to provide broader stimuli, influencing performance across a wider range of sprint phases.

Recent findings suggest that at a specific speed, variations in load minimally affect spatiotemporal variables and GRFs, indicating that running speed may be more influential than load (29). While speed is widely recognized as a key determinant of training intensity, it may not fully encompass/capture sprint mechanics under ecological conditions. This limitation is particularly evident when training stimulus is solely focused on the plateau phase of sprint runs.

Regardless of the load used, sprints typically exhibit a progressive decline in acceleration capability until maximum velocity is reached (14). Consequently, current methodologies based on velocity loss are most applicable to phases where velocity has stabilized. However, our findings suggest that the plateau phase (90%–100% of maximum velocity) accounts for only 20%–30% of the steps required to reach peak velocity depending on loading condition (see Figure 2). This observation implies that relying solely on the plateau phase for stimuli characterization might be particularly compromised when speed stabilization is delayed. To address current methodological limitations (12, 34, 35), this study employs cluster analysis to

identify scenarios that best replicate the mechanical characteristics of free sprinting across various overload conditions. The categories derived from selected mechanical determinants appear to align closely with the sprint phases identified in the literature, such as block start, early acceleration, late acceleration, and top speed (31, 36).

Analysis of these clusters reveals consistent patterns across analyzed sprint runs, regardless of overload condition. Typically, the distribution of forces transitions from a balanced force ratio -around 50% at initial contact- to a gradual decline, primarily due to the rapid decrease in horizontal force application, while vertical forces steadily increase. This shift is often attributed to changes in body segment orientation that occur with increasing displacement speed (36, 37). Notably, although higher speeds result in reduced contact times, this is accompanied by a continuous increase in step length and stabilization or decline in step rate, indicating a dynamic adaptation of force application scenarios throughout the sprint (see Supplementary File S1).

Cluster 1, corresponding to initial contact data for each athlete, was characterized by longer contact times, greater horizontal force application, and higher force ratios compared to the subsequent clusters. Additionally, shorter step lengths and reduced vertical force applications were observed, regardless of the applied overload (Tables 2, 3). These step mechanics align with the findings of previous studies, which identified low to null displacement velocities and specific body arrangements as primary factors influencing kinetic and kinematic conditions (38–40). The consistent clustering of all initial contacts indicates a high level of specificity during this phase, suggesting that stimulating scenarios is not conditioned by the type of overload used, as the mechanical characteristics of these conditions are consistently reproduced across all analyzed scenarios (Figure 1).

Horizontal force remains consistent with the preceding steps ($p > 0.05$) but differs from the following ones in Cluster 2. While horizontal force stays stable during the early steps of acceleration, RF decreases due to an increase in mean vertical force compared to initial contact steps (Cluster 1). This shift marks the beginning of a trend of progressive decline that persists throughout the entire acceleration curve. Separately, our analysis reveals that the number of steps recreating the mechanical characteristics of the initial acceleration phase (Cluster 2) is influenced by the type of overload applied. For lighter loads, such as OS, unresisted, or VL25, steps 2–4 fall into cluster 2. However, with heavier loads, particularly those classified as VL50 and VL65, this cluster extends to steps 7–8. This observation highlights a key distinction in the diverse training methodologies aimed at enhancing early-acceleration (27, 41). In this sense, some approaches recommend using light loads to avoid mechanical disturbances and maintain the natural sprint mechanics observed under free sprint conditions (11, 12, 22). These approaches, involving loads less than 20% of body weight or with velocity losses under 10%, are usually applied over short distances of 20 and 30 meters per set (42–45). However, while light loads are effective in preserving natural sprint mechanics, they may lack the specificity needed/required for the sustained replication of initial contact conditions. This reduced specificity, resulting from

TABLE 3 Mean ranges for biomechanical variables across clusters.

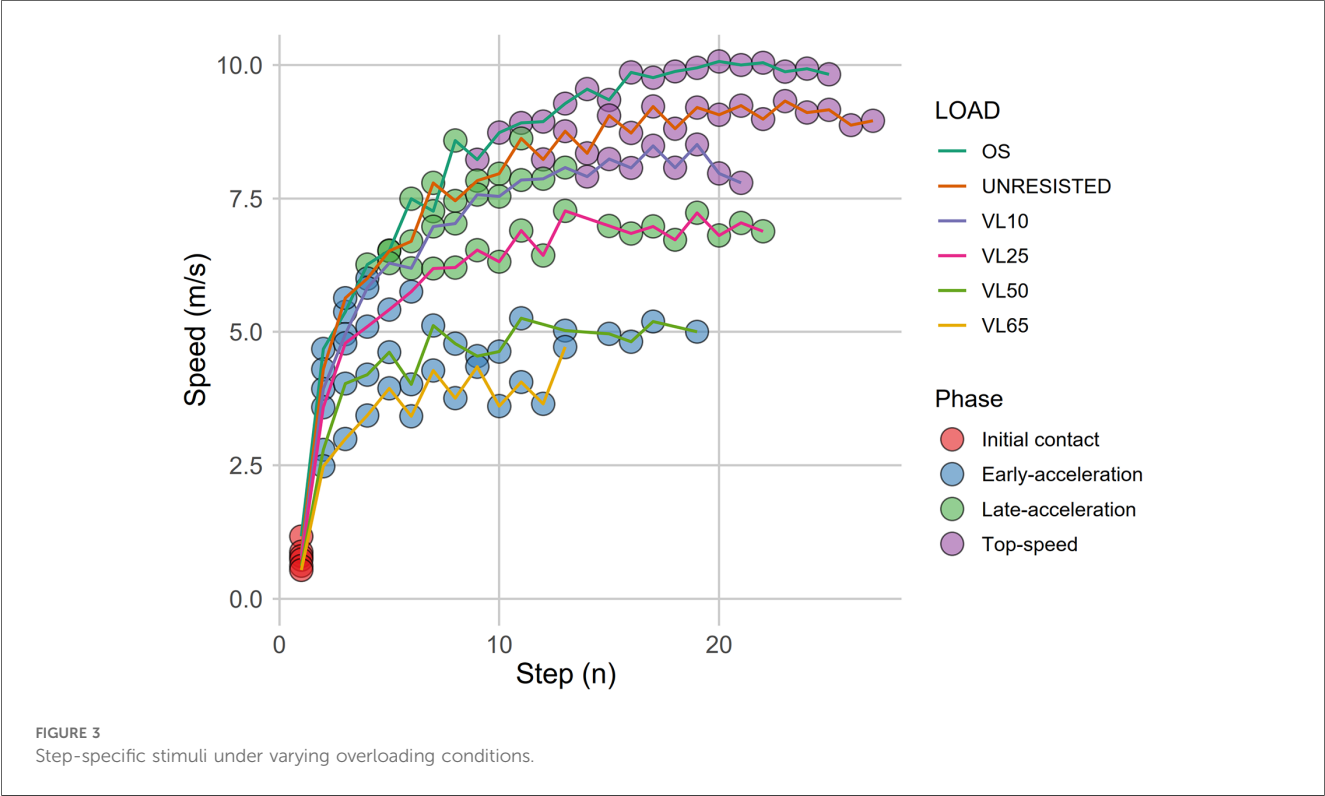
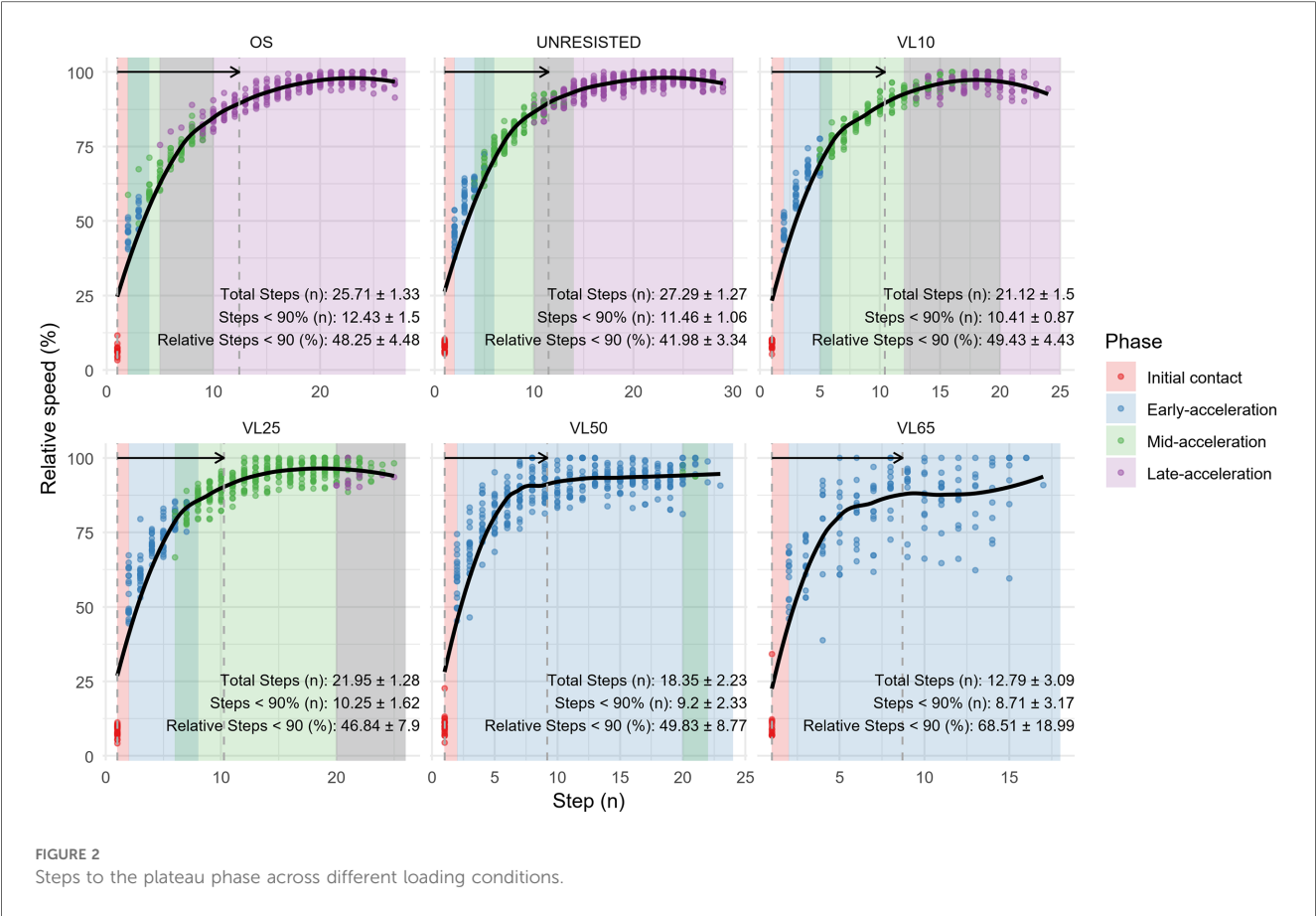
			Distance	Step	Speed	Contact time	Step length	Horizontal force	Vertical force	Ratio of force
CLUSTER 1. Initial Contact	OS	Absolute	0.0–0.0	1.0–1.0	0.7–0.7	0.9–0.9	0.7–0.7	3.9–3.9	11.8–11.8	–
		Relative	0.0–0.0	3.9–3.9	7.2–7.2	136.9–136.9	29.6–29.6	56.4–56.4	44.0–44.0	31.1–31.1
	UNRESISTED	Absolute	0.0–0.0	1.0–1.0	0.8–0.8	0.64–0.64	0.5–0.5	5.9–5.9	12.1–12.1	–
		Relative	0.0–0.0	3.7–3.7	7.9–7.9	96.8–96.8	23.6–23.6	85.5–85.5	45.0–45.0	43.9–43.9
	VL10	Absolute	0.0–0.0	1.0–1.0	0.7–0.7	0.64–0.64	0.5–0.5	6.3–6.3	12.1–12.1	–
		Relative	0.0–0.0	4.8–4.8	7.8–7.8	99.1–99.1	23.2–23.2	91.2–91.2	45.3–45.3	46.2–46.2
	VL25	Absolute	0.0–0.0	1.0–1.0	0.6–0.6	0.69–0.69	0.4–0.4	6.8–6.8	12.2–12.2	–
		Relative	0.0–0.0	4.5–4.5	6.2–6.2	105.0–105.0	19.8–19.8	96.2–96.2	45.4–45.4	48.4–48.4
	VL50	Absolute	0.0–0.0	1.0–1.0	0.5–0.5	0.73–0.73	0.4–0.4	8.1–8.1	12.6–12.6	–
		Relative	0.0–0.0	4.9–4.9	5.6–5.6	112.7–112.7	18.6–18.6	114.1–114.1	46.5–46.5	54.0–54.0
CLUSTER 2. Early acceleration	OS	Absolute	0.7–1.8	2.0–2.9	4.7–5.4	0.16–0.18	1.2–1.4	5.4–6.4	15.4–16.7	–
		Relative	1.4–3.78	7.7–11.3	49.9–57.3	25.0–27.7	55.2–62.0	76.1–89.9	56.8–61.8	30.8–38.1
	UNRESISTED	Absolute	0.5–2.8	2.0–4.0	4.2–6.0	0.15–0.18	1.1–1.4	5.5–6.8	14.4–16.7	–
		Relative	1.12–5.84	7.3–14.5	45.1–63.3	22.4–27.5	47.7–61.2	78.1–97.4	53.5–61.9	31.6–41.9
	VL10	Absolute	0.5–3.4	2.0–4.5	4.0–5.9	0.15–0.19	1.0–1.4	5.2–6.6	13.7–16.4	–
		Relative	1.6–10.49	9.5–21.5	42.3–62.4	23.6–29.8	46.2–60.9	74.9–95.2	51.1–61.3	30.9–42.8
	VL25	Absolute	0.4–5.0	2.0–6.1	3.8–5.8	0.15–0.2	1.0–1.3	5.2–7.3	13.6–17.1	–
		Relative	1.47–16.71	9.1–27.5	39.8–61.0	23.1–31.2	44.0–59.5	73.9–102.7	50.1–63.0	30.2–46.4
	VL50	Absolute	0.4–20.5	2.0–20.1	3.0–5.1	0.16–0.24	0.8–1.3	5.1–7.9	13.2–17.8	–
		Relative	1.99–98.21	9.8–98.5	31.2–53.9	24.5–36.7	37.6–58.3	71.3–110.9	48.6–65.4	29.4–48.6
CLUSTER 3. Mid-acceleration	OS	Absolute	3.2–10.0	3.8–7.9	6.1–8.1	0.11–0.15	1.5–1.8	3.1–4.8	18.3–22.7	–
		Relative	6.71–21.24	14.7–30.8	64.0–85.8	17.1–22.6	68.3–83.2	43.6–68.3	67.4–83.4	13.6–25.2
	UNRESISTED	Absolute	4.1–14.7	5.0–11.2	6.2–8.5	0.11–0.14	1.5–1.9	2.6–4.7	17.4–22.4	–
		Relative	8.76–31.17	18.2–41.2	66.2–89.8	16.6–22.1	64.9–83.9	37.5–67.0	64.8–83.2	12.0–25.3
	VL10	Absolute	4.7–20.2	5.5–14.9	6.1–8.2	0.11–0.15	1.4–1.9	2.5–4.7	17.0–22.2	–
		Relative	14.7–62.66	26.3–70.4	64.9–86.9	17.1–23.1	64.5–83.2	36.4–67.5	63.4–82.9	11.6–26.1
	VL25	Absolute	6.2–28.6	7.0–21.4	5.8–7.1	0.12–0.15	1.4–1.9	2.7–5.1	17.1–21.7	–
		Relative	20.71–95.49	31.7–96.5	60.9–75.4	18.8–23.6	62.8–84.9	38.1–71.9	63.3–80.3	12.8 to 27.1
	VL50	Absolute	11.8–47.1	8.9–25.7	8.4–10.3	0.09–0.11	1.9–2.3	–1.1–2.6	23.0–27.9	–
		Relative	25.13–100	34.6–100.0	88.3–109.0	13.7–16.7	85.9–104.6	–15.7–37.0	84.6–103.0	–4.1–10.9
CLUSTER 4. Late acceleration	OS	Absolute	15.2–47.1	11.5–27.3	8.3–9.4	0.1–0.11	1.9–2.2	–0.2–2.4	22.3–26.7	–
		Relative	32.16–100	42.1–100.0	87.8–99.6	14.8–17.2	83.4–99.4	–3.8–34.5	83.0–99.3	–0.9–10.4
	VL10	Absolute	20.6–32.4	15.1–21.1	7.9–8.5	0.11–0.12	1.9–2.2	–0.6–2.4	22.4–25.7	–
		Relative	63.71–100	71.4–100.0	83.2–89.6	16.5–18.1	83.2–99.3	–9.0–34.5	83.3–95.6	–2.4–10.4
	VL25	Absolute	29.8–30.3	21.7–21.9	6.7–6.7	0.13–0.14	2.0–2.0	1.7–1.9	23.2–23.4	–
		Relative	98.33–100	98.8–100.0	70.3–71.0	19.8–20.3	88.0–88.9	24.3–27.0	84.4–85.1	7.4–8.2

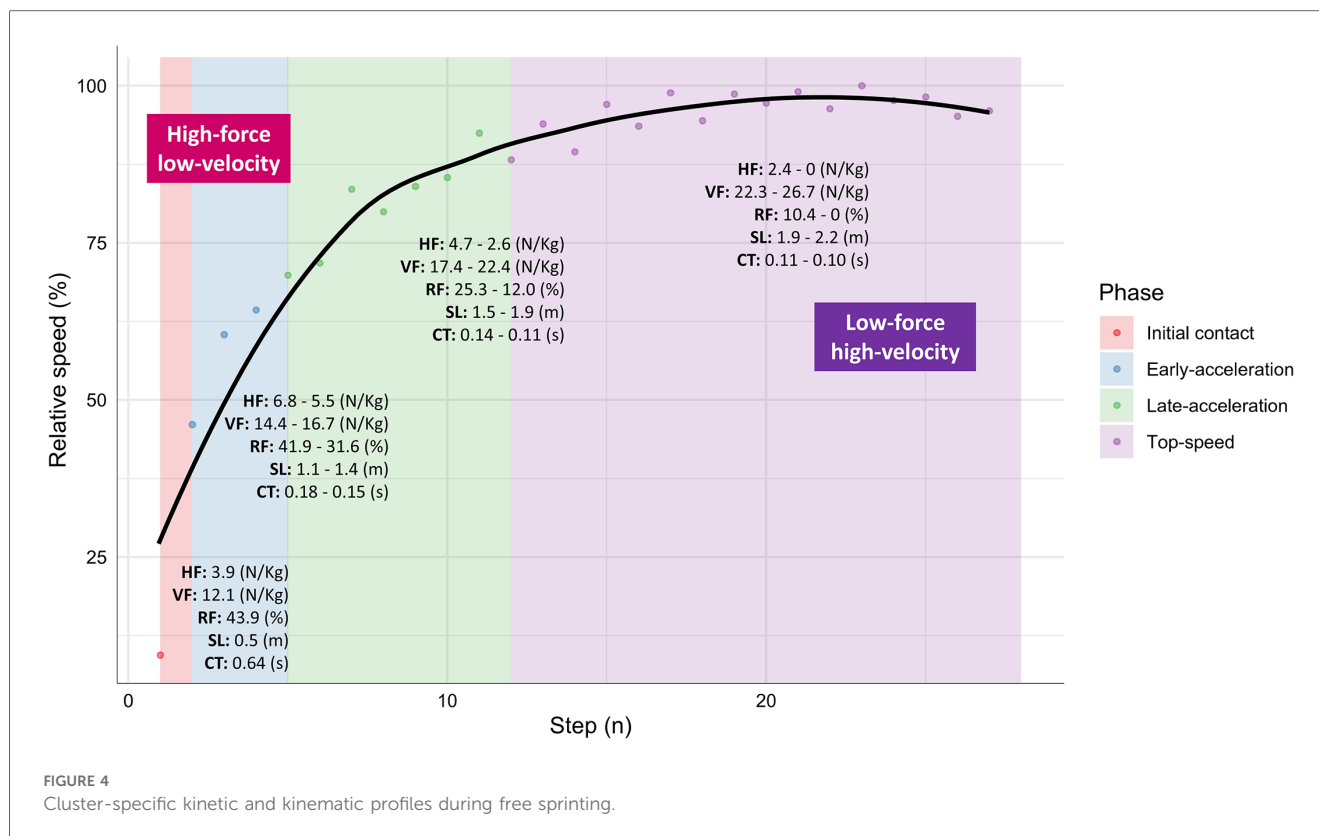
Absolute units for the described values: distance (m); Step (n); Speed (m/s); contact time (s); step length (m); horizontal force (N/Kg); vertical force (N/Kg).

the rapid increase in velocity that light loads facilitate, could limit the effectiveness of these approaches compared to heavier loads, which allow for a more prolonged replication of the mechanical characteristics necessary for early acceleration (see Figures 2, 3).

Cluster 3 corresponds to steps in the middle acceleration phase, also referred as the transition phase, characterized by a marked decrease in horizontal force compared to the preceding clusters, aligning with the concept of a decreasing ratio of forces throughout the acceleration phase, as described by Morin et al. (7). While this cluster includes steps from all overload conditions, it primarily comprises contacts associated with the late acceleration phase of lighter overloads (OS, unresisted, VL10, and VL25) and the plateau phase of VL10 and VL25. Although cluster spread varies depending on the overload type, similar onset points can be identified, typically occurring

around the fourth or fifth step. This observation aligns with previous findings by Nagahara et al. (31, 36), who reported the transition phase beginning around 4–5 steps under free-sprint conditions in elite sprinters. As the overload increases, the transition to the next cluster is delayed, with the upper limits extending from steps 9–10 under OS and unresisted conditions to potentially encompassing the entire plateau phase for VL25 loads. This delay indicates that heavier overloads prolong the scenario typically observed during the free-sprint acceleration phase, potentially enhancing the training stimulus for this crucial phase of sprinting (46). By understanding these dynamics, coaches can strategically select and adjust overloads, considering both the specific conditions and the steps required to optimally target and prolong the transition phase, thereby maximizing training effectiveness.





Cluster 4 corresponds to steps associated with mechanical factors typically observed during free-sprint maximum velocity phases. Our analysis reveals that only light overloads (OS, unresisted, and late VL10 steps) successfully replicate conditions featuring reduced contact times (0.09–0.14s) and predominantly vertical force orientation at very high speeds (RF ranging from 10% to 0%), resulting in significantly longer step distances (Table 3). These scenarios, however, are only reproduced from the 11- to 29-meter mark onwards, depending on the overload applied. This variation can substantially affect the effectiveness of the training stimulus over a given distance and exposes the limitations of training prescriptions or analyses that focus exclusively on the sprint plateau phases, which account for only a small portion of overall sprint performance. These findings underscore the importance of identifying and prioritizing specific training phases, as distinct overloads have unique impacts on sprint mechanics at different points in the sprint distance.

In this sense, a central challenge in performance training is determining which specific attributes or performance phases should be prioritized for improvement. For sprint coaches, this often begins with an analysis of the velocity-time curve to pinpoint the acceleration phase most in need of targeted development. Under the principle of specificity, it is hypothesized that stimuli closely aligned with the athlete's target movement contexts may yield more efficient and relevant adaptations. Within this framework, strategies that incorporate sustained velocity loss have been proposed as a means to enhance exposure to these specific contexts, thereby fostering adaptations linked to selected movement velocities.

Our findings support this hypothesis by demonstrating that controlled loads effectively recreate contexts with a high degree of similarity to targeted sections of the velocity-time curve. However, they also reveal previously unconsidered aspects, such as the point at which a prescribed load begins to meaningfully stimulate the intended section. When examining two commonly discussed examples in the literature -early and late acceleration phases- our analysis confirms that once movement velocity stabilizes (i.e., the plateau phase), stimuli are consistently reproduced according to the intended training context. For instance, loads at 50% and 65% velocity loss (VL50 and VL65) effectively target early acceleration, while lighter loads [e.g., overspeed [OS], free sprinting [FS], and 10% velocity loss [VL10]] align well with conditions for later stages of acceleration.

However, by examining these stimuli through the lens presented in this study, distinct variations emerge in the behavior of movement prior to reaching stabilized speed. Although any overload will inevitably include the initial step due to its unique characteristics, heavier loads appear to replicate the demands that characterize early acceleration in free conditions from the second step onward, even without reaching plateau values (typically achieved around steps 8–9 under these conditions). This observation may support the high effectiveness of heavy loads for stimulating high-force, low-velocity contexts, as highlighted in the literature.

On the other hand, lighter loads also reach a stabilized context for training but do so much later, reducing the proportion of steps or distance covered per repetition that effectively targets early acceleration. Based on our findings, lighter loads (such as OS, FS,

and VL10) seem to replicate a broader range of stimulation contexts and are particularly valuable for training low-force, high-velocity scenarios. Under these conditions, the stabilization of recreated contexts occurs around steps 9–15 (see [Table 1](#)), which closely align with the moments at which plateau phase is reached under analyzed conditions (steps 10–12) (see [Figures 2–4](#)).

From a practical perspective, the results not only offer valuable insights into the effectiveness of various overload conditions in replicating the mechanical characteristics critical to sprint performance but also help identify the most effective training stimuli. Furthermore, the discussion enables a more detailed characterization of the training stimulus beyond the plateau phases, thereby offering important insights into how training volume per set is influenced by the chosen overload condition. Thus, monitoring the number of steps associated with each scenario would provide coaches with an alternative tool for the objective quantification of the periodization models applied throughout the season, based on criteria of specificity. For instance, when examining specificity in recreating targeted mechanical contexts within a standard early acceleration session covering 20 meters per set, heavy loads (e.g., VL50 and VL65) replicate the desired phase for a significant portion of the distance (approximately 19 out of 20 steps or nearly the full 20 meters). In contrast, lighter loads (e.g., VL10) recreate the targeted scenario for only 2–3 steps (roughly 3 meters when analyzing the average distance covered under this overload conditions for early acceleration) within the 15 steps required to complete the 20-meter distance (see [Table 3](#)).

The findings present coaches and practitioners with a refined approach to monitoring and adjusting training across distinct phases of sprint performance. Through “phase-specific sprinting exposure,” coaches gain a deeper understanding of how targeted the stimuli are throughout all acceleration phases, from early to late stages. This perspective supports a more precise approach to load monitoring, drawing parallels to methods in velocity-based training by emphasizing the analysis of velocity range distribution across each repetition. Such an approach allows for a more systematic assessment of sprint-specific stimulation, potentially enhancing the effectiveness and specificity of resistance-based sprint training.

Future research should investigate the long-term training effects of manipulating overload conditions to target specific sprint phases to verify if the periodic recreation of acute training stimuli leads to the desired long-term adaptation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Institutional research Ethics Committee (#11–54) of National Institute of

Fitness and Sports in Kanoya, Japan. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

PJ-R: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing, Visualization, Resources. RvT: Data curation, Investigation, Methodology, Supervision, Validation, Writing – review & editing, Project administration, Resources, Visualization. AC-Z: Data curation, Formal Analysis, Validation, Visualization, Writing – original draft, Writing – review & editing. SG: Data curation, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. RN: Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fspor.2024.1510379/full#supplementary-material>

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Longitudinal monitoring of load-velocity variables in preferred-stroke and front-crawl with national and international swimmers

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Load-velocity (LV) profiling in swimming provides key metrics, including theoretical maximal velocity (V_0) and theoretical maximal load (L_0); however, longitudinal studies tracking these variables across competitive seasons are limited. This study investigated LV profiling and competition performance in national and international-level swimmers (Level 1–3) over a 15-month period. Twenty-six swimmers participated (16 males: age: 19.8 ± 3.9 years, body mass: 80.3 ± 7.9 kg, height: 1.84 ± 0.07 m; 10 females: age: 20.7 ± 3.6 years, body mass: 68.2 ± 5.7 kg, height: 1.74 ± 0.03 m), all specializing in 50–200 m events. Swimmers completed 4–6 testing sessions, each involving 3×10 m sprints against resistances of 1, 5, and 9 kg (males) and 1, 3, and 5 kg (females), in both front-crawl and their preferred-stroke. Linear mixed-effects models assessed changes in LV outputs— V_0 , L_0 (absolute and relative to body mass), relative slope ($-V_0/rL_0$), and active drag (AD). Smallest worthwhile change (SWC) assessed within-athlete variation, while Pearson's correlations evaluated relationships between race performance and LV outputs. Analysis of preferred-stroke found males exhibited significantly higher values across all variables except the slope ($p = 0.607$). National-level swimmers had lower L_0 (-2.8 kg, $p = 0.019$), but no statistical difference in rL_0 (-1.5% , $p = 0.244$) or slope (-0.002 m/s/%, $p = 0.558$). AD remained stable across observations, though males produced greater drag ($+30.2$ N, $p < 0.001$), while national-level swimmers produced less (-12.8 N, $p = 0.045$). Analysis of front-crawl performance found males presented higher values across all variables ($p \leq 0.05$) while national-level swimmers were lower ($p < 0.005$). SWC analysis revealed that most within-athlete changes in V_0 and L_0 were trivial or unclear, with only isolated meaningful changes observed. Large to very large correlations existed between race performance and L_0 ($r = 0.67$, $p < 0.05$), V_0 ($r = 0.73$, $p < 0.05$), and AD ($r = 0.58$ – 0.7 , $p < 0.05$) at select observations. These findings highlight the stability of LV profiling metrics over time while reinforcing their relevance in distinguishing between performance levels. This suggests their potential utility in talent identification and informing training prescription.

KEYWORDS

swimming, male, female, semi-tethered, profiling, mixed-effect model

Introduction

Swimming is a highly competitive sport that requires a complex interplay of physiological, biomechanical, and psychological factors to optimize performance (1, 2). The competitive swimmer's annual calendar typically consists of short-course (25 m) swimming from September to December followed by long-course (50 m) swimming from January to August, culminating in major international and national championships. To ensure peak performance at these key competitions, coaches meticulously periodize their training plans, making the identification of relevant performance-monitoring variables essential for optimizing performance.

Biomechanical assessment plays a crucial role in understanding swimming performance. Deterministic modelling suggests that free-swimming velocity is influenced by the ratio of stroke length and stroke rate, with improvements in stroke length largely dependent on maximizing propulsive forces while minimizing resistive forces (3). Fully-tethered swimming is a well-established method for assessing a swimmer's resultant propulsive force (4–6). In relation to sprint performance, peak and average forces obtained in front-crawl, backstroke, breaststroke and butterfly have shown strong correlations with swimming velocity in 50 m ($r = -0.90$ to -0.69 and -0.94 to -0.81 , respectively), and 100 m ($r = -0.89$ to -0.73 and -0.93 to -0.78 , respectively) (6–8). Additionally, impulse measured during front-crawl swimming has been positively correlated with 100 m time-trial performance ($r = 0.76$) (9). However, longitudinal data on fully-tethered swimming performance is scarce. One case study of an elite sprint swimmer reported improvements of 17, 12% and 31% in tethered swimming peak force, average force and impulse respectively, over three years (10), but did not investigate seasonal changes or their impact on competition performance, highlighting a key gap in the current literature.

An emerging alternative to fully-tethered swimming is semi-tethered swimming with load-velocity (LV) profiling, which offers a more context-specific assessment of a swimmer's in-water performance. LV profiling provides coaches and practitioners with key metrics such as maximal theoretical load (L_0), which reflects the swimmer's ability to generate propulsive force, and theoretical velocity (V_0), representing clean swimming speed (11). Advances in commercially available resistance devices have improved the reliability (12) and replicability of these assessments, enabling investigations across different level swimmers and strokes (11, 13–18). Additionally, LV profiling has been utilized to assess active drag (19, 20) and differentiate upper- and lower-body contributions to front-crawl swimming (21). However, most LV studies have been cross-sectional, with the longest investigating the effects of a 5-week cessation period on LV performance (22). Furthermore, most research has focused on front-crawl swimming, with limited investigation into preferred-stroke swimming. While front-crawl dominates training, even among swimmers specializing in other strokes, it remains unclear how these adaptations affect performance in their preferred event (23). To date, no longitudinal study has systematically examined seasonal variations in LV outputs across different strokes and their relationship with elite competition performance.

Despite the importance of tracking performance variables, longitudinal studies involving elite swimmers remain limited, with most existing research focusing on age-group athletes (24–28). A five-year study of 40 elite swimmers monitored changes in anthropometrics, physiology, and swim performance in a 7×200 m incremental step test (29). Variables assessed included body composition, stroke rate, stroke length, blood lactate, and heart rate. While this study offered valuable insight into multi-year training adaptations, it did not examine how these variables changed around competitions or their relationship with competition performance, leaving a gap in understanding how these factors influence peak performance. A subsequent investigation using the same testing protocol across a single competition season found no significant changes in velocity, stroke index, stroke length, or stroke frequency at 4 mmol of blood lactate across three time points (30). These findings suggest two possibilities: (i) commonly monitored physiological and biomechanical training variables may not be sufficiently sensitive to detect meaningful performance fluctuations within a competitive season, or (ii) at the elite level, these variables may have stabilized due to years of training, with further improvements relying on more technical, tactical, or psychological factors. This highlights the need to explore alternative or complementary performance metrics. Additionally, Costa et al.'s study was limited to male, 200 m front-crawl specialists, raising questions about the generalizability of these findings to female swimmers and other strokes and distances.

Therefore, this study aims to monitor longitudinal changes in LV outputs during both preferred-stroke and front-crawl swimming and assess their relationship with competition performance in national- and international-level swimmers. While preferred-stroke performance may influence competition outcomes, the high training volume of front-crawl may also impact LV outputs, warranting the assessment of both strokes. By comparing swimmers across performance levels, this study seeks to uncover how LV metrics relate to competitive success and to provide novel insights into seasonal biomechanical changes in elite swimming.

Materials and methods

Participants

Twenty-six swimmers from three National Performance Centers and one club participated in the study, including 16 males (age: 19.8 ± 3.9 years, body mass: 80.3 ± 7.9 kg, height: 1.84 ± 0.07 m, arm span: 1.92 ± 0.08 m) and 10 females (age: 20.7 ± 3.6 years, body mass: 68.2 ± 5.7 kg, height: 1.74 ± 0.03 m, arm span: 1.79 ± 0.05 m), specializing in 50–200 m events. All participants provided written consent after receiving details about the purpose, procedures, and associated risks. Their anthropometric data and performance levels are shown in Table 1. Using the recently proposed performance classification model (31), swimmers at Levels 1 and 2 were classified as international ($n = 13$), while those at Level 3 were classified as national ($n = 13$). Among the male participants, preferred strokes included front-crawl ($n = 9$),

TABLE 1 Age, anthropometrics and performance level of participants (mean ± SD).

	National		International*	
	Males (n = 8)	Females (n = 5)	Males (n = 8)	Females (n = 5)
Age (years)	17.6 ± 0.9	20.2 ± 4.9	22.0 ± 4.5	21.1 ± 2.1
Body mass (kg)	76.1 ± 6.9	64.9 ± 5.8	84.5 ± 6.7	71.5 ± 3.7
Height (m)	1.78 ± 0.05	1.72 ± 0.02	1.90 ± 0.04	1.77 ± 0.03
Arm span (m)	1.86 ± 0.06	1.76 ± 0.02	1.97 ± 0.04	1.82 ± 0.05
100 m FC SC world aquatic points	651 ± 93	676 ± 93	768 ± 69	756 ± 67
SC level	3	3	3	3
Preferred-stroke LC world aquatic points	744 ± 31	732 ± 47	861 ± 36	855 ± 37
LC level	3	3	2	2

FC, front-crawl; LC, long course competition; SC, short course competition.
*Students *T*-test found *p* < 0.05 for age, body mass, height and arm span.

backstroke (*n* = 1), breaststroke (*n* = 3), and butterfly (*n* = 3). Among the female participants, preferred strokes were front-crawl (*n* = 3), backstroke (*n* = 4), and breaststroke (*n* = 3). The study was ethically approved by Ulster University.

Design

This study was a longitudinal, observational investigation. Each swimmer participated in four to six profiling sessions from February 2023 to April 2024. Profiling was scheduled within two weeks of identified competitions, which were international, national, or regional, depending on the athlete’s goals and performance level. Most competitions were long-course, with short-course events occurring in December 2023. The competition and profiling schedule is outlined in Figure 1.

Procedures

The procedure for LV profiling has been described in a previous study (Keating et al.). Participants performed their individual competition warm-up on land and in-water. At the start of each session, anthropometric measurements were recorded, including standing height (stadiometer, SECA 242, Hamburg, Germany), body mass (weighing scales, SECA 813,

Hamburg, Germany), and arm span (measured from middle fingertip to middle fingertip across outstretched arms using Anthrotape, Rosscraft, Canada). Following 20 min of passive recovery (32), during which swimmers changed into their competition suit, they performed a series of 10 m maximal swims following a 5 m scull. Swimmers wore a swim belt (S11875BLTa, NZ Manufacturing, OH, USA) attached to a portable resistance device (1080 Sprint, 1080 Motion AV, Lidingö, Sweden) mounted on a start block. The height of the device was recorded each session for horizontal correction as part of data processing (11). The device was set to isotonic resistance, and eccentric and concentric velocity of 0.05 and 14 m/s, respectively. Females performed swims with 1, 3, and 5 kg of resistance, while males used 1, 5, and 9 kg. Four minutes of passive rest was given between trials. All participants completed front-crawl trials first, then repeated the process if their preferred-stroke was backstroke, breaststroke or butterfly.

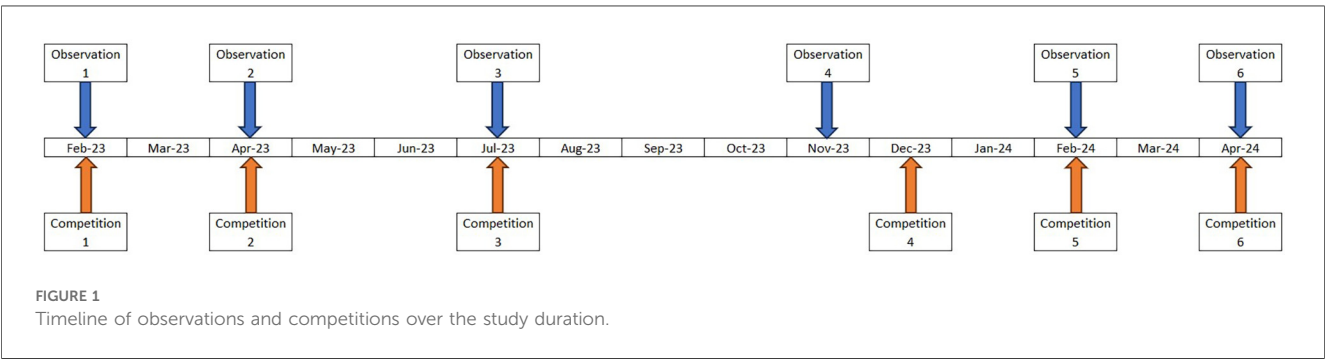
Data processing

Competition data

Times were converted to World Aquatic points to standardize performance across long course and short course competitions (33).

Load-velocity profiling

Position, force, and speed data, sampled at 333 Hz, were exported from 1080 Motion, and processed within a customized script (MATLAB R2023a, MathWorks, Natick, MA, USA). For all front-crawl and backstroke trials, the final 5 m of swimming was extracted for analysis. For breaststroke and butterfly trials, three consecutive stroke cycles within or near to the final 5 m of swimming were extracted (11, 18). Using stroke cycles instead of a fixed distance helps mitigate the risk of over- or underestimating swim velocity, as breaststroke and butterfly exhibit large velocity fluctuations that may not be fully captured over a set 5 m distance. These stroke cycles were identified using MATLAB’s *findpeaks* function and manually selected based on stroke kinematics (34). Following horizontal correction, the average velocity was plotted against the corresponding load to create a load-velocity (LV) plot. Figure 2 presents a typical speed trace produced for each stroke with an external load of 1 kg. A linear regression line was established from each LV plot and



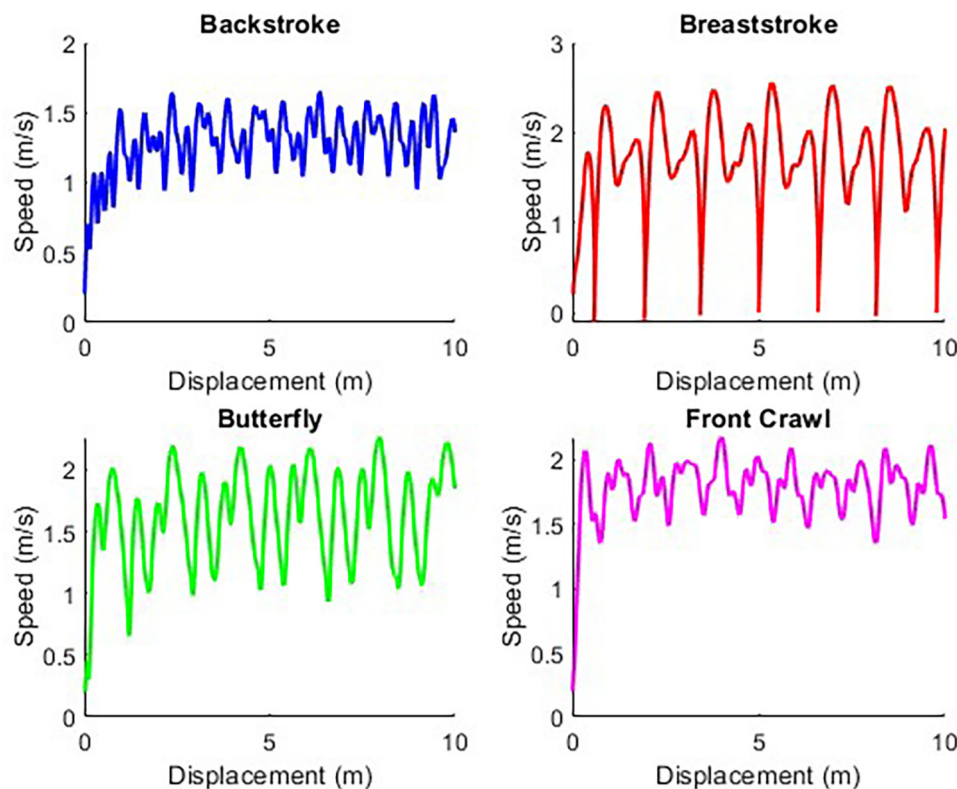


FIGURE 2

Examples of the speed output from the 1080 sprint in each swim stroke using a 1 kg resistance.

extended to intercept the axes, identifying the theoretical maximal velocity (V_0) theoretical maximal load (L_0), with L_0 also expressed relative to body mass (rL_0). The relative slope between these variables calculated as $-V_0/rL_0$. Active drag (AD) was calculated using a modification of the velocity perturbation method (35) proposed by Gonjo and Olstad (20):

$$AD = \frac{F_{add} \times V_{add} \times V_0^2}{V_0^3 - V_{add}^3}$$

where V_0 is derived from the LV relationship; F_{add} and V_{add} are the mean force and velocity extracted from the trial with the second heaviest load, which has been shown to exhibit higher reliability (20).

Statistical analysis

Statistical analysis was performed using R (version 4.4.1) through Rstudio (version 2024.09.1). Data normality was assessed using the Shapiro–Wilk test. Linear mixed-effects models through *lme4* and *lmerTest* packages were used to assess the repeated measurements and account for missing observations (36, 37). The model was developed with maximum likelihood as the method of estimation and a random intercept. Dependent variables included Race Points, and LV outputs— V_0 , L_0 , the relative slope, and AD for both preferred-stroke and front-crawl. Fixed effects included

observation, sex, and level (national or international), while swimmer was included as a random effect. Reference values were set as female swimmer, international level, at observation 1. The linear mixed-effects model is summarized as follows:

$$\text{Dependent Variable} \sim 1 + \text{Observation} + \text{Sex} + \text{Level} + (1|\text{Swimmer})$$

Within-subject changes in preferred-stroke and front-crawl performance for V_0 and L_0 were evaluated by calculating the smallest worthwhile change (SWC) using the between-athlete standard deviation $\times 0.2$ (38). The magnitude of change was assessed by plotting the point estimate with confidence intervals (CI) to determine whether the change was *positive*, *trivial*, or *negative* (39). If the CI spanned only one level, the change was considered *very likely positive*, *negative*, or *trivial*. If the CI spanned two levels, the change was classified as *possibly positive*, *negative*, or *trivial*, depending on the position of the point estimate. If the CI covered all three levels, the inference of change was deemed *unclear* (39). Pearson's correlations between LV outputs and race performance were assessed using the *hmisc* package. Correlation thresholds were interpreted as follows: 0.1 (small), 0.3 (moderate), 0.5 (large), 0.7 (very large), and 0.9 (extremely large) (37). Where possible, 95% CI are reported. Data

visualizations were created using the *ggplot2* package. Statistical significance was defined as $p \leq 0.05$.

Results

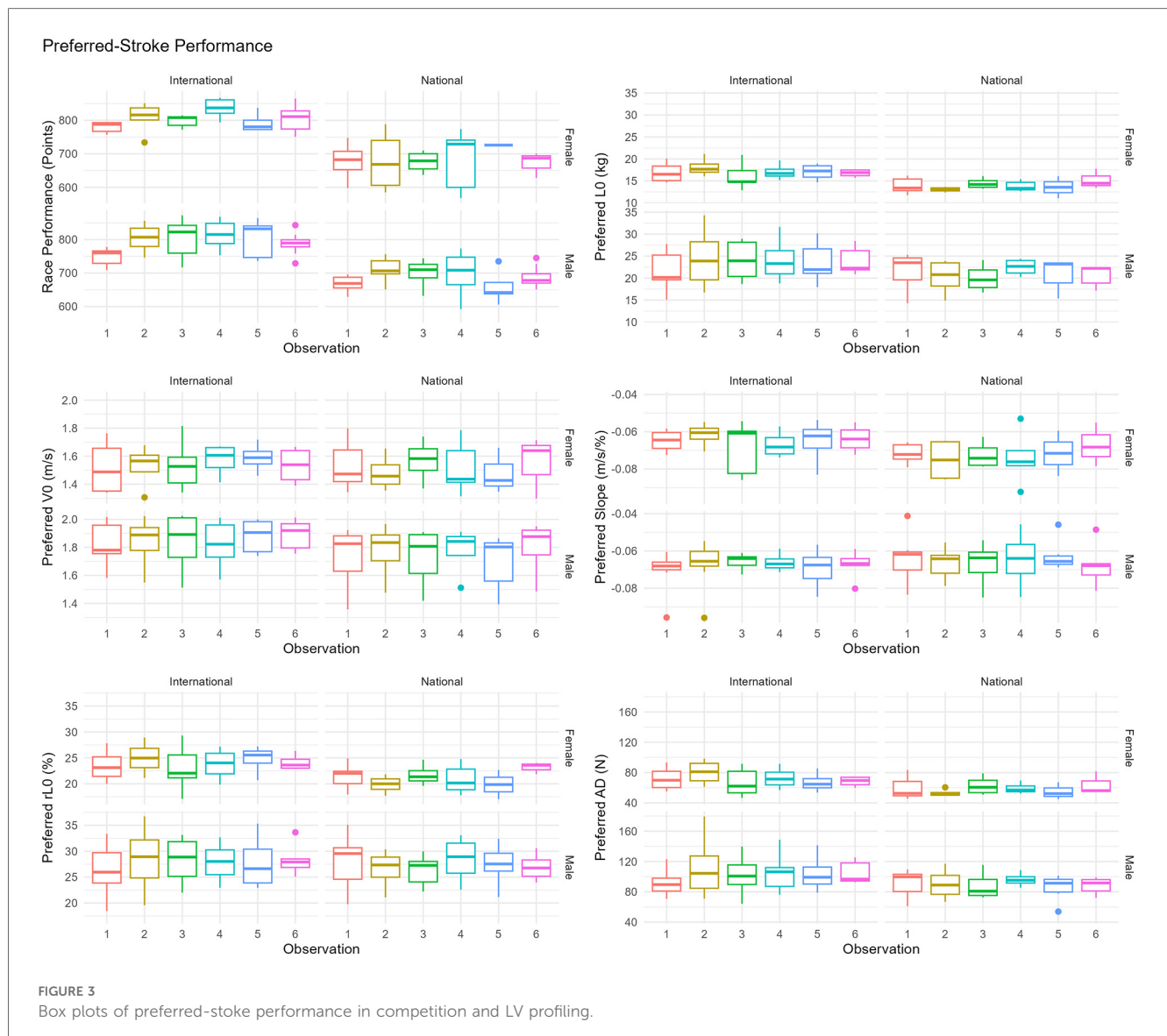
Performance changes across all variables between males and female swimmers of national- and international-level, for both preferred-stroke and front-crawl, are presented as boxplots in Figures 3, 4, respectively. Average $\pm$ SD values for preferred-stroke were V_0 : 1.80 ± 0.17 and 1.54 ± 0.15 m/s; L_0 : 22.3 ± 4.2 and 15.5 ± 2.4 kg for males and females, respectively. For front-crawl performance, V_0 was 1.91 ± 0.07 and 1.68 ± 0.08 m/s; L_0 : 22.6 ± 4.5 and 15.2 ± 2.1 kg, for males and females respectively. The results of the linear mixed-effects model, specifically the parameter estimates of fixed effects for both preferred-stroke and front-crawl, are presented in Tables 2, 3, respectively. Mean within-athlete changes in V_0 and L_0 for preferred-stroke and

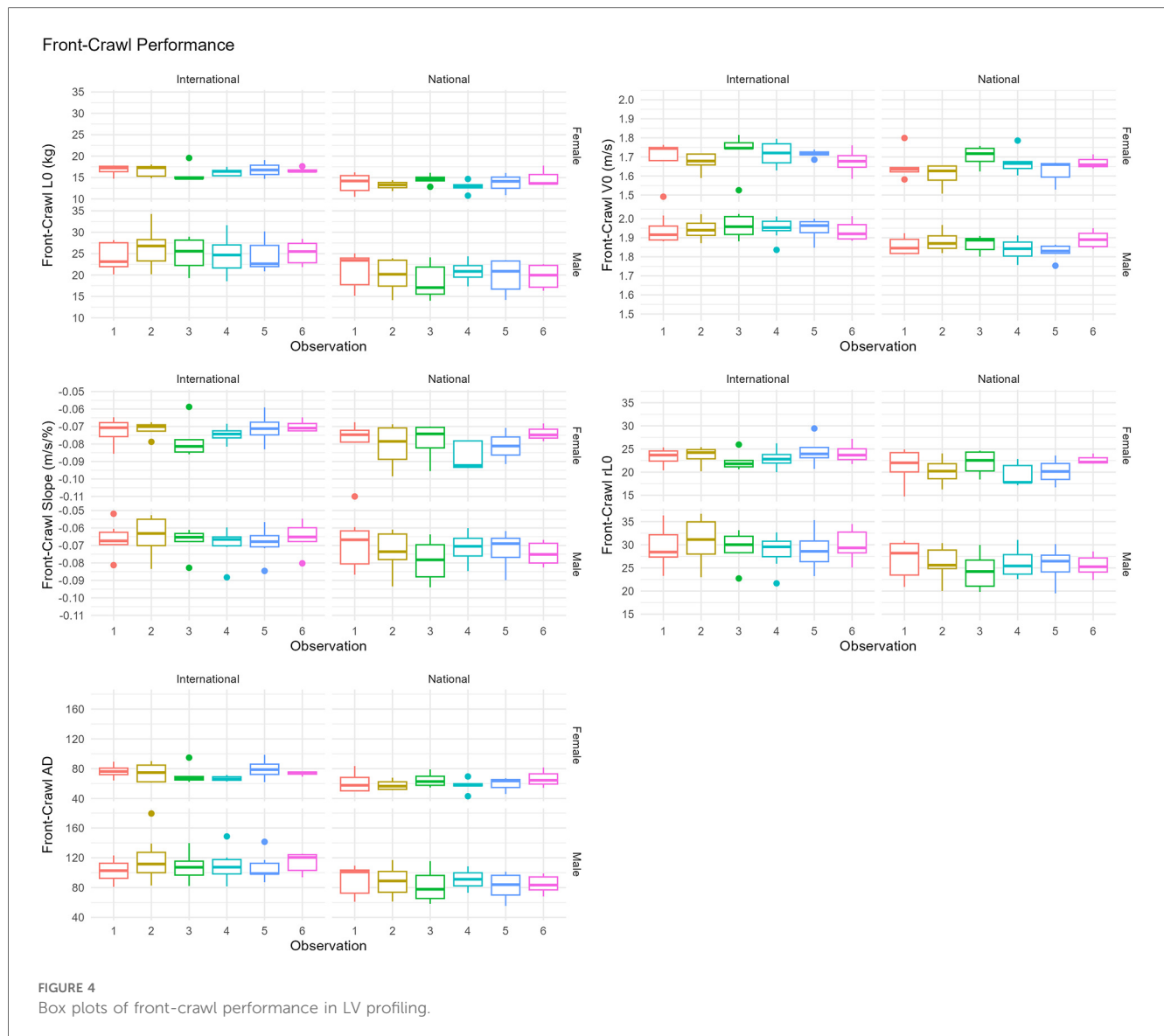
front-crawl performance are displayed in Figures 5, 6, respectively. Finally, correlation results between preferred-stroke performance variables for each observation are presented in Figures 7, 8 for males and females, respectively.

Preferred-stroke performance

As outlined in Table 2, using race performance at observation 1 as a baseline, there was a significant improvement in race points achieved in the following three competitions. However, no significant difference was observed at the competition aligned to observation 5, though performance improved again by observation 6. No significant difference in race points were found between male and female swimmers, but national-level swimmers achieved 14.7% fewer points than their international counterparts.

For the LV variables (V_0 , L_0 , rL_0 and relative slope), no significant changes were observed across the six observations.





However, males presented significant differences compared to females across all variables except the slope ($p = 0.607$). National-level swimmers demonstrated a 16.7% lower L_0 , but presented no statistical difference in rL_0 ($p = 0.244$) or the slope ($p = 0.558$). While AD did not change significantly across observations, males produced 42.8% greater drag, whereas national-level swimmers produced 18.2% less.

Front-crawl performance

For front-crawl performance in LV profiling (Table 3), no significant differences in the variables were reported across observations, except for a reduction in rL_0 and the slope at observation 4 (-1.3% and -0.004 m/s/%, respectively, $p \leq 0.05$). Males presented a 13.5% faster V_0 , 41.1% larger L_0 , and 5.4% higher rL_0 , resulting in a 8.3% flatter slope. In contrast, national-level swimmers produced 3.5% lower V_0 , and 24.6% lower L_0 ,

leading to a 11.1% steeper slope. AD remained stable across observations, though males produced 38.5% greater drag, while national-level swimmers generated 25.7% less drag.

Smallest worthwhile change in preferred-stroke performance

Using the SWC calculated from the between-athlete standard deviation at observation 1, the following mean within-athlete changes in L_0 and V_0 are shown across observations in Figures 5, 6 for preferred-stroke and front-crawl, respectively. Error bars represent 95% CI, indicating whether meaningful changes occurred relative to observation 1. In preferred-stroke LV performance, the magnitude of change of L_0 for both international- and national-level males ranged from *very likely* to *possibly trivial* across all observations. For female, international-level swimmers, changes in L_0 ranged from *very likely* to *possibly*

TABLE 2 Parameter estimates of fixed effects for race and load-velocity performance using preferred-stroke*.

Dependent Variable	Parameter		Estimate	SE	95% CI	df	t-value	p
Race performance (Points)	Intercept		769	15	739 to 798	31.7	50.8	<0.001
	Observation	Observation 2	40	8	25 to 55	113.9	5.3	<0.001
		Observation 3	37	8	22 to 52	113.9	4.8	<0.001
		Observation 4	45	8	30 to 60	113.7	5.9	<0.001
		Observation 5	14	9	−3 to 31	114.1	1.6	0.112
		Observation 6	25	8	10 to 40	114	3.3	0.002
	Sex	Male	2	16	−28 to 32	25.6	0.1	0.897
	Level	National	−113	15	−142 to −83	25.4	−7.5	<0.001
V_0 (m/s)	Intercept		1.56	0.06	1.44 to 1.67	26.7	26.3	<0.001
	Observation	Observation 2	0.01	0.01	−0.01 to 0.03	102.0	0.9	0.362
		Observation 3	0.01	0.01	−0.02 to 0.03	102.1	0.5	0.623
		Observation 4	0.00	0.01	−0.03 to 0.02	102.1	−0.4	0.721
		Observation 5	0.00	0.01	−0.02 to 0.02	102.1	0.0	0.986
		Observation 6	0.01	0.01	−0.02 to 0.03	102.1	0.4	0.665
	Sex	Male	0.26	0.06	0.14 to 0.39	26.0	4.2	<0.001
	Level	National	−0.05	0.06	−0.18 to 0.07	26.0	−0.9	0.388
L_0 (kg)	Intercept		16.8	1.1	14.6 to 19	31.2	14.9	<0.001
	Observation	Observation 2	0.5	0.5	−0.6 to 1.5	102.3	0.9	0.376
		Observation 3	−0.1	0.5	−1.1 to 1	102.4	−0.1	0.890
		Observation 4	0.2	0.5	−0.8 to 1.3	102.3	0.4	0.680
		Observation 5	−0.4	0.6	−1.5 to 0.8	102.9	−0.6	0.534
		Observation 6	−0.1	0.6	−1.2 to 1	102.9	−0.2	0.851
	Sex	Male	6.5	1.2	4.3 to 8.8	25.9	5.6	<0.001
	Level	National	−2.8	1.1	−5.1 to −0.6	25.9	−2.5	0.019
rL_0 (%)	Intercept		23.4	1.2	21 to 25.8	32.1	19.1	<0.001
	Observation	Observation 2	0.3	0.6	−0.9 to 1.5	101.2	0.4	0.660
		Observation 3	−0.1	0.6	−1.3 to 1.2	101.4	−0.1	0.899
		Observation 4	−0.1	0.6	−1.4 to 1.1	101.3	−0.2	0.864
		Observation 5	−0.6	0.7	−2 to 0.7	102.1	−1.0	0.341
		Observation 6	−0.1	0.7	−1.4 to 1.2	102.0	−0.2	0.875
	Sex	Male	4.6	1.3	2.1 to 7.1	25.8	3.7	0.001
	Level	National	−1.5	1.2	−3.9 to 0.9	25.8	−1.2	0.244
Slope (m/s/%)	Intercept		−0.068	0.003	−0.074 to −0.061	33.5	−20.8	<0.001
	Observation	Observation 2	0.000	0.002	−0.003 to 0.004	101.5	0.2	0.870
		Observation 3	0.000	0.002	−0.004 to 0.004	101.7	0.0	0.977
		Observation 4	0.000	0.002	−0.004 to 0.004	101.6	0.0	0.969
		Observation 5	−0.002	0.002	−0.006 to 0.002	102.4	−0.9	0.361
		Observation 6	0.000	0.002	−0.004 to 0.004	102.3	0.1	0.934
	Sex	Male	0.002	0.003	0.005 to 0.004	25.9	0.5	0.607
	Level	National	−0.002	0.003	−0.008 to −0.004	25.9	−0.6	0.558
AD (N)	Intercept		70.5	6.1	58.6 to 82.4	31.8	11.6	<0.001
	Observation	Observation 2	5.0	3.0	−0.9 to 10.8	102.2	1.7	0.097
		Observation 3	0.2	3.1	−5.8 to 6.2	102.4	0.1	0.944
		Observation 4	1.5	3.1	−4.6 to 7.6	102.3	0.5	0.629
		Observation 5	−3.3	3.2	−9.6 to 3	102.9	−1.0	0.302
		Observation 6	−0.2	3.2	−6.5 to 6.1	102.9	−0.1	0.959
	Sex	Male	30.2	6.3	18 to 42.5	25.8	4.8	<0.001
	Level	National	−12.8	6.1	−24.7 to −0.9	25.7	−2.1	0.045

V_0 , theoretical maximum velocity; L_0 , theoretical maximum load; rL_0 , theoretical maximum load expressed as a percentage of body mass; AD, active drag, SE, standard error; CI, confidence intervals; df, degrees of freedom.

*The baseline (intercept value) was estimated for female swimmers, of international level at Observation 1.

trivial in observations 2, 3 and 4, and *unclear* for observations 5 and 6. For national-level females the level of change was *possibly trivial* at observations 2 and 3 and *unclear* for the remaining observations. For V_0 , national-level males are *possibly positive* at observations 2, 3 and 6 and *unclear* at observations 4 and 5. For international-level males, the level of change is *unclear* at observations 2, *possibly negative* at observations 3 and 5, and *possibly trivial* and *very likely trivial* at observations 4 and 6 respectively. For females, the level of change in V_0 was *very likely negative* at observation 2 for international-level swimmers and *possibly negative* at observation 6 for national-level with *unclear* changes at all other observations.

TABLE 3 Parameter estimates of fixed effects for load-velocity performance using front-crawl*.

Dependent variable	Parameter		Estimate	SE	95% CI	df	t-value	p
V ₀ (m/s)	Intercept		1.70	0.02	1.66 to 1.74	32.5	82.2	<0.001
	Observation	Observation 2	0.00	0.01	−0.02 to 0.02	103.3	0.2	0.82
		Observation 3	0.02	0.01	0 to 0.04	103.6	1.8	0.076
		Observation 4	0.01	0.01	−0.01 to 0.03	103.4	1.0	0.325
		Observation 5	−0.01	0.01	−0.03 to 0.01	104.2	−0.8	0.45
		Observation 6	0.00	0.01	−0.02 to 0.02	104.2	0.1	0.907
	Sex	Male	0.23	0.02	0.18 to 0.27	25.8	10.6	<0.001
	Level	National	−0.06	0.02	−0.1 to −0.02	25.9	−3.1	0.004
L ₀ (kg)	Intercept		17.5	1.1	15.4 to 19.6	31.6	16.6	<0.001
	Observation	Observation 2	0.4	0.5	−0.6 to 1.4	103.2	0.7	0.463
		Observation 3	−0.7	0.5	−1.7 to 0.3	103.4	−1.4	0.179
		Observation 4	−0.7	0.5	−1.7 to 0.4	103.2	−1.3	0.204
		Observation 5	−0.6	0.6	−1.6 to 0.5	104.0	−1.0	0.318
		Observation 6	−0.5	0.6	−1.6 to 0.6	104.0	−0.9	0.372
	Sex	Male	7.2	1.1	5.1 to 9.3	25.7	6.6	<0.001
	Level	National	−4.3	1.1	−6.4 to −2.2	25.7	−4.1	<0.001
rL ₀ (%)	Intercept		24.3	1.1	22.1 to 26.5	33.2	21.9	<0.001
	Observation	Observation 2	0.2	0.6	−1 to 1.3	102.1	0.3	0.785
		Observation 3	−1.0	0.6	−2.2 to 0.3	102.5	−1.5	0.129
		Observation 4	−1.3	0.6	−2.5 to −0.1	102.1	−2.1	0.038
		Observation 5	−0.9	0.7	−2.2 to 0.4	103.2	−1.4	0.181
		Observation 6	−0.7	0.7	−1.9 to 0.6	103.1	−1.0	0.325
	Sex	Male	5.4	1.1	3.2 to 7.6	25.5	4.8	<0.001
	Level	National	−3.3	1.1	−5.5 to −1.2	25.5	−3.1	0.005
Slope (m/s/%)	Intercept		−0.072	0.003	−0.078 to −0.066	32.2	−21.6	<0.001
	Observation	Observation 2	0.001	0.002	−0.003 to 0.004	103.0	0.5	0.762
		Observation 3	−0.003	0.002	−0.007 to 0.001	103.3	−1.7	0.097
		Observation 4	−0.004	0.002	−0.008 to 0.000	103.0	−1.6	0.05
		Observation 5	−0.002	0.002	−0.006 to 0.002	103.9	−0.4	0.368
		Observation 6	−0.001	0.002	−0.005 to 0.003	103.9	−0.5	0.549
	Sex	Male	0.006	0.003	0.000 to 0.013	25.5	5.1	0.05
	Level	National	−0.008	0.003	−0.013 to −0.002	25.5	−4.0	<0.001
AD (N)	Intercept		77.5	5.5	66.8 to 88.3	34.4	14.1	<0.001
	Observation	Observation 2	3.9	3.2	−2.3 to 10.1	103.1	1.2	0.221
		Observation 3	−2.0	3.3	−8.4 to 4.5	103.6	−0.6	0.553
		Observation 4	−2.9	3.3	−9.3 to 3.5	103.2	−0.9	0.375
		Observation 5	−1.7	3.4	−8.4 to 5.1	104.3	−0.5	0.625
		Observation 6	−0.6	3.4	−7.4 to 6.1	104.3	−0.2	0.861
	Sex	Male	29.8	5.5	19.0 to 40.6	25.4	5.4	<0.001
	Level	National	−19.9	5.4	−30.4 to −9.3	25.5	−3.7	0.001

V₀, theoretical maximum velocity; L₀, theoretical maximum load; rL₀, theoretical maximum load expressed as a percentage of body mass; AD, active drag, SE, standard error; CI, confidence intervals; df, degrees of freedom.

*The baseline (intercept value) was estimated for female swimmers, of international level at Observation 1.

Smallest worthwhile change in front-crawl performance

In front-crawl LV performance (Figure 6), the magnitude of change of L₀ for both international- and national-level males ranged from *very likely* to *possibly trivial* across all observations. Changes in L₀ for females were *unclear* across all observations except being *possibly trivial* for national swimmers at observation 5 and *very likely trivial* for international swimmers at observation 6. For V₀ in front-crawl, international-level males made *possibly positive* changes in observations 2 and 3 but *unclear* changes in the remaining observations. Change in national-level males was *possibly positive* at observation 2, *unclear* at observation 3, *very likely negative* at observation 4 and 5, then

possibly positive at observation 6. For females, national-level changes across all observations were *unclear* while international-level were *unclear* at observations 2, 4 and 6, but *possibly positive* at observation 3 and *very likely negative* at observation 5.

Correlation to race performance

Correlation results are presented in Figures 7, 8 for males and females, respectively. Results for females at observation 5 are excluded due to a small sample (n = 3) for both competition and profiling at that time-point. For male swimmers, significant, large to very large correlations existed between race performance and L₀ at observation 3 (r = 0.67, p < 0.05); race performance and V₀ and

Preferred-Stroke

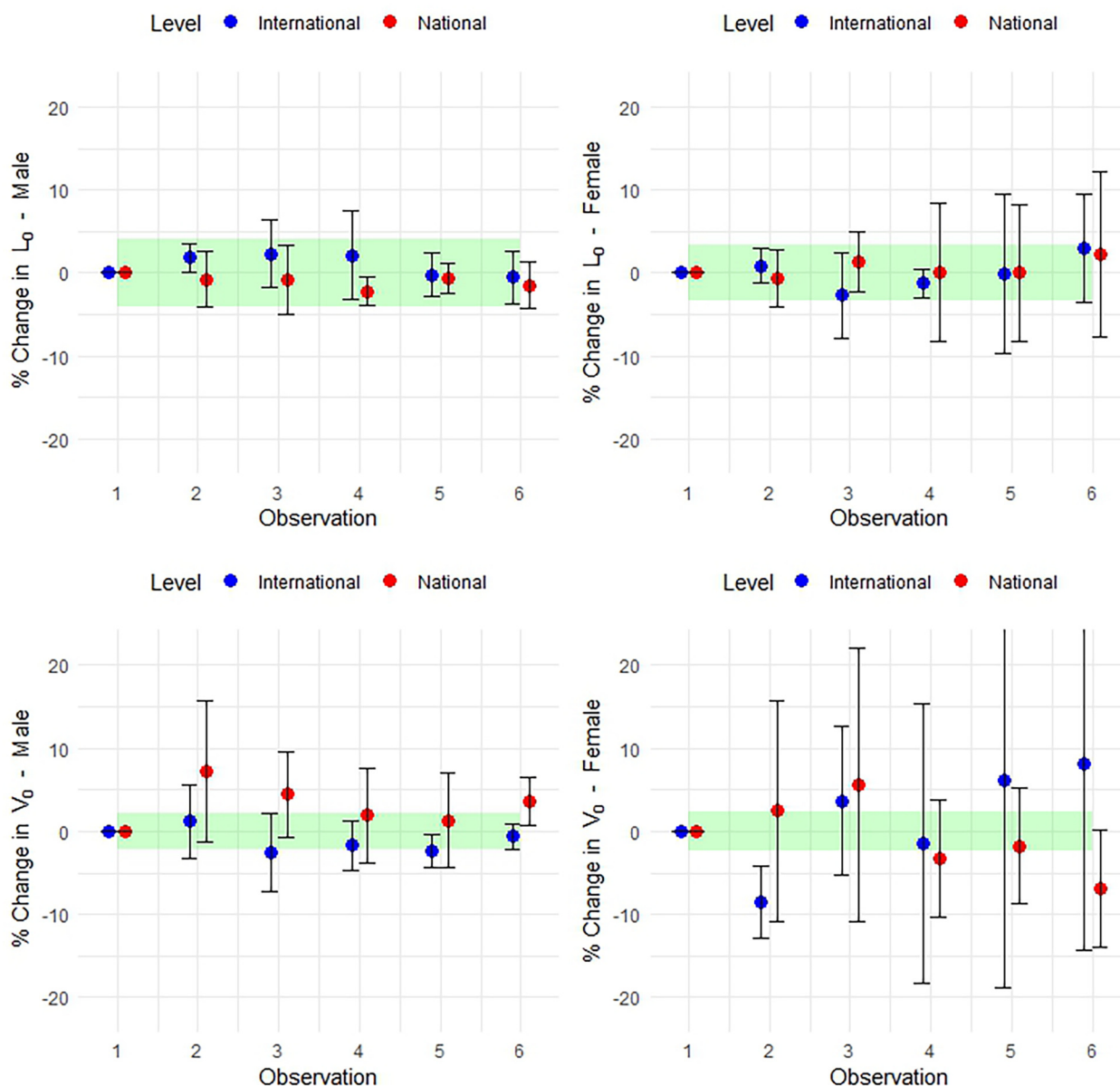


FIGURE 5

Mean within-athlete changes in preferred-stroke LV profiling. (Top row: L_0 in males and females. Bottom row: V_0 in males and females).

AD at observation 5 ($r = 0.73$ and $r = 0.7$, respectively, $p < 0.05$); and between race performance and AD at observation 6 ($r = 0.58$, $p < 0.05$). For female swimmers, a significant, very large correlation existed between race performance and L_0 at observation 4 ($r = 0.75$, $p < 0.05$). No further statistically significant correlations were found between race performance and LV-derived variables in both sexes. Among LV-derived variables, L_0 , rL_0 and V_0 presented large to very large correlations ($r = 0.55$ – 0.74 , $p < 0.05$) for males in observations 2 and 3. A very large and extremely large correlation was found between V_0 and the slope in males ($r = -0.7$, $p < 0.05$) and females ($r = -0.91$, $p < 0.05$) at observation 6. Across both sexes and all observations except observation 6 in females, very

large to extremely large correlations existed between AD and L_0 ; and AD and rL_0 ($r = 0.74$ – 0.97 , $p < 0.05$).

Discussion

This study monitored LV outputs (V_0 , L_0 , rL_0 , relative slope, AD), over a 15-month period in international- and national-level swimmers across both preferred-stroke and front-crawl swimming. While these variables fluctuated throughout the season, no statistically significant differences were found compared to baseline testing in preferred-stroke swimming. In

Front-Crawl

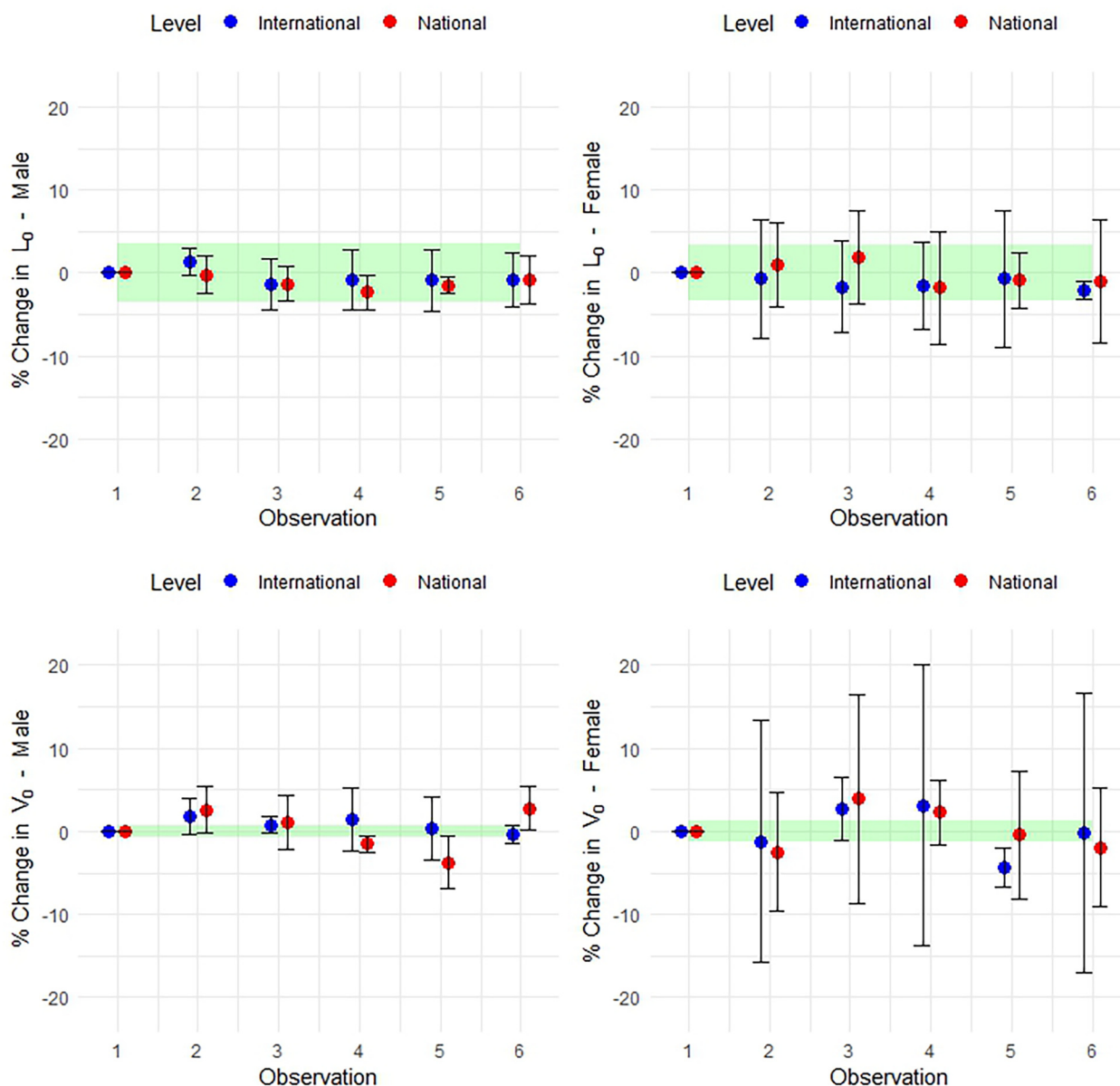


FIGURE 6

Mean within-athlete changes in front-crawl LV profiling. (Top row: L_0 in males and females. Bottom row: V_0 in males and females).

front-crawl swimming, only a single observation showed a significant difference from baseline for rL_0 and relative slope, respectively. Significant differences were evident between sexes and performance levels, with males and international swimmers tending to exhibit higher L_0 , suggesting superior force-generating capacity. These findings were supported by a magnitude-based assessment using the SWC to determine whether observed changes were practically meaningful. While individual analysis may provide further insight, group level changes assessed against the SWC suggest greater stability in international-level swimmers and more variability in national-level athletes, potentially

reflecting differences in training consistency, recovery capacity, or adaptation to load. Despite limited correlations between LV outputs and race performance, large to very large correlations were found at specific time points between race performance and V_0 , L_0 , and AD, indicating that these variables may influence competitive outcomes over the course of a season. These findings suggest that while LV profiling alone is not a definitive predictor of race performance, it offers valuable insights into biomechanical adaptations and individual responses across time.

In LV profiling, V_0 and L_0 are theoretical extrapolations representing maximum velocity at zero load and maximum load

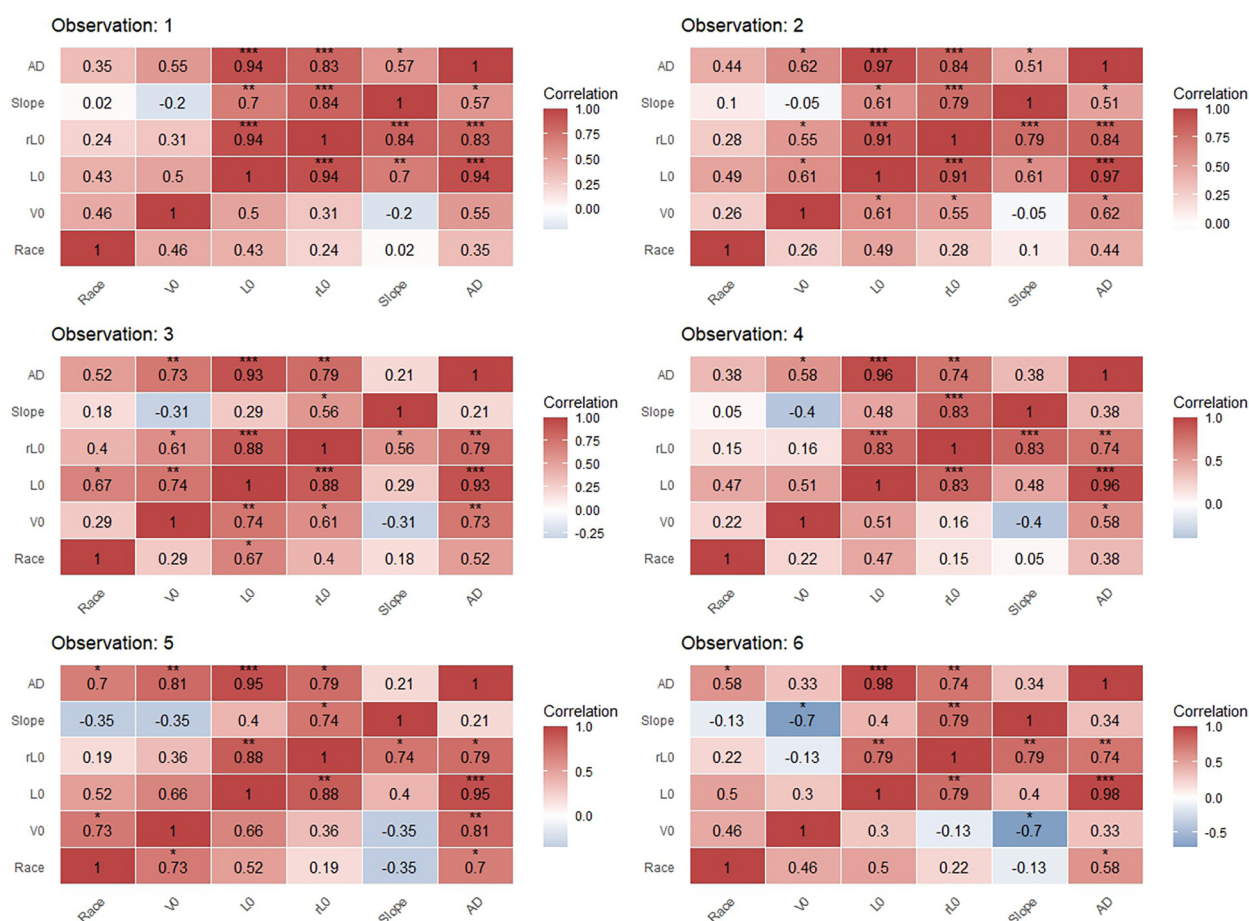


FIGURE 7

Correlation matrices between performance variables for males in preferred-stroke in competition and LV profiling (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

at zero velocity, respectively. V_0 serves as an indicator of free-swimming speed and L_0 reflects the swimmer's propulsive force capabilities (11). While free-swimming speed in competition was not directly assessed, race performance (expressed as points) varied significantly over time, whereas V_0 and L_0 remained relatively stable. Changes in race performance ranged from 3 to 60 points across the six observations, equating to 0.02–0.43 s in the 50 m front-crawl, or 0.1–1.7 s in the 200 m front-crawl. Encouragingly, the progression of race points over the season aligns with the expectation of improved performances for international- and national-level swimmers towards key competition events (despite limited changes in LV outputs). It was also noted that the fastest performances occurred during the most important races in the Irish swimming calendar, indicating that training and tapering strategies were effective in preparing athletes for peak performance at the most critical moments. This underscores the multifaceted nature of race performance, which is influenced not only by free-swimming speed, but also by the start, turn(s), and finish phases (40). Given that the start and turn phases can account for nearly one-third of the total time in a 100 m event (40), improvements in these areas could enhance race performance independent of changes in free-swimming speed.

The LV slope, representing the relationship between V_0 and L_0 , has been suggested to be a strong indicator of AD (19), with steeper slopes associated with a greater ability to minimize resistance (17). In this study, the slope is expressed relative to body mass and calculated using rL_0 to account for anthropometric and performance level differences. Interestingly, no significant difference in the LV slope was observed between sexes or performance levels in preferred-stroke swimming, despite males demonstrating higher L_0 , rL_0 , and faster V_0 . This suggests that while men produce greater absolute and relative loads, and reach higher velocities, the proportional relationship between load and velocity remains consistent across sexes. This supports previous findings that female swimmers may optimize force application through enhanced efficiency, focusing on minimizing resistance rather than generating higher propulsive force (41). Factors such as greater buoyancy, a more streamlined position, reduced frontal area, and technical adaptations to reduce drag may contribute to this efficiency. Similarly, the lack of slope difference between performance levels in preferred-stroke swimming, despite a higher absolute L_0 in the international swimmers, suggests that this cohort applies force more effectively rather than simply increasing force production at the expense of efficiency. This

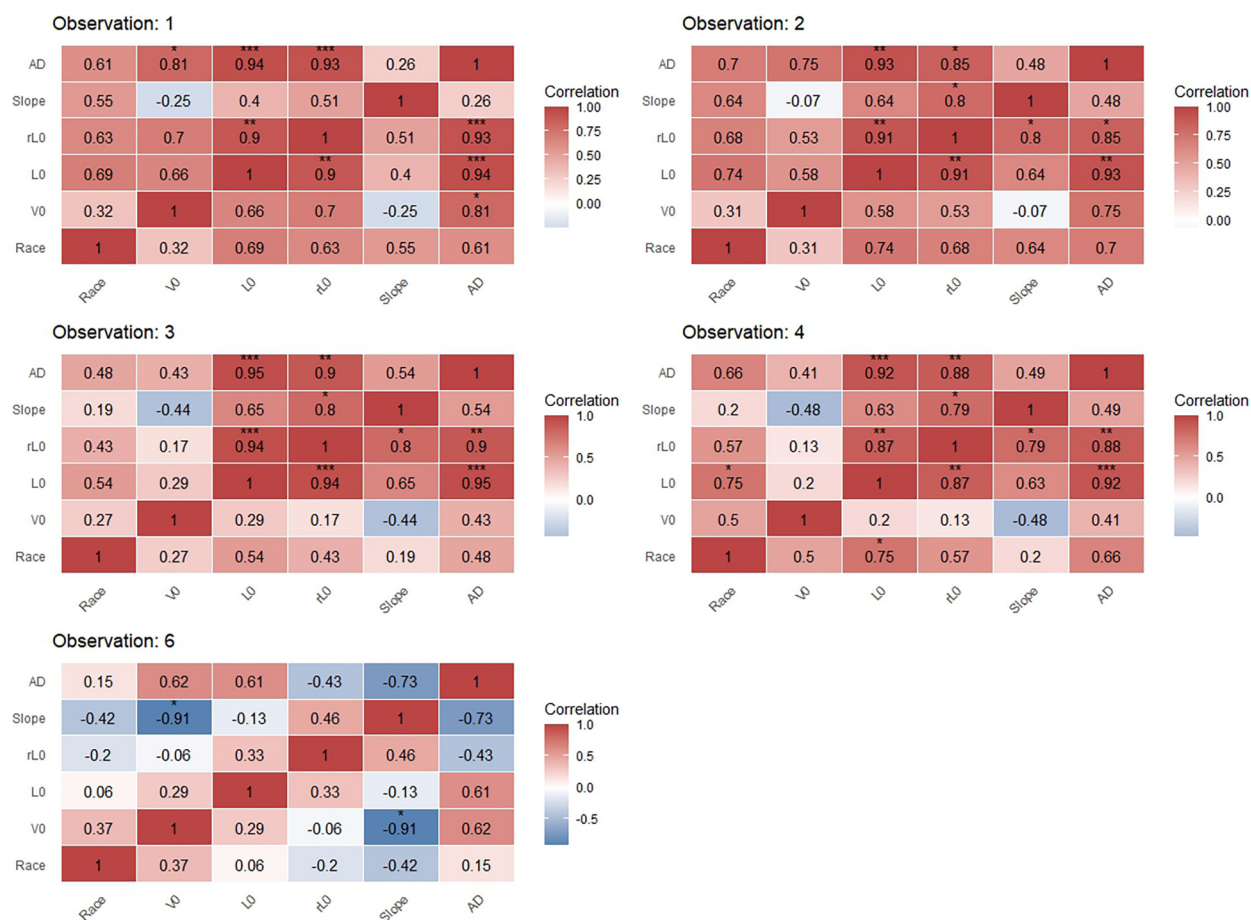


FIGURE 8

Correlation matrices between performance variables for females in preferred-stroke in competition and LV profiling (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).

highlights the importance of refining technique alongside strength development in high-performance swimming.

In front-crawl swimming, a key finding within this study cohort of 50–200 m specialists, was that while V_0 did not differ between international and national-level swimmers, L_0 and rL_0 were significantly greater in the international-level group, resulting in a statistically flatter slope. This difference in force-generating capacity alters the shape of the LV profile, leading to a divergence in slope between performance levels. This suggests that while international swimmers generate greater propulsive force, they do so in a way that does not steepen the LV profile, potentially indicating more effective force application. This supports the idea that elite swimmers are not only stronger but also apply force more effectively to maintain velocity. This study proposes that an optimal LV profile in high-level sprint swimming may therefore be characterized by a high V_0 (indicating greater swim speed) and high L_0/rL_0 (reflecting force-generation capacity), while maintaining a balanced slope that avoids unnecessary loss of effectiveness in force application. These findings highlight the importance of assessing not only the magnitude LV outputs but also the shape of the LV profile,

which may serve as a valuable indicator of technical efficiency and training effectiveness across performance levels, offering coaches a more nuanced tool for tailoring strength and technique interventions in sprint swimming. Further research is required to determine whether this profile extends to swimmers specializing in longer distances.

Despite the lack of statistical differences in slope between sexes and performance levels in preferred-stroke analysis, differences in AD were evident across both preferred-stroke and front-crawl. Since AD is proportional to the square of velocity, an increase in swim velocity results in a quadratic increase in drag (42). Consequently, male swimmers and international-level athletes in this study, who achieved a statistically higher V_0 than females and national-level athletes, are likely to experience larger drag forces. Similarly, a greater capacity for force generation, as indicated by a high L_0 (11, 17), would lead to increased resistive forces in accordance with Newton's Third Law. However, rather than suggesting that females and national-level swimmers are inherently more efficient due to lower L_0 values, these findings highlight the need to further explore *efficiency* in relation to both resistance reduction and propulsive force generation (43).

Higher-performing swimmers may employ different strategies to optimize efficiency, balancing increased force output with effective drag management through biomechanical factors such as buoyancy, streamlined body positioning, and stroke mechanics (43, 44). Future research should examine how these elements contribute to overall efficiency across sex and different performance levels.

This study identified limited statistical changes in variables across observations, however, the application of magnitude-based inferences using the SWC provides additional insight into the degree of change within each observation. The SWC offers a useful benchmark for interpreting whether within-athlete performance changes exceed normal variation and reflect positive or negative trends (38). While group-based changes were generally small, especially among international-level swimmers, the presence of *possible* and *very likely* changes, particularly in V_0 , suggests meaningful trends that a p -value alone may overlook. Differences in change between males and females across different performance levels highlight the complex nature of swim performance. It is possible that meaningful changes were masked due to the range of strokes and distance specializations within each group. Interestingly, the group-based SWC analysis revealed greater variability among national-level swimmers, whereas international-level swimmers presented more stable performances, particularly in L_0 . This may reflect greater consistency in training, technical proficiency, or recovery strategies among higher level swimmers. Additionally, an *unclear* interpretation indicates that more data is required rather than the absence of change (39). Therefore, practitioners may benefit from assessing meaningful changes within more homogenous groups or by complementing group-level analyses with individual swimmer assessments to better capture nuanced performance trends. Furthermore, comparing profiling results alongside training data, specifically any details of in-water resistance training, may provide further insight into the extent and causes of performance changes.

Although training data was not collected as part of this study, a two-year observation of the training centers where these athletes train revealed that swimmers typically complete 6–10 pool sessions per week, along with an average of two strength and conditioning sessions per week (45). While strength was not directly assessed, international-level swimmers in this study were statistically older and heavier, suggesting a longer competitive training history, greater accumulated training volume, and increased exposure to high-level coaching. These factors likely contribute to skill execution in the start and turn phases, while increased lean muscle mass may enhance strength and power, both of which are correlated with improved start and turn performance (46, 47). Furthermore, land-based strength and conditioning routines have been shown to positively impact stroke length, while in-water resistance training may improve stroke rate (48), with both variables associated with greater swim performance (49, 50). This study did not measure race components in terms of stroke length and stroke rate. Future studies should incorporate these metrics to gain a more comprehensive evaluation of seasonal performance variations.

Despite the lack of consistent relationships between LV outputs and race performance (as measured by race points), several cross-sectional studies in sprint swimming support the relevance of LV profiling. In a 50 m short-course time-trial involving Level 3 and 4 swimmers (31), V_0 and L_0 were significantly correlated to finishing time in front-crawl ($r = -0.68$ and -0.55 , respectively), backstroke ($r = -0.71$ and -0.72), butterfly ($r = -0.81$ and -0.62), and breaststroke ($r = -0.52$ and -0.62) (11, 16–18). Similarly, in Level 1–3 swimmers performing their preferred stroke, females exhibited a strong correlation between V_0 and a 50 m time-trial ($r = -0.96$), while L_0 showed a weaker, non-significant correlation ($r = -0.64$) (Keating et al.). For males, both V_0 and L_0 were significantly correlated with a 50 m time-trial ($r = -0.71$ and -0.62 , respectively) (Keating et al.). However, findings were less consistent in a more homogenous sample of Level 1–2 swimmers, with limited significant correlations observed (13). Specifically, rL_0 and the absolute slope showed very largely correlations with stroke rate in 100 m events, while V_0 was reported to have a very large negative correlation with stroke length in 200 m races (13). These findings suggest LV profiling may be more relevant for sprint specialists, though its applicability to distance swimming remains unexplored. It is plausible that distance swimmers present distinct LV profiles characterized by lower values of V_0 and L_0 but with a greater capacity of sustaining these outputs over time.

While LV performance alone does not determine race performance, its relevance to sprint swimming warrants further exploration. LV profiling is a time-efficient method for tracking key variables of V_0 , L_0 , and slope over time. However, optimizing these variables through training remains an area for future research. Evidence from sprint running underscores the benefits of LV profiling in load prescription interventions. Specifically, individualized LV profiles have been used to prescribe training loads corresponding to velocity decrements of 25, 50, and 75%, targeting speed-strength, power, and strength-speed adaptations, respectively, in sled pushing and pulling (51, 52). Additionally, Petrakos et al. (53) proposed categorizing resistance training loads based on velocity decrements of <10, 10–15, 15–30, and >30% as light, moderate, heavy, and very heavy, respectively. While exact threshold values may vary depending on the targeted adaptation, velocity-decrement-based prescription is gaining traction (54) and may hold potential for enhancing adaptations in swimming-specific training programs. It is important to note that the present study was not designed to assess a prescribed intervention targeting LV outputs. Instead, it was aimed to examine how these variables naturally evolve within independent training plans across multiple high-performance sites, each with distinct coaching philosophies. Future research should focus on developing a targeted in-water resistance training intervention and evaluating its impact on LV outputs and race performance. By doing so, it may be possible to refine training methodologies that optimize LV characteristics for improved competitive outcomes in sprint swimming. Furthermore, integrating measures such as stroke kinematics, coordination patterns, and blood lactate responses into the LV profiling protocol may provide a more comprehensive understanding of swimmer adaptations and training effects.

This is the first study to assess LV performance in national- and international-level swimmers over a 15-month period. The application of linear mixed-effect models in the statistical analysis represents best practice in sports science (36, 37), allowing for the inclusion of incomplete repeated measures. However, several limitations within the study must be acknowledged: (i) Due to the decentralized, real-world training structure, where swimmers trained at different locations under various coaches, meant that detailed training data were not recorded, limiting our ability to assess its influence on LV outputs. However, this approach provided a valuable opportunity to observe high-level athlete adaptations during critical phases of the competitive season, including preparation for Olympic selection trials; (ii) Race points were used as a standardized measure of performance across long- and short-course competitions over a 15-month period. While commonly employed within the coaching community, conversion calculators for swim times lack academic validation. Additionally, race points do not account for changes in start, turn, or kinematic variables such as stroke length and stroke rate; (iii) Combining different strokes and distances may have masked stroke- or distance-specific changes in LV outputs. Future research should investigate whether targeted interventions aimed at improving V_0 and/or L_0 lead to meaningful changes in LV outputs and, ultimately, race performance. Additionally, monitoring stroke rate and stroke length will be critical for identifying potential adaptations contributing to performance improvements.

Conclusion

This study monitored changes in LV outputs in both preferred-stroke and front-crawl swimming among national- and international-level swimmers over a 15-month competitive season. While LV outputs fluctuated over time, statistically significant changes compared to baseline were limited. Notable differences emerged between sexes and performance levels, with males and international-level swimmers demonstrating greater L_0 , suggesting superior force-generating capacity. However, similar rL_0 values between performance levels indicate this was achieved without compromising efficiency.

Although LV profiling alone is not a direct predictor of race performance, our findings reinforce its value as a tool for monitoring biomechanical adaptations and individual responses over time. These metrics may inform individualized training strategies by identifying meaningful trends that traditional statistics may overlook. Future research should explore targeted interventions designed to enhance V_0 , L_0 , and the slope, and assess their impact on technical and physiological adaptations.

Additionally, incorporating AD monitoring and stroke kinematic measures, such as coordination patterns and hand velocity, may provide a more comprehensive understanding of performance development in sprint swimming. These findings highlight the potential of LV profiling to contribute to training prescription, talent identification, and long-term athlete development in high-performance environments.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by School of Sport and Exercise Science, Ulster University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

RyK: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. RoK: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. CM: Conceptualization, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Test-retest and intrasession reliability of assisted sprint outcome measurements using a motorized resistance device

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The aim of this study was to determine reliability of assisted sprint outcome measurements using a motorized resistance device (MRD). A total of 21 participants (16 males and 5 females; age 22.3 ± 3.9 years, body mass 75.2 ± 6.9 kg, height 177.9 ± 6.8 cm) completed two assisted sprint tests on four different test sessions while exposed to an external load (3 kg) provided by the MRD. Outcome variables included time, top speed, maximum acceleration and 5 m split times and speeds. Intrasession and test-retest reliability was assessed using intraclass correlation coefficient (ICC), coefficient of variation (CV), typical error (TE), smallest worthwhile (SWC) and moderate worthwhile change (MDC). For test-retest reliability mostly high to extremely high ICC values (>0.77), and good ($<5\%$) CV values were observed for all outcome measurements. Specifically, all outcome measurements showed high to extremely high relative reliability ($ICC \geq 0.95$) except 0–5 m time (0.86) and maximum acceleration (0.77). Good absolute reliability was observed for all outcome measurements (CV range: 0.9–3.7) except maximum acceleration (8.7). Furthermore, most outcome variables were rated as good and ok for SWC. Similar findings were observed for intrasession reliability with very high ICC values for all outcome measurements except maximum acceleration (0.85–0.93) and 0–5 time for session 2–4 (0.88–0.92). Similarly, CV was good for all outcome measurements for all sessions except maximum acceleration (5.7–5.9%). In addition, all outcome measurements had good to ok SWC, except for maximum acceleration. In conclusion, the present study shows that the MRD can obtain reliable assisted sprint outcome measurements and thereby provide coaches and researchers with new opportunities to advance, monitor and evaluate sprint training.

KEYWORDS

reliability, motorized resistance technology, assisted sprinting, overspeed, sprint

1 Introduction

Sprinting is crucial for performance in various individual and team ball sports. Assisted sprinting is one of three common sprint training methods, alongside normal and resisted sprinting, used to enhance speed and acceleration (1). However, resisted sprinting is more widely implemented than assisted sprinting (2), likely due to challenges in individualizing assistance (towing force) and difficulties in quantifying responses and progress. Assisted sprinting can be performed using different equipment, including high-speed treadmills, towing systems [bands, pulleys, motorized resistance devices (MRD)], and environmental conditions such as downhill slopes or tailwinds

(2–4). A common misconception is equating assisted sprinting with overspeed or supramaximal sprinting. Specifically, overspeed is exceeding the speed that can be voluntarily achieved in maximal non-assisted sprinting. However, assisted sprinting also includes sprinting at submaximal velocities. In fact, assisted sprinting has been used to target acceleration and top speed (2, 5). Moreover, assisted sprinting may enable more submaximal sprint repetitions by reducing perceived effort (4), potentially due to decreased acceleration demands.

The effects of assisted sprinting have traditionally been classified as acute or chronic, focusing on technique (e.g., temporal characteristics, kinematics), acceleration, and top speed. The observed acute effects on assisted sprinting include decreased time, increased top speed, shorter contact time longer flight time, increased step length, and increased frequency (3, 6–9). Despite these findings, assisted sprinting has not been widely included in technical training programs described in the literature (4), even if it has been suggested that assisted sprinting may be used to produce greater ground reaction forces at comparable speeds (6). The observed chronic effects of assisted sprinting include decreased contact time, increased step frequency, better acceleration (decreased 10 and 20 m times) with a possible effect on top speed (2, 10–12). In addition, pilot data show acceleration improvement in NFL prospects (5). However, no studies have to the authors knowledge specifically examined sprint-specific endurance, despite its perceived importance as a training method (4). Even if the current research is limited (2) it appears that assisted sprinting has a positive effect on performance.

Despite documented performance benefits limited application of assisted sprinting may stem from a lack of suitable equipment to precisely set towing forces or environments (e.g., the absence of a downhill slope). In addition, concerns regarding potential negative effects and injury risks may also contribute to its underutilization. For instance, improper assistance may lead to increased foot touchdown relative to the center of mass, resulting in greater braking forces making it a counterproductive training stimulus (4). Furthermore, overstriding, seeking and finding balance at high speeds, and injury fears are frequently cited as reasons why assisted sprinting is avoided (13).

Recent advancements in MRD technology may facilitate a wider application of assisted sprinting as it allows for individualized prescription and monitoring of assisted sprinting. MRDs have been validated and shown to provide reliable measurements in resisted sprinting (14, 15). However, to the knowledge of the authors no reliability data exists for assisted sprinting. Thus, the purpose of this study was to establish intrasession and test-retest reliability of assisted sprint outcome measurements.

2 Methods

2.1 Subjects

Sample size calculation ($n = 19$) was based on a minimal acceptable ICC of 0.50, expected ICC of 0.80 based on previous

studies using MRD (16), with significance and power level of 0.05 and 0.80 respectively. Twenty-one athletes (16 males: age: 23.0 ± 3.7 years; body mass: 77.3 ± 6.8 kg; height: 179.9 ± 3.7 cm; 5 females: age: 20.0 ± 0.0 years; body mass: 68.6 ± 3.7 kg, height: 171.4 ± 9.5 cm) participated. Participants were recruited from soccer ($n = 8$), handball ($n = 8$), and floorball ($n = 5$), and participated in organized sports since first or second grade (15.3 ± 3.3 years). Inclusion criteria were familiar with ball sports, change of direction movements, linear sprinting and no musculoskeletal injury or illness at time of test sessions limiting maximum effort. The study was approved by the local Ethical committee and the National Data Protection Agency for Research (ref number: 148213) and conducted in accordance with the Declaration of Helsinki. Prior to participation all participants signed a written informed consent after being given a detailed verbal and written explanation of the purpose, procedures and risks associated with participation.

2.2 Procedures

Anthropometric measurements (height and body mass) were obtained prior to a standardized warm-up, which included dynamic lower extremity mobility exercises, jogging (forward and backward), butt kicks, front kicks, high knee lifts, side shuffle, carioca, unilateral anterior-posterior and lateral jumps, three progressive sprints (80%, 90–95% of subjective maximal effort) with the last sprint having assistance. Specifically, the subjective effort of these sprints were based on the participants perception of their own top speed. Then, two modified 505 (m505) on each limb both with and without the MRD were performed. In total the warm-up lasted approximately 25 min. The same warm-up was used for all four sessions, and all participants were instructed to standardize their training two days prior to testing. There were 7 days (median, interquartile range: 7 days) between test sessions. All participants were tested at the same time of day (morning or afternoon) based on the first test session using the same footwear.

All test sessions took place in an indoor sports hall at the Norwegian School of Sport Sciences. Tests included assisted and resisted sprinting, resisted anterior and lateral jumps and change of direction tests (modified 505, 10-0-5 and 15-0-5). Only assisted sprint will be presented in this study. Specifically, two assisted sprints were performed with the MRD positioned 65 m away from the starting line. Specifically, the starting line was marked with two cones 1.2 m apart with a finish line at 40 m away from the starting line also marked with cones. The fiber cord from the MRD was attached to the participant via a velcro strap with a handle to a pelvic belt. The participants were instructed to pull up and away on the handle on the velcro strap after having passed the finish line. This to avoid having to decelerate with an additional pulling force. The sprints were initiated from a standing, self-selected split-stance position (left or right foot in front) with the tip of the toe of the front foot placed on the start line. All starts were commenced from a static position, meaning that “leaning backward before rolling forward”

was not allowed. After a ready signal was given by the test leader, the participants started on their own initiative. All participants were instructed to complete the 40 m sprint as fast as possible. Recovery time between each sprint was a minimum of 4 min.

2.3 Equipment

A portable MRD (1080 Sprint; 1080 Motion, Lidingö, Sweden) was used to provide external resistance and measure time, distance and speed at 333 Hz. The 1080 Sprint has a servo motor (2000 RPM OMRON G5 Series Motor; OMRON Corp., Kyoto, Japan) that is attached to a carbon fiber spool around which a fiber cord is wrapped. The device was positioned on a table at a height of 75 cm to approximately align with participants hip height. Both assisted and resisted load was set to 3 kg since it is a common load used when first exposed to assisted sprinting. From this initial load incremental loading is used to individualize assisted load based on top speed and technical execution. Since the participants were team sport athletes and not previously exposed to assisted sprinting, we kept the assisted load constant at 3 kg for all sessions. Furthermore, the resistance setting was set to isotonic with speed settings set to 2 and 14 m/s for resisted and assisted speeds respectively. The auto start function of the MRD was used (onset of measurement with speed >0.2 m/s) (15).

2.4 Data analysis

Assisted sprints were quantified based on time, distance, speed and acceleration. Specifically, top speed, max acceleration with time and average speed for all 5 m splits were analyzed. All outcome measurements are described in Table 1 for clarity. All data were filtered with a fourth order Butterworth filter with a 1.3 Hz cut-off frequency prior to analysis.

2.5 Statistical analysis

The observed performance of important assisted sprint outcome measurements of session four based on gender (16 males: time: 5.59 ± 0.27 s; top speed: 8.98 ± 0.45 m/s; 0–5 m time: 1.33 ± 0.09 s; 5 females: time: 6.15 ± 0.26 s; top speed: 7.98 ± 0.58 m/s; 0–5 m time: 1.41 ± 0.12 s) was different, but not statistically tested due to group size. Consequently, both genders were grouped for analysis. Statistical analysis was performed using Statistical Package for Social Sciences (SPSS version 24.0, IBM Corp, Armonk, NY, USA) and specifically designed spreadsheets (17). Normality of data was assessed using Shapiro Wilk's test ($p < 0.05$) and qualitatively by visual inspection of Q-Q plots. Test-retest reliability was calculated based on grand mean of all for test sessions, while intrasession reliability was calculated for each test session. Relative reliability was explored using Intraclass Correlation Coefficient (ICC) (3,1 model) with 95% confidence intervals. The magnitude of the ICC was assessed using the following thresholds: >0.99 , extremely high; $0.99-0.90$, very high; $0.90-0.75$, high; $0.75-0.50$, moderate; $0.50-0.20$, low; <0.20 , very low (18). Absolute reliability was calculated as the typical error of measurement (TE in the unit of the metric) which was then expressed as the coefficient variation (CV, %) with 95% confidence intervals. CV values of $>15\%$, $10-15\%$, $5-10\%$, and $<5\%$ was used as indication of very poor, poor, acceptable, and good absolute reliability, respectively. In addition, TE was standardized using Cohen's d effect size principle with magnitudes interpreted as follows: trivial ($0.00-0.19$), small ($0.20-0.60$), moderate ($0.60-1.20$), large ($1.20-1.99$), very large ($2.00-3.99$) and extremely large (≥ 4.00) (18). To assess the usefulness of each outcome measurement TE was compared with thresholds of small (SWC) and moderate (MWC) worthwhile changes or differences (based on 0.2 and 0.6 of between-participant SD). When the TE was smaller than these magnitude thresholds, the test metric was rated as "good" to

TABLE 1 Definitions of all outcome measurements with pros and cons.

Phase	Outcome variables	Definition	Pros	Cons
0–40 m	Time	Time taken to complete the entire 40 m run	Simple overall measurement	Overall measurement with limited information on top speed
	Top speed	The highest speed reached during a specific test	Practical measurement to determine sprint performance (assisted vs. overspeed)	New measurements for coaches based on using split times
	Max accel	0.5 s interval with greatest average acceleration	Information of how the assisted sprint is approached	Might not be relevant if top speed is focus. and how aggressive acceleration is approached is not important
	Best 5 m split time	5 m interval with the lowest time	Automatically find best 5 m split. Split times are commonly used in testing and training	Not comparable to splits based on specific positions
	Best 5 m avg speed	Average speed 5 m interval with lowest time	Top speed based on traditional split	Not comparable to splits based on specific positions
	Best 10 m split time	10 m interval with the lowest time	Automatically find the best 5 m split. Split times are commonly used in sprint testing and training	Not comparable to splits based on specific positions
	Best 10 m split avg speed	Average speed of 10 m interval with lowest time	Top speed based on traditional split	Not comparable to splits based on specific positions
5 m splits	Time	Time to complete 5 m interval	Split times are commonly used in sprint testing and training	Might be obsolete with current technology
	Top speed	Top speed based on filtered data of 5 m interval	Top or maximum speed obtained for a given 5 m interval	Average speed is commonly used with 5 m splits

assess changes/differences of that given magnitude. If the TE was similar to these thresholds, the test metric was rated as “ok.” If the TE exceeded these thresholds, the test metric was rated as “poor,” indicating that only larger changes/differences would be detectable (19).

3 Results

Descriptive data for all outcome measurements for the different test sessions with test-retest reliability are presented in Table 2. Absolute reliability (CV) was good for all outcome measurements (0.9–3.7) except Max Accel (8.7). Similar findings were observed for relative reliability (ICC) with very high reliability (0.95–0.99) for all variables except high reliability for 0–5 Time (0.86) and Max Accel (0.77). Similarly, trivial effects were observed for all outcome measurements except small effects for all 5 m top speeds (0.20–0.23), 0–5 m time (0.39) and Max Accel (0.50). A similar pattern was observed with good to ok SWC, except for most 5 m split top speeds, 0–5 m time and Max Accel.

Intrasession reliability for all test sessions with descriptive data is presented in Table 3. Similar patterns were observed for intrasession as for test-retest reliability. Specifically, absolute reliability (CV) was good for all outcome measurements for all sessions except Max Accel, which ranged from 5.7 to 5.9%. Similar findings were observed for relative reliability (ICC) with very high reliability for all outcome measurements except Max Accel (0.85–0.93), 0–5 Time for session one through four (0.88–0.92). Furthermore, trivial effects were observed for all outcome measurements for all sessions except small effects for Max Accel (0.29–0.46), 0–5 m time (0.20–0.40) and 0–5 m Top Speed session one (0.24). Furthermore, all outcome measurements had good to ok SWC, except for Max Accel and 0–5 m Top Speed session one. A summary of findings for both test-retest and intrasession reliability of session four of key outcome measurements (Time, 0–5 m time, Max Accel and Top speed) are provided in Figure 1.

4 Discussion

The present study aimed to assess both intrasession and test-retest reliability of assisted sprint outcome measurements using an MRD. Overall, the observed reliability values were good to acceptable for absolute reliability and high to extremely high for relative reliability. These findings are comparable to or better than those reported for change-of-direction performance (16) and resisted sprint outcome measurements obtained by a MRD (15).

Both resisted and assisted sprint training rely on speed monitoring, which can be managed by adjusting the assisted (pulling) load and controlling the speed at which the athlete is pulled. In this study, an assisted load of 3 kg was applied, with the assisted speed set to 14 m/s, well beyond the top speed capacity of all participants. This methodology was informed by

practical coaching experience and common practices in assisted sprinting using MRDs. Speed manipulation is typically achieved indirectly by adjusting the assisted load and monitoring the resulting speed of the athlete. Alternatively, one could prescribe a target assisted speed (e.g., 10 m/s) for the athlete to reach; however, this approach is less commonly used. Coaches have reported that reaching a prescribed speed often results in an inconsistent and less fluid experience, potentially due to inter-step speed fluctuations causing slack in the towing line. Given that the current study maintained a constant assisted load, both absolute and relative intrasession and test-retest reliability were found to be good to excellent (Tables 2, 3). In addition, small worthwhile change (SWC) values were mostly classified as good to ok across all outcome measurements.

The reliability of assisted sprint outcome measurements has direct practical applications, particularly as MRDs are increasingly utilized for assisted and overspeed sprint training across various sports. Monitoring speed is crucial for both training and performance assessment. Based on the present findings, both scientists and coaches can now systematically track speed responses to a given load prescription. This is particularly relevant for evaluating training effectiveness and identifying performance changes over time.

In a recent pilot study, Cecilia-Gallego and co-authors examined the effects of a 10-session overspeed training program (10). Their findings indicated that overspeed training had non-significant effects on top speed, as measured by both unloaded sprints and various overspeed conditions. However, considering that the SWC for top speed in the present study was 0.15 m/s for the test-retest reliability, and that they observed a 0.34 m/s increase in an overspeed condition with a similar assisted load, one could argue that meaningful changes occurred. Furthermore, Clark and co-authors reported an acute increase of 0.9 m/s in average speed during the 30–40 m split when transitioning from free sprinting to assisted sprinting (7 kg assisted load), as measured by dual-beam photocells (20). Although their measurements were obtained using a different method, the 0.9 m/s increase substantially exceeds the MWC for the best 10 m split in the present study (test retest: 0.45 m/s; intrasession: 0.14–0.17 m/s). Additionally, the SWC for top speed across different splits ranged from 0.08 to 0.16 m/s, with good MWC values (range: 0.23–0.48 m/s) for the test-retest condition. Furthermore, good SWC were observed for all 5 m split top speed measurements for intrasession reliability that ranged from 0.07 to 0.17 m/s with one exception, 0–5 m top speed session 1 with MWC of 0.24 m/s. In combination these results suggest that the MRD used in this study can detect small but meaningful changes in performance. This ability allows for precise fine-tuning of assisted load prescriptions and training progressions, as well as the detection of performance adaptations in response to training interventions.

Among the various performance metrics analyzed, early acceleration outcomes—specifically maximum acceleration and 0–5 m time—exhibited the lowest reliability for both intrasession and test-retest reliability. Maximum acceleration showed the lowest ICC (test-retest: 0.77; intrasession: 0.85–0.93) and the

TABLE 2 Descriptive statistics of all test sessions with test-retest reliability of all outcome measurements.

Phase	Outcome variables	Session 1	Session 2	Session 3	Session 4	ICC (95% CI)	CV (95% CI)	TE (95% CI)	Stand TE (95% CI)	SWC	MWC
0–40	Time	5.77 ± 0.49	5.80 ± 0.46	5.77 ± 0.47	5.71 ± 0.36	0.98 (0.97; 0.99)	1.1 (0.9; 1.4)	0.06 (0.05; 0.08)	0.14 (0.11; 0.17)	0.09 (0.07; 0.13)	0.27 (0.21; 0.39)
	Top speed	8.65 ± 0.83	8.56 ± 0.75	8.63 ± 0.79	8.75 ± 0.65	0.98 (0.96; 0.99)	1.4 (1.2; 1.8)	0.12 (0.10; 0.15)	0.16 (0.13; 0.20)	0.15 (0.12; 0.22)	0.46 (0.35; 0.66)
	Max accel	6.34 ± 1.19	6.31 ± 1.04	6.39 ± 1.06	6.36 ± 0.91	0.77 (0.60; 0.89)	8.7 (7.2; 11.5)	0.53 (0.44; 0.67)	0.50 (0.41; 0.63)	0.21 (0.16; 0.31)	0.63 (0.49; 0.92)
	Best 5 m split time	0.58 ± 0.06	0.58 ± 0.06	0.58 ± 0.06	0.57 ± 0.05	0.98 (0.97; 0.99)	1.3 (1.1; 1.7)	0.01 (0.01; 0.01)	0.13 (0.11; 0.17)	0.01 (0.01; 0.02)	0.03 (0.03; 0.05)
	Best 5 m avg speed	8.73 ± 0.84	8.65 ± 0.76	8.71 ± 0.80	8.83 ± 0.66	0.98 (0.96; 0.99)	1.3 (1.1; 1.7)	0.11 (0.09; 0.14)	0.15 (0.12; 0.19)	0.15 (0.12; 0.22)	0.46 (0.35; 0.67)
	Best 10 m split time	1.17 ± 0.12	1.18 ± 0.11	1.17 ± 0.12	1.17 ± 0.09	0.99 (0.97; 0.99)	1.2 (1.0; 1.6)	0.01 (0.01; 0.02)	0.12 (0.10; 0.15)	0.02 (0.02; 0.03)	0.07 (0.05; 0.10)
	Best 10 m split avg speed	8.63 ± 0.81	8.56 ± 0.74	8.61 ± 0.78	8.74 ± 0.66	0.98 (0.97; 0.99)	1.2 (1.0; 1.6)	0.10 (0.08; 0.13)	0.14 (0.11; 0.17)	0.15 (0.12; 0.22)	0.45 (0.35; 0.65)
0–5	Time	1.35 ± 0.13	1.35 ± 0.12	1.35 ± 0.13	1.35 ± 0.11	0.86 (0.75; 0.94)	3.7 (3.1; 4.9)	0.05 (0.04; 0.06)	0.39 (0.32; 0.49)	0.02 (0.02; 0.04)	0.07 (0.06; 0.11)
	Top speed	5.87 ± 0.41	5.81 ± 0.43	5.86 ± 0.37	5.89 ± 0.33	0.96 (0.93; 0.98)	1.6 (1.3; 2.0)	0.08 (0.07; 0.10)	0.20 (0.17; 0.26)	0.08 (0.06; 0.11)	0.23 (0.18; 0.34)
5–10	Time	0.76 ± 0.05	0.76 ± 0.05	0.76 ± 0.05	0.75 ± 0.04	0.99 (0.97; 0.99)	0.9 (0.7; 1.1)	0.01 (0.01; 0.01)	0.12 (0.10; 0.16)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed	7.19 ± 0.51	7.10 ± 0.58	7.16 ± 0.49	7.23 ± 0.44	0.96 (0.92; 0.98)	1.8 (1.5; 2.3)	0.11 (0.09; 0.14)	0.21 (0.17; 0.27)	0.10 (0.08; 0.15)	0.31 (0.23; 0.44)
10–15	Time	0.67 ± 0.05	0.67 ± 0.05	0.67 ± 0.05	0.66 ± 0.04	0.99 (0.97; 0.99)	0.9 (0.8; 1.2)	0.01 (0.00; 0.01)	0.12 (0.10; 0.15)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed	7.82 ± 0.60	7.71 ± 0.68	7.81 ± 0.56	7.88 ± 0.51	0.95 (0.91; 0.98)	2.1 (1.7; 2.7)	0.14 (0.11; 0.17)	0.23 (0.19; 0.29)	0.12 (0.09; 0.17)	0.36 (0.27; 0.51)
15–20	Time	0.63 ± 0.05	0.63 ± 0.05	0.63 ± 0.05	0.62 ± 0.04	0.98 (0.96; 0.99)	1.2 (1.0; 1.5)	0.01 (0.01; 0.01)	0.14 (0.12; 0.18)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed	8.18 ± 0.67	8.08 ± 0.75	8.18 ± 0.65	8.27 ± 0.55	0.95 (0.91; 0.98)	2.2 (1.8; 2.9)	0.15 (0.13; 0.19)	0.23 (0.19; 0.29)	0.13 (0.10; 0.19)	0.40 (0.31; 0.58)
20–25	Time	0.61 ± 0.06	0.61 ± 0.05	0.61 ± 0.05	0.60 ± 0.04	0.98 (0.97; 0.99)	1.2 (1.0; 1.5)	0.01 (0.01; 0.01)	0.13 (0.11; 0.17)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Top speed	8.41 ± 0.74	8.29 ± 0.81	8.39 ± 0.70	8.50 ± 0.60	0.96 (0.91; 0.98)	2.3 (1.9; 3.0)	0.16 (0.13; 0.20)	0.22 (0.18; 0.28)	0.14 (0.11; 0.21)	0.43 (0.33; 0.62)
25–30	Time	0.60 ± 0.06	0.60 ± 0.05	0.60 ± 0.06	0.58 ± 0.04	0.98 (0.96; 0.99)	1.3 (1.1; 1.8)	0.01 (0.01; 0.01)	0.14 (0.12; 0.18)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Top speed	8.53 ± 0.77	8.41 ± 0.86	8.50 ± 0.75	8.65 ± 0.62	0.95 (0.91; 0.98)	2.4 (2.0; 3.2)	0.17 (0.14; 0.22)	0.22 (0.19; 0.29)	0.15 (0.09; 0.19)	0.46 (0.35; 0.66)
30–35	Time	0.59 ± 0.06	0.59 ± 0.05	0.59 ± 0.06	0.58 ± 0.05	0.98 (0.96; 0.99)	1.5 (1.3; 2.0)	0.01 (0.01; 0.01)	0.15 (0.13; 0.20)	0.01 (0.01; 0.02)	0.03 (0.03; 0.05)
	Top speed	8.64 ± 0.82	8.47 ± 0.86	8.59 ± 0.78	8.72 ± 0.66	0.96 (0.92; 0.98)	2.4 (1.9; 3.1)	0.17 (0.14; 0.22)	0.22 (0.18; 0.28)	0.16 (0.12; 0.23)	0.47 (0.36; 0.68)
35–40	Time	0.58 ± 0.06	0.58 ± 0.06	0.58 ± 0.06	0.57 ± 0.05	0.98 (0.97; 0.99)	1.4 (1.2; 1.8)	0.01 (0.01; 0.01)	0.13 (0.11; 0.17)	0.01 (0.01; 0.02)	0.03 (0.03; 0.05)
	Top speed	8.61 ± 0.83	8.48 ± 0.87	8.62 ± 0.80	8.74 ± 0.66	0.96 (0.93; 0.98)	2.3 (1.9; 2.9)	0.16 (0.14; 0.21)	0.20 (0.17; 0.26)	0.16 (0.12; 0.23)	0.48 (0.37; 0.69)

Definition and description of all outcome variables are presented in Table 1. Max, maximum; Accel, acceleration; Avg, average; ICC, intra-class correlation coefficient; CI, confidence interval; CV, coefficient of variation; TE, typical error; Stand TE, standardized typical error (light grey, trivial; grey, moderate); SWC, smallest worthwhile change; MWC, moderate worthwhile change [grey shading identifying magnitude (SWC or MWC) of good or ok change/difference].

TABLE 3 Descriptive statistics of all tests with intrasession reliability session 1 through 4.

Phase	Outcome variables	Test 1	Test 2	ICC (95% CI)	CV (95% CI)	TE (95% CI)	Stand TE (95% CI)	SWC	MWC
0–40	Time S1	5.74 ± 0.48	5.75 ± 0.50	0.99 (0.97; 1.00)	1.1 (0.8; 2.4)	0.06 (0.05; 0.09)	0.12 (0.09; 0.18)	0.10 (0.07; 0.15)	0.29 (0.21; 0.46)
	Time S2	5.75 ± 0.47	5.76 ± 0.45	0.99 (0.98; 1.00)	0.8 (0.6; 1.2)	0.05 (0.04; 0.07)	0.11 (0.08; 0.16)	0.09 (0.07; 0.14)	0.27 (0.20; 0.43)
	Time S3	5.76 ± 0.50	5.75 ± 0.48	1.00 (0.97; 1.00)	0.9 (0.7; 1.3)	0.05 (0.04; 0.08)	0.11 (0.08; 0.16)	0.10 (0.07; 0.14)	0.29 (0.22; 0.43)
	Time S4	5.68 ± 0.38	5.70 ± 0.39	0.99 (0.96; 0.99)	0.9 (0.6; 1.3)	0.05 (0.04; 0.08)	0.13 (0.10; 0.20)	0.08 (0.06; 0.12)	0.23 (0.17; 0.35)
	Top speed S1	8.61 ± 0.83	8.64 ± 0.84	0.98 (0.95; 0.99)	1.4 (1.1; 2.1)	0.12 (0.09; 0.17)	0.15 (0.11; 0.21)	0.17 (0.12; 0.26)	0.50 (0.37; 0.77)
	Top speed S2	8.63 ± 0.76	8.61 ± 0.75	1.00 (0.99; 1.00)	0.6 (0.5; 0.9)	0.06 (0.04; 0.08)	0.08 (0.06; 0.11)	0.15 (0.11; 0.24)	0.45 (0.33; 0.71)
	Top speed S3	8.66 ± 0.83	8.64 ± 0.81	0.99 (0.99; 1.00)	0.8 (0.6; 1.2)	0.06 (0.05; 0.09)	0.08 (0.06; 0.11)	0.16 (0.12; 0.24)	0.49 (0.37; 0.72)
	Top speed S4	8.79 ± 0.72	8.78 ± 0.70	0.99 (0.98; 1.00)	0.7 (0.6; 1.1)	0.06 (0.05; 0.10)	0.09 (0.07; 0.14)	0.14 (0.11; 0.21)	0.42 (0.32; 0.64)
	Max accel S1	6.56 ± 1.13	6.29 ± 1.15	0.93 (0.82; 0.97)	5.4 (4.1; 7.8)	0.33 (0.25; 0.48)	0.29 (0.22; 0.42)	0.23 (0.17; 0.36)	0.68 (0.50; 1.08)
	Max accel S2	6.49 ± 1.12	6.30 ± 0.98	0.91 (0.78; 0.97)	5.8 (4.4; 8.5)	0.34 (0.26; 0.49)	0.32 (0.25; 0.47)	0.21 (0.15; 0.33)	0.63 (0.46; 1.00)
	Max accel S3	6.31 ± 0.94	6.45 ± 1.04	0.86 (0.69; 0.94)	5.9 (4.5; 8.8)	0.38 (0.29; 0.56)	0.42 (0.32; 0.61)	0.20 (0.15; 0.29)	0.59 (0.45; 0.87)
	Max accel S4	6.32 ± 0.79	6.34 ± 0.94	0.85 (0.63; 0.94)	5.7 (4.3; 8.7)	0.36 (0.27; 0.54)	0.46 (0.34; 0.68)	0.17 (0.13; 0.26)	0.52 (0.39; 0.78)
	Best 5 m split time S1	0.58 ± 0.06	0.58 ± 0.06	0.98 (0.96; 0.99)	1.5 (1.1; 2.1)	0.01 (0.01; 0.01)	0.14 (0.11; 0.20)	0.01 (0.01; 0.02)	0.04 (0.03; 0.06)
	Best 5 m split time S2	0.58 ± 0.06	0.58 ± 0.06	1.00 (0.99; 1.00)	0.7 (0.5; 1.0)	0.00 (0.00; 0.01)	0.07 (0.05; 0.10)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Best 5 m split time S3	0.58 ± 0.06	0.58 ± 0.06	0.99 (0.98; 1.00)	0.9 (0.7; 1.3)	0.01 (0.00; 0.01)	0.10 (0.07; 0.14)	0.01 (0.01; 0.02)	0.04 (0.03; 0.05)
	Best 5 m split time S4	0.57 ± 0.05	0.57 ± 0.05	0.99 (0.98; 1.00)	0.7 (0.5; 1.1)	0.00 (0.00; 0.01)	0.08 (0.06; 0.13)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Best 5 m avg speed S1	8.74 ± 0.84	8.77 ± 0.84	0.98 (0.95; 0.99)	1.5 (1.1; 2.1)	0.13 (0.10; 0.18)	0.15 (0.11; 0.22)	0.17 (0.12; 0.26)	0.50 (0.37; 0.79)
	Best 5 m avg speed S2	8.72 ± 0.78	8.71 ± 0.77	1.00 (0.99; 1.00)	0.7 (0.5; 1.0)	0.06 (0.05; 0.09)	0.08 (0.06; 0.11)	0.15 (0.11; 0.24)	0.46 (0.34; 0.73)
	Best 5 m avg speed S3	8.74 ± 0.85	8.72 ± 0.83	0.99 (0.99; 1.00)	0.8 (0.7; 1.1)	0.07 (0.05; 0.10)	0.08 (0.06; 0.12)	0.17 (0.13; 0.25)	0.50 (0.38; 0.74)
	Best 5 m avg speed S4	8.88 ± 0.72	8.87 ± 0.71	0.99 (0.99; 1.00)	0.7 (0.5; 1.1)	0.06 (0.05; 0.09)	0.09 (0.06; 0.13)	0.14 (0.11; 0.21)	0.43 (0.32; 0.64)
	Best 10 m split time S1	1.17 ± 0.12	1.16 ± 0.12	0.98 (0.96; 0.99)	1.4 (1.1; 2.0)	0.02 (0.01; 0.02)	0.14 (0.10; 0.20)	0.02 (0.02; 0.04)	0.07 (0.05; 0.11)
	Best 10 m split time S2	1.17 ± 0.11	1.17 ± 0.11	1.00 (0.99; 1.00)	0.6 (0.5; 0.9)	0.01 (0.01; 0.01)	0.06 (0.05; 0.09)	0.02 (0.02; 0.04)	0.07 (0.05; 0.11)
	Best 10 m split time S3	1.17 ± 0.13	1.17 ± 0.12	0.99 (0.98; 1.00)	0.8 (0.7; 1.1)	0.01 (0.01; 0.02)	0.10 (0.08; 0.14)	0.02 (0.02; 0.04)	0.07 (0.05; 0.11)
	Best 10 m split time S4	1.14 ± 0.10	1.15 ± 0.10	0.99 (0.99; 1.00)	0.7 (0.5; 1.0)	0.01 (0.01; 0.01)	0.08 (0.06; 0.12)	0.02 (0.01; 0.03)	0.06 (0.04; 0.09)
	Best 10 m split avg speed S1	8.65 ± 0.82	8.68 ± 0.83	0.98 (0.95; 0.99)	1.4 (1.1; 2.0)	0.12 (0.09; 0.17)	0.15 (0.11; 0.21)	0.17 (0.12; 0.26)	0.50 (0.36; 0.78)
	Best 10 m split avg speed S2	8.62 ± 0.76	8.61 ± 0.75	1.00 (0.99; 1.00)	0.6 (0.5; 0.9)	0.05 (0.04; 0.08)	0.07 (0.05; 0.10)	0.15 (0.11; 0.24)	0.45 (0.33; 0.71)
	Best 10 m split avg speed S3	8.65 ± 0.83	8.64 ± 0.81	0.99 (0.98; 1.00)	0.9 (0.7; 1.3)	0.07 (0.05; 0.10)	0.08 (0.06; 0.12)	0.16 (0.12; 0.24)	0.49 (0.37; 0.72)
	Best 10 m split avg speed S4	8.79 ± 0.71	8.78 ± 0.71	0.99 (0.98; 1.00)	0.7 (0.5; 1.0)	0.06 (0.04; 0.09)	0.08 (0.06; 0.13)	0.14 (0.11; 0.21)	0.43 (0.32; 0.64)
0–5	Time S1	1.34 ± 0.13	1.35 ± 0.13	0.97 (0.92; 0.99)	2.0 (1.5; 2.9)	0.03 (0.02; 0.04)	0.20 (0.15; 0.29)	0.03 (0.02; 0.04)	0.08 (0.06; 0.12)
	Time S2	1.34 ± 0.13	1.35 ± 0.11	0.92 (0.80; 0.97)	2.8 (2.1; 4.1)	0.04 (0.03; 0.05)	0.31 (0.24; 0.45)	0.02 (0.02; 0.04)	0.07 (0.05; 0.12)
	Time S3	1.35 ± 0.12	1.34 ± 0.13	0.92 (0.82; 0.97)	2.8 (2.1; 4.1)	0.04 (0.03; 0.05)	0.31 (0.23; 0.45)	0.02 (0.02; 0.04)	0.07 (0.06; 0.11)
0–5	Time S4	1.34 ± 0.10	1.35 ± 0.12	0.88 (0.70; 0.95)	3.0 (2.3; 4.6)	0.04 (0.03; 0.06)	0.40 (0.30; 0.60)	0.02 (0.02; 0.03)	0.06 (0.05; 0.10)
	Top speed S1	5.90 ± 0.40	5.89 ± 0.39	0.95 (0.88; 0.98)	1.6 (1.2; 2.2)	0.09 (0.07; 0.14)	0.24 (0.18; 0.34)	0.08 (0.06; 0.13)	0.24 (0.17; 0.38)
	Top speed S2	5.90 ± 0.37	5.88 ± 0.36	0.99 (0.97; 1.00)	0.8 (0.6; 1.2)	0.05 (0.04; 0.07)	0.13 (0.10; 0.18)	0.07 (0.05; 0.12)	0.22 (0.16; 0.35)
	Top speed S3	5.89 ± 0.38	5.87 ± 0.37	0.98 (0.96; 0.99)	0.9 (0.7; 1.3)	0.05 (0.04; 0.08)	0.14 (0.11; 0.21)	0.08 (0.06; 0.11)	0.23 (0.17; 0.33)
	Top speed S4	5.96 ± 0.36	5.92 ± 0.35	0.98 (0.96; 0.99)	0.8 (0.6; 1.2)	0.05 (0.04; 0.07)	0.14 (0.10; 0.21)	0.07 (0.05; 0.11)	0.21 (0.16; 0.32)
5–10	Time S1	0.75 ± 0.05	0.75 ± 0.05	0.98 (0.94; 0.99)	1.2 (0.9; 1.7)	0.01 (0.01; 0.01)	0.16 (0.12; 0.23)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S2	0.75 ± 0.05	0.75 ± 0.05	0.99 (0.97; 1.00)	0.8 (0.6; 1.1)	0.01 (0.00; 0.01)	0.12 (0.09; 0.17)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S3	0.76 ± 0.05	0.76 ± 0.05	0.99 (0.96; 0.99)	0.9 (0.7; 1.3)	0.01 (0.01; 0.01)	0.13 (0.10; 0.19)	0.01 (0.01; 0.01)	0.03 (0.02; 0.05)
	Time S4	0.74 ± 0.05	0.75 ± 0.05	0.99 (0.98; 1.00)	0.6 (0.4; 0.9)	0.00 (0.00; 0.01)	0.10 (0.07; 0.15)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed S1	7.20 ± 0.51	7.23 ± 0.51	0.97 (0.93; 0.99)	1.3 (1.0; 1.9)	0.09 (0.07; 0.14)	0.18 (0.14; 0.27)	0.10 (0.07; 0.16)	0.31 (0.22; 0.48)

(Continued)

TABLE 3 Continued

Phase	Outcome variables	Test 1	Test 2	ICC (95% CI)	CV (95% CI)	TE (95% CI)	Stand TE (95% CI)	SWC	MWC
10–15	Top speed S2	7.21 ± 0.49	7.19 ± 0.48	0.99 (0.98; 1.00)	0.7 (0.5; 1.0)	0.05 (0.04; 0.07)	0.11 (0.08; 0.16)	0.10 (0.07; 0.15)	0.29 (0.21; 0.46)
	Top speed S3	7.19 ± 0.52	7.18 ± 0.51	0.99 (0.98; 1.00)	0.7 (0.5; 1.1)	0.05 (0.04; 0.07)	0.09 (0.07; 0.14)	0.10 (0.08; 0.15)	0.31 (0.24; 0.45)
	Top speed S4	7.29 ± 0.47	7.26 ± 0.46	0.99 (0.99; 1.00)	0.5 (0.4; 0.8)	0.04 (0.03; 0.06)	0.08 (0.06; 0.12)	0.08 (0.06; 0.12)	0.28 (0.21; 0.42)
	Time S1	0.66 ± 0.05	0.66 ± 0.05	0.98 (0.94; 0.99)	1.3 (1.0; 1.9)	0.01 (0.01; 0.01)	0.16 (0.12; 0.24)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S2	0.66 ± 0.05	0.66 ± 0.05	0.99 (0.99; 1.00)	0.6 (0.5; 0.9)	0.00 (0.00; 0.01)	0.08 (0.06; 0.12)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S3	0.66 ± 0.06	0.66 ± 0.05	0.99 (0.99; 1.00)	0.7 (0.6; 1.1)	0.01 (0.00; 0.01)	0.10 (0.07; 0.14)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S4	0.66 ± 0.05	0.66 ± 0.05	0.99 (0.98; 1.00)	0.6 (0.5; 0.9)	0.00 (0.00; 0.01)	0.09 (0.07; 0.13)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed S1	7.87 ± 0.61	7.88 ± 0.61	0.98 (0.94; 0.99)	1.3 (1.0; 1.9)	0.10 (0.08; 0.15)	0.16 (0.13; 0.24)	0.12 (0.09; 0.19)	0.37 (0.27; 0.58)
	Top speed S2	7.83 ± 0.57	7.83 ± 0.57	1.00 (0.99; 1.00)	0.5 (0.4; 0.7)	0.04 (0.03; 0.06)	0.07 (0.05; 0.10)	0.11 (0.08; 0.18)	0.34 (0.25; 0.54)
	Top speed S3	7.83 ± 0.61	7.84 ± 0.59	0.99 (0.96; 0.99)	1.1 (0.8; 1.6)	0.08 (0.06; 0.11)	0.13 (0.10; 0.19)	0.12 (0.09; 0.18)	0.36 (0.27; 0.53)
15–20	Top speed S4	7.93 ± 0.55	7.91 ± 0.55	0.99 (0.98; 1.00)	0.7 (0.5; 1.0)	0.05 (0.04; 0.08)	0.09 (0.07; 0.14)	0.11 (0.08; 0.16)	0.33 (0.25; 0.49)
	Time S1	0.63 ± 0.05	0.62 ± 0.05	0.98 (0.95; 0.99)	1.3 (1.0; 1.9)	0.01 (0.01; 0.01)	0.16 (0.12; 0.23)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S2	0.63 ± 0.05	0.63 ± 0.05	1.00 (0.99; 1.00)	0.5 (0.4; 0.8)	0.00 (0.00; 0.00)	0.07 (0.05; 0.09)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S3	0.63 ± 0.06	0.62 ± 0.05	0.98 (0.95; 0.99)	1.2 (0.9; 1.7)	0.01 (0.01; 0.01)	0.15 (0.11; 0.22)	0.01 (0.01; 0.02)	0.03 (0.03; 0.05)
	Time S4	0.62 ± 0.05	0.62 ± 0.05	0.99 (0.98; 1.00)	0.7 (0.5; 1.1)	0.00 (0.00; 0.01)	0.10 (0.07; 0.15)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed S1	8.22 ± 0.68	8.24 ± 0.68	0.98 (0.95; 0.99)	1.3 (1.0; 1.8)	0.10 (0.08; 0.15)	0.15 (0.12; 0.22)	0.14 (0.10; 0.21)	0.41 (0.30; 0.64)
	Top speed S2	8.19 ± 0.64	8.20 ± 0.65	1.00 (0.99; 1.00)	0.6 (0.5; 0.9)	0.05 (0.04; 0.07)	0.07 (0.06; 0.11)	0.13 (0.09; 0.20)	0.39 (0.28; 0.61)
	Top speed S3	8.21 ± 0.70	8.23 ± 0.67	0.99 (0.98; 1.00)	1.0 (0.8; 1.4)	0.07 (0.05; 0.10)	0.10 (0.08; 0.15)	0.14 (0.10; 0.20)	0.41 (0.31; 0.60)
	Top speed S4	8.30 ± 0.60	8.31 ± 0.60	0.99 (0.98; 1.00)	0.7 (0.5; 1.1)	0.06 (0.04; 0.09)	0.10 (0.07; 0.14)	0.12 (0.09; 0.18)	0.36 (0.27; 0.54)
20–25	Time S1	0.60 ± 0.06	0.60 ± 0.06	0.98 (0.96; 0.99)	1.4 (1.0; 2.0)	0.01 (0.01; 0.01)	0.14 (0.11; 0.21)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S2	0.61 ± 0.05	0.61 ± 0.05	0.99 (0.99; 1.00)	0.7 (0.5; 1.0)	0.00 (0.00; 0.01)	0.08 (0.06; 0.11)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S3	0.61 ± 0.06	0.61 ± 0.06	0.99 (0.97; 1.00)	1.0 (0.7; 1.4)	0.01 (0.01; 0.01)	0.12 (0.09; 0.17)	0.01 (0.01; 0.02)	0.04 (0.03; 0.05)
20–25	Time S4	0.60 ± 0.05	0.60 ± 0.05	0.99 (0.98; 1.00)	0.8 (0.6; 1.2)	0.00 (0.00; 0.01)	0.10 (0.08; 0.15)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed S1	8.44 ± 0.75	8.46 ± 0.75	0.98 (0.95; 0.99)	1.4 (1.1; 2.1)	0.12 (0.09; 0.17)	0.16 (0.12; 0.23)	0.15 (0.11; 0.24)	0.45 (0.33; 0.71)
	Top speed S2	8.41 ± 0.70	8.42 ± 0.69	0.99 (0.98; 1.00)	0.8 (0.6; 1.1)	0.07 (0.05; 0.09)	0.09 (0.07; 0.14)	0.13 (0.09; 0.20)	0.41 (0.30; 0.65)
	Top speed S3	8.42 ± 0.75	8.45 ± 0.73	0.99 (0.98; 1.00)	0.9 (0.7; 1.3)	0.07 (0.05; 0.10)	0.09 (0.07; 0.13)	0.15 (0.11; 0.22)	0.44 (0.34; 0.65)
	Top speed S4	8.55 ± 0.65	8.54 ± 0.65	0.99 (0.98; 1.00)	0.7 (0.5; 1.0)	0.06 (0.04; 0.09)	0.09 (0.07; 0.13)	0.13 (0.10; 0.19)	0.39 (0.29; 0.58)
25–30	Time S1	0.59 ± 0.06	0.59 ± 0.06	0.98 (0.95; 0.99)	1.5 (1.2; 2.2)	0.01 (0.01; 0.01)	0.15 (0.12; 0.22)	0.01 (0.01; 0.02)	0.04 (0.03; 0.06)
	Time S2	0.60 ± 0.05	0.59 ± 0.05	0.99 (0.98; 1.00)	0.8 (0.6; 1.2)	0.00 (0.00; 0.01)	0.09 (0.07; 0.13)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S3	0.60 ± 0.06	0.59 ± 0.06	0.99 (0.97; 1.00)	1.0 (0.8; 1.5)	0.01 (0.01; 0.01)	0.11 (0.09; 0.17)	0.01 (0.01; 0.02)	0.04 (0.03; 0.05)
	Time S4	0.58 ± 0.05	0.58 ± 0.05	0.99 (0.97; 1.00)	1.0 (0.7; 1.5)	0.01 (0.00; 0.01)	0.12 (0.09; 0.19)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed S1	8.55 ± 0.78	8.59 ± 0.80	0.98 (0.95; 0.99)	1.4 (1.0; 2.0)	0.12 (0.09; 0.17)	0.15 (0.11; 0.21)	0.16 (0.12; 0.25)	0.47 (0.35; 0.75)
	Top speed S2	8.53 ± 0.73	8.53 ± 0.72	0.99 (0.99; 1.00)	0.7 (0.5; 1.0)	0.06 (0.05; 0.09)	0.08 (0.06; 0.12)	0.15 (0.11; 0.23)	0.44 (0.32; 0.69)
	Top speed S3	8.54 ± 0.80	8.56 ± 0.77	0.99 (0.98; 1.00)	0.9 (0.7; 1.3)	0.07 (0.05; 0.10)	0.09 (0.07; 0.13)	0.16 (0.12; 0.23)	0.47 (0.36; 0.69)
	Top speed S4	8.70 ± 0.80	8.67 ± 0.66	0.99 (0.97; 1.00)	0.8 (0.7; 1.1)	0.07 (0.05; 0.11)	0.11 (0.08; 0.16)	0.13 (0.10; 0.20)	0.40 (0.30; 0.60)
30–35	Time S1	0.59 ± 0.06	0.59 ± 0.06	0.98 (0.96; 0.99)	1.5 (1.1; 2.2)	0.01 (0.01; 0.01)	0.14 (0.11; 0.21)	0.01 (0.01; 0.02)	0.04 (0.03; 0.06)
	Time S2	0.59 ± 0.06	0.59 ± 0.05	1.00 (0.99; 1.00)	0.7 (0.6; 1.1)	0.00 (0.00; 0.01)	0.08 (0.06; 0.11)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Time S3	0.59 ± 0.06	0.59 ± 0.06	0.99 (0.97; 1.00)	1.1 (0.8; 1.6)	0.01 (0.01; 0.01)	0.11 (0.09; 0.17)	0.01 (0.01; 0.02)	0.04 (0.03; 0.05)
	Time S4	0.58 ± 0.05	0.58 ± 0.05	0.99 (0.98; 1.00)	0.8 (0.6; 1.2)	0.00 (0.00; 0.01)	0.09 (0.07; 0.14)	0.01 (0.01; 0.01)	0.03 (0.02; 0.04)
	Top speed S1	8.63 ± 0.82	8.66 ± 0.82	0.98 (0.95; 0.99)	1.5 (1.2; 2.2)	0.13 (0.10; 0.19)	0.16 (0.12; 0.26)	0.16 (0.11; 0.22)	0.49 (0.36; 0.78)
	Top speed S2	8.60 ± 0.75	8.59 ± 0.74	0.99 (0.99; 1.00)	0.7 (0.5; 1.0)	0.06 (0.05; 0.09)	0.08 (0.06; 0.12)	0.15 (0.11; 0.24)	0.45 (0.33; 0.71)

(Continued)

TABLE 3 Continued

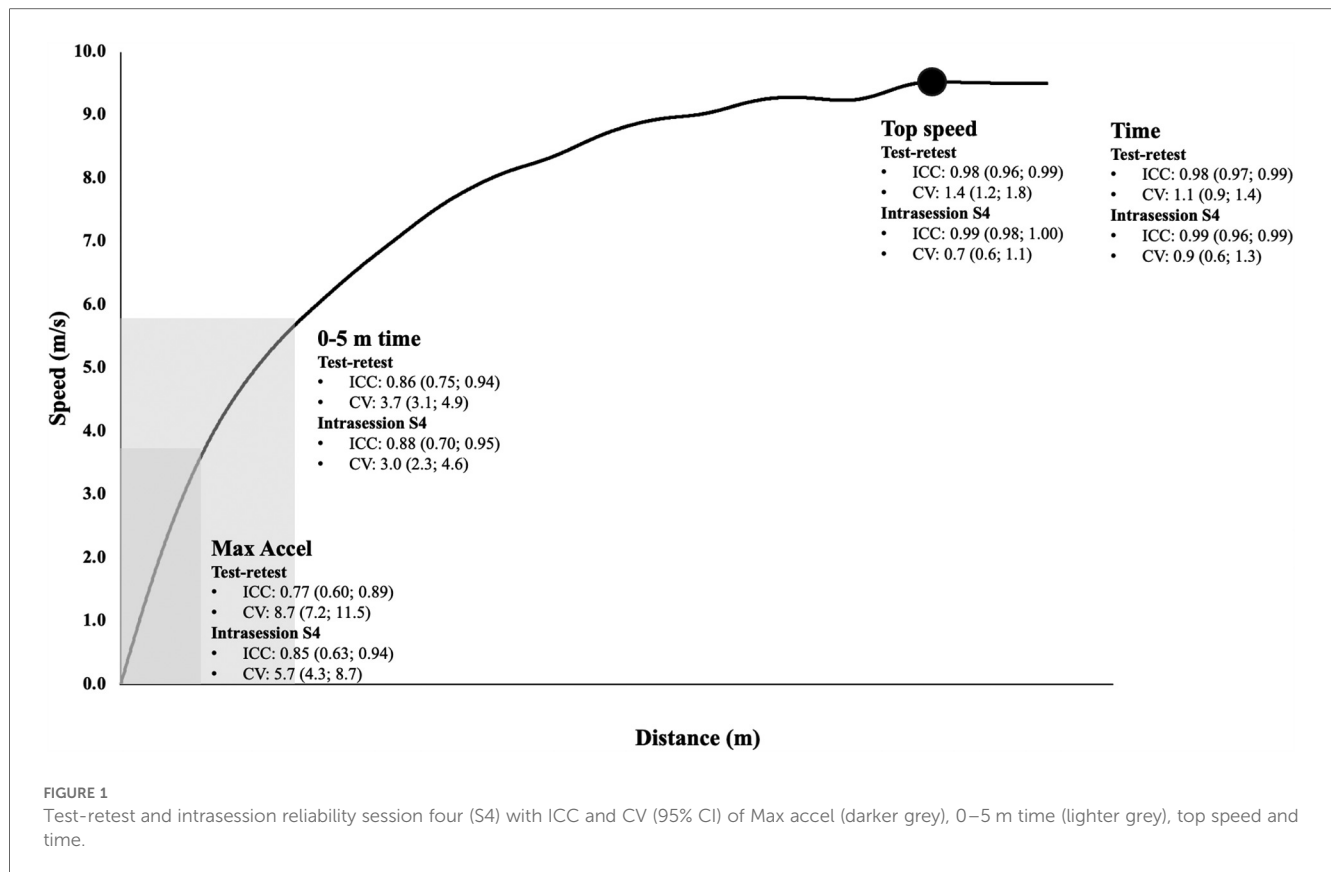
Phase	Outcome variables	Test 1	Test 2	ICC (95% CI)	CV (95% CI)	TE (95% CI)	Stand TE (95% CI)	SWC	MWC
35–40	Top speed S3	8.62 ± 0.82	8.60 ± 0.81	0.99 (0.99; 1.00)	0.9 (0.6; 1.2)	0.07 (0.05; 0.10)	0.08 (0.06; 0.12)	0.16 (0.12; 0.24)	0.49 (0.37; 0.71)
	Top speed S4	8.77 ± 0.71	8.75 ± 0.71	0.99 (0.98; 1.00)	0.7 (0.5; 1.0)	0.06 (0.04; 0.09)	0.08 (0.06; 0.12)	0.14 (0.11; 0.21)	0.43 (0.32; 0.64)
	Time S1	0.57 ± 0.06	0.58 ± 0.07	0.98 (0.96; 0.99)	1.6 (1.2; 2.3)	0.01 (0.01; 0.01)	0.14 (0.11; 0.21)	0.01 (0.01; 0.02)	0.04 (0.03; 0.06)
	Time S2	0.58 ± 0.06	0.58 ± 0.05	1.00 (0.99; 1.00)	0.7 (0.5; 1.0)	0.00 (0.00; 0.01)	0.06 (0.05; 0.09)	0.01 (0.01; 0.02)	0.04 (0.03; 0.06)
	Time S3	0.58 ± 0.07	0.58 ± 0.06	0.98 (0.95; 0.99)	1.4 (1.1; 2.0)	0.01 (0.01; 0.01)	0.15 (0.11; 0.22)	0.01 (0.01; 0.02)	0.04 (0.03; 0.06)
	Time S4	0.57 ± 0.05	0.56 ± 0.05	0.99 (0.97; 0.99)	1.0 (0.7; 1.5)	0.01 (0.00; 0.01)	0.11 (0.08; 0.17)	0.01 (0.01; 0.02)	0.03 (0.02; 0.05)
	Top speed S1	8.64 ± 0.83	8.67 ± 0.85	0.98 (0.95; 0.99)	1.5 (1.1; 2.1)	0.13 (0.10; 0.18)	0.15 (0.11; 0.22)	0.17 (0.12; 0.27)	0.50 (0.37; 0.80)
	Top speed S2	8.62 ± 0.77	8.60 ± 0.76	0.99 (0.99; 1.00)	0.7 (0.5; 1.0)	0.06 (0.05; 0.09)	0.08 (0.06; 0.11)	0.15 (0.11; 0.24)	0.46 (0.33; 0.72)
	Top speed S3	8.64 ± 0.85	8.62 ± 0.82	0.99 (0.98; 1.00)	1.0 (0.8; 1.5)	0.08 (0.06; 0.11)	0.09 (0.07; 0.14)	0.17 (0.13; 0.24)	0.50 (0.38; 0.73)
	Top speed S4	8.77 ± 0.72	8.78 ± 0.70	0.99 (0.98; 1.00)	0.7 (0.5; 1.0)	0.06 (0.04; 0.09)	0.08 (0.06; 0.13)	0.14 (0.11; 0.21)	0.42 (0.32; 0.64)

Definition and description of all outcome variables are presented in Table 1. Max, maximum; Accel, acceleration; Avg, average; ICC, intra-class correlation coefficient; CI, confidence interval; TE, typical error; Stand TE, standardized typical error (light grey, trivial; grey, moderate); SWC, smallest worthwhile change [grey shading identifying magnitude (SWC or MWC) of good or ok change/difference]. S1, session one; S2, session two; S3, session three; S4, session four.

highest CV (test-retest: 8.7; intrasession: 5.4–5.9). In contrast, better relative reliability was observed for 0–5 m time (test-retest: 0.86; intrasession: 0.88–0.97) and absolute reliability (test-retest: 3.7; intrasession: 2.0–3.0). This discrepancy may be attributed to how these variables are defined and quantified, as well as the way participants executed the test. Maximum acceleration is defined as the 0.5-s interval with the highest average acceleration (21), which typically occurs at the very start of the sprint. Due to the assisted load, participants may not have consistently exerted maximum effort during the initial steps, instead requiring some time to regulate their effort and speed based on the assisted load. This inconsistency could explain the lower reliability observed for maximum acceleration. However, range of differences for Max Accel for all eight tests was 0.27 m/s², which is slightly greater than the observed SWC values for both test-retest and intrasession reliability (0.17–0.23 m/s²), making it useful in both scientific and applied settings. Furthermore, the improved reliability for 0–5 m split time and top speed suggests that participants likely self-regulated their speed by the 5 m mark. In addition, both absolute and relative reliability for 0–5 m time is comparable to that of intrasession reliability for resisted sprint with the same load condition (ICC: 0.81; CV: 2.3) (15). Despite the lower reliability of early acceleration metrics, the observed MWC for 0–5 m time (test-retest: 0.07; intrasession: 0.06–0.08) was smaller than the reported changes in 0–5 yard times (0.12 s) following assisted sprint training in NFL prospects (5), indicating that meaningful improvements may still be detected.

The observed lower reliability of acceleration metrics could also be due to the participants as well as the length of the test (40 m). Specifically, the participants were all from team sports and consequently had not been exposed to assisted sprinting with an MRD. The findings might have been different had track and field athletes been included since they might have been more familiar with the type of stimulus. If acceleration is to be targeted is also raises the question if 40 m is the right distance to be used. It might be that shorter distances and more specific cuing on the acceleration phase would be better for team sport athletes. In the current study the only cue used was to complete the sprint as fast as possible. Since it was 40 m, it could be that team sport athletes were trying different pacing strategies during the acceleration phase. Regardless, reliability of acceleration outcome measurements for both test-retest and intrasession is good, but maybe shorter distances with an emphasis on acceleration should be further explored.

Test-retest reliability data were reported across all four test sessions, which potentially may mask learning effects. Many outcome measurements were included in the current study, but based on how assisted or overspeed sprinting traditionally has been applied one could argue that top speed is an important variable to monitor. This variable is very consistent between sessions with an observed increase of 0.10 m/s from session one to four, which is smaller than TE (0.12 m/s) and SWC (0.15 m/s). Furthermore, time provide an overall impression of performance, which decreased from 5.77 to 5.71 s from session



one to four, which is the same as TE (0.06 s), but smaller than SWC (0.09 s). Lastly, the acceleration metrics (Max Accel and 0–5 m time) had minimal and no changes from session one to four, well below TE and SWC (Table 2). Thus, it appears that at the group level measurements are very consistent between sessions.

Regarding performance outcomes, the top speeds recorded in this study were comparable to or lower than those observed in previous research. Given that both male and female participants were included, the present findings (8.61–8.79 m/s) (Tables 2, 3) are consistent with those reported by van den Tillaar, who observed speeds of 7.98 m/s for females and 9.00 m/s for males using a 3 kg assisted load (9). Conversely, other studies have reported higher running speeds. For instance, Clark and co-authors reported a top speed of 10.9 m/s (20) while Gleadhill and co-authors reported 10.14 m/s (6).

4.1 Limitations and implications for future research

The present study has identified both limitations and avenues for future research. One key limitation is that only a single assisted condition (3 kg) was assessed. Given that various absolute and relative loading conditions (% body mass) have been used in prior studies (10, 20), evaluating the reliability of different assisted loads would have enhanced

the generalizability of the findings. Nevertheless, considering the strong reliability observed for both resisted (15) and assisted sprint measurements in the current study, it appears that MRD-based assessments maintain high reliability across different conditions.

Additionally, while the top speeds recorded in this study among athletes from various ball sports align with findings from some previous studies, they are notably lower than those reported in more elite populations (6, 20). Despite this, the reliability data presented here provide valuable insights for coaches and researchers, particularly in the interpretation of speed measurements. Future studies should explore a broader range of assisted loads and investigate their effects on reliability across different athletic populations to further refine training and performance assessment protocols.

5 Conclusion

Assisted sprint outcome measurements derived from data captured by an MRD are reliable. The analysis revealed predominantly high to extremely high ICC values, along with generally good CV values for both test-retest and intrasection reliability across multiple sessions. These findings of assisted sprint measurements offer coaches and researchers valuable opportunities to further evaluate and optimize assisted sprinting testing and training protocols.

6 Practical applications

Our findings have practical implications for field-based testing and training in assisted sprinting. Building on the previously established validity and reliability of MRD outcome measurements (14–16) the current results offer valuable insights into interpreting performance data, making real-time adjustments during training sessions, and assessing athletes' responses to training programs.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Norwegian School of Sport Sciences. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

OE: Software, Investigation, Resources, Writing – review & editing, Writing – original draft, Formal analysis, Validation, Data curation, Methodology, Visualization, Supervision, Project administration, Conceptualization. FW: Resources, Writing – review & editing, Visualization, Writing – original draft, Formal analysis, Data curation, Project administration, Methodology, Conceptualization, Investigation.

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OE is a shareholder in 1080 Motion AB.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Evolution of documents related to strength training research on competitive swimmers: a bibliometric review

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Background: The purpose of this study is to conduct a bibliometric and scoping review to map the evolution of scientific literature on strength training in competitive swimmers.

Methods: Web of Science database was used considering the time frame between 1980 and 2024. The following terms were used to search documents: “swimmers”, “strength”, and “training”. A total of 460 documents were included for statistical analysis

Results: Until 2000, fewer than 5 manuscripts were published annually, and only after 2011 did the number regularly exceed 20, peaking in 2021 with 43 publications. Among the top 10 authors, 7 are Portuguese, each with at least 7 published papers. A total of 726 institutions were identified, with 29 having published at least 5 studies. The “Universidade da Beira Interior” had the most publications (20), while the “University of Copenhagen” received the most citations (619) with just 3 papers. Sixty countries contributed overall, with 10 publishing at least 20 documents; the United States of America led with 83. The most prominent keywords over time were “sports performance,” “speed,” and “swimming performance.”

Conclusion: These results highlight that bibliometric analysis provides pertinent information, very useful regarding research trends and networks, aiming for future research on the topic of strength in swimmers.

KEYWORDS

research, trends, swimming, scientific literature, academic production

1 Introduction

Swimming is the second most popular sport in the Olympic Games based on the number of athletes (1). The goal in competitive swimming is to cover a given distance in the shortest possible time (2) and these days, due to the increased professionalization of the sport, it has become increasingly difficult for amateur athletes to reach finals or medal positions at the international level (3). As the level of performance has continuously improved, competition results reflect this shift. Sports performance has been enhanced from decade to decade, breaking previous records and reaching previously unreachable performances recently (4, 5).

A podium finish in swimming competitions can be separated by a 100 ms time difference (6), and dry-land performance has been shown to contribute to overall swim performance in different events (7). Human locomotion in water results from the interaction of propelling limbs with the fluid. Swimmers' capacity to move through the water depends on the amount of applied propulsive force and on the drag forces opposed to a forward motion (8). Swimming performance is related to a deterministic model since strength will influence the force, being this determined by kinematics, which in turn is influenced by anthropometrics, which in turn, influences the kinetics (9–12).

Since the early 20th century, there has been discussion over the significance of strength or strength training (ST) for swimming performance. This was linked to Robert Kiphuth, who was probably among the first swimming instructors in the 1920s and 1930s to use dry-land training—training outside of a pool to build the muscles necessary for swimming performance (13). The ST is one method of training that helps athletes improve their muscular force-velocity function and ability to enhance endurance athletes' performance through neuromuscular adaptations, increasing economy and endurance-specific muscle power components (14), increasing the rate at which force is produced, which leads to improved performance (15). Improvements in swimming sprint performance ranging from 1.3% to 4.4% have been documented when dry-land ST is used (16).

To reduce water resistance in short race distances, research has specifically concentrated on the impact of force production and strength on speed enhancement (7). Thus, it is important to carry out programs to promote ST in swimmers and evaluate the programs and their impact on the swimmers' profiles and performance. This demonstrates a steadfast commitment to learning and a noteworthy contribution to literature. Previously, Veiga and Roig (17) pointed out that underwater phases and stroke efficiency are important factors that determine success, which emphasizes the need for ST in swimming. Stronger core, lower, and upper body muscles enable swimmers to exert more force during each stroke's pull phase, increasing stroke efficiency and distance per stroke, according to scientific research (18). In a similar vein, strong leg muscles help produce stronger, quicker kicks, which are essential for sustaining high water velocity (19). Swimmers can improve propulsion and body positioning by overcoming hydrodynamic drag more successfully with both strength and power (20). Furthermore, higher muscular power

improves the swimmer's capacity to maintain high kick frequencies and stroke rates, both of which are essential for sustaining top speed during the sprint (7).

However, when ST is paired with aerobic stimulus, which is frequently used in aquatic sports training, these improvements appear to be adversely damaged (21). Studies to ascertain if ST improves swimming competition performance are scarce (22), while several studies have shown that muscle strength is strongly linked to performance in short- and high-intensity efforts; swimmers with greater strength also performed better over longer distances (21). According to some previous studies, strength plays a crucial part in swimming since it increases a swimmer's ability to generate force against water resistance, which in turn improves their speed and, eventually, their swimming performance (23).

A significant body of study in sprint swimming has surfaced intending to comprehend the critical performance components. Research has specifically examined the impact of force output and strength on speed development to overcome the water resistance in short race distances (24). Dry-land ST effect on performance, however, varies depending on the kind of training and adaptations made in addition to the exercises performed. Low-volume, high-force, or high-velocity resistance training regimens are advised for the best transfer to sprint performance (25).

A methodical approach to evaluating vast amounts of scientific data, bibliometric reviews provide important insights into research topics and future directions (26). By carefully analyzing publication patterns, fundamental contributors, and emerging clusters in the step test literature, they offer a unique perspective. They also identify the nations, journals, institutions, and authors that are most active in each field of study, as well as the current partnerships between authors, institutions, and nations (27). Through the review of abstracts obtained from the analysis of numerous articles from the past to the present, bibliometric studies allow researchers to effectively understand literature (28). Research on swimming competitions can reveal networks of collaboration among scientists, institutions, and countries. As far as we are aware, no bibliometric research has been done on strength training for competitive swimmers; this information is useful in understanding the global scientific collaboration on this subject (29). Therefore, the purpose of this study was to conduct a bibliometric and scoping review to map the evolution of scientific literature on strength training in competitive swimmers.

2 Materials and methods

2.1 Study design

The main objective of the present work was to develop a bibliometric review of the existing literature, which is framed within the Theoretical Studies (30). In addition, due to the evaluation of existing information, it is classified within the studies with retrospective methodology (31). This method allows obtaining more information related to the research topic, as well as understanding the state of the art (32). In the same way, it

allows collecting documents from the same database, as well as filtering and refining the search simply (33). Therefore, the following phases were followed for the elaboration of the present study: (1) selection of the topic, (2) selection of the research method, (3) collection of information, (4) analysis of the information, (5) visualization, and (6) interpretation.

The analysis of scientific production regarding the effect of the ST on swimmers between 1980 and June of 2024 was conducted using bibliometrics as a research technique with the assistance of the Web of Science (WoS) database (34, 35).

2.2 Search strategy

The following terms were used to search documents: “swimmers”, “strength”, and “training”, using the following search equation (“swimmers AND strength AND training”) using the WoS database. Firstly, J.M.G. and V.H.B. carried out the search and selection of the documents. Secondly, if there was any disagreement, M.C.E. and T.F.V. discussed whether the study was valid and reliable to be selected for the bibliometric analysis.

The following inclusion criteria were considered: (1) Published articles (e.g., abstracts, presentations, not considered); (2) Documents related to competitive swimmers; (3) Published in English-language journals; and (4) Articles published up to June 2024. Exclusion criteria were: (i) articles written in languages other than English; (ii) articles lacking information related to competitive swimmers; and (iii) articles not retrieved or not retrieved from WoS. All the documents identified were included in the analysis to analyze the co-authorship of the studies regarding different variables. Finally, a total of 460 documents were included.

2.3 Data extraction

For the selection and extraction of information, the Web of Science (WoS) database was used, since it allows obtaining information related to the title, name of the publication (journal), year, abstract, and/or keywords. For this reason, it is one of the most widely used databases for the development of these works (36, 37). Specifically, those documents indexed in the WoS Core Collection database were considered, a series of documents only indexed in this electronic platform. VOSviewer software was used to carry out the analysis, create, and visualization of the figures aiming to analyze keyword co-occurrence, author collaboration networks and other relevant information (38).

2.4 Data analysis

For the statistical analysis, the most relevant laws of bibliometric reviews were considered (39). To evaluate the exponential growth of the selected documents, Price’s law (40) was used through the calculation of the coefficient R^2 . In this

way, the trend in the increase in the number of documents published concerning the topic was deducted. In addition, two time zones were established to categorize the documents in terms of year of publication: older documents, as the documents published before the median of the sample, which was 2009, and newer manuscripts, for those documents published in or after 2010.

To identify those authors with the largest output of published research documents on the topic, the Lotka analysis (41) was carried out, extracting the H-Index for each author identified in the search (42). All the authors of each study were extracted and analyzed, independently of the position they had in the list of authors consigned in the research document. The H-index was defined as the maximum value of h , such that the given author has published at least h papers that have each been cited at least h times (43). The H-Index was employed to identify those authors with higher potential contribution to the field under scrutiny (44). Additionally, the affiliations of each author were also collected and meta-analyzed to detect organizations with the highest research output on the topic.

In addition, to analyse the keywords most used by the authors in each of the papers ($n = 372$), Zipf’s law was used (45, 46). Finally, for data analysis and visualization, Microsoft Excel (2006 version: Microsoft Corporation, Redmond, WA, USA) and VOSviewer (v.1.6.19 for macOS, Center for Science and Technology Studies, Leiden, The Netherlands) were used. For the creation and visualization of the results, a fragmentation analysis was used (attraction: 3 and repulsion: -3), depending on the theme and the temporality of the results (47).

3 Results

3.1 Evolution of the number of documents

Bearing in mind the number of publications since the beginning in 1980, there is no continuity until 1992, with at least one document published per year until 2024, in which 2021 was the period with the highest number of published studies ($n = 43$), followed by 2020 and 2022, each year with 41 studies (Figure 1).

3.2 Interactions between the authors

Table 1 shows the most prolific authors, seven were identified with a minimum of 10 published manuscripts, with Marinho, D.A., associated with the largest number, with 17. In this line, Figure 2 shows the interactions between the most prolific authors regarding the study’s aims.

3.3 Interactions between the institutions

Table 2 considering the institutions associated with the studies, a total of 726 institutions were identified, with 29 of them with a minimum of five published studies. In this regard, the “Universidade da Beira Interior” is associated with the highest

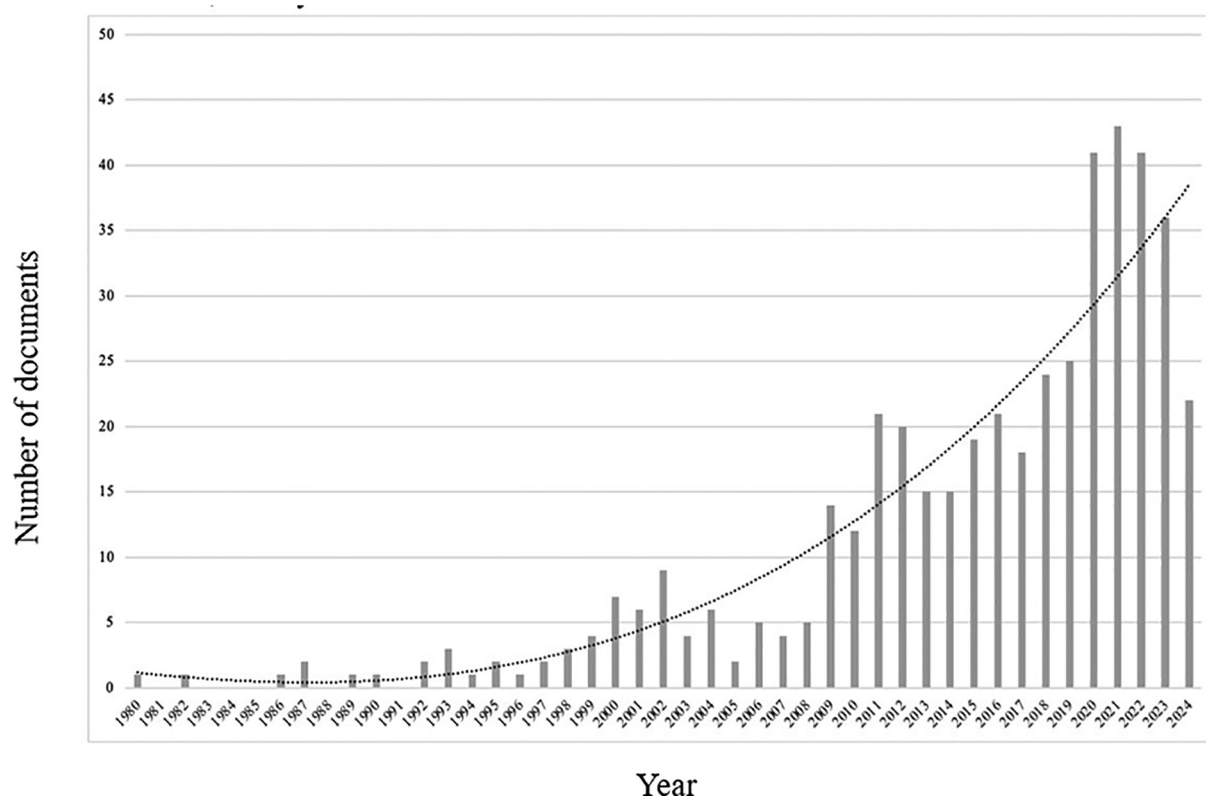


FIGURE 1

Evolution of the number of documents published by year between 1980 and 2024.

TABLE 1 Top 10 authors associated with the publication of manuscripts within the ST topic.

Authors	Documents	% of 460
Marinho, D.A.	17	3.69
Barbosa, T.M.	13	2.82
Silva, A.J.	13	2.82
Pyne, D.B.	12	2.60
Toubekis, A.G.	11	2.39
Arellano, R.	10	2.17
Fernandes, R.J.	10	2.17
Batalha, N.	8	1.73
Costa, M.J.	7	1.52
Marques, M.C.	7	1.52

number of documents ($n = 20$). On the other hand, the “University of Copenhagen” is the organization with the highest number of citations ($n = 619$), with only three documents published. Figure 3 shows the interactions between the most prolific institutions.

3.4 Interactions between countries

Figures 4, 5 show that a total of 60 countries were identified, of which 10 have a minimum of 20 published documents. The United States of America is the country with the highest number of documents ($n = 83$) (Table 3).

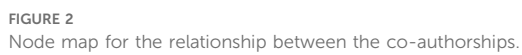
TABLE 2 Most prolific affiliations considering number of publications and citations.

Affiliations	Documents	% of 460	Citations
Universidade da Beira Interior	20	4.34	410
Universidade do Porto	16	3.47	200
University of Granada	16	3.47	184
National Kapodistrian University of Athens	14	3.04	27
University of Trás-os-Montes Alto Douro	14	3.04	333
Instituto Politécnico de Bragança	11	2.39	164
University of Canberra	11	2.39	259
University of Evora	11	2.39	184
University of North Carolina	11	2.39	190
Australian Institute of Sport	10	2.17	282

3.5 Most prolific keywords

A total of 1,019 keywords were identified; this number relates to an average of 2.21 keywords for each document. 110 terms were identified with an occurrence of 3 words, particularly “swimming”, “training”, and “strength” the most prolific keywords with an occurrence of 128, 42, and 36, respectively (Figure 6).

Figure 7 shows the interactions between the most prolific keywords considering the timing of publication. In this case, the most recurrent terms used by the authors are “sports



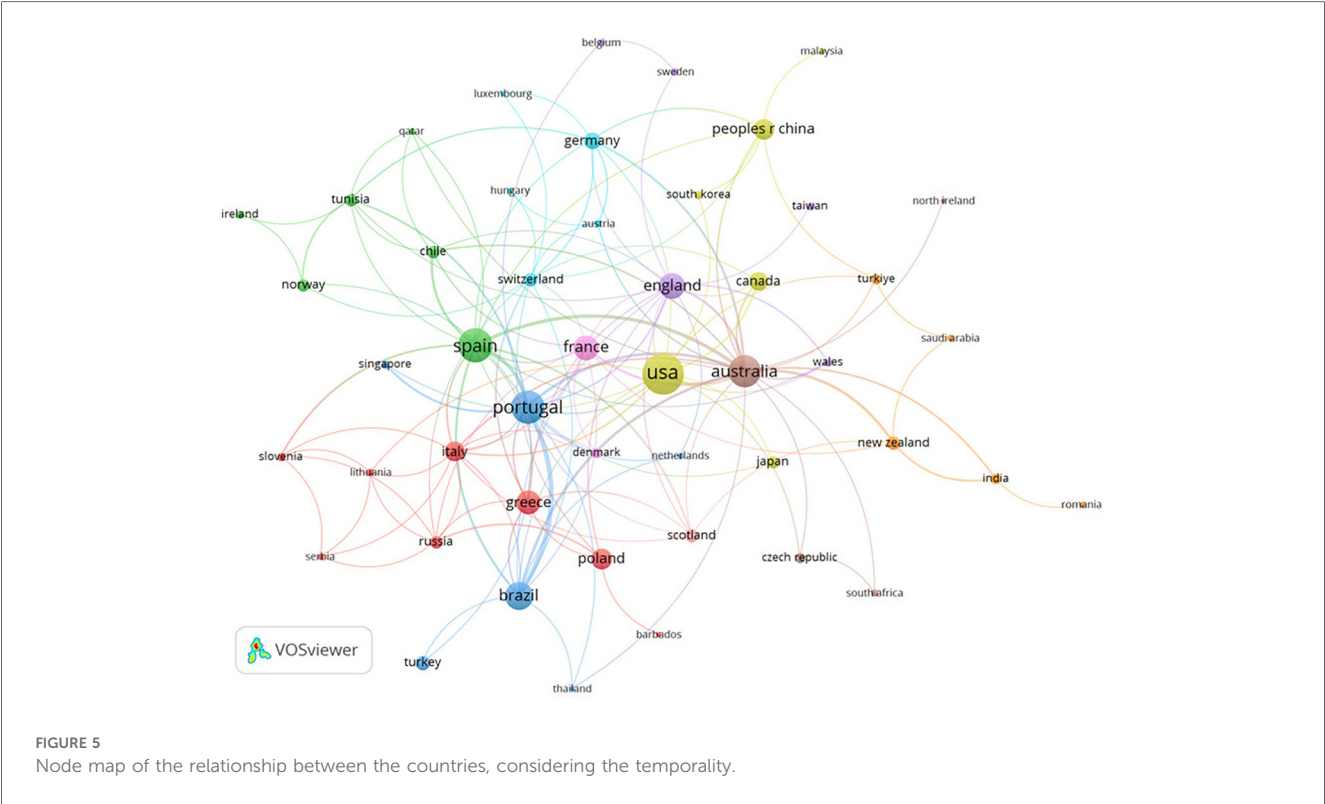
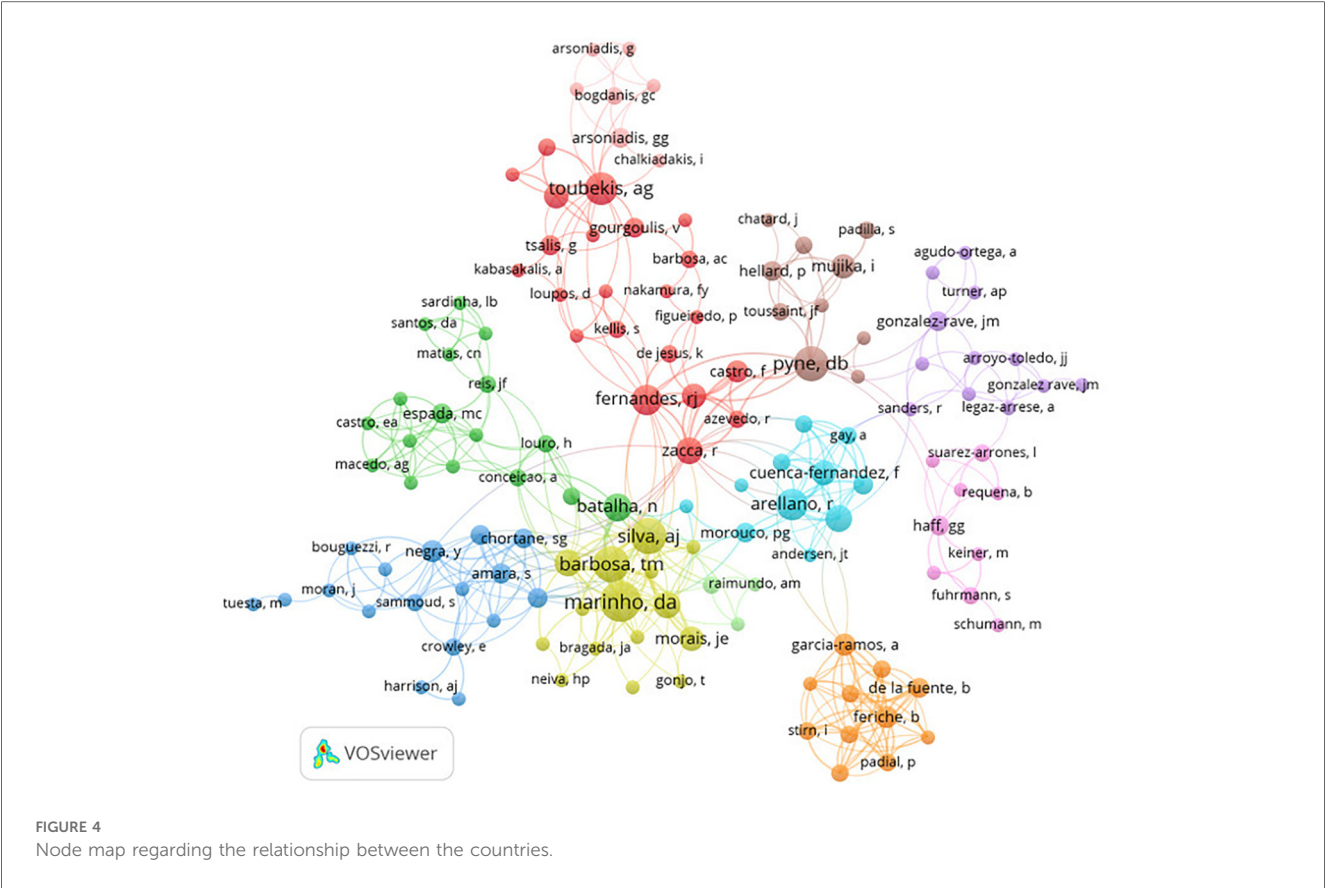


TABLE 3 Countries with more published documents.

Country	Documents	% of 460
United States of America	83	18.04
Spain	57	12.39
Portugal	53	11.52
Australia	50	10.87
Brazil	37	8.04
England	33	7.17
France	29	6.30
Greece	27	5.87
China	20	4.34
Poland	20	4.34

performance”, “speed”, and “swimming performance”. These terms exhibit a change in the scientific paradigm since the lines of research have evolved to the evaluation of swimmers’ performance, considering speed as a determinant variable for a better performance.

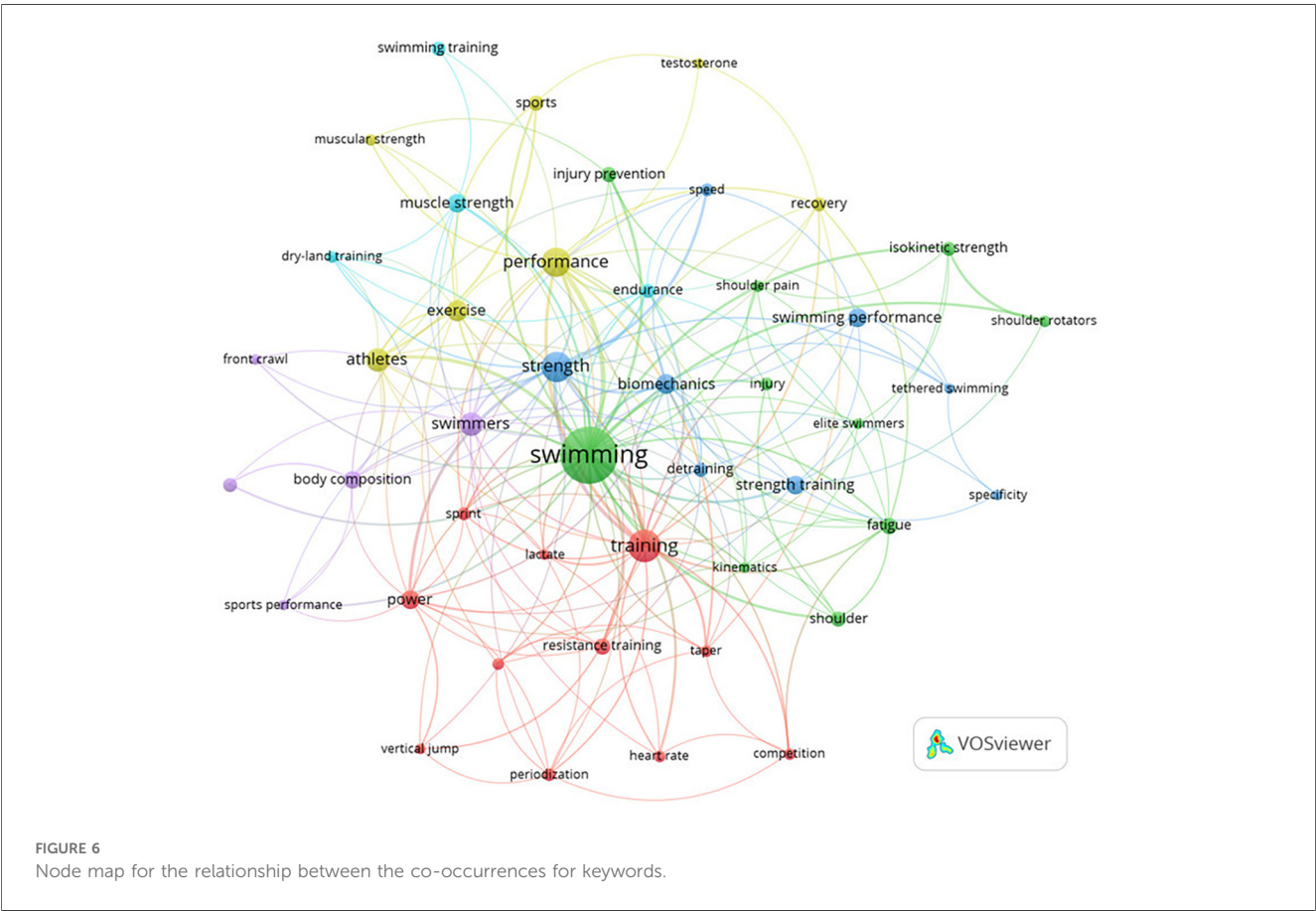
4 Discussion

The purpose of this study was to conduct a bibliometric and scoping review to map the evolution of scientific literature on strength training in competitive swimmers. The primary conclusions of this scoping and bibliometric review show that, particularly after 2010, there was a notable increase in the amount

of research on strength training for competitive swimmers, with a peak in publications in 2021. The University of Beira Interior and the University of Copenhagen were found to have made significant contributions to the field in terms of publications and citations, respectively. A change in the research paradigm toward variables directly related to competitive performance was reflected in the keyword analysis, which showed an evolution in the thematic focus with increasing emphasis on terms like “sports performance,” “speed,” and “swimming efficiency.”

The results showed that the first document was published in 1980. However, there was no regular publication until 1992, which was the first year with at least one document published. We identified Marinho, D.A., associated with 17 publications and “Universidade da Beira Interior” with more citations ($n = 410$), followed by the “University of Trás os Montes Alto Douro” with 333. Nonetheless, the University of Copenhagen possesses the highest citation count ($n = 619$), despite having published only three documents. The United States of America is the country with more published documents ($n = 83$), followed by Spain and Portugal, with 57 and 53, respectively. The keywords “swimming”, “training”, and “strength” were found to be the most prolific keywords.

The ramifications of these classifications in the context of ST in swimming research were examined, extending the classification within the WoS database. The classification sheds light on the study and emphasizes how multidisciplinary the field is, including connections to sports science, physiology, biomechanics, and training techniques (48).



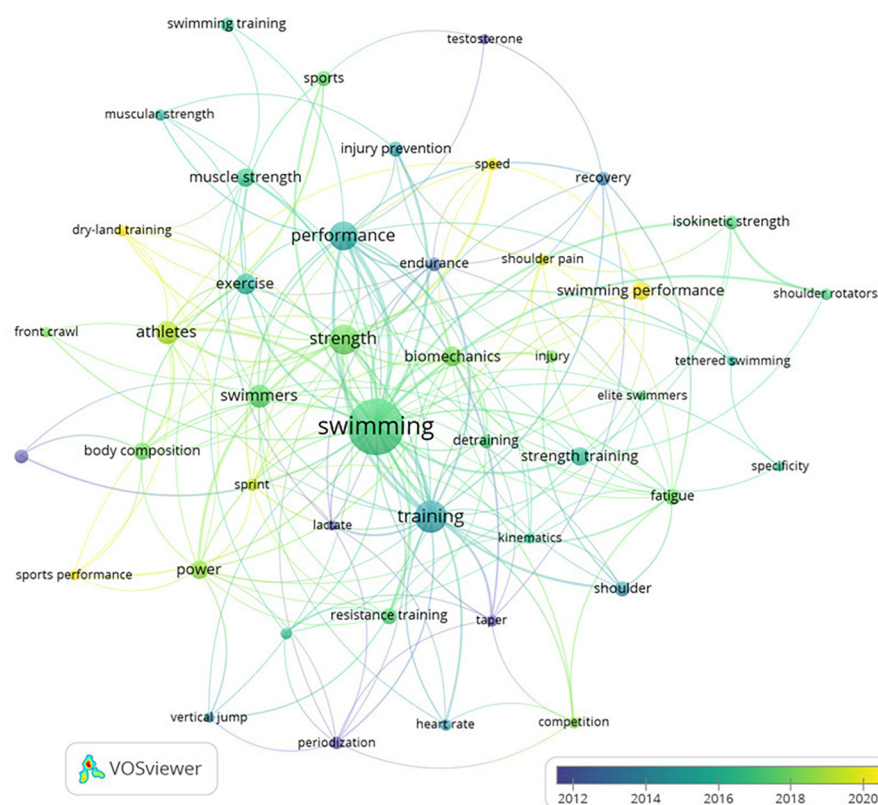


FIGURE 7

Node map for the relationship between the co-occurrences for keywords considering the timing.

When the participating institutions were analysed, 726 were found, indicating a wide research network. The “University of Copenhagen” has the highest number of citations ($n=619$) with just three publications, whereas the “University of Beira Interior” stands out for having the highest number of published documents ($n=20$). The disparity between the quantity of publications and citations seems to indicate that the productions from the University of Copenhagen are of particularly high caliber and influence, and thus, were mainly for long years the focus of citations, with other institutions such as the “University of Beira Interior” or the “University of Trás os Montes Alto Douro” associated to more recent research, years with globally more scientific production, as consequently, a more distributed citation between research. The contacts between the most active institutions are depicted in Figure 3, which shows global cooperation and information sharing important contributors, including researchers from Australia, Spain, Portugal, and Switzerland.

The present results identified 60 countries, which underlines the research topic’s worldwide significance, particularly in the United States of America ($n=83$). This country plays a pivotal role in Sports Science research, as evidenced by its high level of international cooperation (Figure 4). The increasing body of research demonstrates the value of ST for swimmers and the ongoing pursuit of better training methods (Table 3). The main themes of the study are revealed by examining the most popular terms (Figure 6). Based in the findings of this study, in our

perspective, the distinguished factor regarding scientific production in strength training in competitive swimmers is the network between authors and institutions, not the international level of athletes’ or results in international events such as the Olympic Games, in which, countries such as the United States of America, China and Australia have dominated over the years.

A variety of methods and interests within the area are suggested by the discovery of 1,019 keywords, with an average of 2.21 per document, that lead us to observe a range of approaches and interests within the field (48). The chronological history of the keywords (Figure 7) indicates a shift in the scientific perspective. Terms such as “sports performance,” “speed,” and “swimming performance” have gained popularity due to the increased emphasis on assessing swimmers’ performance and the importance of speed as a determining factor. This change in focus can be connected to the creation of more precise measurement instruments (8), and the growing demand for high-performance results in competitive sports, something Morouco et al. (49) previously stated whether ST improves swimming performance and how such training should be planned to maximize performance are not well understood from a scientific standpoint.

The results of the research have significant implications for the training of swimmers. The importance of ST has been recognized, and the advances in performance evaluation methods have allowed for the creation of more customized and effective training programs. Collaboration between academic institutions and

foreign organizations regarding ST in swimming facilitates the sharing of best practices and expertise (50).

These findings demonstrate a maturing understanding of strength training in the context of competitive swimming, in addition to reflecting the rise in scientific output on the topic. The fact that the most productive nations include the USA, Portugal, and Spain indicates that efforts to comprehend the mechanisms underlying elite performance are becoming more widespread. However, the high concentration of inter-institution collaborations suggests that networks of cooperation are crucial to scientific advancement in this field. The increasing emphasis on words like “speed” and “performance” as key terms points to an effort by the scientific community to convert strength training’s benefits into quantifiable and objective gains. This marks a significant shift from studying ST as a stand-alone element to incorporating it into applied and deterministic performance models. Furthermore, the findings highlight the necessity of standardizing procedures to more effectively compare effects across studies and conducting longitudinal research to examine the long-term effects of ST. These results highlight how crucial it is to incorporate strength training into swimmers’ regimens while honoring the unique characteristics of each swimmer and the particulars of the events. As a result, bibliometric analysis offers a strategic roadmap to direct future research, enabling us to pinpoint areas of application, possible partnerships, and gaps that have the biggest effects on sports practice.

In summary, this review is important since it thoroughly examines and compiles the literature showing the substantial impact of ST on swimmers. Additionally, it shows how the scientific community is becoming more interested in this research topic. These results offer direction for further research and targeted interventions meant to persuade all coaches not to fear swimmers’ dry-land training, targeting interventions designed to persuade all coaches that swimmers’ dry-land training is not a source of apprehension and may serve as a crucial factor in enhancing swimming performance. One of the limitations of the study is the selection of keywords, and another, the consideration of only manuscripts written in English. Aiming the correct progress of the study, we selected those words that are closest to the topic, eliminating biases in the results, therefore, ensuring that the studies identified were specifically related to the study topic. Future research may also use different databases, not only WoS and consider different areas closely related to swimming performance.

5 Conclusion

The findings revealed that the initial document was published in 1980. However, there were no regular publications of such documents until 1992, which marked the first year with at least one document published.

The country with the highest number of documents published was the United States of America, with a total of 83. It should be

emphasized that Portuguese authors and institutions are among those who have focused the most on this research topic.

These results highlight that bibliometric analysis provides pertinent information, very useful regarding research trends and networks, aiming for future research on the topic of strength in swimmers.

Author contributions

TV: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. MC: Formal analysis, Visualization, Writing – review & editing. CS: Formal analysis, Supervision, Visualization, Writing – review & editing. NB: Visualization, Writing – review & editing. VH-B: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. JG: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. ME: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effect of different breathing frequencies with breath-holding on muscle activity and coordination during butterfly swimming in national-level female swimmers

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The aim of this study was to clarify the effect of different breathing frequencies with breath-holding on muscle activity and coordination during butterfly swimming in competitive swimmers. Eight national-level female swimmers participated in this study. They performed 25-m maximal butterfly swims with two breathing frequencies (task 1: swimming with the frontal breathing action for every stroke, and task 2: swimming while alternating the cycles with frontal breathing action and with breath-holding). From these tasks, the three different cycles (breathing cycle in task 1, breathing and breath-holding cycles in task 2) were analyzed. Surface electromyography was measured from 12 muscles of the right upper and lower limb, and trunk. A nonnegative factorization algorithm was used for muscle synergy analysis from the electromyographic data. Our results showed the activity timing for Triceps brachii, Deltoideus anterior, Latissimus dorsi, Biceps femoris and Gastrocnemius became earlier in the breath-holding cycle compared to those in the breathing cycle of task 1. However, the activity timing of all the muscles did not change between the breathing and breath-holding cycles of task 2. The number of muscle synergies was the same across the three cycles, except for one swimmer. The muscle combination of all the synergies was very similar across the three cycles. In contrast, the drive timing of the two synergies, which relate to the arm-pull movement and the first and second upward kicks, respectively, became earlier in the breath-holding cycle compared to those in the breathing cycle of task 1, while the drive timing did not change between the breathing and breath-holding cycles of task 2. These results suggest that the temporal characteristics of muscle activity and synergies are more influenced by different breathing frequencies than by frontal breathing action. Therefore, researchers should consider these effects when analyzing muscle activity during butterfly swimming.

KEYWORDS

competitive swimming, performance, motion analysis, electromyography, muscle synergy analysis

1 Introduction

Breathing action is necessary to continue swimming and is one of the basic aquatic skills. In butterfly stroke, competitive swimmers have used two breathing styles (frontal breathing and lateral breathing). Most current swimmers seem to use frontal breathing style, as seen in recent competitions. For example, at the 2024 Paris Olympics, all of the finalists in the men's and women's 100 m and 200 m butterfly events used the frontal breathing style. In frontal breathing style, competitive swimmers lift their head, shoulders, and trunk toward the surface during the late half of underwater arm stroke to inhale (1). This action causes an increase in the angle of body inclination (2); therefore, it has been discussed whether breathing action causes a reduction in performance (1–3). In addition, Seifert et al. (4) reported that the frontal breathing action during butterfly swimming reduced the continuity of arm and leg propulsive actions during sprint paces. Moreover, Barbosa et al. (5) reported that horizontal hand velocity during the out-sweep phase was higher in breath-holding cycles than in cycles with forward breathing, suggesting that propulsive force may be generated earlier in the stroke with breath-holding. These findings support the possibility that breathing reduces swimming speed, while breath-holding increases it. In fact, when observing the breathing frequency during the first 50 m of the men's and women's 100-m butterfly finals at the 2024 Paris Olympics, four swimmers breathed once per stroke, 11 swimmers breathed once every two strokes, and one swimmer breathed twice every three strokes. Accordingly, the typical breathing frequency for many swimmers is once every two strokes (4), and such swimmers perform the swimming movement without breathing action (breath-holding), which has the potential to increase swimming speeds (3), during butterfly stroke races. Nevertheless, it can be observed that some swimmers breathe with each stroke, even at international level.

Surface electromyography (EMG) has been used to assess neuromuscular activity in sports movements and to clarify the mechanisms for achieving the technique in terms of muscle activity and neural control (6). However, a review of swimming EMG studies indicated that none of the studies performed on

swimming focused on the influence of the breathing action on skeletal muscles (7). Therefore, it was unclear how the breathing action affects muscle activity. Furthermore, recent swimming EMG studies have conducted muscle synergy analysis (8–10). This analysis is a method for quantifying motor control by using multi-channel EMG recordings (11). Muscle synergy is defined as the synchronous activation of a group of muscles, and muscle synergy analysis extracts multiple muscle synergies from a movement, revealing the underlying mechanisms of the muscular coordination required to control the movement (9). Previous studies on butterfly swimming have revealed that four muscle synergies were extracted from the movement during butterfly swimming in swimmers with different history of shoulder injury or with different performance levels (8, 9). This result indicates that swimmers perform the butterfly stroke movements using a small number of muscle synergies. However, these results were obtained by analyzing the movements that the swimmers breathed frontally with each cycle. Investigating the effects of breathing action and frequency on muscle activity and coordination would provide clearer evidence to help researchers exclude these effects. Therefore, the aim of this study was to clarify the effect of different breathing frequencies with breath-holding on muscle activity and coordination during butterfly swimming in competitive swimmers. We hypothesized that the intensity of muscle activity increases during the breathing cycle as swimmers need to lift their body to inhale, and that the cooperation between the upper and lower limb muscles in the muscle synergy increases in the breath-holding cycle as the continuity of arm and leg propulsive action improves.

2 Materials and methods

2.1 Participants

Eight female competitive swimmers (age: 19.6 ± 0.7 years, height: 1.61 ± 0.04 m, and body mass: 55.9 ± 4.3 kg, years of experience as a competitive swimmer: 9.6 ± 0.7 years) participated in this study. As differences in swimmer's performance levels affect butterfly stroke movement (12), we decided to include only competitive swimmers classified as Tier 3 (national level) according to the classification of McKay et al. (13). As the exclusion criteria, swimmers who were unable to perform at their best in the butterfly stroke due to an injury or illness were excluded from this study. All participants belonged to a university swimming club and had undergone training on swimming 6,000–10,000 m per day, six days a week. Their specialties included four butterfly, one backstroke, one freestyle, and two individual medley swimmers. All participants preferred to use the frontal breathing style for butterfly swimming. Their average personal best time in the 100 m short-course butterfly was $61.97 (\pm 1.37)$ s, which was $87.3 (\pm 0.19)$ % of the world record. All participants were fully informed of the risks, benefits, and stressors of the study and written informed consent was obtained from all participants. The study was conducted in

Abbreviations

EMG, electromyography; BE, cycle with breathing action every stroke in task 1; BABH, cycle with breathing action after breath-holding cycle in task 2; BH, cycle with breath-holding in task 2; catch, Catch phase of arm stroke; Pull, pull phase of arm stroke; Push, push phase of arm stroke; Recovery, recovery phase of arm stroke; DK-1st, downward kick phase of first kick; UK-1st, upward kick phase of first kick; DK-2nd, downward kick phase of second kick; UK-2nd, upward kick phase of second kick; SR, stroke rate; SL, stroke length; V, swimming velocity; V_{mean} , average swimming velocity; V_{max} , maximum swimming velocity; V_{min} , minimum swimming velocity; dV, intra-cycle variation in swimming velocity; BB, biceps brachii; TB, triceps brachii; DA, deltoideus anterior; DP, deltoideus posterior; PM, pectoralis major; LD, latissimus dorsi; RA, rectus abdominis; ES, erector spinae; RF, rectus femoris; BF, biceps femoris; TA, tibialis anterior; GAS, gastrocnemius medialis; MVC, maximum voluntary contraction; aEMG, averages of normalized electromyography; NMF, non-negative matrix factorization; E, initial matrix; W, weight coefficient or loading of muscle synergy; C, basic temporal component of muscle synergy; VAF, variance accounted for; SP, scalar product; r , correlation coefficient; r_{max} , maximum correlation coefficient; ANOVA, analysis of variance; η^2 , eta squared.

accordance with the Declaration of Helsinki and approved by the University Research Ethics Committee (2021-4).

2.2 Swim trials

The experiment was conducted in a 25-m indoor pool that had a water depth of 1.35 m and a water temperature of 28 degrees Celsius. The participants performed a self-determined warm-up for 30 min before the swim trials. After the warm-up, they performed 25-m butterfly swims with two breathing frequencies: (1) swimming with the breathing action for every stroke and (2) swimming while alternating the cycles with and without breathing. The selection of these tasks was based on the description in a previous study by Seifert et al. (4) that typical swimmers breathe once every two arm strokes or once per stroke. For these tasks, participants were instructed to breathe using a frontal style and to accelerate from the push-off start in order to cover 12.5 m, followed by a maximum effort swim from 12.5 to 25 m. The participants performed these trials twice in random order, with a 3-min rest period. The following three cycles were analyzed from a total of four trials: (1) a breathing cycle in task 1 (BE); (2) a breathing cycle in task 2 (BABH); and (3) a breath-holding cycle in task 2 (BH).

2.3 Kinematic analysis

The sagittal movements during the trials were recorded at a sampling rate of 60 Hz using a synchronous above-water and underwater video-recording system (Figure 1a). This system was placed at 17.5 m from the start wall and recorded the video ranging from 12.5 to 22.5 m. As a body landmark, an LED marker was attached to the greater trochanter of the femur (hip) of each swimmer. The hip coordinates were digitized using a motion analysis software (Tracker, Open-Source-Physics), and the digitised coordinates were converted into global coordinates using the 2D-DLT method.

In this study, one stroke cycle was defined as the period from the right-hand entry to the next-hand entry. The arm stroke and leg kick movements were divided into four phases, as shown in Figure 1b, based on the definitions provided by Chollet et al. (14). The stroke rate (SR, cycles/min), stroke length (SL, m/cycle), and relative duration (%) of the arm and leg phases were calculated from the video and hip coordinates. Swimming velocity (V , m/s) was defined as the horizontal hip velocity, and the mean, maximum, and minimum swimming velocities (V_{mean} , V_{max} , and V_{min} , respectively) were calculated from the hip coordinates. The intra-cycle variation in swimming velocity (dV) was calculated using Equation 1:

$$dV (\%) = \frac{\sqrt{\sum_i (V_i - V_{\text{mean}})^2 F_i / n}}{\sum_i V_i F_i / n} \times 100 \quad (1)$$

where V_i represents the instant swimming velocity, F_i represents the absolute frequency, and n represents the number of observations. This parameter is related to the energy cost of butterfly swimming (15). The averages of these parameters from the data of 2–4 cycles were used for statistical analysis.

2.4 EMG analysis

Surface EMG was measured using a wireless system with a data logger (BioLog System, S&ME Inc., Japan) at a sampling rate of 1,000 Hz. EMG signals were collected using dry electrodes with an interelectrode distance of 0.02 m. The measured muscles were the following twelve muscles: Biceps brachii (BB), triceps brachii (TB), anterior deltoid (DA), posterior deltoid (DP), pectoralis major (PM), latissimus dorsi (LD), rectus abdominis (RA), erector spinae (ES), rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and medial head of gastrocnemius (GAS). The electrode locations were determined according to Yamakawa et al. (9), as shown in Table 1. Before the electrodes were fixed, the skin surface was shaved, abraded, and cleaned with alcohol.

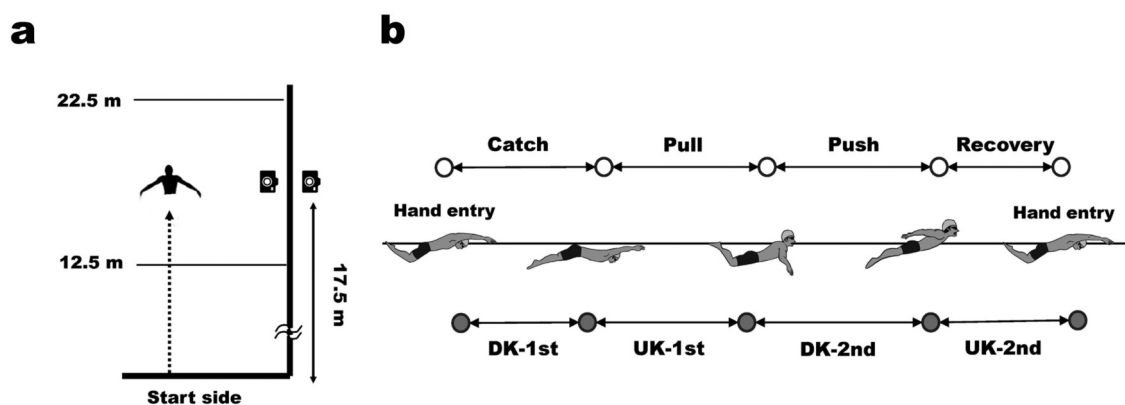


FIGURE 1
Experimental setting (a) and definition of arm stroke and leg kick phases in butterfly swimming (b).

TABLE 1 Muscle abbreviations and electrode placement.

Muscle name	Electrode placement
Biceps brachii (BB)	On the line between the medial acromion and the fossa cubiti at 1/3 from the fossa cubiti
Triceps brachii (TB)	50% on the line between the posterior crista of the acromion and the olecranon at 2 finger widths medial to the line
Deltoides anterior (DA)	One finger width distal and anterior to the acromion
Deltoides posterior (DP)	Center the electrodes in the area about two finger breaths behind the angle of the acromion
Pectoralis major (PM)	2 cm below the clavicle, precisely medial to the axillary fold
Latissimus dorsi (LD)	The oblique angle over the LD muscle, approximately 4 cm below the inferior tip of the scapula and midway between the spine and lateral edge of the torso
Rectus abdominis (RA)	3 cm lateral to the umbilicus
Erector spinae (ES)	Two finger width laterals from the proc. spin. of L1
Rectus femoris (RF)	50% on the line from the anterior spina iliac superior to the superior part of the patella
Biceps femoris (BF)	50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia
Tibialis anterior (TA)	1/3 on the line between the tip of the fibula and the tip of the medial malleolus
Gastrocnemius medialis (GAS)	On the most prominent bulge of the muscle

The placements of electrodes were determined according to the SENIAM project (<http://www.seniam.org>) and as described in a previous study (9).

According to the methodology of Kobayashi et al. (16), The attached EMG sensors were waterproofed by covering them with water-resistant tape.

Using the MATLAB software (version R2023b, MathWorks Inc.), the raw EMG data were filtered using a bandpass filter between 20 and 500 Hz. The filtered EMG data were rectified and then passed through a low-pass filter (12-Hz, fourth-order Butterworth) to derive the EMG envelopes. The EMG envelopes were interpolated to 101 percentiles for time normalization, and the mean ensemble curves were created using the data of 2–4 cycles. The EMG amplitude was normalized by the peak values during the 5-s exercises of the maximum voluntary isometric contraction (MVC) which was conducted after the swim trials. The averages of the normalized EMG (aEMG) during the stroke cycle were calculated for statistical analysis.

2.5 Muscle synergy analysis

The average EMG envelopes were used for muscle synergy analysis. The amplitudes were then renormalized to peak values in a cycle (i.e., 0–1), according to previous studies (8–10). Non-negative matrix factorization (NMF) was performed for muscle synergy analysis, and the NMF was implemented using the algorithm described by Lee and Seung (17). In this procedure, the initial matrix of the EMG data (E) was factorized into the following two components: weighting coefficients or loadings (W), which reflect the combination of muscles, and basic temporal components (C), which

correspond to the timing of activation. We performed NMF analysis using Equations 2, 3:

$$E = WC + e \quad (2)$$

$$\min_{\substack{W > 0 \\ C > 0}} \|E - WC\|_{FRO} \quad (3)$$

where E represents the residual error. In Equation 2, E is an $m \times p$ initial matrix (m is the number of muscles, and p is the number of time points), W is an $m \times s$ matrix, (s is the number of synergies), C is an $s \times p$ matrix, and e is an $m \times p$ matrix. Equation 3 indicates that matrix E is minimized in Equation 2. The analysis was repeated for each participant, varying the number of synergies between 1 and 11 and selecting the lowest number of synergies that satisfied the criteria of variance accounted for (VAF). The VAF (%) was defined as $100 \times$ the coefficient of determination of the uncentered Pearson's correlation coefficient and was calculated using Equation 4:

$$VAF(\%) = \left(1 - \frac{\sum_{i=1}^p \sum_{j=1}^n (e_{ij})^2}{\sum_{i=1}^p \sum_{j=1}^n (E_{ij})^2} \right) \times 100 \quad (4)$$

where $p = 12$, $n = 101$, and i and j are $1 < i < 12$ and $1 < j < 101$, respectively. Referring to a previous study (8, 9), s was calculated as the lowest number of synergies with a VAF of $>90\%$.

The extracted synergies in BABH and BH cycles were sorted based on the scalar product (SP) values and those in BE cycle for each participant. The formula for SP is presented in the following sections. After the sorting within a participant, the extracted synergies in BE cycle were sorted based on the values of SP with that in BE cycle of the arbitrary reference participant.

To identify the main muscles contributing to the synergy, a muscle was considered to contribute highly to the synergy if the mean W was above 0.30, referring to a previous study (9). The SP was used to assess the similarity in W between the different cycles. The SP is equal to the uncentered Pearson's correlation and was calculated using Equation 5:

$$SP = \frac{W_i^A \cdot W_k^B}{\|W_i^A\| \|W_k^B\|} \quad (-1 < SP < 1) \quad (5)$$

where i and k are the i - (k -) th synergies, respectively. According to Matsunaga et al. (18), it was defined that two W were similar if the SP was >0.75 . The similarities of waveform in the individual EMG and C between the different cycles were assessed using the maximum correlation coefficient ($r_{\max}$) and lag time (%) calculated from the cross-correlation analysis. $r_{\max}$ corresponds to the maximum similarity of the waveforms, and the lag time corresponds to the time difference in the muscle or synergy activity. According to Oliveira et al. (19), a $r_{\max}$ above 0.8 was defined as indicating similarity.

2.6 Statistical analysis

A priori power analysis using G*Power software (version 3.1.9.7) indicated that a total sample size of five participants would be required to detect a large effect size [Cohen's $f = 0.73$, referring to the minimum effect size of breathing effect reported by Seifert et al. (4)] in repeated one-way analysis of variance (ANOVA) with three measurements, with an alpha level of 0.05 and power of 0.80. Therefore, the sample size of this study was considered sufficient for the statistical analysis.

Statistical analysis was performed using Jamovi software (version 2.6.13, Open source). The normality of all datasets was checked using the Shapiro–Wilk test. If normality was confirmed in the dataset, the parameter was compared between the different three cycles using repeated one-way ANOVA. Then, a *post-hoc* test was performed using Bonferroni's correction. If normality was not confirmed in the dataset, the parameter was compared using Friedman's test. Then, a *post-hoc* test was performed using Wilcoxon signed-rank test. To evaluate the differences in lag time between the different three cycles, a non-parametric one-sample test (Wilcoxon signed-rank test) with zero as the reference value was performed. All statistical significance levels were set at 5%. In addition, eta-squared (η^2) values were used to present the effect sizes for the repeated one-way ANOVA. The threshold values of η^2 that represented small, medium, and large were 0.01, 0.06, and 0.14 (20). The effect sizes (r) for the Wilcoxon signed-rank test were calculated by dividing the z-score by the square root of the number of participants. The threshold values of the $|r|$ that represented low, medium, and large were 0.1, 0.3, and 0.5 (20).

3 Results

Table 2 lists the results of kinematic parameters in the BE, BABH, and BH cycles. The results of the repeated ANOVA confirmed that there was a main effect in the relative durations

of the push, recovery and DK-1st phases (all $p < 0.05$, $\eta^2 = 0.09$ –0.24). The results of the *post-hoc* tests showed that the push phase in the BH cycle was longer than those in the BE and BABH cycles (both $p < 0.05$) and that the recovery phase in the BH cycle was longer than that in the BE cycle ($p < 0.05$).

Figure 2a shows the mean ensemble EMG curves for the individual muscles. Table 3 lists the results of the $r_{\max}$ and lag time of the individual muscle activity between the two different cycles. The mean $r_{\max}$ was above 0.80 for all the muscles. The results of the one-sample test for the lag time showed that the timing of activity for the DA, LD, RF, BF and GAS in the BABH cycle became earlier than those in the BE cycle (all $p < 0.05$, $r = 0.72$ –0.90) and that the timing of activity for the TB, DA, LD, BF and GAS in the BH cycle became earlier than those in the BE cycle (all $p < 0.05$, $r = 0.72$ –0.84). Figure 2b shows the results of aEMG for the individual muscles in the BE, BABH and BH cycles. From the results of the repeated ANOVA and Friedman's test, it was confirmed that there was no main effect on any of the muscles.

Figure 3 shows the VAF results of the muscle synergy analysis. Based on this result, we determined that the number of synergies in the BE cycle was four for the 7 swimmers and five for the 1 swimmer, that the number in the BABH cycle was four for the 7 swimmers and five for the 1 swimmer and that the number in the BH cycle was three for the 1 swimmer and four for the 6 swimmers and five for the 1 swimmer. Figures 4a,b show the results of W and C for the BE, BABH and BH cycles. The sorted four synergies extracted from all participants were defined as Synergy 1 ($n = 8$), 2 ($n = 8$), 3 ($n = 7$), and 4 ($n = 8$), and the fifth synergy observed from one swimmer was categorized as a subject-specific synergy. In Synergy 1, the main contributors were BB, PM, and RA in the BE cycle; BB, PM, and RA in the BABH cycle; and BB, PM, and RA in the BH cycle. In Synergy 2, the main contributors were TB, DA, DP, and BF in the BE cycle, TB, DA, and DP in the BABH cycle, and DA and DP in the BH cycle. For Synergy 3, the main contributors were RF, and TA in

TABLE 2 Results of the kinematic parameters in the BE, BABH and BH cycles.

Variable, unit	BE	BABH	BH	ANOVA	
				F-value	η^2
V_{mean} , m/s	1.50 ± 0.07	1.52 ± 0.05	1.53 ± 0.07	1.13	0.06
V_{max} , m/s	1.96 ± 0.20	1.96 ± 0.07	2.08 ± 0.14	1.48	0.14
V_{min} , m/s	1.00 ± 0.09	0.99 ± 0.12	1.03 ± 0.10	0.88	0.03
SR, cycle/min	54.4 ± 2.1	55.2 ± 2.1	55.4 ± 2.2	1.63	0.04
SL, m/cycle	1.65 ± 0.08	1.65 ± 0.08	1.65 ± 0.07	0.18	< 0.01
dV (%)	18.1 ± 2.2	17.9 ± 1.6	18.2 ± 1.5	0.10	< 0.01
Catch phase, %	31.1 ± 5.6	30.4 ± 2.4	28.6 ± 4.3	2.57	0.06
Pull phase, %	23.4 ± 3.8	24.1 ± 1.9	22.3 ± 3.1	0.92	0.06
Push phase, %	23.8 ± 2.0	23.2 ± 2.9	25.9 ± 1.7 ^{ab}	17.20*	0.24
Recovery phase, %	21.7 ± 2.2	22.3 ± 1.9	23.1 ± 1.6 ^a	10.50*	0.09
DK-1st phase, %	18.0 ± 2.3	16.0 ± 1.7	17.3 ± 1.7	4.43*	0.17
UK-1st phase, %	28.7 ± 3.4	30.2 ± 3.0	28.7 ± 1.9	2.78	0.06
DK-2nd phase, %	23.5 ± 2.0	23.1 ± 2.1	22.2 ± 2.2	0.65	0.04
UK-2nd phase, %	29.7 ± 2.8	30.7 ± 2.2	31.5 ± 4.1	2.00	0.06

All data presented as Mean ± SD. An asterisk indicates a significant main effect in a repeated ANOVA, $p < 0.05$.

^aMeans a significant difference from BE, $p < 0.05$.

^bMeans a significant difference from BABH, $p < 0.05$.

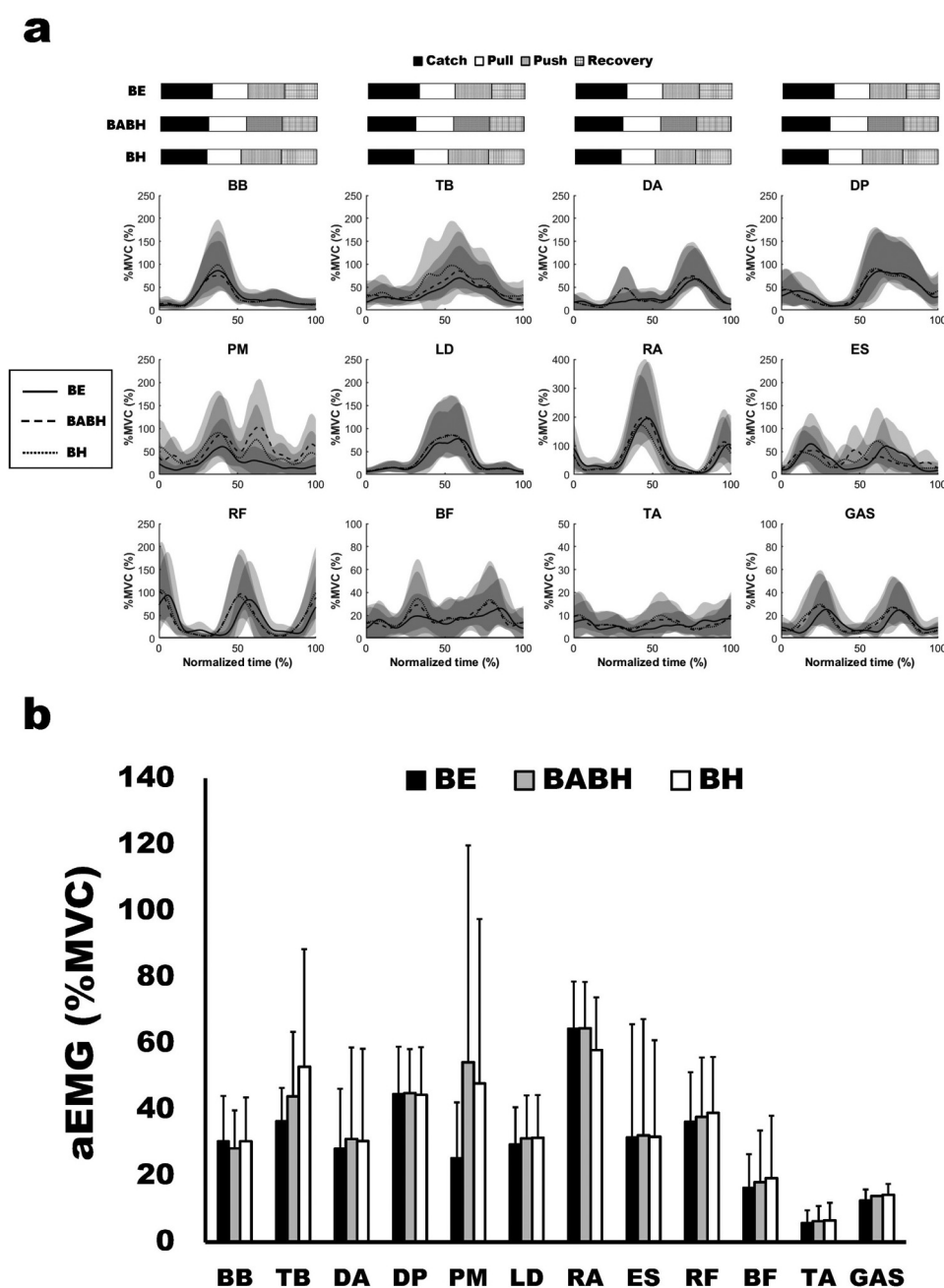


FIGURE 2

Mean ensemble curves of the normalized EMG for the individual muscles (a) and results of aEMG (b). In (a), the solid lines show the results in the BE cycle, the dash lines show the results in the BABH cycle, and the dotted lines show the results in the BH cycle. The horizontal bar graphs show the timing of the average arm stroke phases in each cycle. In (b), the black bars show the results in the BE cycle, the gray bars show the results in the BABH cycle, and the white bars show the results in the BH cycle.

the BE cycle; RF and TA in the BABH cycle; and RF and TA in the BH cycle. In Synergy 4, the main contributors were BF and GAS in the BE cycle, BF, and GAS in the BABH cycle, and ES, BF, and GAS in the BH cycle. Table 4 lists the SP results of W for the five synergies. Table 5 lists the results of $r_{\max}$ and lag time for C in the five synergies. The results of the one-sample test for the lag time showed that the drive timing of Synergy 1 and 4 in the BH cycle became earlier than those in the BE cycle (both $p = 0.03$, both $r = 0.78$).

4 Discussion

This study aimed to clarify the effect of different breathing frequencies with breath-holding on muscle activity and coordination during butterfly swimming in competitive swimmers. The main findings revealed that the activity timing for some muscles became earlier in the BABH and BH cycles than in the BE cycle and that the drive timing for two muscle synergies became earlier in the BH cycle than in the BE cycle.

TABLE 3 Results of the waveform similarity ($r_{\max}$) and lag time for the individual EMG curves.

Variable, unit	BE vs. BABH	BE vs. BH	BABH vs. BH
$r_{\max}$			
BB	0.98 ± 0.03	0.98 ± 0.02	0.99 ± 0.01
TB	0.97 ± 0.02	0.97 ± 0.03	0.97 ± 0.03
DA	0.93 ± 0.08	0.97 ± 0.03	0.99 ± 0.01
DP	0.97 ± 0.03	0.97 ± 0.03	0.98 ± 0.01
PM	0.92 ± 0.08	0.93 ± 0.11	0.97 ± 0.04
LD	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01
RA	0.95 ± 0.06	0.97 ± 0.02	0.97 ± 0.02
ES	0.97 ± 0.07	0.96 ± 0.06	0.96 ± 0.04
RF	0.91 ± 0.09	0.94 ± 0.04	0.96 ± 0.02
BF	0.96 ± 0.04	0.96 ± 0.02	0.96 ± 0.02
TA	0.92 ± 0.09	0.96 ± 0.03	0.96 ± 0.02
GAS	0.93 ± 0.11	0.97 ± 0.02	0.98 ± 0.02
Lag time, %			
BB	1.3 ± 1.8	1.8 ± 2.9	0.4 ± 2.6
TB	0.4 ± 0.5	1.4 ± 2.3*	0.5 ± 1.5
DA	2.4 ± 1.3*	2.3 ± 1.5*	−0.1 ± 0.4
DP	1.6 ± 2.6	1.1 ± 2.5	−0.4 ± 1.5
PM	0.9 ± 4.1	1.9 ± 3.1	0.8 ± 1.5
LD	2.8 ± 3.5*	2.5 ± 3.7*	−0.3 ± 0.7
RA	−3.0 ± 10.1	−2.9 ± 10.3	0.5 ± 1.7
ES	−1.1 ± 7.4	−1.4 ± 7.3	−2.1 ± 5.4
RF	5.0 ± 7.8*	5.1 ± 7.9	0.3 ± 0.7
BF	2.6 ± 2.7*	3.1 ± 3.1*	0.6 ± 1.2
TA	4.5 ± 10.1	4.9 ± 10.0	0.4 ± 0.7
GAS	6.4 ± 8.7*	7.4 ± 8.5*	0.8 ± 1.6

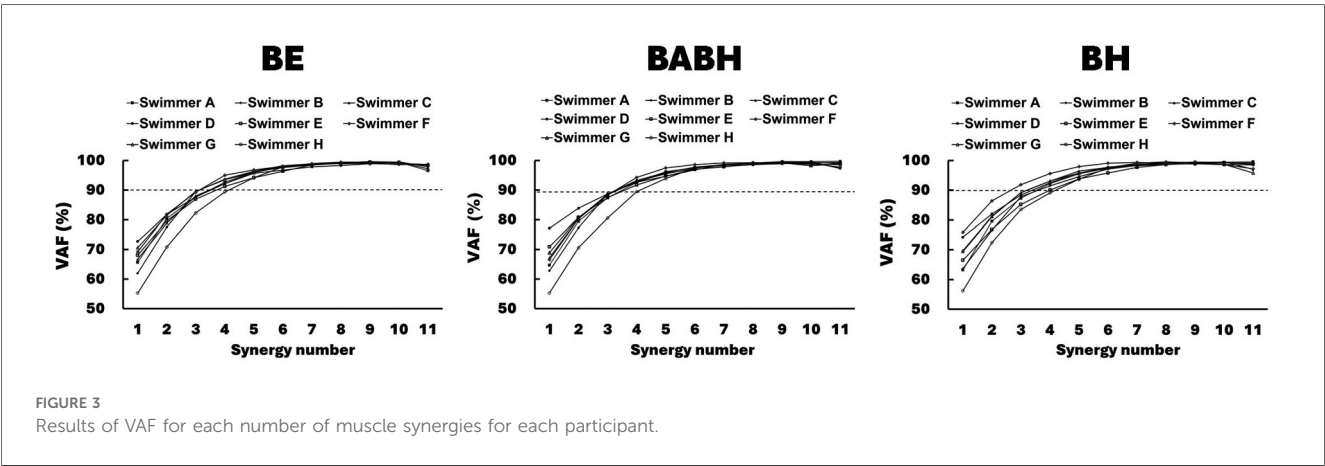
All data presented as Mean ± SD. A negative value for lag indicates a backward shift compared to BE cycle or BABH cycle. An asterisk indicates a significant difference from zero, $p < 0.05$.

These results suggest that muscle activity and synergies during butterfly swimming are affected by breathing action and different breathing frequencies.

The kinematic results showed that V_{mean} , V_{max} , V_{min} , SR, SL and dV did not change between the three different cycles (Table 2). Therefore, it was suggested that our participants maintained their performance while performing breathing actions and different breathing frequencies. However, there was a large effect size in the result in V_{max} and the average V_{max} in the BH cycle was higher than that in the BE and BABH cycles (Table 2). Some studies have

indicated that butterfly swimming without breathing may have a higher performance than swimming with breathing action (1, 3–5). Hence, it was considered that the butterfly stroke movement with breath-holding improved the maximum swimming velocity for some swimmers. Furthermore, the push and recovery phases became longer in the BH cycle (Table 2). Overall, the changes in the phase structure of arm stroke related to the BH cycle seemed to reduce the time gap between the start of the arm stroke and the start of the first upward kick and to increase the time gap between the start of the arm recovery and the start of the second upward kick. These changes between the breathing and breath-holding cycles were consistent with the results of a previous study (4). In addition, it was observed that the DK-1st phase exhibited a tendency to decrease in the BABH cycle compared to other cycles (Table 2). From this result, it was suggested that different breathing frequencies cause slight changes in the phase structure of leg movement.

Some studies on butterfly swimming have reported the activity patterns of individual muscles of the upper limb, trunk, and lower limb during a cycle (9, 21–23). Our results for the activity patterns of individual muscles are similar to those of previous studies. The timing of activity for TB, DA, LD, BF, and GAS became earlier in the BH cycle than in the BE cycle (Table 3). These changes in activity timing correspond well with the changes in the arm phase structure between the BE and BH cycles. Interestingly, the activity timing for DA, LD, RF, BF and GAS also became earlier in the BABH cycle than in the BE cycle (Table 3) while the activity timing for all the muscle did not change between the BABH and BH cycles. Therefore, it was suggested that different breathing frequencies may change the activity timing for some muscles. The aEMG for all muscles did not change between the three different cycles (Figure 2b). From this result, it was suggested that the intensity of activity for all the muscles analyzed in this study remained across the different breathing frequencies or with and without frontal breathing action, and one of our hypotheses was not approved. Alves et al. (3) indicated that elite swimmers could reduce unnecessary movements of the trunk and lower limbs during frontal breathing action. Therefore, it was considered that the muscle activity did not increase by the frontal breathing action because our participants were national-level competitive swimmers.



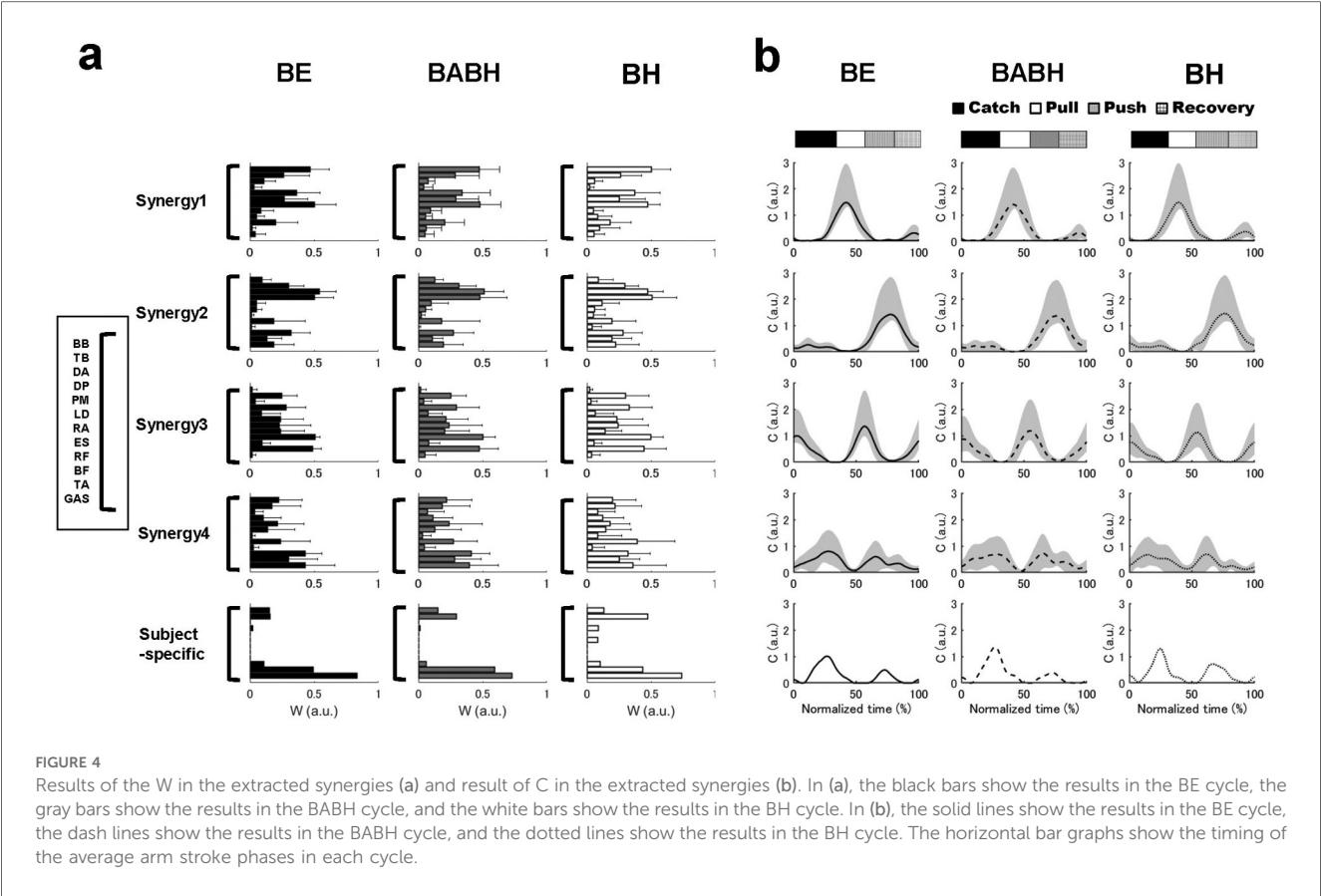


FIGURE 4 Results of the *W* in the extracted synergies (a) and result of *C* in the extracted synergies (b). In (a), the black bars show the results in the BE cycle, the gray bars show the results in the BABH cycle, and the white bars show the results in the BH cycle. In (b), the solid lines show the results in the BE cycle, the dash lines show the results in the BABH cycle, and the dotted lines show the results in the BH cycle. The horizontal bar graphs show the timing of the average arm stroke phases in each cycle.

TABLE 4 Results of the SP for the *W* of the extracted muscle synergies.

Synergy name	SP (<i>r</i>)		
	BE vs. BABH	BE vs. BH	BABH vs. BH
Synergy1	0.97 ± 0.03	0.94 ± 0.04	0.93 ± 0.04
Synergy2	0.97 ± 0.04	0.90 ± 0.09	0.92 ± 0.13
Synergy3	0.97 ± 0.02	0.94 ± 0.06	0.95 ± 0.07
Synergy4	0.96 ± 0.05	0.86 ± 0.18	0.79 ± 0.29
Subject-specific	0.98	0.94	0.96

All data presented as Mean ± SD.

The *W* values of all synergies had high similarity between the three different cycles (Table 4). From this result, it was suggested that our participants achieved the same synergy-based movement across the three different cycles, and our hypothesis was not supported. Yamakawa et al. (9) reported that less-skilled swimmers coordinated their arm-catch and arm-push movements with their downward kicks to prevent the lower limb from sinking in response to the arm-catching movement or the breathing action, whereas skilled swimmers did not. In addition, elite swimmers are able to perform breathing movements without compromising their swimming speed (3). Therefore, it has been speculated that our participants achieved both movements with and without the breathing action using the same muscle synergies to effectively perform propulsive action. In contrast, the results of the *C* showed that the drive timing of Synergies 1 and 4 in the BH cycle became earlier than in the BE cycle (Table 5), suggesting that our

TABLE 5 Results of the waveform similarity (*r*_{max}) and lag time for the *C* of the muscle synergies.

Variable, unit	BE vs. BABH	BE vs. BH	BABH vs. BH
<i>r</i> _{max}			
Synergy 1	0.98 ± 0.02	0.97 ± 0.02	0.98 ± 0.02
Synergy 2	0.98 ± 0.03	0.97 ± 0.01	0.98 ± 0.01
Synergy 3	0.98 ± 0.01	0.95 ± 0.02	0.95 ± 0.04
Synergy 4	0.94 ± 0.11	0.92 ± 0.09	0.95 ± 0.04
Subject-specific	0.98	0.95	0.94
Lag time, %			
Synergy 1	1.0 ± 2.1	2.5 ± 2.4*	1.6 ± 2.7
Synergy 2	0.8 ± 0.9	0.8 ± 1.5	−0.1 ± 2.2
Synergy 3	0.3 ± 1.0	0.7 ± 1.0	0.4 ± 1.3
Synergy 4	0.3 ± 2.3	6.1 ± 8.5*	3.1 ± 7.1
Subject-specific	0.0	2.0	2.0

All data presented as Mean ± SD. A negative value for lag indicates a backward shift compared to the slower trial. An asterisk indicates a significant difference from zero, *p* < 0.05.

participants changed the temporal component of the synergies between the BH and BE cycles. Based on the values of *W* and *C* for Synergies 1 and 4, we judged that Synergy 1 is a synergy acting on the arm-pull movement and Synergy 4 is a synergy acting on the first and second upward kicks. The changes in the temporal component for Synergies 1 and 4 corresponded well with the changes in the activity timing of some muscles and the changes in the arm phase structure. Barbosa et al. (5) reported that during the out-sweep phase of the breath-holding cycle the

horizontal hand velocity was higher and the vertical displacement of the hands was smaller than those in the cycles with frontal breathing action, and they concluded that propulsive force may be generated earlier in the stroke during non-breathing phases. Therefore, it was considered that the changes in the temporal components of these synergies caused the changes in the activity timing of some muscles, resulting in moving arm and leg movements earlier. Furthermore, the results of the C showed that the drive timing of all synergies was consistent between the BABH and BH cycles. From these results, it was speculated that changes in the temporal components of the muscle synergy observed in this study were more influenced by different breathing frequencies than by breathing action. Therefore, researchers should consider the effect of different breathing frequencies when analyzing muscle activity or muscle synergy during butterfly swimming.

In terms of practical implications, our results emphasize the importance of learning the timing of arm and leg movements to achieve better breathing action. The neural basis of muscle synergy related to W and C has been elucidated in recent neurophysiological studies. In a review of the neural basis of muscle synergies (24), it indicated that the organizing (i.e., W) and driving (i.e., C) of the muscle synergies may originate from neurons at different levels that may be anatomically localized to different regions of the central nervous system. Accordingly, the different temporal characteristics of muscle synergies may promote different motor learning in the central nervous system region associated with driving C. Therefore, we recommend that athletes should train with the same breathing pattern that they will use during the race. Furthermore, one swimmer, who reduced the number of muscle synergies in the BH cycle, had the largest difference in the V_{mean} between the BE and BH cycles, and it was observed that this swimmer increased the cooperation between the upper and lower limb muscles in the BH cycle from the results of the W in Synergy 1 and 2. As in this case, there is a possibility that motor control will change dramatically in some swimmers whose performance has changed significantly between the breathing and non-breathing cycles. Thus, muscle synergy analysis can be useful for assessing changes in motor control during different swimming movements.

This study has some limitations. As this study did not measure neck muscle activity because these muscles are not directly involved in generating propulsion, it was possible that there were changes in muscle activity and muscle synergy associated with changes in head movements. Future studies should examine the additional muscles involved in this composite technique. We attached a marker and wireless EMG devices to the swimmers' bodies. As the attachment of this experimental equipment affects movement and water resistance (25), the swimming movement during the trials included its effects. All participants of this study were female national-level swimmers. A kinematic study of butterfly swimming (12) reported significant differences in the swimming velocity and arm-to-leg coordination based on sex and skill level. Although a previous study reported that there were no differences between elite-level male and female swimmers, differences in sex and achievement levels may have affected our results. In the experimental tasks of this study, participants were asked to perform butterfly swimming at different

breathing frequencies. Hence, it is possible that they performed the tasks at unfamiliar frequencies. Of the participants, two preferred to breathe once per stroke and six preferred to breathe once every two strokes. Therefore, the familiarity of breathing frequency may have influenced our results. Moreover, participants were also asked to perform butterfly swimming with sprint pace using frontal breathing action. In butterfly swimming, lateral breathing style tends to produce a flatter swimming movement than frontal breathing style (26). At slower swimming speeds, duration of arm catch increases (14), emphasizing undulating movements and eliminating differences in the timing of arm and leg movements between breathing and breath-holding cycles (4). Therefore, the results of this study are only considered applicable to frontal breathing action and sprint pace. Finally, the limitations also included the small sample size, the participants' different stroke specialties, and the different pool conditions compared to those in the competition.

5 Conclusion

In national-level female swimmers, the different breathing frequencies with breath-holding did not affect the butterfly swimming speed, whereas the arm and leg phase structure changed in the breath-holding cycle. The intensity of activity in all the muscles remained consistent throughout the three cycles. The spatial components of all the synergies were very similar across the three different cycles, suggesting that the swimmers achieved the same synergy-based movements in these cycles. In the breath-holding cycle, the activity timing of the five muscles and the drive timing of the two muscle synergies changed earlier compared to the cycle in which the swimmers breathe with each stroke. In contrast, the activity timing for all the muscles and the drive timing for all the muscle synergies did not change between the breathing and breath-holding cycles when swimmers performed cycles alternating between breathing and breath-holding. These results suggest that standardising breathing frequency is more important than considering with and without breathing actions when the researchers analyse the muscle activity during butterfly swimming.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethics committee of Japan Women's College of Physical Education. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

KY: Formal analysis, Visualization, Data curation, Validation, Resources, Project administration, Investigation, Software, Methodology, Funding acquisition, Conceptualization, Writing – original draft. YS: Supervision, Writing – review & editing, Resources. HT: Supervision, Writing – review & editing, Resources.

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The effect of repeated sprints on immunological modulation and the role of fat-free mass, biological maturation and dietary inflammatory index in male athletes: a quasi-experimental study with insights for training loads control

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Background: Repeated sprint exercise (RSE) induces inflammation, which may be modulated by fat-free mass (FFM), biological maturation (BM), and dietary patterns, assessed by the Dietary Inflammatory Index (DII).

Aim: To examine the influences of FFM, BM, and DII on cytokine responses to RSE in male athletes.

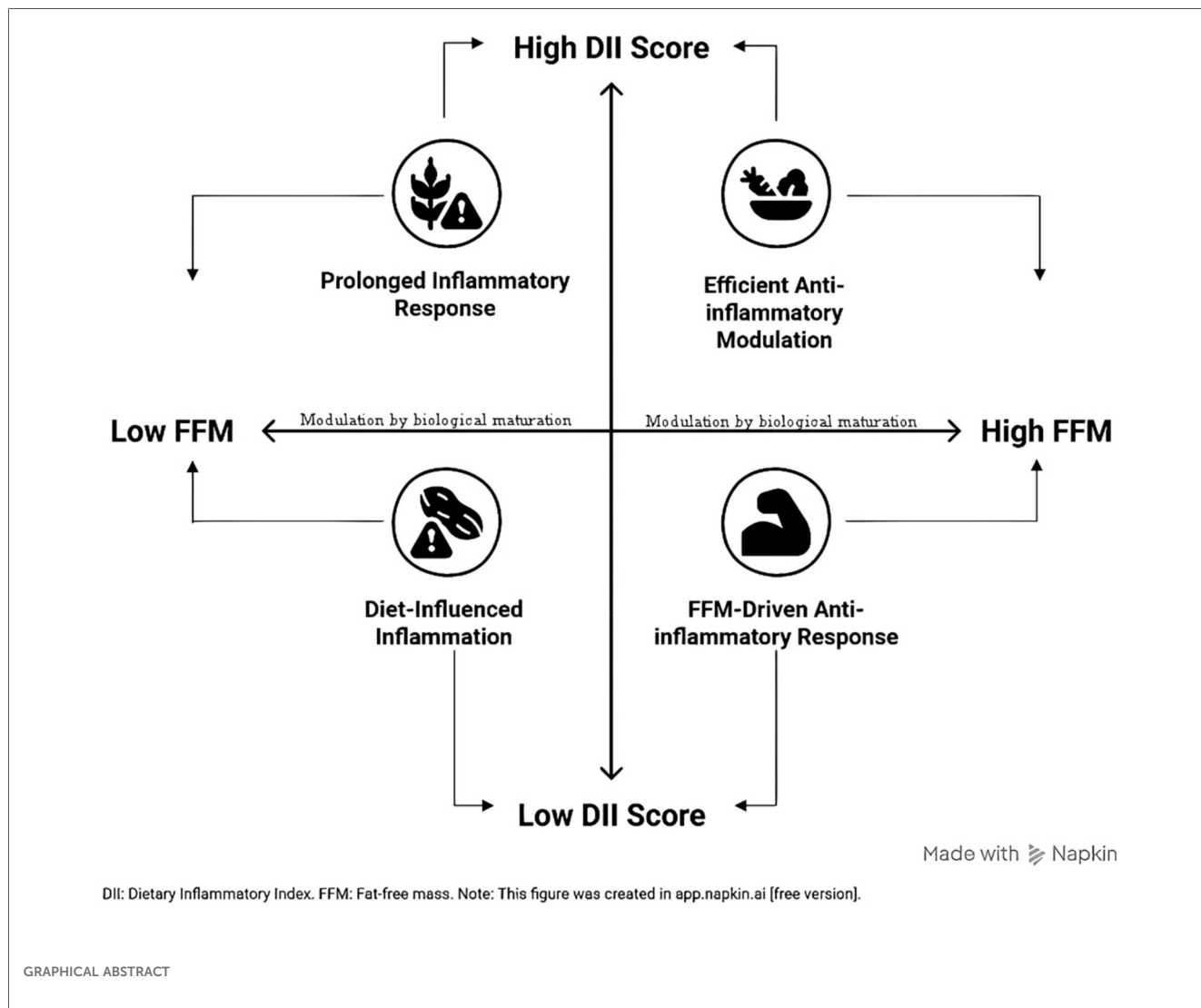
Methods: A study with a quasi-experimental approach and cross-sectional design with a sample of 30 male athletes (20-adolescents, 10-adults). Blood samples were collected pre-, immediately after, 2 h and 24 h after RSE (3-sets of 6 × 35-m sprints). IL-1 β , IL-6, IL-8, and IL-10 were analyzed via flow cytometry. FFM was assessed by DXA, BM by predictive models, and DII by 24 h dietary recalls. Prior exploratory analyses included Spearman's and partial correlations, and Mann-Whitney-U-tests. Main analyses were conducted using Generalized-Linear-Mixed-Models (GLMM).

Results: The GLMMs confirmed that BM, FFM, and DII significantly influenced cytokine responses ($p < 0.05$). FFM emerged as a significant predictor of IL-1 β ($p = 0.0023$). For IL-6, there was a time effect ($p < 0.001$) and a Time $\times$ BM interaction ($p = 0.040$), with FFM and DII being significant predictors in both groups. A similar interaction was observed for IL-8 ($p = 0.036$). For IL-10, there was a Time $\times$ BM interaction ($p < 0.001$), where adults showed superiority over adolescents ($p < 0.05$). *Post hoc* analyses revealed that adolescents with lower FFM had a more prolonged inflammatory response (increased-IL-6), while adults with higher FFM demonstrated a more effective anti-inflammatory capacity (increased-IL-10).

Conclusion: FFM, BM, and DII play key roles in shaping the inflammatory response to RSE and should be considered when prescribing training loads to optimize recovery and performance.

KEYWORDS

cytokines, inflammation, high-intensity exercise, sport, diet



Highlights

- Fat-free mass (FFM) and Dietary Inflammatory Index (DII) are significant predictors of post-exercise cytokine responses. FFM influences both pro-inflammatory (IL-6 & IL-8) and anti-inflammatory (IL-10) responses, while DII is associated with a more efficient modulation of the immune response.

Abbreviations

RSE, repeated sprint exercise; BM, biological maturation; PHV, peak height velocity; IPAQ, international physical active questionnaire; MET^s, metabolic equivalents; RPE, rate of perceived exertion; URTI, upper respiratory tract infection; WURSS-21, Wisconsin upper respiratory symptom survey-21; DXA, dual-energy x-ray absorptiometry; Δ, delta coefficient; DII, dietary inflammatory index; FFM, fat-free mass.

- Biological maturation is a key determinant of the immune response to exercise. Less mature athletes (adolescents with lower FFM) exhibit a more prolonged inflammatory response, whereas more mature athletes (adults with higher FFM) demonstrate a more effective and acute anti-inflammatory capacity.

Introduction

Fat-free mass (FFM), particularly, the skeletal muscle tissue plays an essential role in immunoinflammatory regulation through the expression of myokines. In fact, the muscle is considered an endocrine organ due to an increased release of

such myokines as interleukin-6 (IL-6) and interleukin-10 (IL-10) (1), also known as exerkines, in response to mechanical and metabolic stress induced by high-intensity exercises (2, 3). IL-6 is involved in metabolic adaptations and contribute to inflammatory processes, while IL-10 essentially exerts an anti-inflammatory function that supports muscle recover (4, 5).

Athletes involved in intermittent sports, such as soccer, basketball, and handball, are frequently exposed to repeated high-intensity efforts interspersed with brief recovery periods (6, 7). This type of physical demand elicits substantial metabolic and mechanical stress, which in turn activates immune and inflammatory pathways, including the release of myokines (8, 9). Previously, it was evidenced that the sport discipline (jiu-jitsu, soccer, and volleyball) did not exert a significant influence on the immune responses derived from repeated sprint exercise (RSE) in adolescent athletes of intermittent sports, suggesting that the physiological demands at the immunological level are similar across different intermittent sports (10).

These athletes are particularly susceptible to acute and chronic inflammatory responses due to the cyclical nature of training and competition, which may influence performance, recovery, and injury risk (9). Understanding the inflammatory milieu in this context is critical, especially because the regulation of pro- and anti-inflammatory cytokines can impact the balance between adaptation and overtraining (11).

The RSE is a high intensity short training strategy for athletes engaged in intermittent sports (12, 13). We have previously shown that RSE induces an increase in leukocyte counts and the neutrophil-to-lymphocyte ratio in adolescents for up to two hours after the exercise, suggesting its modulatory effect on inflammatory processes (10). Also, such effect seems to be even higher in adults (8). This led to the sense that the biological maturation (BM) might be a modulator of immune responses to RSE (10, 14). However, inflammatory responses may be influenced by several other factors like dietary patterns (15). The BM status is determined by various markers associated with physiological mechanisms that promote increases in the total FFM, especially during adolescence (16), like secondary sexual characteristics (pubertal stages), peak height velocity (PHV), and the degree of epiphyseal ossification (skeletal maturation) (14). Thus, it is possible that adolescent muscle production of myokines is influenced by BM stages.

However, to investigate how FFM levels can modulate exercise-induced myokine release it is necessary to control both BM and dietary patterns. This can be achieved through subgroup analyses based on the levels of FFM and dietary patterns or through appropriate statistical techniques such as partial Pearson correlation or analysis of covariance (17, 18). FFM is determined using dual-energy x-ray absorptiometry (DXA) (19), and dietary patterns can be evaluated through a 24-h dietary recalls (24h-R) of the Dietary Inflammatory Index (DII) (20). It is also possible to verify relationships among these variables in adults and observe the behavior of patterns in adolescents undergoing BM to examine how DII may modulate the effect of FFM on myokine release after RSE in adults.

Although a previous study (21) by our group investigated the immune response to RSE in athletes of different age groups, it did not address the influence of critical covariates such as FFM and the DII on cytokine modulation. The present study advances the knowledge in the field by uniquely analyzing the role of these variables, particularly DII (22), an index of easy clinical use for sports nutrition, which can offer valuable insights into the modulation of inflammatory responses in athletes of intermittent sports.

Considering that the inflammatory response to exercise is relevant for adjusting training volume, intensity, and frequency (14), and that the understanding of factors that modulate myokine release—such as FFM, BM, and DII— offers valuable insights for training management in sports; we hypothesized that the relationship between FFM and RSE-induced myokine release is modulated by BM and dietary patterns in adolescents. Therefore, the aim of this study was to analyze the influence of FFM, BM, and DII on myokine release after RSE in male athletes, and to identify inflammatory markers that can guide decision-making in training loads control.

Methods

A study with a quasi-experimental approach and cross-sectional design, was conducted with a sample of 30 male athletes, including 20 adolescents [Age: 12.9 ± 1.1 years; PHV = -0.7 ± 1.1 ; Puberty score = 0.7 ± 1.4 ; Skeletal maturation = 0.8 ± 1.2 ; Total body mass (kg) = 45.5 ± 16.7 ; FFM (kg) = 34.7 ± 10.2] and 10 adults [Age: 23.2 ± 2.1 years; Total body mass (kg) = 69.9 ± 9.9 ; FFM (kg) = 56.1 ± 6.0]. All participants were athletes involved in intermittent sports (soccer, volleyball, basketball, karate, and jiu-jitsu) and regularly participated in regional and national competitions (Tier 3/4) (23). We emphasize that intermittent sports have similar physiological demands, which is why the sample can be treated as a homogeneous group from this perspective. In addition, all participants reported a weekly training frequency of 4–6 days, with daily sessions lasting between 2 and 4 h. They were also duly affiliated with the federations of their respective sports and ranked among the top 20 athletes at the regional level in their categories.

The participants were voluntarily recruited from sports clubs in the city of Natal (Northeast Brazil, state of *Rio Grande do Norte*). To be included in the sample, individuals were required to meet the following criteria: (a) engage in at least two training sessions per week, each lasting a minimum of 60 min, for at least six months prior to the study; (b) participate in intermittent sports; and (c) have a competition history at the regional, national, or international level for at least one year. Exclusion criteria included: presence of upper respiratory tract infection symptoms, use of supplements with potential effects on the immune system (such as vitamin C, glutamine, among others), diagnosis of clinical diseases, or musculoskeletal injuries within the six months preceding the study.

The study was approved by the Ethics Committee of the Federal University of Rio Grande do Norte

(#35197020.8.0000.5537) and complies with the Declaration of Helsinki. The study was registered in the Open Science Framework Registries (<https://doi.org/10.17605/OSF.IO/NPZQX>). All participants, and their legal guardians in the case of minors, were informed about the procedures and signed the consent or assent form, as applicable.

Procedures

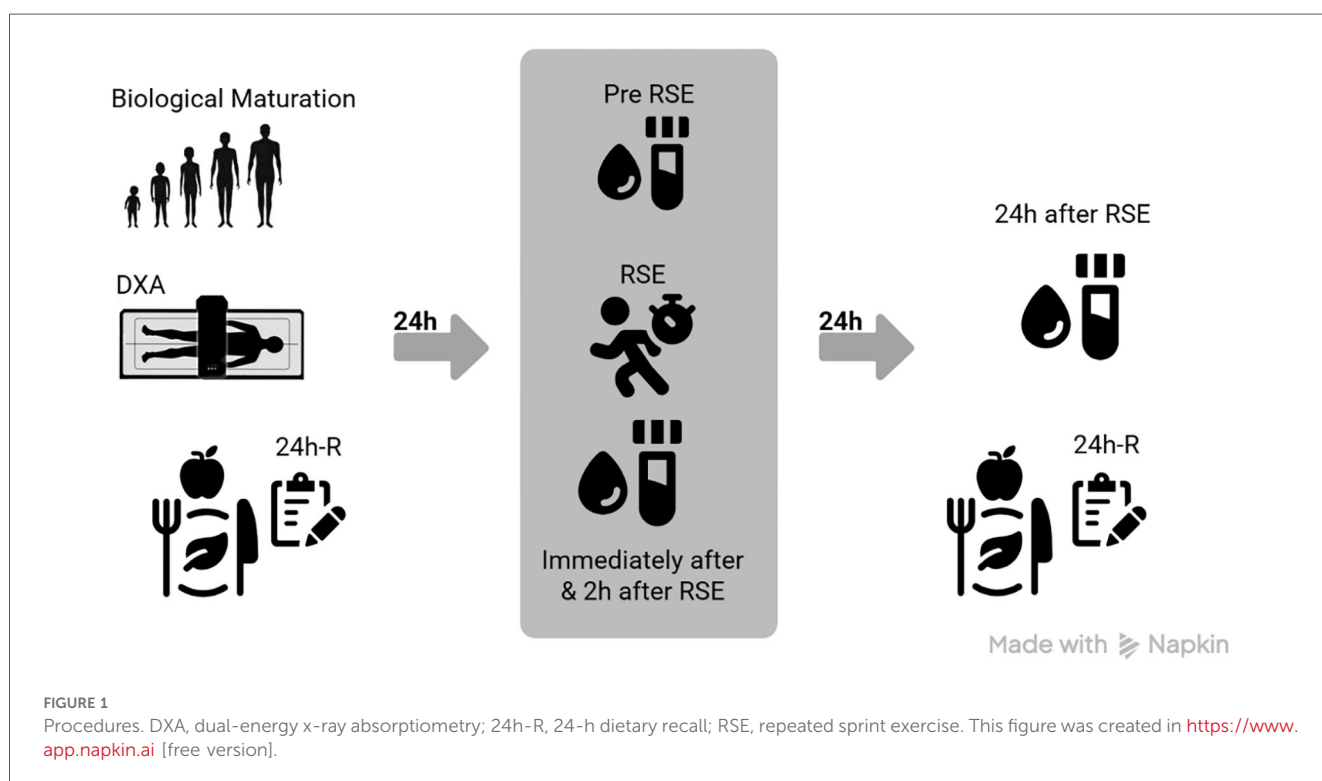
On the first day of the protocol, participants underwent anthropometric and body composition assessments to estimate BM and quantify FFM levels. At this time, the first 24h-R was also administered to characterize the participants' dietary pattern prior to the intervention. After a 24-h interval, resting blood samples were collected. Subsequently, participants were taken to an official athletics track, where they performed a brief five-minute warm-up consisting of jumps and short walks. This was followed by the RSE protocol, which consisted of three sets of six sprints, with 10 s of passive rest between sprints and five minutes of passive rest between sets. Additional blood samples were collected immediately after the RSE, as well as 2 h and 24 h after exercise, to analyze serum cytokine levels at different time points (pre, immediately after, 2 h, and 24 h after RSE). It is worth noting that, at the 24-h after protocol time point, participants completed the second 24h-R, allowing for the monitoring of dietary intake during the after-intervention period as well (Figure 1).

To ensure blinding regarding the implementation of the RSE protocol, the intervention was conducted by an external collaborator not affiliated with the research team, thereby guaranteeing impartiality at this stage of the study. The 24h-R

were administered by a registered dietitian who was also external to the research team. Blood sample collection was carried out by an independent professional, ensuring the neutrality of the procedure. During the laboratory analyses of cytokines, all data were coded to conceal participant identities, preventing evaluators from knowing the origin of each sample. Similarly, during statistical analyses, the data remained masked, making it impossible to identify the groups or individual participants. These measures reinforced the objectivity and integrity of the results obtained.

Anthropometry

Body mass was measured using a Filizola® digital scale with a 200 kg capacity and 0.10 kg precision (São Paulo, Brazil). For this assessment, participants were barefoot and wore light clothing. Height was measured using a Sanny® stadiometer with a precision of 0.1 mm (São Paulo, Brazil). All measurements were taken by a single evaluator following the protocols of the International Society for the Advancement of Kinanthropometry (ISAK) (24). The intra-observer technical error for anthropometric measurements was $\leq 1.0\%$ (25). FFM levels were assessed using dual-energy x-ray absorptiometry (DXA) with a LUNAR®/GE PRODIGY - LNR 41.990 device (Washington, DC, USA), employing the enCORE software, GE Healthcare®, version 15.0 (Madison, WI, USA). For adolescent participants, population-specific algorithms were applied (26). During the assessments, the DXA device operated under the following configuration: whole-body scan; voltage (kV): 76.0; current (mA): 0.150; radiation dose (μGy): 0.4 (very low, with no health risk).



Biological maturation profile

The BM profile was assessed through estimates of peak height velocity (PHV), puberty scores, and skeletal maturity. PHV stage was determined using the mathematical model proposed by Moore et al. (27), for males aged between 8 and 18 years: $PHV = -8.128741 + [0.0070346 \times Age[years] \times Sitting\ height(cm)]$, where: (cm) = centimeters. Based on the outcome of this model, PHV classification was defined as: Pre PHV (<-1), Circum PHV (entre -1 e 1) e Post PHV (>1). The puberty score was calculated using the model proposed by Almeida-Neto et al. (28), for males aged between 6 and 18 years: $Puberty\ (score) = -17.357 + (0.603 \times Age[years]) + [0.127 \times Sitting\ height\ (cm)]$. From these scores, Tanner stages were classified as follows: I ≤ -1.815 ; II = -1.816 to -0.605 ; III = -0.606 – 0.695 ; IV = 0.696 – 3.410 & V > 3.410 . Stage I corresponds to the prepubertal phase, stages II to IV correspond to the pubertal phase, and stage V represents the postpubertal phase (28). Skeletal age was determined based on the mathematical model proposed by Cabral et al. (29): $Skeletal\ age = -11.620 + 7.004 \times (Height_{(m)}) + 1.226 \times (Dsex) + 0.749 \times (Age_{(years)}) - 0.068 \times (Triceps\ skinfold_{(mm)}) + 0.214 \times (Corrected\ arm\ circumference_{(cm)}) - 0.588 \times (Humerus\ diameter_{(cm)}) + 0.388 \times (Femoral\ diameter_{(cm)})$, where, Dsex: For male sex = 0; for female sex = 1. (m): meters. (mm): millimeters. (cm): centimeters. The corrected arm circumference was calculated using the formula: $Corrected\ Arm\ Circumference_{(cm)} = Contracted\ biceps\ circumference_{(cm)} - (Triceps\ skinfold_{(mm)}/10)$, where, (mm): millimeters. (cm) centimeters. After determining skeletal age, skeletal maturity was classified using the equation proposed by (30): $Skeletal\ maturity = Skeletal\ Age - Chronological\ age$. Based on this difference, skeletal maturation was categorized as follows: Delayed (<-1.0), Synchronous (between -1.0 and 1.0), and Accelerated (>1.0).

Upper respiratory tract infection symptoms

On the day of the RSE protocol, prior to the first blood collection, upper respiratory tract infection symptoms (URTIS) were assessed using the Wisconsin Upper Respiratory Symptom Survey-21 (WURSS-21) questionnaire (31, 32). Only volunteers who showed no signs of URTIS were retained as participants in the study. It is worth noting that this tool has been previously used in a study involving young athletes and validated for pediatric populations (33, 34). In the present study, none of the participants needed to be excluded due to URTIS symptoms on the day of RSE.

Physical activity level

The physical activity level was assessed using the web-based version of the International Physical Activity Questionnaire (IPAQ) (33), validated for estimating metabolic equivalents (METs) related to energy expenditure from physical activities

(35). The questionnaire covers activities at work, during transportation, household tasks, and leisure/sports. The web-IPAQ automatically calculates METs for habitual energy expenditure, providing scores for each domain and a total score. Based on total METs, the web-IPAQ classifies physical activity level as low, moderate, or high. Participants completed the web-IPAQ in the presence of at least one researcher and, in the case of adolescents, with a guardian to assist with interpreting the questions. All participants in the present study reported a high level of physical activity.

Sleep pattern

Sleep patterns were assessed using a sleep diary, in which participants recorded the time they went to bed, perceived time to fall asleep, wake-up time, total time in bed, and whether there were interruptions during the night (36). Based on these entries, sleep efficiency was calculated (considered good when $>85\%$) (36). Records were made on the day of the RSE (referring to the previous night) and on the day following the RSE (referring to the intervention night). All participants in this study presented sleep efficiency between 85% and 92%.

Dietary pattern and dietary inflammatory Index (DII)

The dietary pattern was assessed using two 24h-R, applied on non-consecutive days, including one typical day and one atypical day (37). To estimate habitual intake, the *Brazilian Food Composition Table* (38) and the virtualized *Multiple Source Method* (version 1.0.1.87) were used to adjust for intra- and interpersonal variability (39). The inflammatory potential of the diet was measured using the DII, which quantifies the pro- or anti-inflammatory effect of diet based on scores associated with inflammatory biomarkers and health outcomes (40).

The DII calculation was based on the regional dietary pattern of the city of Natal (Northeast Brazil), where the participants of the present study live and train. The specific version used was characterized and validated by the BRAZUCA study (22), which includes 35 of the 45 items from the original DII model described by Shivappa et al. (41). It is noteworthy that the 10 additional items from the original model were not assessed in the 24h-R analyses of the participants in this study, aligning with the specific parameters adapted from the BRAZUCA study (22).

Each parameter was assigned a score of +1 (pro-inflammatory), -1 (anti-inflammatory), or 0 (neutral). The DII score was calculated based on the Z-score of individual intake, converted to a centered percentile and weighted by the nutrient's inflammatory effect score. The global DII corresponds to the sum of the individual parameter values and is interpreted as follows: anti-inflammatory diet (<0) or pro-inflammatory diet (≥ 0) (42). Details of the DII analysis are provided in [Supplementary Material 1](#) (Data spreadsheet).

Repeated sprint exercise

In the 24 h prior to the RSE protocol, participants were instructed to refrain from engaging in high-intensity physical activities. The RSE involved 18 high-intensity sprints performed on an official athletics track, under an average temperature of $26.8 \pm 0.8^\circ\text{C}$. The protocol was divided into three sets, each consisting of six 35-m sprints with 10 s of passive rest between repetitions. Between sets, participants were given a 5-min passive rest period, during which they remained seated on chairs with back support and knees flexed at 90° . During the RSE, participants received verbal encouragement, and the rest intervals between each sprint were monitored by two timekeepers. A third timekeeper monitored the rest periods between sets. All timekeepers used digital stopwatches (TecTime®, São Paulo, Brazil). Participants were instructed to sprint at maximal effort to ensure the high intensity of the exercise.

The Rating of Perceived Exertion (RPE) scale, proposed by Borg (43), was used to assess the subjective intensity of the RSE. The scale was applied immediately after the final sprint. This visual, monochromatic scale ranges from 6 to 20, where 6 corresponds to complete rest and 20 to maximal effort. Participants underwent prior familiarization with the RPE scale 72 h before the RSE and were re-familiarized on the day of the protocol. All participants reported RPE scores between 17 and 20, indicating a high-intensity effort during RSE.

Blood analyses

At each time point in the present study (pre, immediately after, 2 h, and 24 h after RSE), 10 ml of peripheral blood was collected from the antecubital vein using the vacuum method. The blood was stored in dry tubes (BD-Vacutainer, 5.4 mg Plus Plastic) and processed for laboratory analysis. We analyzed the serum concentrations of the cytokines [interleukin (IL)] IL-1 β , IL-6, IL-8 and IL-10 (44). For this purpose, peripheral blood samples were assessed by flow cytometry using a BD Biosciences® device (Model: BD FACSCanto™ II Flow Cytometer, Serial Number: V96100619, New York, USA), with the BD™ Cytometric Bead Array (CBA) Human Inflammatory Cytokines kit (São Paulo, Brazil). All procedures followed the manufacturer's instructions provided in the kit manual (45). After flow cytometry, the data were processed using BD Biosciences® FCAP Array™ software (Version 3.0; New York, USA).

Statistical analysis

All statistical analyses were performed using the open-source software JAMOV® (version 2.3, Sidney, Australia), and figures were produced using GraphPad Prism® (version 8.01, California, USA). The significance level was set at $p < 0.05$.

Preliminary non-parametric analyses

Data distribution was assessed using the Shapiro–Wilk test, skewness and kurtosis coefficients (acceptable range: -1.96 to

$+1.96$), and visual inspection of Q-Q plots. Since assumptions of normality were violated, initial analyses relied on non-parametric tests as an exploratory step.

Associations between FFM and cytokine concentrations were evaluated using Spearman's rank correlation coefficient (ρ). To account for potential confounders, partial correlations were conducted, controlling for BM in adolescents (puberty score, PHV, and skeletal maturity) and for the DII in both adolescents and adults. Ninety-five percent confidence intervals (95% CI) for Spearman's coefficients were estimated through bias-corrected bootstrapping with 1,000 resamples (46). The magnitude of Spearman's ρ was interpreted as (47): insignificant (<0.10), weak (0.10 – 0.39), moderate (0.40 – 0.69), strong (0.70 – 0.89), and very strong (0.90 – 1.00).

For group comparisons, participants were categorized by median split into lower vs. higher subgroups for FFM, DII, and BM stage, separately within adolescents and adults. Percent changes in cytokine concentrations ($\Delta\%$) across time points were compared using the Mann–Whitney U -test. Effect sizes were reported as rank-biserial correlation coefficients (48) and interpreted as (49): small (≤ 0.05), medium (0.06 – 0.25), large (0.26 – 0.50), or very large (>0.50).

Samples were categorized based on the median split of the following variables of interest:

- FFM (lower vs. higher);
- DII (lower vs. higher);
- Stage of BM [Pre-PHV (lower mature) vs. Circum/Post-PHV (higher mature)].

We emphasize that age groups were considered in this process, as described below: (i) adolescents with lower levels vs. adolescents with higher levels; (ii) adults with lower levels vs. adults with higher levels. Thus, comparisons were made within each age group.

Thus, when grouping the subjects for the sub-analyses, the division was balanced: 50% for *lower levels* and 50% for *higher levels*, as shown below:

- Adolescents FFM lower ($n = 10$) vs. Adolescents FFM higher ($n = 10$);
- Adults FFM lower ($n = 05$) vs. Adults FFM higher ($n = 05$);
- Adolescents DII lower ($n = 10$) vs. Adolescents DII higher ($n = 10$);
- Adults DII lower ($n = 05$) vs. Adults DII higher ($n = 05$);
- Adolescents BM lower ($n = 10$) vs. Adolescents BM higher ($n = 10$).

Subsequently, percent changes in cytokine levels ($\Delta\%$) between subgroups were compared. $\Delta\%$ was calculated as:

$$\Delta\% = [(After\ RSE\ value / Pre\ RSE\ value) - 1] \times 100$$

Post hoc statistical power

Since 16 correlation analyses were performed between FFM and various cytokines across four time points (pre, immediately after, 2 h, and 24 h after RSE), Bonferroni correction was applied to control for type I error. The adjusted alpha level (adjusted p) was set at <0.003125 for correlations.

Similarly, 12 subgroup comparisons were conducted for $\Delta\%$ values across three after RSE time points (immediately after, 2 h, and 24 h). For these comparisons, the adjusted p -value was defined as <0.0042 .

Post hoc power analyses were conducted for the main significant findings (based on the adjusted p -values), indicating statistical power greater than 0.80 for effects with $r \geq 0.66$. This provides greater confidence in the inferences drawn in these cases. Power analyses were performed using G*Power software (version 3.1, Düsseldorf, Germany). Nevertheless, caution is advised when interpreting subgroup results with small samples, such as the adult group, due to lower statistical power.

Main analysis: generalized linear mixed models (GLMM)

Given the longitudinal and repeated-measures nature of the dataset (four time points per participant: pre, immediately after, 2 h, and 24 h after RSE), the small and unbalanced sample size (20 adolescents, 10 adults), and the need to control for covariates, the primary analyses were performed using Generalized Linear Mixed Models (GLMM). This approach allowed us to: (i) leverage the within-subject design, (ii) adjust for individual differences in FFM and DII, and (iii) provide greater robustness against violations of normality and sample imbalance.

GLMMs were implemented in JAMOVI[®] using the GAMLj module. For each cytokine (IL-1 β , IL-6, IL-8, IL-10), log-transformed concentrations were specified as the dependent variable, assuming a Gamma distribution with log link function due to the skewness of cytokine data. The fixed-effects structure included:

- Time (four levels: pre, immediately after, 2 h and 24 h after RSE),
- Age group [BM] (adolescents vs. adults),
- FFM (standardized z -scores),
- DII (standardized z -scores),
- and the interaction Time $\times$ Age group.

Random effects were modeled at the participant level (ID), with random intercepts and slopes for time ($1 + \text{Time} \mid \text{ID}$), thereby accounting for intra-individual variability. Estimation was based on restricted maximum likelihood (REML), and convergence was checked across multiple optimizers (*bobyqa*, *Nelder-Mead*, *nloptrwp*).

In our study, the repeated-measures design, with data collection at four time points, allowed us to use each athlete as their own control. The analysis using GLMM was specifically adopted to model intra-subject effects over time, mitigating the risks associated with the absence of a control group.

Model outputs and *post hoc* testing

For each model, type III Wald chi-square tests were used to evaluate omnibus fixed effects. Fixed-effect parameter estimates (B), standard errors (SE), z -values, p -values, and 95% confidence intervals were reported. Estimated marginal means (EMMs) were calculated, and pairwise comparisons between time points were adjusted using Bonferroni correction. Interaction effects

(Time $\times$ Age group) were explored through simple-effects analyses, keeping other covariates constant at their means.

Results

In the total sample analysis, a positive correlation was identified between FFM and IL-6 levels both pre and immediately after RSE, as well as a negative correlation with IL-10 at 24 h after RSE (Table 1). Among adolescents, a positive association was found between FFM and IL-6 at 2 h after RSE, while negative correlations were observed with IL-6 and IL-8 at 24 h after RSE.

When adjusting for BM profile markers (puberty score, PHV, and skeletal maturity) within the adolescent group, the following were observed: a positive correlation between FFM and IL-10 pre RSE; a positive correlation with IL-6 at 2 h after RSE; and a negative correlation with IL-1 β at 24 h after RSE (Table 1).

Among adults, FFM showed a negative correlation with IL-10 at three time points (pre, 2 h, and 24 h after RSE), and a positive correlation with IL-6 at 2 h after the protocol (Table 1).

After controlling for the effect of the DII in the correlation analyses between FFM and cytokine levels in the total sample, significant correlations were observed between FFM and IL-6 at the pre RSE time point, and between FFM and IL-10 at 24 h after RSE.

In the adult group, significant correlations were identified between FFM and IL-10 both immediately and 24 h after RSE. Additionally, after controlling for DII, no significant correlations were found between FFM and cytokine levels in the adolescent group (Table 2).

Adolescents with lower levels of FFM exhibited greater percent variation ($\Delta\%$) in IL-6 levels at 24 h after RSE [$r = 0.66$; Power = 0.81 (Figure 2B)], compared to their peers with higher FFM levels. No significant differences were observed between groups for the other cytokines ($p > 0.05$) (IL-1 β , IL-8 & IL-10).

Among adults, individuals with higher FFM levels showed greater percent variation ($\Delta\%$) in IL-10 levels at 2 h after RSE [$r = 0.84$; Power = 0.88 (Figure 2H)] compared to those with lower FFM levels. As observed in the adolescent group, no significant differences were found between groups for the remaining cytokines analyzed ($p > 0.05$) (IL-1 β , IL-6 & IL-8).

Lower biologically mature adolescents exhibited greater percent variation ($\Delta\%$) in IL-6 levels at 24 h after RSE [$r = 0.66$; Power = 0.81 (Figure 3B)] compared to their more mature peers. No significant differences between groups were observed for the other cytokines (IL-1 β , IL-8 & IL-10).

When adolescents and adults were grouped according to DII levels, differences were observed only among adolescents at 2 h after RSE. At this time point, individuals with higher DII levels presented higher IL-6 concentrations compared to those with lower DII levels [$r = 0.540$; Power = 0.80 (Figure 4C)]. Additionally, in the adult group, individuals with lower DII levels exhibited higher IL-10 concentrations than their counterparts with higher DII levels immediately after RSE [$r = 0.840$; Power = 0.99 (Figure 4H)].

TABLE 1 Correlation analysis of FFM levels with cytokine levels considering the interference of BM in adolescent athletes.

Cytokine	Total sample (n = 30)				Adolescent (n = 20)				Adult (n = 10)							
					Controlling BM markers (partial correlation)											
	ρ	p	CI 95%		ρ	p	CI 95%		ρ	p	CI 95%					
	FFM Kg		Bootstraps (1.000)		FFM Kg		Bootstraps (1.000)		FFM Kg		Bootstraps (1.000)					
Pre Repeated Sprints Exercise				Pre Repeated Sprints Exercise				Pre Repeated Sprints Exercise				Pre Repeated Sprints Exercise				
IL-1 β (pg/ml)	0.148	0.444	-0.232	0.493	0.118	0.619	-0.365	0.547	-0.184	0.480	-0.735	0.473	0.209	0.562	-0.691	0.858
IL-6 (pg/ml)	0.423*	0.0022	0.059	0.699	0.143	0.548	-0.301	0.583	0.200	0.441	-0.593	0.806	0.042	0.919	-0.774	0.805
IL-8 (pg/ml)	0.358	0.057	-0.024	0.629	-0.301	0.197	-0.665	0.150	-0.116	0.657	-0.569	0.603	-0.164	0.657	-0.789	0.585
IL-10 (pg/ml)	-0.034	0.862	-0.401	0.298	0.292	0.212	-0.159	0.674	0.508*	0.003	-0.138	0.844	-0.752*	0.0012	-0.988	-0.229
Immediately after Repeated Sprints Exercise				Immediately after Repeated Sprints Exercise				Immediately after Repeated Sprints Exercise				Immediately after Repeated Sprints Exercise				
IL-1 β (pg/ml)	0.203	0.290	-0.153	0.534	0.199	0.400	-0.284	0.628	-0.254	0.325	-0.690	0.572	0.486	0.154	-0.261	0.946
IL-6 (pg/ml)	0.377*	0.003	0.039	0.639	0.132	0.580	-0.287	0.584	0.233	0.368	-0.606	0.798	-0.006	1.000	-0.689	0.699
IL-8 (pg/ml)	0.328	0.083	-0.037	0.615	-0.003	0.992	-0.479	0.522	0.142	0.587	-0.386	0.660	-0.079	0.838	-0.673	0.801
IL-10 (pg/ml)	0.209	0.276	-0.146	0.556	0.331	0.154	-0.047	0.628	0.196	0.450	-0.520	0.666	-0.673*	0.003	-0.925	-0.118
2 h after Repeated Sprints Exercise				2 h after Repeated Sprints Exercise				2 h after Repeated Sprints Exercise				2 h after Repeated Sprints Exercise				
IL-1 β (pg/ml)	0.065	0.738	-0.392	0.450	0.321	0.168	-0.192	0.777	-0.246	0.342	-0.661	0.462	0.328	0.354	-0.401	0.852
IL-6 (pg/ml)	0.356	0.058	-0.050	0.693	0.619*	0.003	0.202	0.920	0.710*	0.001	-0.014	0.922	0.745*	0.0018	0.150	1.000
IL-8 (pg/ml)	0.333	0.078	-0.068	0.668	0.014	0.955	-0.508	0.552	0.261	0.312	-0.367	0.730	0.333	0.349	-0.400	0.889
IL-10 (pg/ml)	0.009	0.964	-0.306	0.353	0.239	0.310	-0.255	0.702	0.371	0.143	-0.307	0.794	0.143	0.694	-0.754	0.800
24 h after Repeated Sprints Exercise				24 h after Repeated Sprints Exercise				24 h after Repeated Sprints Exercise				24 h after Repeated Sprints Exercise				
IL-1 β (pg/ml)	-0.091	0.639	-0.510	0.364	0.012	0.960	-0.459	0.514	-0.552*	0.0022	-0.843	0.216	0.334	0.345	-0.368	0.805
IL-6 (pg/ml)	-0.105	0.588	-0.486	0.267	-0.495*	0.0026	-0.803	-0.092	-0.160	0.540	-0.609	0.480	-0.061	0.868	-0.700	0.676
IL-8 (pg/ml)	-0.142	0.462	-0.521	0.198	-0.534*	0.0015	-0.845	-0.079	-0.214	0.409	-0.645	0.578	-0.333	0.349	-0.837	0.358
IL-10 (pg/ml)	-0.440*	0.0017	-0.739	-0.003	-0.136	0.568	-0.573	0.308	-0.135	0.607	-0.664	0.491	-0.681*	0.0030	-0.962	-0.038

ρ , Spearman Rho coefficient; FFM, fat-free mass; IL, interleukin; β , Beta; Rho, Spearman's correlation coefficient; CI, confidence interval; BM, biological maturation.
*Statistically significant (Bonferroni correction p -adjusted <0.003125).

TABLE 2 Correlation analysis of FFM levels with cytokine levels considering the interference of the inflammatory index of the diet.

Cytokine	Total Sample (n = 30)				Adolescent (n = 20)				Adult (n = 10)			
	Controlling DII (Partial Correlation)				Controlling DII (Partial Correlation)				Controlling DII (Partial Correlation)			
	ρ	ρ	CI 95%		ρ	ρ	CI 95%		ρ	ρ	CI 95%	
	FFM Kg		Bootstraps (1.000)		FFM Kg		Bootstraps (1.000)		FFM Kg		Bootstraps (1.000)	
	Pre Repeated Sprints Exercise				Pre Repeated Sprints Exercise				Pre Repeated Sprints Exercise			
IL-1 β (pg/ml)	0.155	0.4	−0.241	0.496	0.186	0.4	−0.218	0.520	0.522	0.1	−0.737	0.931
IL-6 (pg/ml)	0.441*	0.001	0.077	0.680	0.033	0.8	−0.258	0.418	−0.399	0.2	−0.851	0.776
IL-8 (pg/ml)	0.343	0.07	−0.091	0.608	−0.265	0.2	−0.666	0.045	−0.397	0.2	−0.895	0.804
IL-10 (pg/ml)	−0.015	0.9	−0.364	0.320	0.228	0.3	−0.148	0.574	−0.661	0.053	−0.981	−0.171
	Immediately after Repeated Sprints Exercise				Immediately after Repeated Sprints Exercise				Immediately after Repeated Sprints Exercise			
IL-1 β (pg/ml)	0.178	0.3	−0.193	0.491	0.192	0.4	−0.123	0.524	0.588	0.09	−0.380	0.935
IL-6 (pg/ml)	0.361	0.054	0.045	0.630	0.109	0.6	−0.205	0.486	−0.321	0.4	−0.805	0.669
IL-8 (pg/ml)	0.327	0.08	−0.083	0.628	0.223	0.3	−0.387	0.651	−0.329	0.3	−0.805	0.932
IL-10 (pg/ml)	0.183	0.3	−0.245	0.582	0.295	0.2	−0.045	0.606	−0.677*	0.003	−0.919	−0.403
	2 h after Repeated Sprints Exercise				2 h after Repeated Sprints Exercise				2 h after Repeated Sprints Exercise			
IL-1 β (pg/ml)	0.048	0.8	−0.319	0.430	−0.139	0.5	−0.403	0.330	0.623	0.07	−0.419	0.945
IL-6 (pg/ml)	0.347	0.06	−0.051	0.700	0.426	0.06	0.182	0.824	0.663	0.052	0.442	0.973
IL-8 (pg/ml)	0.338	0.07	−0.073	0.650	0.394	0.09	−0.307	0.910	0.324	0.4	−0.540	0.935
IL-10 (pg/ml)	0.02	0.9	−0.334	0.486	0.186	0.447	−0.268	0.604	0.274	0.5	−0.722	0.922
	24 h after Repeated Sprints Exercise				24 h after Repeated Sprints Exercise				24 h after Repeated Sprints Exercise			
IL-1 β (pg/ml)	−0.087	0.6	−0.533	0.327	−0.342	0.1	−0.622	−0.126	0.660	0.051	−0.478	0.943
IL-6 (pg/ml)	−0.124	0.5	−0.472	0.256	−0.351	0.1	−0.627	0.013	−0.365	0.3	−0.877	0.640
IL-8 (pg/ml)	−0.136	0.5	−0.525	0.240	−0.435	0.06	−0.667	−0.195	−0.456	0.2	−0.888	0.475
IL-10 (pg/ml)	0.416*	0.003	−0.719	0.555	−0.119	0.6	−0.457	0.177	−0.700*	0.003	−0.951	−0.241

ρ , Spearman rho coefficient; DII, dietary inflammatory index; FFM, fat-free mass; IL, interleukin; β , beta; Rho, Spearman's correlation coefficient; CI, confidence interval; BM, biological maturation.
*Statistically significant (Bonferroni correction p -adjusted <0.003125).

The GLMM analyses revealed distinct effects of time, age, and covariates (FFM and DII) on cytokine levels. IL-1 β showed no significant changes over time or due to the Time $\times$ Age group (Adolescent vs. Adult) interaction (Table 3). However, FFM emerged as a significant predictor, indicating that in both adolescents and adults, individuals with higher FFM presented with elevated levels of IL-1 β .

For IL-6, there was a main effect of time and a significant Time $\times$ Age group interaction. *Post hoc* analyses showed that, in adults, IL-6 levels were significantly elevated immediately after exercise and 2 h later compared to the 24 h time point. Fixed effect estimates also indicated that adults had higher IL-6 levels than adolescents at the immediately after exercise and 24 h time points. FFM and DII were also significant predictors for this cytokine, with the effects applying to both groups.

IL-8 presented a strong time effect and a significant Time $\times$ Age group interaction. IL-8 levels were consistently higher at all pre and immediately after exercise time points compared to the 24 h time point, indicating a robust response to the effort. The interaction suggests that adults have consistently higher IL-8 levels before and after RSE compared to adolescents.

Finally, IL-10 did not show a main effect of time, but it did demonstrate a highly significant Time $\times$ Age group interaction.

While adolescents showed no significant changes in IL-10 levels over time, adults exhibited a remarkable increase, with significantly higher levels 2 h and immediately after RSE compared to 24 h. This finding suggests that the anti-inflammatory response mediated by IL-10 is more effectively and acutely activated in adults in response to resistance exercise than in adolescents.

Discussion

This study investigated the influence of FFM, BM, and the DII on cytokine responses to a repeated sprint exercise (RSE) protocol in male athletes. The findings revealed distinct associations between adolescent and adult groups, suggesting that the after exercise inflammatory profile appears to be modulated by FFM levels, BM stage, and dietary patterns.

Inflammatory responses and fat-free mass

The results of this study demonstrate that FFM plays a crucial role in immunoregulation, as reflected in the modulation of cytokine levels in response to exercise (Table 3). Both group

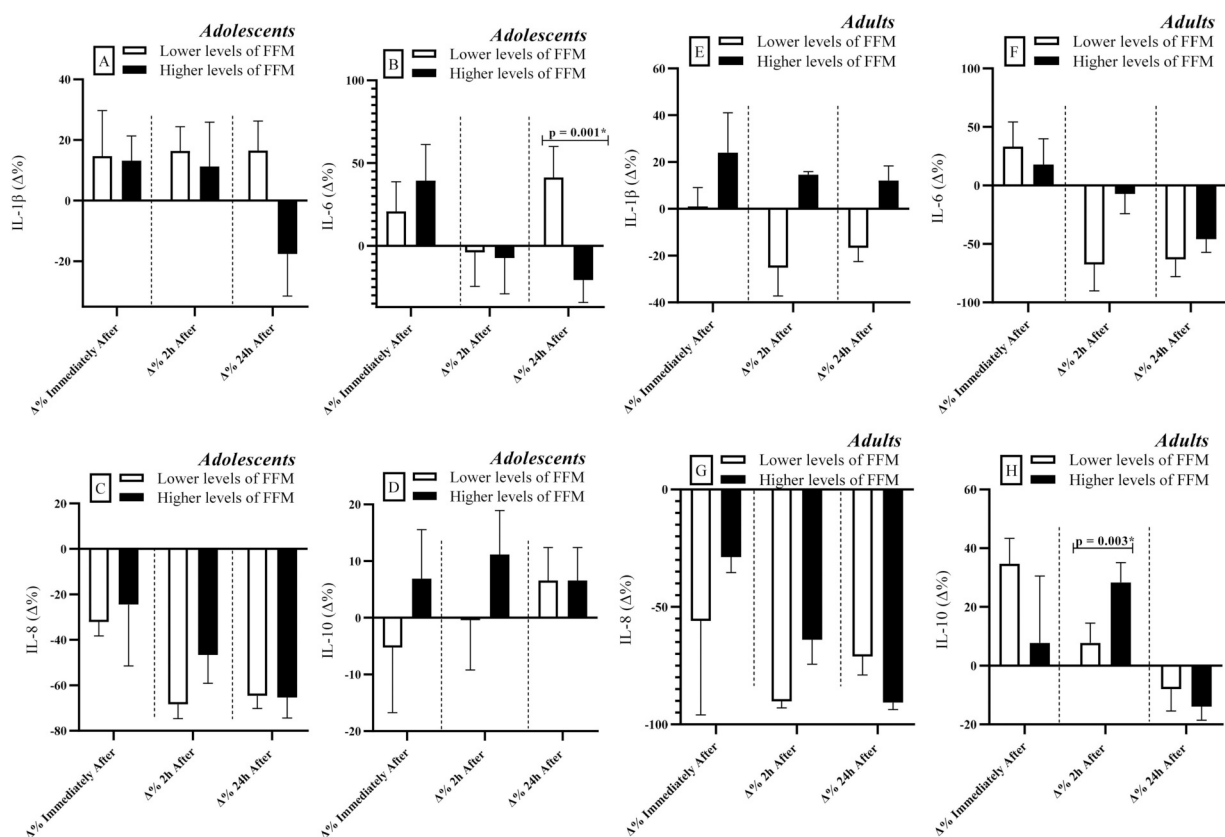


FIGURE 2

Comparisons of cytokine levels considering the division of groups based on FFM levels (lower vs. higher levels). FFM: Fat-free mass. IL: Interleukin. Δ : Delta Coefficient. *Statistically significant (Bonferroni correction p -adjusted <0.00417).

comparisons (Figures 2, 3 and Table 3) and correlation analyses (Table 1) indicate that individuals with higher FFM exhibit elevated IL-6 levels at rest and immediately after RSE. These findings may be attributed to the endocrine function of muscle tissue, which releases IL-6 in response to mechanical and metabolic stress (2). However, the negative correlation between FFM and IL-10 observed in adults (pre, 2 h, and 24 h after RSE) deserves special attention. Although IL-10 is classically considered an anti-inflammatory cytokine, its reduction in individuals with higher FFM may suggest a distinct immunological adaptation in adult athletes, in which there is a greater demand for acute inflammatory responses at the expense of chronic anti-inflammatory modulation. This hypothesis warrants further investigation (5, 44).

During adolescence, the growth and maturation of muscle tissue may influence inflammatory responses (14). This may serve as a metabolic adaptation and repair mechanism, which could explain why adolescents with higher FFM showed negative correlations with IL-6 and IL-8 at 24 h after RSE (Tables 1, 3), suggesting a more efficient inflammatory recovery (4). IL-8, a cytokine associated with neutrophil recruitment and maintenance of the inflammatory response (44, 50), may have been downregulated to prevent a prolonged inflammatory state in better-conditioned athletes (51, 52).

In contrast, adolescents with lower FFM showed a greater percent increase ($\Delta\%$) in IL-6 at 24 h after RSE compared to their peers (Figure 2B), suggesting that lower muscle reserves may compromise repair mechanisms and prolong the inflammatory response (2). Among adults, those with higher FFM consistently exhibited lower IL-10 levels (pre, 2 h, and 24 h after RSE) and a positive association between FFM and IL-6 at 2 h after RSE (Table 1), reinforcing the importance of additional regulatory mechanisms in the modulation of the inflammatory response (1, 4, 5). It is worth noting that the absence of significant correlations between FFM and IL-1 β in adolescents may indicate that this cytokine is less sensitive to variations in body composition at this age or that other factors (e.g., training load or nutritional status) exert a greater influence (Tables 1, 3) (53).

Inflammatory profile and biological maturation

When controlling for BM (Table 1), a positive association was observed between FFM and IL-10 levels, suggesting that adolescents with higher FFM may present an anti-inflammatory predisposition, regardless of maturation stage.

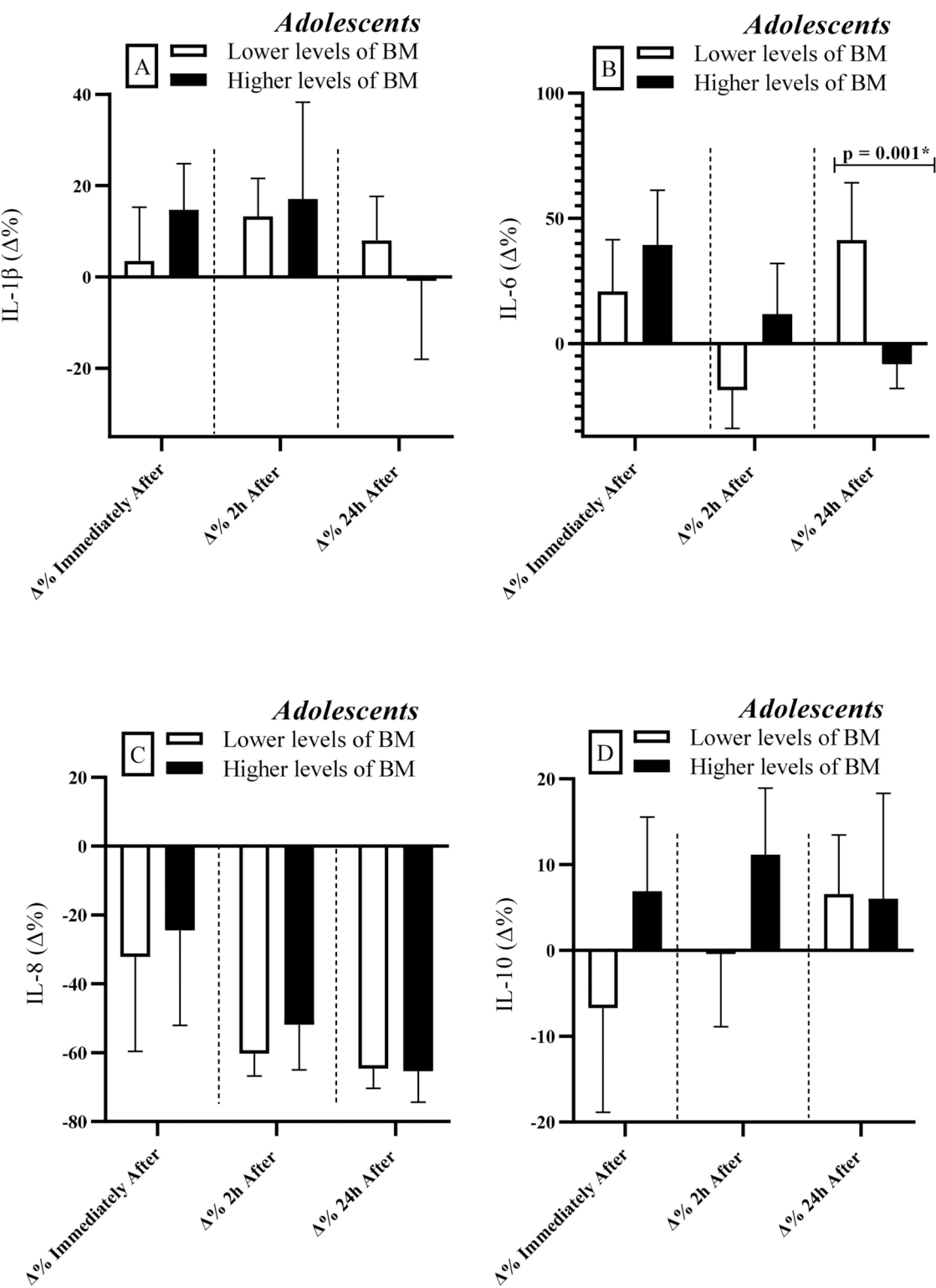


FIGURE 3
Comparisons of cytokine levels considering the division of the adolescent group based on BM levels (lower vs. higher levels). IL, interleukin; BM, biological maturation; Δ , delta coefficient. *Statistically significant (Bonferroni correction p -adjusted <0.00417).

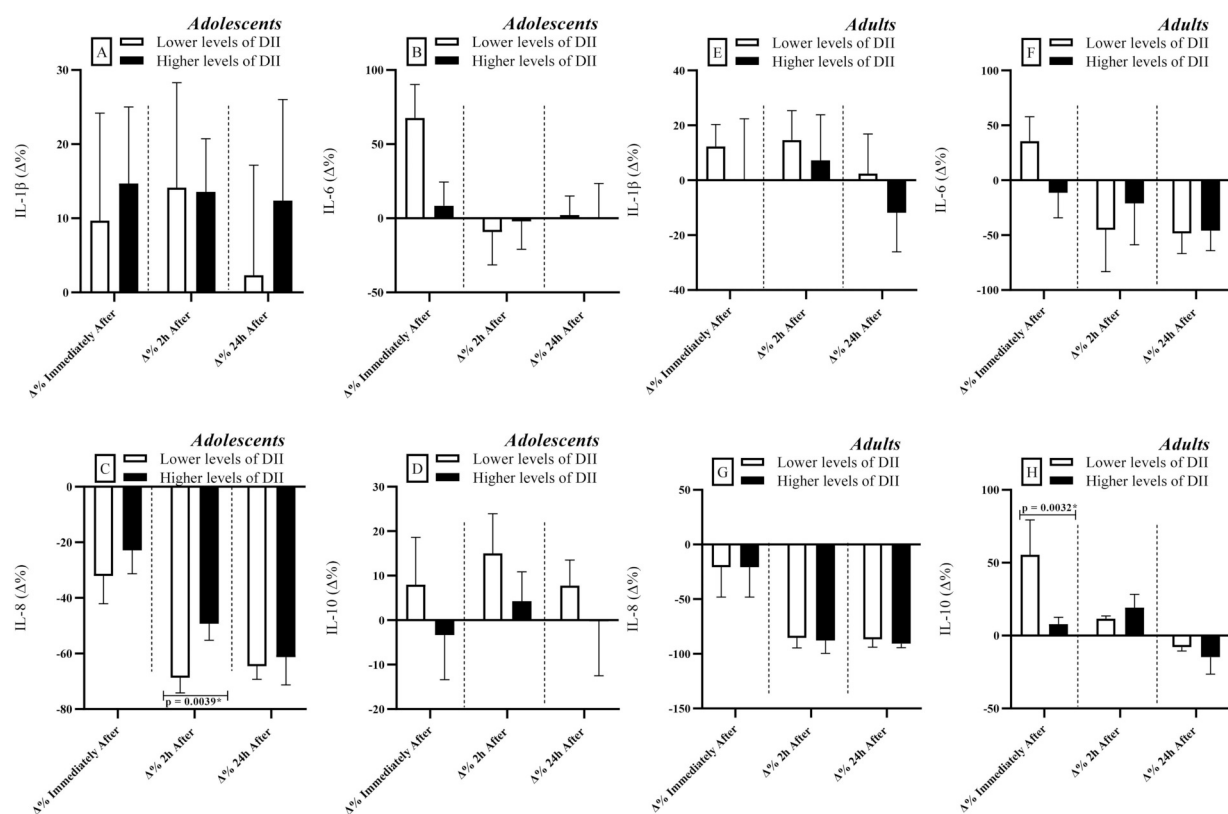


FIGURE 4

Comparisons of cytokine levels considering the division of groups based on dietary inflammatory index [DII] levels (lower vs. higher levels). IL, interleukin; Δ, delta coefficient. *Statistically significant (Bonferroni correction p -adjusted <0.00417).

This adjustment also revealed a similar correlation for IL-6 levels, indicating that individuals with more muscle mass exhibit an acute IL-6 response to exercise, reinforcing the role of muscle tissue as a potential source of this cytokine (Table 3) (1). In this context, the inverse correlation with IL-1 β at 24 h after RSE in adolescents suggests that FFM may attenuate late inflammatory responses, possibly due to greater tissue repair capacity (44, 53).

Consistently, less mature adolescents showed a greater percent increase (Δ%) in IL-6 at 24 h after RSE compared to their more mature peers (Figure 3B), suggesting that inflammatory markers may be influenced by BM (10), possibly due to a still developing physiological system (14). Less mature individuals also tend to have lower FFM levels compared to their more biologically advanced peers (54), which may explain the similarity of findings when adolescents were grouped by FFM levels and BM status (Figures 2B, 3B). These findings may not be exclusively linked to lower FFM, but also to hormonal variations (e.g., testosterone and GH) that influence both muscle development and immune activity (53, 54).

Furthermore, adolescents with higher FFM appeared to exhibit lower IL-1 β levels at 24 h after RSE (Table 1). IL-1 β is a pro-inflammatory cytokine involved in initiating the inflammatory response and muscle soreness (44, 53). Lower

concentrations at 24 h after RSE in individuals with higher FFM may indicate a more controlled inflammatory response and more efficient recovery, potentially associated with training-induced adaptations and greater anti-inflammatory capacity (1, 2).

Inflammation and DII

The results of this study demonstrate that DII significantly influenced cytokine responses following RSE (Figures 4C,H). Specifically, lower DII scores (indicating a more anti-inflammatory dietary pattern) were associated with higher IL-8 levels in adolescents and higher IL-10 levels in adults. These findings align with literature showing an inverse relationship between anti-inflammatory diets and pro-inflammatory markers such as IL-1 β , IL-6, IL-8, TNF- α , and C-reactive protein (CRP) (40, 41). The production of pro-inflammatory interleukins by muscle tissues during exercise is well documented and is considered an adaptive response that triggers anti-inflammatory pathways, mobilizes glycogen, and promotes metabolic adaptations (1, 55).

Among adults with higher FFM and anti-inflammatory dietary patterns, the observed increase in IL-10 after exercise may reflect enhanced anti-inflammatory responses. This aligns

TABLE 3 Generalized linear mixed models (GLMM) results for cytokine responses to repeated sprint exercise (RSE).

Cytokine	Omnibus effects (χ^2 , df, p)	Fixed effect estimates [β (95% CI), SE, z, p]	Significant pairwise comparisons (Bonferroni-adjusted)	Simple effects (Time $\times$ Age group)
IL1 β	- FFM ($\chi^2 = 5.19$, df = 1, $p = 0.0023^*$); - Time ($\chi^2 = 4.56$, df = 3, $p = 0.207$); - Age group trend ($\chi^2 = 3.25$, df = 1, $p = 0.072$); - Time $\times$ Age group ($\chi^2 = 3.43$, df = 3, $p = 0.330$).	FFM: $\beta = 0.078$ [0.011–0.145], SE = 0.034, $z = 2.28$, $p = 0.023^*$.	There were no significant time contrasts.	There were no significant Time $\times$ Age group effects.
IL6	- Time ($\chi^2 = 17.2$, df = 3, $p < 0.001^*$); - Time $\times$ Age group ($\chi^2 = 8.3$, df = 3, $p = 0.040^*$); - FFM ($p = 0.007^*$); - DII ($p = 0.005^*$).	- Immediately after vs. 24h: $\beta = 0.245$ [0.087–0.403], SE = 0.081, $z = 3.04$, $p = 0.002^*$; - Pre vs. 24h: $\beta = 0.159$ [0.033–0.285], SE = 0.064, $z = 2.47$, $p = 0.014^*$.	- $\uparrow$ IL-6 immediately after and 2 h after vs. 24 h after ($p < 0.05^*$); - Adults > Adolescents in Pre & 24 h after ($p < 0.05^*$).	Adults showed stronger increases in IL-6 after and 24 h ($p < 0.05^*$).
IL8	- Time ($\chi^2 = 205.9$, df = 3, $p < 0.001^*$); - Age group ($\chi^2 = 2.50$, df = 1, $p = 0.114$); - Time $\times$ Age group ($\chi^2 = 8.5$, df = 3, $p = 0.036^*$).	- 2 h vs. 24h: $\beta = 0.072$ [0.008–0.136], SE = 0.033, $z = 2.19$, $p = 0.028^*$; - Immediately after vs. 24h: $\beta = 0.331$ [0.267–0.395], SE = 0.033, $z = 10.14$, $p < 0.001^*$; - Pre vs. 24h: $\beta = 0.389$ [0.325–0.453], SE = 0.033, $z = 11.93$, $p < 0.001^*$.	- All time points >24 h ($p < 0.001^*$); - Adults > Adolescents (Pre & Immediately after).	Adults had higher IL-8 levels pre- and immediately after RSE ($p < 0.05^*$).
IL10	- Time ($\chi^2 = 1.139$, df = 3, $p = 0.767$); - Age group ($\chi^2 = 3.94$, df = 1, $p = 0.047^*$); - Time $\times$ Age group ($\chi^2 = 23.493$, df = 3, $p < 0.001^*$).	- Time (2 h vs. 24 h): $\beta = 0.0887$ [0.04785–0.12954], SE = 0.0208, $z = 4.2560$, $p < 0.001^*$; - Time (Immediately After vs. 24 h): $\beta = 0.1088$ [0.06792–0.14963], SE = 0.0208, $z = 5.2181$, $p < 0.001^*$; - Age group (Adult - Adolescent): $\beta = -0.1482$ [-0.29459– -0.00188], SE = 0.0747, $z = -1.9852$, $p = 0.047^*$.	- Adults: 2 h vs. 24 h ($p < 0.001^*$); - Immediately After vs. 24 h ($p < 0.001^*$); - Pre vs. Immediately After ($p < 0.001^*$).	- Adults: significant time effects ($\chi^2 = 20.08$, df = 3, $p < 0.001^*$); - Adolescents: no significant time effects ($\chi^2 = 3.46$, df = 3, $p = 0.326$).

IL, interleukin; FFM, fat-free mass; $\uparrow$, increase; >, greater than; Group age, analysis of biological maturation when comparing adolescents [subjects in the process of maturation] with adults [biologically mature subjects].

with previous evidence that IL-6 induces IL-10 and IL-1ra, modulating the inflammatory cascade (56, 57). Individuals with less inflammatory dietary patterns tend to present a more favorable redox and immune basal state, facilitating effective immune responses to physical stress (52, 58–61).

Individuals with less inflammatory dietary patterns tend to present a more favorable redox and immune basal state, facilitating effective immune responses to physical stress (14, 61). The DII reflects the inflammatory potential of various macronutrients and micronutrients, which directly affect cytokine levels (41). Diets rich in saturated fats, refined sugars, and low in fiber are associated with higher IL-6, IL-8, CRP, and TNF- α , whereas diets rich in fruits, vegetables, and omega-3 fatty acids promote anti-inflammatory responses, including IL-10 (40, 60).

Although the exact mechanisms remain to be clarified, it is presumed that an anti-inflammatory dietary pattern contributes to redox balance, reduced baseline expression of nuclear factor kappa B (NF- κ B), and lower secretion of pro-inflammatory adipokines (e.g., TNF- α , IL-1 β), thereby enabling a rapid and transient IL-6 response to exercise without prolonged inflammation (62–64). During the recovery phase, the modulatory effect of DII is manifested through more efficient IL-10 expression, aiding inflammation resolution.

Practical applications: insights for training load control

The findings of this study provide relevant insights for training load management, particularly in adolescent and adult athletes involved in intermittent sports. The observation that individuals with lower FFM exhibit greater inflammatory variation (especially IL-6 at 24 h after RSE) suggests a slower inflammatory recovery and a potentially higher risk of immune overload. This implies that athletes with lower muscle development may require longer recovery intervals between high-intensity sessions or complementary interventions (e.g., nutritional and sleep strategies) that support inflammation resolution.

In adolescents, the influence of BM on inflammatory responses reinforces the need to individualize training loads according to maturation status. Biologically less mature athletes showed more prolonged inflammatory responses (Figure 3B), which may hinder training adaptations. Monitoring PHV status, skeletal maturation, and puberty stages can help coaches and strength professionals avoid overloading immature athletes, promoting safer and more sustainable development.

In adults, greater FFM was associated with more effective IL-10 modulation, indicating a more favorable anti-inflammatory profile and enhanced recovery potential. This information may

assist in adjusting training load based on athletes' morphological status, as individuals with higher FFM may tolerate greater volumes and intensities with lower risk of chronic inflammation.

Finally, the DII emerges as a practical and promising tool for sports science. Our findings indicate that dietary patterns with lower inflammatory potential (as reflected in lower DII values) are associated with more efficient immune responses to exercise, particularly in adults with higher FFM (greater IL-10) and adolescents (lower IL-8) (Figures 4C,H). This reinforces the need to incorporate regular nutritional assessments into training load monitoring. Nutritional intervention programs focused on healthy and anti-inflammatory diets, aimed at reducing DII, may serve as important complementary strategies. This nutritional approach seeks to reduce exercise-induced immune overload, optimizing recovery and sports performance across age groups and maturation stages.

Limitations and future directions

Despite its relevant findings, the present study presents the following limitations: (i) Only athletes from intermittent sports were included, requiring caution when generalizing the findings to endurance sports; (ii) Only male athletes were analyzed, and extrapolation to female athletes should be made with caution; (iii) Although intragroup comparisons, statistical corrections, *post hoc* power analyses, and control for interaction variables (FFM, BM, and DII) were performed, caution is warranted when interpreting the results of the adult group due to the small sample size. We note that while the sample size and group imbalance are considerable limitations, the statistical methodology employed (GLMM) was chosen to minimize the impact of these factors, thereby increasing the internal validity of the results with the observation of 120 events when considering the time points (pre, immediately after, 2 h, and 24 h after RSE); (iv) Finally, a limitation to be considered is the absence of a control group for the RSE protocol; however, the repeated-measures design, combined with the GLMM analysis, allowed each participant to serve as their own control, strengthening the study's internal validity.

Future studies should seek to address the limitations outlined in this section.

Conclusion

This study concludes that FFM, BM, and the DII significantly influence the inflammatory response to repeated sprint exercise (RSE) in male athletes. In adolescents, BM appears to modulate the interaction between FFM and interleukin dynamics after intense exercise. Lower FFM levels were associated with a more pronounced and prolonged IL-6 response, indicating a potentially greater risk of immune overload and the need for more cautious recovery strategies. In adults, greater FFM was linked to a more robust IL-10 response, suggesting a more efficient anti-inflammatory profile. DII, in turn, independently

modulated the immune response, with less inflammatory dietary patterns associated with cytokines that favor recovery (e.g., IL-10).

These findings highlight the importance of an integrated approach to training load management that considers not only body composition and BM, but also athletes' dietary patterns. The incorporation of DII as a nutritional monitoring tool may represent a strategic advancement in the personalization of training and the promotion of safe and effective immunometabolic adaptations. It is recommended that strength and conditioning coaches, sports scientists, and nutritionists adopt a multidimensional approach that include regular assessments of FFM, BM, and DII in training and recovery planning. Integrating these markers into evaluation and planning processes may significantly enhance the personalization of sports interventions, contributing to athletes' health, performance, and long-term development.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://figshare.com/articles/dataset/Raw_Data_-_Cytokines_DII_FFM_BM_Sprints_/29506262.

Ethics statement

The studies involving humans were approved by Ethics Committee of the Federal University of Rio Grande do Norte (#35197020.8.0000.5537). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

PA-N: Writing – review & editing, Investigation, Conceptualization, Validation, Methodology, Writing – original draft, Formal analysis, Visualization, Data curation. EF: Data curation, Validation, Investigation, Methodology, Writing – review & editing, Formal analysis, Writing – original draft, Visualization. GA: Writing – review & editing, Writing – original draft, Resources, Visualization, Validation. KS: Writing – review & editing, Resources, Visualization, Validation, Supervision. RC: Writing – review & editing, Visualization, Resources, Validation. LA: Validation, Writing – review & editing, Visualization, Software, Resources. VP: Supervision, Methodology, Validation, Writing – original draft. FA: Supervision, Methodology, Validation, Writing – original draft, Conceptualization, Visualization. BC: Conceptualization, Project administration, Supervision, Validation, Methodology, Writing – review & editing, Writing – original draft, Resources, Visualization, Investigation. PD: Software, Resources, Writing – original draft, Investigation, Visualization, Validation, Formal

analysis, Data curation, Supervision, Conceptualization, Writing – review & editing, Project administration, Methodology.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effect of pacing strategy modification on 200 m performance in athletics

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In the 200 m sprint, it remains unclear whether modifying pacing distribution can lead to improved performance. This study aimed to address this question through three approaches: (1) cross-sectional analysis of world-class sprinters, (2) longitudinal analysis of an elite Japanese sprinter, and (3) an intervention involving pacing strategy modification for that sprinter. The study comprised three components: (1) cross-sectional analysis of 53 official races by world-class sprinters, (2) longitudinal analysis of 8 official races by an elite Japanese sprinter, and (3) a pacing intervention based on these analyses. Pacing distribution was assessed using two indices: the percentage of each 10 m split time relative to the 200 m record (%ST), and the percentage of each 100 m split time relative to the 100 m personal record (%PR). Cross-sectional analysis showed that world-class sprinters tended to sprint relatively slow in the first half and faster in the second half of the 200 m. Longitudinal analysis indicated that the Japanese sprinter achieved faster overall times when his speed in the 100–200 m segment was higher. Based on these findings, the modified pacing strategy improved his 200 m record from 20.43 to 20.14 s. These findings suggest that a pacing strategy focusing on maintaining speed in the latter half of the race, by moderating early acceleration, may contribute to performance improvement in elite-level 200 m sprinting.

KEYWORDS

split time, pace distribution, race strategy, running speed, step frequency, step length, re-acceleration

1 Introduction

The 200 m race in athletics is a sprinting event where athletes transition from a curved to a straight track at extremely high speeds (1–4). Sprinters typically complete the distance in approximately 20 s (3, 4). In simulated 200 m events, anaerobic energy supply declines significantly within that 20 s duration (5). A previous study has demonstrated that anaerobic energy stores are substantially depleted during the 200 m sprint (6). This is likely due to rapid declines in ATP-PCr levels and muscle glycogen at the onset of high-intensity exercise (7–9). Therefore, 200 m performance appears to depend on the magnitude of anaerobic work capacity.

The 200 m race differs from the 100 m in that sprinters must transition from a curve to a straight. Similar to the 400 m, the 200 m also begins on a curve, but sprinters are required to

achieve high running speeds primarily through greater step frequency (10–12). An Olympic 200 m gold medalist not only attains a high running speed but also maintains a high step frequency in the latter half of the race, facilitated by short ground contact times (13). It remains unclear whether this strategy enables maximal speed in the first 100 m that is then sustained or whether athletes deliberately moderate early acceleration. Little information is available on pacing strategies in 200 m track events. In 400 m races, an initial high step frequency allows sprinters to reach high speed in the first 200 m. However, this often leads to a rapid decrease in frequency and a significant speed drop in the second 200 m (14–16). Conversely, controlling step frequency in the first half and moderating speed minimizes the frequency in the second half, helping to maintain high speed throughout (14, 15). In cyclic knee-joint movement, decreases in external force and mechanical power are less pronounced at lower tempos than in higher tempos (17). Additionally, in 400 m races, improved performance is associated with increased stride length (15). In 400 m races, adopting a more driven pacing strategy (around 93% of the 200 m personal best) has been linked to a smaller decline in both step frequency and step length during the latter half of the 400 m race, together with a reduced discrepancy between the first and second halves compared with a more leading strategy (98%) (12). Additionally, personal record improvement is associated with increased stride length with more or less constant step frequency (15). Based on the aforementioned studies, we hypothesized that moderating step frequency in the first half of the race, thereby suppressing speed acquisition, could reduce the subsequent frequency decline, ultimately allowing athletes to maintain high speed and long strides.

Therefore, this study aimed to investigate the relationship between 200 m performance and pace distribution in elite sprinters and to clarify an effect of pacing modification on race outcomes and spatiotemporal parameters. To test this, we analyzed 200 m races to clarify the relationship between 200 m records and pace distribution across the world's elite sprinters and within an elite sprinter. Furthermore, we examined how modifying the pacing strategy of the Japanese sprinter affected his 200 m record and spatiotemporal parameters.

2 Materials & methods

2.1 Data collection and procedures

To test the aforementioned hypothesis, we analyzed 53 official 200 m races to elucidate the characteristics of pacing strategy employed by world male elite sprinters competing in the Olympics and Diamond League series (Experiment 1; Exp. 1) (18, 19). In total, 207 races were initially collected; however, when sprinters appeared in multiple races, only their best-performance race was included in the analysis. The tracking data were obtained from the official “Race Analysis Graphical” reports provided by OMEGA Timing, the official timekeeper of the Diamond League and the Olympic Games. For the 2023 season, these data were based on OMEGA's Real-Time Tracking System, which utilizes a lightweight chip embedded in the bib number worn on the athletes' chests. The

system transmits real-time data to 16 receivers positioned around the outside of the track and 4 on the inside, capturing split times and speed data in real time with a resolution of 0.01 s (i.e., to the hundredth of a second). Official finishing times were determined by the Scan'O'Vision Myria photofinish camera, which records up to 10,000 digital images per second (20, 21). For the 2024 season, including the Paris Olympic Games, OMEGA introduced a new system featuring Computer Vision technology for tag-free athlete tracking and the Scan'O'Vision Ultimate capable of capturing up to 40,000 images per second (22, 23). Although we did not collect the data ourselves, the data source is internationally recognized and serves as the official basis for performance data at the Diamond League and Olympic Games, which guarantees the highest standards of validity and reliability for cross-sectional analyses. Additionally, we analyzed eight races of a Japanese elite sprinter, including data on 200 m times and split times for each 100 m segment (Exp. 2). Combining the results of Exp. 1 and Exp. 2, we created a training program to modify the sprinter's pace-distribution strategy. We then prescribed this program to the elite Japanese sprinter and examined whether altering his pacing strategy would change his pace distribution and yield a new 200 m race record (Exp. 3). This study was approved by the ethics committee of the National Institute of Fitness and Sports in Kanoya (Approval Number: 23-1-39), and all procedures conformed to the Declaration of Helsinki. Prior to participation, the athlete was fully informed of the study's purpose and risks and provided written consent.

2.2 Study design in Exp. 1

Fifty-three races by 53 sprinters who competed in the Diamond League series during 2023 and 2024, as well as in the 2024 Paris Olympics (18, 19), were analyzed. The data included their 200 m times ranging from 19.47 s to 20.87 s, broken down into 10 m segments, along with their 100 m personal records. For sprinters who competed in multiple races, only their fastest time was included in the analysis. We categorized the races into two groups: those completed under 20 s (fast races, $N = 9$) and those completed in over 20 s (slow races, $N = 44$). This threshold was adopted based on the historical observation that no athlete has failed to reach the World Championships final with sub-20 s performance in the 200 m (24). Therefore, a time under 20 s was considered a practical indicator of world-class performance. To clarify the pacing distribution associated with faster 200 m records, we computed the following variables.

3.2.1 Running speed per 10 m and percentage of each 10 m split time relative to the 200 m record (%St)

Running speed per 10 m was derived from the 10 m split time (25). The %ST was calculated by dividing the time for each 10 m split by the 200 m record time and expressing it as a percentage. A higher %ST value indicates that sprinters ran relatively slower during that specific segment compared to other segments of the races.

3.2.2 Percentage of passing time at each 100 m segment of a 200 m race relative to 100 m personal record (%PR)

The %PR for each 100 m segment was calculated by dividing the time for that segment by the sprinter's personal best time for 100 m and expressing it as a percentage (25). A higher %PR value indicates that sprinters ran at a speed closer to their 100 m personal record. The individual 100 m records used in the analysis were obtained from the same year as the corresponding 200 m race records. The analysis of %PR was based on 46 races, as seven sprinters did not have a 100 m record in the same season (faster races, $N = 8$; slower races, $N = 38$).

2.3 Study design in Exp. 2

To validate the effectiveness of the pacing strategy proposed in Exp. 1, an elite Japanese sprinter (MS) (age 25 years, height 1.736 m, body mass 72.0 kg), who had a PR of 10.14 s for 100 m and 20.43 s for 200 m prior to modifying his pacing strategy, implemented this strategy during an official national race. MS also served as a reserve member of the 4 × 100 m relay team at the 2023 World Athletics Championships. MS engaged in specific training program for at least 3 h per day, 5 days per week, under the guidance of coaches YC and TY. His 200 m race time was recorded at 20.43 s during the 65th East Japan Corporate Athletics Championship. MS initially adopted a pacing strategy that emphasized sprinting as fast as possible from the start. In addition to the results of Exp. 1, the data from before the MS changed their pace distribution was also examined, and based on those results, the MS adjusted their pace-distribution strategy with the advice of the coaches.

To determine the pacing strategy before modifying his race strategy, we analyzed the data ($N = 8$) from MS's 200 m race using the methods mentioned in previous studies (11, 26, 27). MS participated in the 6th Fuji North Foot World Trials held on August 18, 2024. MS's races were recorded using a digital video camera (Lumix FZ300, Panasonic, Japan; frame rate: 239.76 fps; shutter speed: auto; f-ratio: 2.8; resolution: 640 × 480 pixels) for two races and obtained from internet broadcasts for seven races. Running time, speed, and spatiotemporal variables were analyzed at each 100 m segment (Table 1). The camera was positioned in the spectator stands, directly aligned with the finish line on the back straight and elevated above track level. This placement enabled clear lateral capture of both the 100 m mark and the finish line. To account for the timing discrepancies characteristic of broadcast footage, the analysis was performed based on a frame rate of 29.97 fps without relying on the on-screen timer. The start time in the 200 m race was estimated by back-calculating from the official finish time and the frame number at which MS crossed the finish line, taking into account the video frame rate.

If a line was present at the 100 m mark, the time to reach that mark was measured directly. If no line was visible at the 100 m mark, we performed a linear regression using the split times at the entrance (80 m mark) and exit (110 m mark) of the fourth-

corner takeover zone to interpolate the 100 m time. We then calculated the average running speed for each segment by dividing segment distance by its time. Step frequency was obtained by counting ground contacts within each 100 m segment and dividing that count by the segment time. Finally, we calculated average step length for each segment by dividing average running speed by average step frequency.

2.4 Concept for the proposed race strategy and sprint training program (Exp. 3)

Based on the pace distributions obtained in Exp. 1 and Exp. 2, MS adjusted his race strategy to run relatively slower in the first half and faster in the second half than in his previous races. Target values were set at 96% (10.58 s) for the 0–100 m segment and 106% (9.58 s) for the 100–200 m segment, relative to his personal best 100 m record.

In addition to regular training—warm-up exercises (e.g., medicine-ball throws, mini-hurdle high knees, hurdle drills), resistance training (e.g., squats, deadlifts, power cleans, bench presses), and plyometric drills (e.g., hurdle jumps, bounding, hopping)—he performed sprint sessions focused on pacing twice weekly from July 1 to August 17, 2024. The sprint program comprised distances of 120, 150, 200, and 250 m. In each drill, MS completed the first 100 m in no less than 10.60 s, regardless of total distance, then sprinted maximally over the final 100 m. For 200 m repetitions, he was further instructed to control speed up to the 80 m mark, re-accelerate between 80 m and 110 m (exit of the curve), and sprint the last 100 m at maximal effort. Other training loads during the intervention were kept consistent with previous levels.

During this intervention period, no races were run using the pre-intervention pacing strategy. We evaluated its effectiveness by comparing post-intervention race records and spatiotemporal variables with those from previous official races. To ensure adherence to the desired pacing strategy, split-time targets were provided during training, and real-time verbal feedback reinforced appropriate pacing.

2.5 Statistical analyses

Descriptive statistics are presented as means and standard deviations (SDs). All analyses were conducted using SPSS software (version 26.0; IBM, Armonk, NY, USA).

In Exp. 1, a two-way repeated-measures analysis of variance was conducted to assess main effects and interactions for running speed, %ST in each 10 m segment, and %PR in each 100 m segment between faster and slower races. When interactions were significant, simple main-effects tests were carried out for *post hoc* comparisons. Additionally, Pearson's correlation coefficient (r) was used to examine the relationship between 200 m race time and each independent variable.

In Exp. 2, Pearson's product-moment correlation coefficients (r) were calculated between 200 m race times and running speed

for each 100 m segment, step frequency, step length, %ST, and %PR across the eight races MS completed prior to the pacing trial.

In Exp. 3, small-worth criteria (SWCs) were established based on the mean and SD of each 100 m split time from those eight pre-intervention races, with each SD multiplied by 0.2 to derive the SWC (28). We then determined whether each independent variable deviated from its SWC following the pace-distribution modification.

3 Results

3.1 Comparisons of faster races to slower races in the independent variables during the 200 m races (Exp. 1)

Faster races exhibited higher running speeds across almost all segments compared with slower races, except the 0–10 m segment (Figure 1A). The %ST values for the first 50 m were greater in faster races; conversely, %ST values from 100 m to 200 m were smaller in faster races (Figure 1B). Additionally, %PR in the 100–200 m segment was higher in faster races, whereas no significant difference was observed in %PR for the 0–100 m segment (Figure 1C).

3.2 Associations of 200 m times with the independent variables across all races (Exp. 1)

Across all races (Exp. 1), almost all 10 m segment mean running speeds and maximal running speed were negatively correlated with 200 m times, except in the 0–10 m segment. In contrast, the 200 m time showed significant negative correlations with %ST in the first 70 m and significant positive correlations with %ST from 110 m to 200 m (Figure 2A).

The %PR in the second half of the 200 m was significantly negatively correlated with overall 200 m time (Figure 2B), whereas no significant correlation was found for %PR in the first half (Figure 2C).

3.3 Effects of changing pace distribution during a 200 m race on the independent variables (Exp. 2 and 3)

Table 1 shows the relationship between MS's pre-intervention 200 m race record and running speed, step frequency, step length, %ST, and %PR for each 100 m segment. A better 200 m performance was associated with higher values in the 100–200 m segment. After pace-specific sprint training, MS improved his personal best from 20.43 s to 20.14 s, a reduction of 0.29 s. Running speed in the first 100 m remained below the SWC threshold, whereas speed in the second 100 m exceeded it (Table 2). Similarly, step frequency and step length in the

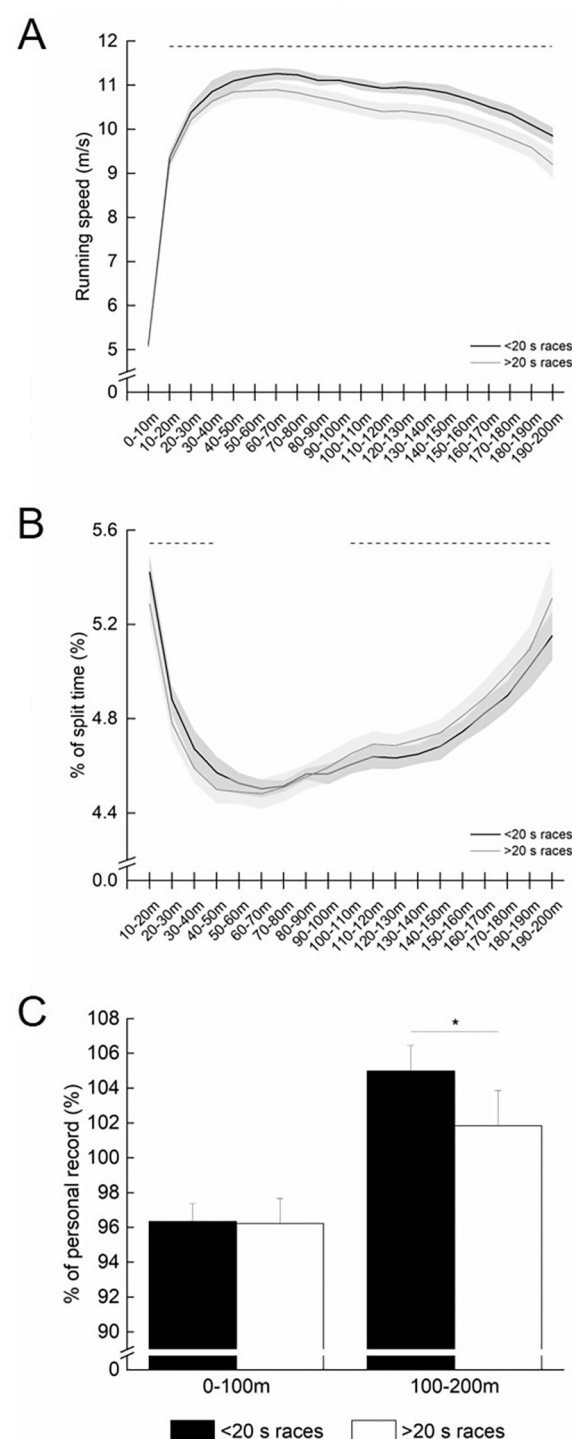


FIGURE 1

(A) running speed for each 10 m segment during 200 m races. (B) The percentage of each 10-m segment time relative to the 200 m race time (%ST). The black solid line represents data for faster races (<20 s), while the grey solid line represents data for slower races (>20 s). The dotted line indicates segments where significant group-related differences are found ($p < 0.05$). The %ST in the 0–10 m segment is not shown for readability due to its higher value. In the corresponding section, faster races exhibited a significant higher %ST compared to slower races (29.47% vs. 28.79%). (C) Comparison of the percentage of each 100 m segment time relative to the personal record of the 100-m race (%PR) between the 0–100 and 100–200 m sections. The black filled bar represents faster races, and the grey filled bar represents slower races. * denotes a significant difference ($p < 0.05$).

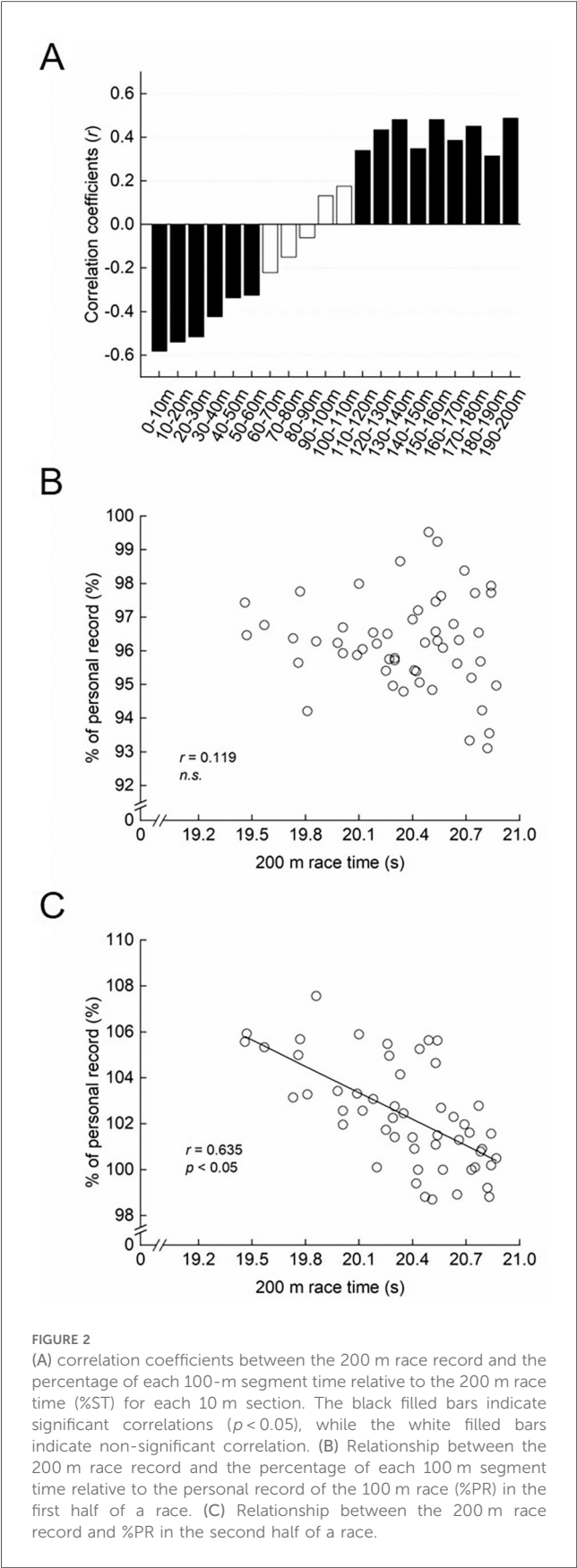


FIGURE 2
(A) correlation coefficients between the 200 m race record and the percentage of each 100-m segment time relative to the 200 m race time (%ST) for each 10 m section. The black filled bars indicate significant correlations ($p < 0.05$), while the white filled bars indicate non-significant correlation. (B) Relationship between the 200 m race record and the percentage of each 100 m segment time relative to the personal record of the 100 m race (%PR) in the first half of a race. (C) Relationship between the 200 m race record and %PR in the second half of a race.

TABLE 1 Correlation coefficients between the 200 m race records before pace modification and the measured variables for MS.

Variable	Segment	Correlation with 200 m race record
Running speed	0–100 m	–0.302
	100–200 m	–0.965*
Step frequency	0–100 m	–0.387
	100–200 m	–0.646
Step length	0–100 m	0.402
	100–200 m	–0.090
%ST	0–100 m	–0.866*
	100–200 m	0.866*
%PR	0–100 m	0.369
	100–200 m	–0.905*

%ST, the percentage of each 100 m segment time relative to the 200 m race time; %PR, the percentage of each 100 m segment time relative to the personal record of the 100 m race. *Denotes $p < 0.05$.

second 100 m surpassed SWC thresholds, while both variables in the first 100 m stayed within the SWC range (Table 2). %ST increased in the first 100 m segment but decreased in the second, relative to the SWC threshold (Table 3). Conversely, %PR decreased in the first 10 m segment but increased in the second, compared with the SWC threshold (Table 2).

4 Discussion

In this study, to examine pace distribution, we analyzed the percentage of each segment within the 200 m race (%ST) and the percentage of each segment relative to each sprinter’s 100 m personal best time (%PR). Results from Exp. 1 showed that 200 m races completed in under 20 s exhibited smaller %ST and higher %PR in the second half than races lasting 20 s or more. Exp. 2 revealed that better 200 m records correlated with higher performance in the 100–200 m segment of MS’s previous races. The pacing strategy derived from these observations successfully improved an elite Japanese sprinter’s 200 m time in Exp. 3. Additionally, analysis of MS’s pacing in his record race showed that, in the first 100 m, his running speed and %PR fell below SWC values derived from pre-intervention races while %ST was higher, indicating more controlled early pacing. In the 100–200 m segment, his running speed, step frequency, step length, and %PR all exceeded SWC thresholds, whereas %ST was lower. These findings demonstrate that MS successfully executed the targeted pace distribution, optimizing his second-half performance. Therefore, modifying strategy from emphasizing early acceleration to prioritizing sustained speed in the second half may enhance personal records in the 200 m.

This is the first study to characterize pace development among elite 200 m sprinters and to demonstrate that adjusting strategy based on these characteristics can enhance performance. Notably, MS maintained his usual training regimen throughout

TABLE 2 100 m race season record, 200 m race time, segment time, running speed, step frequency, step length and data collection method in MS.

Date	Season record [s]		Time [s]		Speed [m/s]		Frequency [Hz]		Length [m]		Method of data collection
	100 m	200 m	0–100 m	100–200 m	0–100 m	100–200 m	0–100 m	100–200 m	0–100 m	100–200 m	
2020.9.13	10.14	20.75	10.55	10.20	9.48	9.80	4.62	4.72	2.05	2.08	Internet broadcasts
2021.3.28	10.33	20.92	10.49	10.43	9.53	9.59	4.65	4.55	2.05	2.11	Internet broadcasts
2022.4.10	10.27	20.94	10.57	10.37	9.46	9.64	4.63	4.54	2.04	2.12	Internet broadcasts
2023.5.21	10.20	20.43	10.47	9.96	9.55	10.04	4.79	4.74	1.99	2.12	Internet broadcasts
2023.6.3	10.20	20.66	10.48	10.18	9.54	9.82	4.84	4.52	1.97	2.17	Internet broadcasts
2023.7.28	10.20	20.55	10.59	9.96	9.44	10.04	4.55	4.84	2.07	2.07	Internet broadcasts
2024.6.27	10.15	20.55	10.47	10.08	9.55	9.92	4.76	4.65	2.01	2.14	Digital video camera
2024.6.28	10.15	20.61	10.53	10.08	9.50	9.92	4.68	4.65	2.03	2.14	Digital video camera
Mean	10.21	20.68	10.52	10.16	9.51	9.85	4.69	4.65	2.03	2.12	–
SD	0.06	0.18	0.05	0.17	0.04	0.17	0.10	0.11	0.03	0.03	–
SWC	10.19–10.22	20.64–20.71	10.51–10.53	10.12–10.19	9.50–9.52	9.81–9.88	4.67–4.71	4.63–4.67	2.02–2.03	2.11–2.12	–
2024.8.18	10.15	20.14	10.60	9.54	9.43	10.48	4.68	4.86	2.02	2.16	Internet broadcasts
Feasible	Favor	Favor	Favor	Favor	Favor	Favor	Disfavor	Favor	Disfavor	Favor	–

Bold values indicate results outside the SWC range.

TABLE 3 Percentage of each 100 m segment 200 m race, percentage of time of each 100 m segment relative to personal record of 100 m race in MS.

Date	%ST [%]		%PR [%]	
	0–100 m	100–200 m	0–100 m	100–200 m
2020.9.13	50.84	49.16	96.11	99.41
2021.3.28	50.14	49.86	98.47	99.04
2022.4.10	50.48	49.52	97.16	99.04
2023.5.21	51.25	48.75	97.42	102.41
2023.6.3	50.73	49.27	97.33	100.20
2023.7.28	51.53	48.47	96.32	102.41
2024.6.27	50.95	49.05	96.94	100.69
2024.6.28	51.09	48.91	96.39	100.69
Mean	50.88	49.12	97.02	100.49
SD	0.44	0.44	0.15	0.27
SWC	50.79–50.96	49.04–49.21	96.87–97.17	100.21–100.76
2024.8.18	52.63	47.37	95.75	106.39
Feasible	Favor	Favor	Favor	Favor

%ST, the percentage of each 100 m segment time relative to the 200 m race time; %PR, the percentage of each 100 m segment time relative to the personal record of the 100 m race. Bold values indicate results outside the SWC range.

the observation period, with the sole addition of pacing strategy drills, and no significant improvements occurred in manually recorded sprint times during standard sessions. As [Tables 2, 3](#) show, pacing modifications were clearly reflected in race data. For example, although MS recorded his slowest 0–100 m split (10.60 s) post-intervention—slower than his slowest pre-intervention split (10.57 s; finish time: 20.94 s)—he achieved a personal best 200 m time of 20.14 s thanks to a fastest-ever 100–200 m split (9.54 s). Based on [Exp. 1](#), we adjusted pace distribution for MS in a 200 m race. Consequently, he improved his personal best by 0.29 s, from 20.43 s to 20.14 s, surpassing the 20.16 s qualifying standard for the 2025 World Championships in Tokyo. This performance also exceeds the 20.31 s mark required to reach the final of the 2024 Paris Olympics, matching the 7th-place finalist’s time. These findings indicate that performance gains stemmed from the revised pacing strategy rather than general training adaptations.

While it is widely recognized that the first half of a 200 m sprint is naturally slower due to the block start, curve running, and early acceleration ([29](#)), our study quantifies how performance in the latter half distinguishes sub-20 s outcomes. Although [Exp. 3](#) represents a single-case intervention, it rests on robust evidence from 207 race observations of 53 elite male sprinters ([Exp. 1](#)). By combining cross-sectional analysis with a longitudinal case study and implementing a targeted pacing intervention, we demonstrate both the practicality and efficacy of this approach. These insights may guide individualized coaching strategies, even if not universally applicable.

In this study, 200 m races completed in under 20 s displayed consistently higher running speeds throughout than those lasting 20 s or longer. Moreover, maximal running speed was strongly and significantly correlated with 200 m performance for all segments except the 0–10 m segment. In 100 m events, elite sprinters attain higher maximal speeds than average sprinters, with differences becoming particularly pronounced after the 30 m mark ([30](#)). As in the 100 m sprint, the 200 m event underscores that achieving high running speed is crucial for superior performance.

The pace distribution analysis showed that elite 200 m sprinters exhibited a larger %ST in the 0–60 m segments and a smaller %ST in the 110–200 m segments than those exhibited by sub-elite sprinters, suggesting a strategy of slower pacing in the first half and faster pacing in the second. Furthermore, elite sprinters’ %PR was higher in the 100–200 m segment than that of sub-elite athletes.

When examining the race after the pacing strategy modification, the %PR in the 0–100 m segment was 95.75%, and that in the 100–200 m segment was 106.39%, both falling outside the SWC range calculated from MS’s previous race data. This suggests that in order to maximize running speed in the 100–200 m segment, MS could control running speed in the 0–100 m segment. At both the 2023 World Championships and the 2024 Paris Olympics, analysis of the 200 m winners showed a renewed increase in running speed between the 110–120 m and 120–130 m segments ([Supplementary Data S1](#)), a phenomenon hereafter referred to as re-acceleration. Similarly, the Biomechanical Report of the 2017 IAAF World Championships documented a speed-maintenance strategy with re-acceleration in those same segments ([31](#)). In this study, %PR in the

second half of the 200 m was significantly negatively correlated with race time. These findings indicate that elite 200 m sprinters strategically manage speed and adopt a pace distribution, including re-acceleration when transitioning from the curve to the straight, that enables higher second-half speeds. A possible factor enabling re-acceleration in the latter half of the race may be due to changes in the recruitment patterns of the ATP-PCr, glycolytic, and oxidative energy systems (12, 32, 33). In maximal sprinting, the ATP-PCr system, which provides the highest power output (33), is rapidly depleted, after which the relative contributions of glycolysis and oxidative phosphorylation increase (6, 32). Therefore, in the 200 m sprint, starting at full intensity leads to a rapid depletion of ATP-PCr stores, whereas moderating early speed can attenuate ATP-PCr utilization, thereby preserving energy supply for speed maintenance and re-acceleration in the latter half of the race. Furthermore, in the 400 m sprint, it has been demonstrated that when sprinters pass the 200 m point at 93% of their personal record for 200 m, compared with passing at 98%, the 0–200 m split time and step frequency in the first 200 m were significantly lower, while both blood lactate concentration at the finish and 400 m race time showed large effect sizes, indicating a tendency toward lower values in the 93% condition (12). This finding suggests that in the 400 m sprint, adjusting step frequency can be used to control early race speed, thereby suppressing glycolytic energy utilization in the first half of the race and preserving glycolytic energy supply for speed maintenance and re-acceleration in the latter stages. In the present study, although step frequency in the 0–100 m segment of the 200 m sprint was within the SWC range, running speed was outside the SWC range, tending to be lower than in previous races. Therefore, adjusting running speed in the early phase might have suppressed glycolytic energy consumption, thereby contributing to re-acceleration passing at 100 m.

In the current study, although step frequency and step length in the 0–100 m segment remained within the SWC, running speed fell below this threshold, suggesting a deliberate pacing adjustment in the early phase. In contrast, a previous study of a 400 m sprinter (15) showed that shifting from a front-loaded strategy to a more conservative first half enabled the athlete to lower his personal best from 45.31 s to 44.77 s. That improvement was attributed to limiting early step frequency while maintaining long step length throughout. Unlike the 400 m approach, where only step frequency was reduced, our findings indicate that both step frequency and step length were intentionally curtailed in the first half of the 200 m to decrease early running speed.

5 Limitation

Some limitations warrant consideration in this study. First, the pacing intervention involved a single elite sprinter, and video analysis was confined to 100 m segments because the footage was recorded at 29.97 fps, which corresponds to 0.033 s intervals and may introduce a potential error of approximately 0.01–0.02 s compared with official records measured to 0.01 s. Future studies should recruit large samples and use high-frame-rate recordings with more fine-grained segmental analyses to test generalizability.

Second, the intervention lacked a control trial in which the athlete replicated the race under matched conditions using the previous pacing strategy. Consequently, evaluation relied on comparisons with the athlete's past official records. Although target split times and real-time verbal feedback reinforced adherence to the new strategy, the absence of a repeated race under the former strategy limits isolation of intervention effects from physiological or contextual factors.

Third, this study examined pace distribution changes only in running speed and spatiotemporal variables—step frequency and step length—but pacing modifications may also affect kinematics and physiological responses. Therefore, testing this strategy in sprinters with varied performance levels and characteristics is necessary.

Fourth, environmental factors such as wind and track conditions, as well as the competitive level of each sprinter, may also influence pacing outcomes, and future studies should consider these aspects.

Finally, because this study focused on male sprinters, future research should include female athletes. Addressing these limitations will strengthen subsequent investigations.

6 Practical applications

For sprinters such as MS, who initiate the race with maximal effort, adjusting both step frequency and step length to achieve approximately 96% of their 100 m personal best during the first 100 m may help optimize performance. In training, sprinters may target no more than 96% of their 100 m personal best in the first 100 m and then emphasize attaining and maintaining near-peak speed in the latter straight. Furthermore, sprinters already adopting this type of pace distribution could further improve their 200 m performance by lowering their 100 m personal best. These insights emphasize the importance of tailoring pacing strategies to individual characteristics when seeking to maximize 200 m sprint performance. In practice, coaches may monitor such pacing strategies by using timed training segments and providing sprinters with real-time feedback on split times to reinforce the desired distribution.

7 Conclusion

In this study, we investigated the relationship between 200 m race times and pacing strategies among world-class sprinters and an elite Japanese sprinter. Inter-subject analysis showed that world-class athletes tend to run relatively slower in the first half and faster in the second half. A within-subject analysis of the Japanese sprinter revealed that higher running speed in the 100–200 m segment was associated with faster 200 m times across eight races. Guided by these findings, we modified his pacing strategy to emphasize latter-half speed, improving his personal best from 20.43 s to 20.14 s. These results suggest that moderating early-phase acceleration to sustain speed in the latter half may enhance performance in elite 200 m sprinters.

Data availability statement

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by the ethics committee of National Institute of Fitness and Sports in Kanoya (Approval Number: 23-1-39). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

TY: Project administration, Data curation, Visualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Funding acquisition, Conceptualization, Writing – original draft. YC: Writing – original draft, Investigation, Methodology, Conceptualization, Writing – review & editing. SM: Writing – review & editing. KS: Writing – review & editing. HO: Writing – review & editing. YT: Project administration, Conceptualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fspor.2025.1657245/full#supplementary-material>

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