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Factors determining biomechanical characteristics of the swimming start, their contribution to starting enhancement and its performance prediction

Daria Małgorzata Rudnik

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Factors determining biomechanical characteristics of the swimming start, their contribution to starting enhancement and its performance prediction

Following the thesis co-supervision agreement, signed in 2017, regarding the doctoral student Daria Malgorzata Rudnik, the thesis are written in order to achieve the PhD degree in Sports Science included in the doctoral course in Sports Science designed by the Center of Research, Education, Innovation, and Intervention in Sport CIFI2D, Faculty of Sport, University of Porto (Decree- Law n-ª 74/2006, of March 24th), and Faculty of Physical Education and Sport, Wroclaw University of Health and Sport Sciences (The General Law of 20 July 2018. The Law of Science and Higher Education (Dz.U. poz. 1668 with subsequent amendments).

Thesis supervisors:

Professor Dr. João Paulo Vilas Boas

Faculty of Sport

University of Porto

Dr hab. Marek Rejman, Profesor AWF

Faculty of Physical Education and Sport

Wroclaw University of Health and Sport Sciences

Daria Małgorzata Rudnik

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Dedications

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ABSTRACT

The thesis complements current knowledge about ventral swimming start, its structure as well as factors determining its performance and optimization. Five experimental studies were conducted to expose key factors affecting the biomechanical characteristics of the swimming start. Two of them focused on consequences brought by different starting positions, one explores back plate placement effect on the temporal structure of swimming start, next compared ventral start performed by males and females, and last searched for the link between starting performance and lower body motor abilities measured with the countermovement jump (CMJ). During pool tests, all participants completed ventral starts which were monitored from starting signal up to the 15-m mark. To collect spatiotemporal data describing swimming starts the video cameras, Qualisys Motion Capture system, and 3D dynamometric starting block were used. During the CMJ test, force platforms were employed to collect signals of ground reaction forces. Acquired data were analyzed using dedicated software. Analyses conducted in the thesis revealed that: (i) for national-level athletes, the kick-start forward demonstrates superiority at start time measured at 5-m and 15-m over kick-start backward, followed by handle-start and grab-start; (ii) the kick-start forward provides a temporal advantage over its backward variant in a group of international level female junior swimmers; (iii) back plate position has a significant effect on lower limb temporal movement characteristics measured as duration of rear foot take-off and front foot stand; (iv) male swimmers, by spending less time in the block phase, swimming faster while in the water, reaching higher take-off velocity and longer flight distance, take a starting advantage over their female counterparts; (v) depending on the starting features, a different strategy regarding movement structure and their contribution has to be addressed with reference to overall start performance enhancement; (vi) the CMJ test results correlate with the overall kick-start performance, as well as variables of the start that particularly rely on the movements performed by the lower limbs. By examining the link between various individual contributing parameters, the predicting variables constituting key factors in starting performance assessment and its future development were disclosed. This way, the priority areas and recommendations for wider assessment and monitoring were exposed, which should serve for more comprehensive approaches in swimming start enhancement.

Key words: swimming start, performance determinants, starting position, back plate, gender effect, CMJ.

RESUMO

Esta tese complementa o conhecimento atual relativamente às partidas ventrais em natação, a sua estrutura, bem como fatores determinantes no seu desempenho e otimização. Foram realizados cinco estudos experimentais para expor fatores que afetem decisivamente as caraterísticas biomecânica da partida em natação. Dois destes focam-se nas consequências que advêm das diferentes posições de partida, um explora o efeito do posicionamento da placa traseira na estrutura temporal da partida de natação, o seguinte compara a partida ventral realizada por nadadores do sexo masculino e feminino, e a última procura encontrar a ligação entre o desempenho da partida e as habilidades motoras dos membros inferiores, medidas pelo salto em contramovimento (CMJ). Durante os testes na piscina, todos os participantes completaram partidas ventrais monitorizadas desde o sinal de partida até a marca de 15-m. Para a recolha de dados espácio-temporais que descrevam as partidas de natação, foram utilizadas câmaras de vídeo, o sistema Qualisys Motion Capture e o bloco de partida dinamométrico 3D. Durante o teste de CMJ, foram utilizadas plataformas de força para registar as forças de reação do solo. Os dados adquiridos foram analisados usando um software dedicado. As análises realizadas nesta tese revelaram que: (i) para atletas de nível nacional, o pontapé inicial para a frente revela-se superior no tempo de início medido a 5-m e 15-m do pontapé inicial para trás, seguido da partida com barra lateral e partida com agarre; (ii) o pontapé inicial para a frente fornece uma vantagem temporal sobre sua variante para trás num grupo de nadadoras juniores de nível internacional; (iii) a posição da placa traseira tem um efeito significativo nas características temporais do movimento dos membros inferiores medidas durante a fase de contacto com o bloco; (iv) os nadadores do sexo masculino, por manterem um menor período de contacto com o bloco, nadarem mais rápido na água, alcançando maior velocidade de descolagem e maior distância de voo, apresentam uma vantagem na partida comparativamente com as suas contrapartes do sexo feminino; (v) dependendo das características de partida, uma estratégia diferente em relação à estrutura do movimento e sua contribuição deve ser abordada relativamente à melhoria global do desempenho de partida; (vi) os resultados do teste de CMJ correlacionam-se com o desempenho geral da partida com pontapé inicial, bem como com variáveis da partida que dependem particularmente dos movimentos realizados pelos membros inferiores. Ao examinar a relação do contributo individual de vários parâmetros, as variáveis de previsão que constituem fatores-chave na avaliação do desempenho da partida em natação foram evidenciados. Deste modo, as áreas prioritárias e recomendações para avaliação e monitorização mais amplas foram expostos, o que deverá servir para abordagens mais abrangentes na melhoria da partida em natação.

Palavras-Chave: partida em natação, determinantes de desempenho, posição de partida, placa traseira, efeito do sexo, CMJ.

STRESZCZENIE

Rozprawa doktorska uzupełnia aktualną wiedzę o informacje z zakresu biomechanicznej charakterystyki skoku startowego w pływaniu. Składa się na nią cykl oryginalnych, powiązanych ze sobą tematycznie prac badawczych tworzących spójną całość i wpisujących się w nurt poszukiwań czynników determinujących skuteczność skoku startowego w pływaniu. Za pomocą metod i narzędzi biomechaniki przeprowadzono wielostronną analizę startu pływackiego uwzględniając pozycję startową, ustawienie panelu tylnego platformy startowej, płeć oraz potencjał motoryczny pływaków. Uogólnienia wyłonione w toku badań stały się kanwą modelowania statystycznego i wyznaczenia równań regresji służących predykcji skuteczności wykonania skoku startowego. Celem badań omawianych w pierwszym artykule było porównanie struktury czasowo-przestrzennej ruchu w kierunku identyfikacji elementów węzłowych, determinujących skuteczność startu z uwzględnieniem jego różnych technik („grab-start", „handle-start", oraz dwa warianty „kick start"). W kolejnej pracy, analizy uszczegółowiono do najpowszechniej stosowanej techniki startu - „kick-start", skupiając się rozpatrzeniu jej wariatów („forward" i „backward"). Do badań wybrano także odmienną, wyselekcjonowaną grupę pływaczek reprezentujących poziom międzynarodowy. Następne badania dostarczyły informacji w obszarze wpływu indywidualnych preferencji pływaków w ustawieniach panelu tylnego platformy startowej na skuteczność startu. Kolejny rozdział poświęcono analizie wpływu wybranych, indywidualnych cech morfo-funkcjonalnych pływaków na skuteczność wykonania startu z uwzględnieniem płci badanych. W ostatniej z cyklu prezentowanych prac badawczych podjęto poszukiwania zależności pomiędzy wybranymi parametrami testu CMJ a biomechaniczną charakterystyką skoku startowego w pływaniu. Grupę badawczą stanowili pływacy obu płci reprezentujący głownie międzynarodowy poziom sportowy. Do zebrania danych wykorzystano kamery filmowe, system Qualisys Motion Capture oraz blok startowy wyposażony w platformy dynamometryczne. Parametry CMJ zostały wyliczone w oparciu o zebrane w jego trakcie wartości sił reakcji podłoża. Zebrany materiał został poddany analizom wykorzystującym oprogramowanie dedykowane do konkretnych urządzeń pomiarowych. Przeprowadzano także zawansowane analizy statystyczne. Sformułowano następujące wnioski: (i) wykazano istnienie istotnych różnic pomiędzy alternatywnymi technikami skoku; ii) jako najskuteczniejszą technikę skoku startowego u pływaków reprezentujących zróżnicowany poziom sportowy, wskazano „kick-start" z przednią projekcją środka ciężkości ciała; (iii) indywidualne ustawienie

panelu tylnego platformy startowej wpływa na strukturę czasowo-przestrzenną ruchów kończyn dolnych podczas odbicia i skutkuję efektywnością startu; (v) rozpoznano, że biomechaniczne determinanty skuteczności skoku startowego oraz strategie realizacji techniki tego elementu wyścigu pływackiego są odmienne w przypadku kobiet i mężczyzn; (vi) stwierdzono istnienie zależności pomiędzy wybranymi parametrami testu skoczności CMJ a biomechaniczną charakterystyką skoku startowego w pływaniu; (vii) skonstruowanie matematyczne modele odzwierciedlające determinanty skuteczności skoku startowego. W wymiarze poznawczym stworzono obiektywne przesłanki mogące służyć poprawie skuteczności techniki skoku startowego, które w wymiarze praktycznym mogą wspomagać proces treningowy. Takie wieloaspektowe, holistyczne podejście do identyfikacji związków przyczynowo-skutkowych tłumaczących efektywność techniki skoku startowego powinno usprawnić monitorowanie aktualnego potencjału motorycznego pływaka i ułatwić prognozowaniu jego rozwoju.

Słowa kluczowe: pływanie, skok startowy, determinanty skuteczności, pozycja startowa, różnice płciowe, CMJ

ABBREVIATIONS

ANOVA	Analysis of Variance
B_hv	Average horizontal velocity at block phase
BP	Backward position of back plate
BT	Block time
B_v	Average vertical velocity at block phase
B_vv	Average resultant velocity at block phase
CM	Center of mass
cm	Centimetre
CMJ	Countermovement jump
Dec1	Decrease in horizontal velocity between the take-off and the 5-m mark
Dec2	Decrease in horizontal velocity between the 5-m mark and the 15-m mark
EA	Entry angle
e.g.	For example
E_hv	Entering horizontal velocity
F	Females
FC ratio	Ratio between the flight time and the contraction time
FD	Flight distance
FF	Front foot stand
FINA	Fédération Internationale de Natation
FP	Forward position of back plate
FT	Flight time
F_hv	Average horizontal velocity at flight phase
F_v	Average resultant velocity at flight phase
F_vv	Average vertical velocity at flight phase
G	Grab-start
GRF	Ground reaction force
H	Handle-start
Hip displacement	Hip displacement during flight phase
Hoff	Hands take-off
Hoff-RT	Hands take-off - RT
Hz	Hertz (frames per second)
KB	Kick-start backward
KF	Kick-start forward
kg	Kilogram
LED	Light emiting diode
M	Males
m	Meter
Max	Maximum

m/s	Meter per second
N	Newton
MT	Movement time
offA	Take-off angle
Off_hv	Take-off horizontal velocity
Off_v	Take-off resultant velocity
OSB11	Omega OSB11 starting block
PP	Preferred position of back plate
RFD (N/s)	Rate of force development
RFoff	Rear foot take-off
RFoff - RT	Rear foot take-off - RT
RT	Reaction time
R^2	Coefficient of determination (R-squared)
s	Second
±SD	Standard deviation
SJ	Squat jump
T5	5-m time
T5-10	5-10-m time
T10-15	10-15-m time
T5-15	5-15-m time
T10	10-m time
T15	15-m times
UK	United Kingdom
USA	United States of America
W	Watt
Wc_hv	Horizontal velocity at water contact
WT	Water time
3D	Three Dimensional
5_v	Entering horizontal velocity
α	Alpha
*****	Asterisk
p	P-value
η_p^2	Partial eta squared
%	Percentage
^{2}	Quadratic polynomial
<	Lower than
>	Higher than

CHAPTER I

GENERAL INTRODUCTION; PURPOSE AND FORMAL STRUCTURE OF THE THESIS

GENERAL INTRODUCTION

Success in competitive swimming is determined by many factors, as well as by complex relationships between them (Morais et al., 2013; Vilas-Boas, 2014a, 2014b). There are numerous areas used to describe and understand swimmers' performance. Notwithstanding, it is consensual that biomechanical and physiological factors are among the most favorably studied and applied determinants to enhance athletic performance and, consequently, the achievement of a high level in competitive sport (Zacca et al., 2018). In swimming, as an individual competitive sport, the main goal is to be the fastest over a set distance. Indeed, only the race time is a decisive factor for the swimmer's ranking position. A swimming event classification is based on small differences in race times, whereas the success depends on the very small temporal gap between the results achieved by each of the swimmers (Garcia-Hermoso et al., 2013, 2017; Simbana-Escobar et al., 2018). It is well known (Mason and Cossor, 2000) that a swimming race is a sum of four distinct phases that includes not only free-swimming but also other technical elements (start, turn, finish). Thus, success in this sport demands optimizing the efficacy and efficiency of all parts of the race (Bishop et al., 2009). In the existing literature, there is evidence of multiple detailed reports describing the compartments of swimming races and their profiles, including multiple events performed during major competitions (Arellano et al., 1994; Cossor and Mason, 2001; Da Silva et al., 2019; Garcia-Hermoso et al., 2013; Issurin and Verbitsky, 2003; Jesus et al., 2011; Marinho et al., 2020; Morais et al., 2019). Recently, increasing attention toward swimming start, turns, and finish has been observed (Da Silva et al., 2019; Gonjo and Olstad, 2021; Hermosilla et al., 2021; Marinho et al., 2020; Mason and Mackintosh, 2020; Morais et al., 2019; Qiu et al., 2021; Trinidad et al., 2020; Veiga et al., 2016; Veiga and Roig, 2017).

It has to be underlined that research in the swimming field is among the most abundant within sports science, taking into account the number of scientific publications (Vilas-Boas, 2014a). It has been shown that interest in swimming-specific research has begun to accelerate (Pelayo and Alberty, 2011). Furthermore, as summarized by Vilas-Boas (2014a, 2014b), this interest may be related to the recent modifications in the swimming rules (governed internationally by the Fédération Internationale de Natation [FINA]), driven by changes in swimming techniques and technologies (Vantorre et al., 2014). Here, the swimming start depends on a swimmer's individual capacities and abilities, starting conditions, features of the competitive event, type of the starting platform, as well as the starting technique (including the initial body position) (Blanco et al., 2017; Maglischo, 2003; Mason et al., 2007; Mason and Mackintosh, 2020; Peterson et al., 2018; Tor et al., 2015; Vantorre et al., 2014).

Over the years, also the swimming start technique has evolved as a result of searching for time reserves or evaluations of swimmers' proficiency. In short, the swimming start technique has been developed to enhance benefits for swimmers by offering them more freedom (Vantorre et al., 2014). As mentioned above, the final classification in swimming is based on a very small difference in time intervals, and that technical elements of start will probably proceed to change. Thus, sports biomechanists and engineers aim at optimizing equipment for higher sensibility and multi-condition analysis purposes. The noticeable technological advances provided by these devices supply mainly scientists with new research directions and possibilities for further understanding of start mechanisms. For swimmers and their coaches, innovative and more accurate solutions for the development and assessment of the technical training in swimming start helping improve understanding about its optimization process are also offered in this way.

During a training routine, the time measurements are commonly favored while evaluating the performance of the swimming start. However, depending on the specification of the training period or profile of the training methods applied, different expectations toward specific skills are articulated (Amaro et al., 2019; Newton, 2014; Bischop et al., 2013; Sweetenham and Atkinson, 2003; Thing et al., 2019). Consequently, not only morpho-functional characteristics might change, but also neuromuscular properties have to be taken under consideration (Nagano and Gerritsen, 2001; Newton, 2014; Thing et al., 2019; 2021) and, consequently, technical and tactical solutions applied by the athlete or any other compensations driven by them (Cormie et al., 2010; Muniz-Pardos et al., 2019; Thing et al., 2019, 2021). Therefore, the performance evaluation based only on time measurement may provide some fulfillment misunderstandings. Consequently, the result obtained in this way would rather expose the current overall effectiveness as a summary of different skills and techniques, all of which could change to a varied degree, depending on the profile of the training method applied (Muniz-Pardos et al., 2019). As it is crucial to select the accurate performance diagnostic protocol that would correspond to the specification of the assessment, the conscious and intentional design of the training process demands progress monitoring (Smith et al., 2002; Thing et al., 2021). Then, the test implemented needs to be specific for a given condition and has to bring the focus to the key parameters.

Swimming start as a technical element of the swimming race

Over the last few decades, several researchers have reported analyses of swimming race elements and profiles, including multiple events held during major competitions (Arellano et al., 1994; Cossor and Mason, 2001; Da Silva et al., 2019; Garcia-Hermoso et al., 2013; Issurin and Verbitsky, 2003; Jesus et al., 2011; Marinho et al., 2020; Morais et al., 2019). Start as the technical element that always initiates a competition leads to subsequent phases, regardless of the event, swimming technique, or distance of the race. Moreover, ventral swimming start from a starting platform is used in 22 of 26 (across all four main swimming techniques and medley races) individual events performed during Olympic Games. That is a reason for a great scientific interest in the assessment of ventral start techniques (Blanco et al., 2017).

The competition analysis shed more light on start time contribution to final race performance, indicating that it can have a significant impact on overall start performance (Slawson et al., 2011). In sprint events, the 15-m start time can account for approximately up to a quarter of the overall time spent on swimming over these distances (Cossor and Mason, 2001). Naturally, the percentage of time that athletes spend starting is highly dependent on the distance covered in the race and it decreases with race distance extension. Moreover, it was found that, as a result of individual technical training of the swimming start, a shorter time by a minimum of 0.1 s might be achievable (Blanksby et al., 2002; Maglischo, 2003). Considering that a very small margin (e.g. 0.01 s) may be decisive in the final competition classification, an effective start seems to be crucial for success in swimming. To illustrate how small differences between ranking positions can occur, one may indicate the results of the European Championships in London 2015, where the differences between the 3rd and 7th places in the men's 50 m butterfly event were 0.1 s, and the difference measured between the starting signal at take-off from the block equaled 0.11 s (considering the block time). Numerous similar examples could be easily quoted. This confirms the high importance of starts, mainly for high-level competitive swimmers, in whom thousandths of seconds could decide about losing or winning. These facts again imply the relevance of starting technique optimization in order to enhance the race performance.

The FINA swimming rules relating to start techniques limit the body positioning over the starting block: *On the starter's command "take your marks", the swimmers shall immediately take up a starting position with at least one foot at the front of the starting platform. The position of the hands is not relevant* (FINA swimming rules 2017–2021 SW 4.1). As a consequence, the swimmers are free to choose (making a conscious decision) from a wide range of body position variants, all considered as ventral starts. A considerable variability can be therefore encountered in swimmers' preferences, depending on the level of experience, swimming technique, or race type (individual or relays).

One of the most important changes in the FINA rules from the point of view of the development of ventral starting techniques was the authorization of the new start block construction (OMEGA OSB 11, Figure 1). In accordance with these rules, the flat surface (covered with non-slip material) dimensions shall be at least 0.5 m × 0.5 m, with a maximally 10° slope in relation to the horizontal plane, and it shall be situated at the height of 0.5–0.75 m above the water surface. The construction of the platform shall allow to grip in the front as well as on the sides. The starting block has an additional adjustable element (commonly termed a back plate, kick plate, or footrest) inclined at 30° in relation to the main deck; the plate can be moved across five positions in the longitudinal direction parallel to the surface of the starting block.

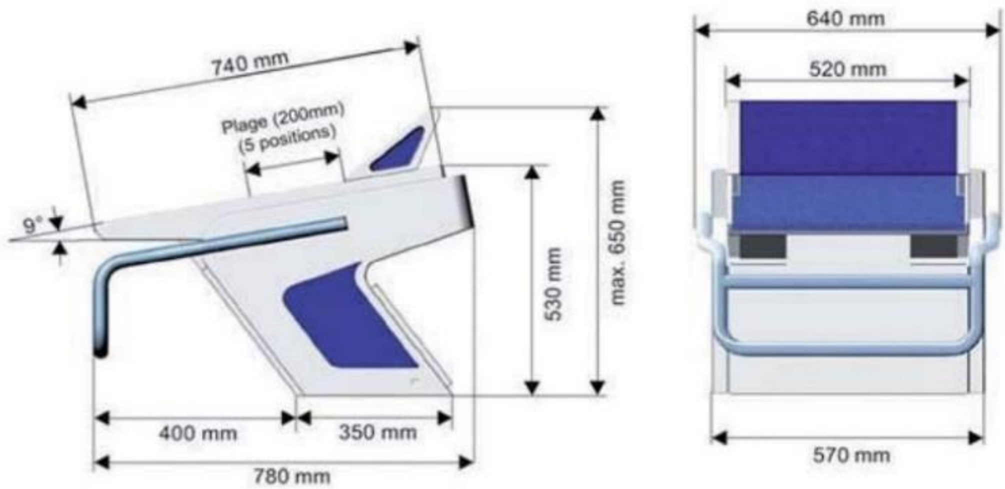
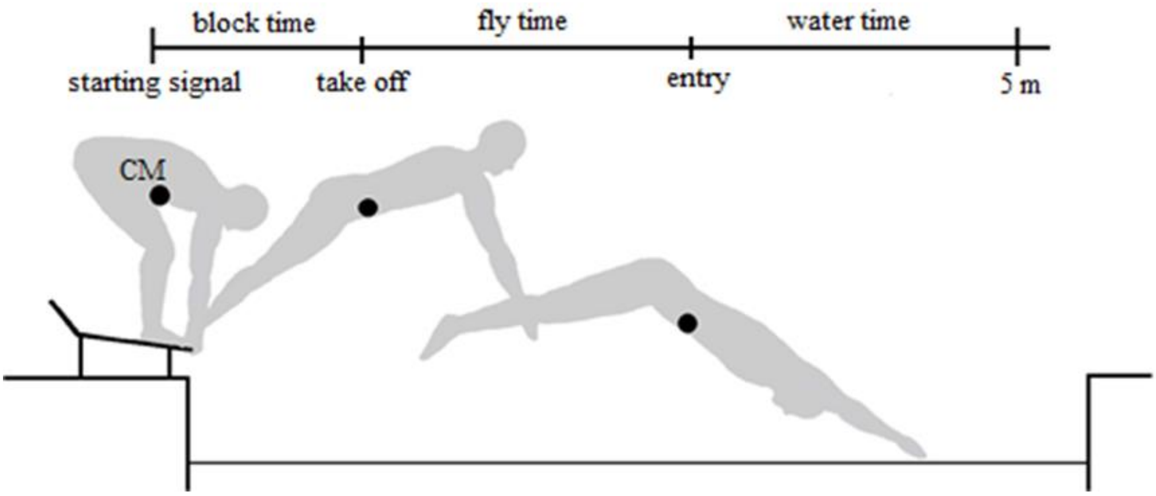


Figure 1. The OMEGA OSB 11 starting block construction.

Still, regardless of the swimming technique, owing to its kinematic description, that technical element has been usually compartmentalized into the corresponding phases: block time, flight time, water time (Cossor and Mason, 2001; Vantorre et al., 2014; Vilas-Boas et al., 2003). Each of these phases' duration could share approximately 11%, 5%, and 84% of time spent starting, respectively (Tor et al., 2014). The water phase could be further divided into the underwater phase (from emersion to the transition moment, which includes gliding followed by the undulatory or other event specific movements) and free swimming (Vantorre et al., 2014). On the other hand, the scientists have been inconclusive about the distinction of the start phases. The subsequent swimming start phases proposed by Hay (1986) are presented in Figure 2. In turn, Vantorre et al. (2010, 2014) enumerated the following start phases to 15-m considering freestyle events: block phase, flight phase, entry phase, glide phase, leg kicking phase, and swimming phase. Yet further, the exact moment of transition from one phase to another is also indistinct with regard to the flight phase. Therefore, the values of variables describing the given start phase might differ among studies.



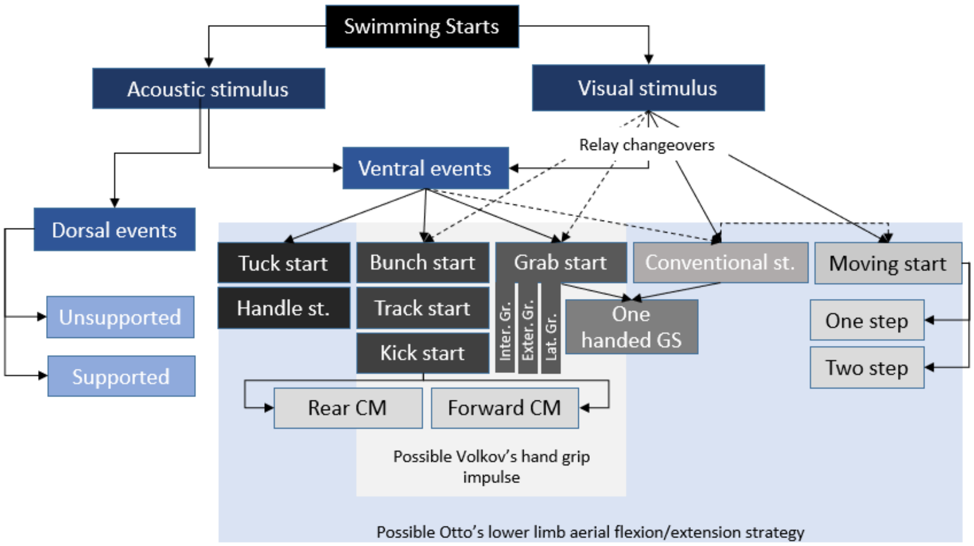
CM: center of mass.

Figure 2. Swimming start phases (adapted from: Hay, 1986).

The velocity obtained just after push-off is mainly a consequence of a swimmer's body placement over the platform, movements' organization during push-off, the force exerted over the platform and body position while leaving the platform (Blanco et al., 2017; Vantorre et al., 2014). During pushing-off from the starting block, an athlete aims to displace the body as far as possible in the forward direction over water, enabling maintenance of the highest velocity. Here, it is important to highlight that the start is the only part of the race when a swimmer is changing from the terrestrial to the aquatic environment and needs to suddenly deal with water constraints. Following this reasoning, a significantly higher density of the water in comparison with the air creates higher resistance for objects moving through it. Then, the instantaneous velocity rapidly decreases. It has even been shown that the maximum instantaneous horizontal velocity of the above-water phases of the start can account for more than twice the average free-swimming speed (Kiuchi et al., 2010).

The evolution of swimming start technique

Throughout the years, the swimming start technique has evolved, and many starting techniques have been in use (Figure 3). Indeed, swimmers can encounter a considerable variability in starting technique options (Vilas-Boas et al., 2014b). Firstly, conventional start was in use (trunk was placed nearly in a horizontal position, slightly flexed lower limbs were positioned parallel, and both feet were placed over the front of the starting block, while the upper limbs could be extended backwards or hang in front) (Bloom, 1978). At that time, different styles of starting were observed: forward arm swing, full arm swing, arms back, straight arm backswing, and circular arm backswing from swing start (Zatsiorsky et al., 1979). Grab-start (the swimmer's feet were placed parallel to each other, with the toes curling over the front edge of the starting platform, but knees and hips were flexed, allowing hands to grasp the front of the block – between or outside the feet) was introduced to swimmers' world in the 1960s, by Erick Hanauer, and rapidly gained popularity (Hanauer, 1967; Maglischo, 2003). Then, in the 1970s, the track-start position (with a staggered stance: one foot positioned at the front edge of the block and the other towards the back) appeared, and its dissemination started to accelerate over the next few years (Ayalon et al., 1975). It was copied from track and field and adapted to the swimming requirements. Using that technique, athletes could choose from a wide range of options. They could displace their position forwards (front-weighted) or backwards (rear-weighted) (Vilas-Boas et al., 2000; Vilas-Boas et al., 2003). The next implementation of the starting option modification came from the engineering side, represented by the Anti Wave Company (Blanksby et al., 2002). They tried to introduce a Super Block, with grips placed at the sides, which allowed swimmers to achieve a more forward position and reduce the block time through the use of the handle-start (Pearson et al., 1998). Meanwhile, there have been even more combinations based on the already described techniques, which include the following examples: the forward position of an athlete with hands grasping at the sides of the block (tuck), feet placement as in track-start with hands like in conventional start (bunch-start) (Aylon et al., 1975; Woelber, 1983). Finally, the lately proposed kick-start is the same technique as track-start but performed with the support of the rear foot and with a meaningful advantage of the incline element (Vantorre et al., 2014).



CM: center of mass, GS: grab-start.

Figure 3. Swimming start positions, with the consideration of limb placement (adapted from: Vilas-Boas and Fernandes, 2003).

With time passing by, together with the evolution of block-phase techniques, changes in the aerial trajectory of the swimmer's body in the flight phase have also been observed (Maglischo, 2003). Firstly, athletes were landing almost flat on the water surface (flat entry), with a very shallow entry of their head. As the main disadvantage was driven by a low entry angle, it resulted in a higher drag encounter at the point of entry. After some time, the pike/scoop start was adopted by swimmers (Seifert et al., 2010; Vantorre et al., 2014). In this option, after traveling through the air in a high arc, the athlete can cross the water surface at a very steep angle and, by taking advantage of drag reduction, they are able to travel faster during the gliding phase (Rakowski, 2010). Meanwhile, Seifert et al. (2010) distinguished four flight trajectories, yet still all of them led to similar 15-m start time.

Assessment of swimming start and its performance

The effectiveness of a movement is a result of motor abilities and techniques – the structure of the movement described in time and space (Lee et al., 2001). The exposure of changes in movement technique and its consequences in performance are brought about only with multi-directional testing. Then, the diagnostics of the technique and its permanent monitoring are important factors to include as integral elements of the training program (Smith et al., 2002). This involves the accurate assessment of numerous performance components, chosen deliberately to examine the specific purposes undertaken by the athlete. The efficacy of a sports technique is understood as a measure of the achievement of the result planned as an aim of the activity (Kent, 2006). Shortly – the shorter time an athlete spends over a given distance, the better the sports result is (Hay et al., 1986). Therefore, the time elapsed from the starting signal until the moment when the swimmer passes given distance is widely used for performance assessment (Arellano et al., 2000; Blanco et al., 2017; Vantorre et al., 2014).

Swimming start performance is commonly defined as the time elapsed between the starting signal and the moment when the swimmer's head reaches 15-m from the starting line (Issurin and Verbitsky, 2003; Mason and Cossor, 2000). That description is consistent with the FINA rules, allowing the athlete to swim totally immersed along the 15-m distance from the starting block. Besides, the 15-m time has been shown as a good predictor of the overall race time (Mason and Cosor, 2000). However, in numerous studies, the start time is quantified at distances varying from 5-m up to 15-m from the starting line (Arelano et al., 2000; Biel et al., 2010; Blanco et al., 2017; García-Ramos et al., 2015; Issurin and Verbitsky, 2003; Mason and Cossor, 2000; Vantorre et al., 2014). Here, a time exposed for a 5-m distance is rather used for block and flight phases evaluation because the swimmer should start the propulsive movements while gliding in an approximately 6.5-m distance from the wall (Elipot et al., 2009). In turn, the time measured in longer distances (up to 15-m) contains information concerning the consecutive phases of the start (Cossor and Mason, 2001; Tor et al., 2014). Here, the overall start efficiency is widely described by the time measured on the set distance. Yet, focusing only on the shortening of the time interval could cause a significant misunderstanding as, for example, a swimmer could maintain higher velocity gained throughout the course of previous action resulting from positioning the body more forward or backward in the initial phase of the start.

Comparatively, longer time until take-off spent for impulse generation will concurrently allow a swimmer to reach higher take-off velocity. Then, the push-off phase is characterized by a compromise between shorter time spent on acceleration and time extension but with higher take-off velocity (Welcher et al., 2008). Here, the block time correlates inversely with the final performance only when the new starting block with a back plate is in use (Garcia-Hermoso et al., 2013). Furthermore, the time differences among swimmers in sprint events occur in close relation to block time; in some cases, the gap between the final time is even equivalent to the one obtained from the block phase duration (Lepretre et al., 2014). Previously, a significant correlation between block time and 25-m sprint performance was found (Bussieres, 2007). However, more recent studies did not confirm this relationship for shorter distances – either for the block time or for the reaction time (García-Ramos et al., 2015). Here, following Nakamoto and Mori (2008), the reaction time is rather considerably associated with the skill dependent upon experience and learning. Yet still, block phase duration, next to take-off horizontal velocity, and flight distance has been typically identified as good predictors of swimming start efficiency (Arellano et al., 2000, 2005; Slawson et al., 2013; Tor et al., 2014).

According to previous findings, other key factors of a successful swimming start are mainly push-off variables, including horizontal and vertical impulse, average horizontal force, average horizontal acceleration, and velocity at water entry (Benjanuvatra et al., 2004; Galbraith et al., 2008; García-Ramos et al., 2015; Ozeki et al., 2012; Seifert et al., 2010; Tor et al., 2014; Vint et al., 2009). However, the specific variables revealed as major start performance determinants turn out to differ among the available studies. Ones have described start performance as a combination of reaction time, forces produced over the starting block during the block phase and low resistance during the underwater phase (Beretic et al., 2013). Others, like West et al. (2011), included rather the reaction time and the force produced during push-off as the key determinants of swimming start performance. Also, the explosive power generated by lower limbs has been exposed as a factor exerting a significant impact on swimming start performance (Arellano et al., 2005). Finally, according to Maglischo (1993), the three requirements for a good start are as follows: short reaction time, great jumping power and low resistance during the gliding phase.

In this context, training effectiveness verification is an invaluable tool in the training process optimization, especially toward exposure directions of its future development. Although more variables included in the study allow for a deeper understanding of the given issue. In contrast, from the practical point of view, the number of variables used during training practice should be limited to the necessary minimum. Therefore, the applied measurements have to be carefully selected and the starting features as well as swimmers' characteristics should be kept in mind.

The spatiotemporal structure and performance among starting techniques

Among many factors influencing the swimming start, the impact of starting technique on starting performance seems to be the most extensively studied issue. This area of swimming performance is attracting attention mainly to reveal whether there are similarities or differences between starting techniques (Blanco et al., 2017; Rudnik et al., 2021; Vantorre et al., 2014). Researchers focused mainly on the analisys of which swimmer's body placement over the starting block – or its biomechanical consequences – is determinant to achieve the best starting performance. Indeed, the starting position highly determines further phases of the swimming start and contributes to overall starting performance. On the other hand, it has been noted that, in some cases, various starting solutions may ensure similar overall starting performance (Seifert et al., 2010).

Blanco et al. (2017) presented a review of 16 studies, published from 2000 to the end of 2015, concerning the comparison between starting positions. Among these studies, nine compared track-start and grab-start, six compared track-start and kick-start, and one compared all the three mentioned techniques (Biel et al., 2010). In the quoted review, there were also two publications considering grab-start and two variants of track-start (Vilas-Boas et al., 2003; Welcher et al., 2008) and a comparative analysis of track-start and one-handed track technique (Galbraith et al., 2008). Blanksby et al. (2002) collated the grab-, track-, and handle-starts, while Vint et al. (2009) focused rather on the effects of handle (hands place on the lateral hand grips) or block configuration (with or without a back plate) on track-start performance. The next state-of-the-art review of ventral swimming starts included findings presented between the beginning of 2016 and February 2020 collected by Rudnik et al. (2021). These authors found one study that searched for differences between grab-start and track-start (Fischer and Kibele, 2016), one that compared the flight phase of grab-start and kick-start (Taladriz et al., 2017) and one that examined all of those techniques together (Peterson et al., 2018). Additionally, the mentioned authors researched two weighting stance variants of asymmetry positions. Besides, Sakai et al. (2018) investigated the influence of the initial whole-body configuration (kick-start anterior, neutral, and posterior) on the joint torques in both lower and upper limbs during the starting movements. In turn, conference papers presented by Barlow et al. (2014), Honda et al. (2012), and Welcher et al. (2008) searched for differences between and advantages of front, neutral, and rear-weighted variants of techniques implementing staggered foot positions.

Comparison between grab-start and track-start

One of the first discussions concerning the comparison of starting positions was about the advantages of the grab-start and track-start (Ayalon et al., 1975; Benjanuvatra et al., 2004; Bingul et al., 2015; Blanksby et al., 2002; Counsilman et al., 1988; Fisher and Kibele, 2018; Issurin and Verbitsky, 2003; Kruger et al., 2003; Mason et al., 2007; Takeda and Nomura, 2006; Thanopoulos et al., 2012; Vantorre et al., 2010, 2011; Vilas-Boas et al., 2003; Welcher et al., 2008; Zatsiorsky et al., 1979). The main advantage of the grab-start in comparison with the track-start is that the parallel foot placement allows simultaneous push-off with both lower limbs, which engenders comparatively higher take-off velocity (Benjanuvatra et al., 2004; Blanksby et al., 2002; Issurin and Vertebsky, 2003; Kruger et al., 2003; Vantorre et al., 2010). On the other hand, the track-start ensures reduction of the movement time (Benjanuvatra et al., 2004) and block time (Ayalon et al., 1975; Benjanuvatra et al., 2004; Takeda and Nomura, 2006; Welcher et al., 2008). Interestingly, according to Welcher et al. (2008), the backward track-start exceeds grab-start in the take-off horizontal velocity development. In some studies, though, no significant differences in the above-mentioned parameters between those two techniques were observed (Bingul et al., 2015; Blanksby et al., 2000; Thanopoulos et al., 2012; Vantorre et al., 2010). Also, some contrasting findings were presented for both techniques under consideration with regard to the total start time. A shorter total start time for grab-start was noted by Counsilman et al. (1986), Kruger et al. (2003) and Zatsiorsky et al. (1979), while a slightly better start time in the track-start was measured by Peterson et al. (2018) and Welcher et al. (2008). Finally, it was concluded by Vilas-Boas et al. (2003) that even if some considerable differences for block and flight phases existed, they still tended to disappear while swimmers traveled through the water.

Comparison between track-start and kick-start

After the implementation of the kick-start (when the back plate was added to the starting block), the track-start and kick-start became the most often compared starting positions (Beretic et al., 2012, 2013; Biel et al., 2010; Honda et al., 2010; Nomura et al., 2010; Ozeki et al., 2012; Peterson et al., 2018; Vint et al., 2009). It was shown that the kick-start was faster than the track-start when comparing the time measured at 5-m (Honda et al., 2010), 7.5-m (Biel et al., 2010), 10-m (Beretic et al., 2012) and 15-m distances (Ozeki et al., 2012). Indeed, the back plate enhances swimming start performance by shortening the block time (Beretic et al., 2012; Biel et al., 2010; Garcia-Hermoso et al., 2013; Honda et al., 2010; Ozeki et al., 2012), improving take-off velocity (Biel et al., 2010; Honda et al., 2010; Ozeki et al., 2012) and increasing acceleration parameters (Nomura et al., 2010). The above-presented results are in line with analyses based on data collected during swimming competitions (Garcia-Hermoso et al., 2013).

Comparison between forward and backward variants of kick-start

In the recent years, research in two different variants of the track-start and kick start techniques – the forward (front-weighted) and the backward (rear-weighted) projection of the center of mass – has been developed (Barlow et al., 2014; Dragunas et al., 2014; Honda et al., 2012; Peterson et al., 2018; Sakai et al., 2018; Vilas-Boas et al., 2000, 2003; Welcher et al., 2009). Reduced block phase duration was presented as the main benefit of the forward position (Vilas-Boas et al., 2000; Welcher et al., 2008). Here, owing to a shorter distance covered with the center of mass on the starting block, a swimmer is able to take temporal advantage which can be kept for the overall start time. Besides, Sabaghi et al. (2018) noted a significantly longer flight distance for the forward variant. On the other hand, it has been stated that the backward variant allows a swimmer to generate greater impulse and, consequently, leave the block with a significantly higher take-off velocity, which can be maintained throughout a comparatively longer flight distance (Dragunas et al., 2014; Vilas-Boas et al., 2000, 2003; Welcher et al., 2008). It seems that the whole-body center of mass positioned more backward and at lower level would contribute to generating larger moments of both hip joints and, consequently, to producing a greater horizontal take-off velocity (Tanaka et al., 2016). Additionally, it is likely that the muscle activation process (its amplitude and onset) also differs depending on the mentioned kick-start variants (Langholz et al., 2015). Regardless of the above-presented findings, in the majority of the recent publications, no significant difference in overall start performance was revealed. An important aspect when investigating the consequences of those differences is that most of researchers did not consider measurements in distances further than 7.5-m from the starting line. To our knowledge, Barlow et al. (2014) was the only one who took into account performance measured at an extended distance.

Comparison between kick-start and grab-start

Since the back plate implementation, grab-start has rarely been compared with the two kick-start variants. Data collected among seven male swimmers exposed a significant advantage of the kick-start in the block time and take-off horizontal velocity (Biel et al., 2010). Notwithstanding the relevance of the quoted study, the limited number of variables tested and of participants did not allow a full view of these starting techniques characteristics. Peterson et al. (2018) also included those three starting techniques in their research, based on six female and seven male breaststroke swimmers. However, they aimed to determine the biomechanical variables that contributed to 5-m start performance rather than to directly compare the examined techniques. Yet in the mentioned study, for all starts, the flight distance and block time that determined the 5-m start time were the most relevant variables.

Comparisons including handle-start

The swimming start techniques have evolved also in a close relationship with the modifications in the swimming rules and technologies. As far as our knowledge goes, the first swimming starting block with an attached handle (with both vertical and horizontal components of position adjustment with respect to the block to accommodate the stance of a swimmer) was patented by the United States in 1974. Then, the Anti Wave Company tried to implement a Super Block, with grips placed at the lateral side of the block (Pearson et al., 1998). Moreover, in 2019, Anti Wave received a FINA compliance certification, which confirms that their equipment meets all FINA requirements and specifications. Blanksby et al. (2002), on the basis of data collected from five males and seven females, examined the grab-, track-, and handle-starts before and after the intervention period of start practice. During the primary measurement, only the set horizontal position of the center of mass varied among all the three tested trials, and flight time differed between handle-start and track-start. However, as a result of the provided training, the swimmers enhanced the starting performance. Thus, after the implementation of a training program, the handle-start improved the most. In addition, movement and block times measured during handle-start exceeded significantly the other two techniques included in the quoted study. Vint et al. (2009) investigated a group of junior swimmers and did not reveal a significant handle effect for the 6-m start time. Yet, with only minimal instruction and practice provided in the study, they reported substantial advantages offered by the use of side handles during the track-start. In that study, a significant role of hand orientation was shown for extension of block time (longer), increase in peak power and impulse from the arm and horizontal velocity (higher). Here, those discoveries further support the conclusions brought about by Pearson et al. (1998), emphasizing the handle-start potential toward becoming the fastest starting technique. However, at that time, the starting block did not include a back plate, which has been shown to significantly improve starting effectiveness (Beretić et al., 2012; Biel et al., 2010; Honda et al., 2010; Nomura et al., 2010; Ozeki et al., 2012; Takeda et al., 2017). On the other hand, regardless of the benefits of the side handles whenever they are available, the majority of swimming pools are not commonly equipped with any specific side handles – either the elevated/raised ones, described by Blanksby et al. (2002), or the flat ones, as in the project by Vint et al. (2009). This might allow a new perspective in the perception of handle use during the kick-start. Finally, the study of Vint et al. (2009) was the only one to take the current kick block features into account. Yet, there is still limited knowledge about the side handle usage, its consequences and the tradeoff between particular swimming start parameters and their contribution to the overall starting performance. Especially, a modification of the dive-in behavior may be required to fully exploit the potential of the new incline element of the OSB 11 (Biel et al., 2010), which has not been studied extensively so far in comparison with the kick-start and its variants or with other starting techniques.

Spatiotemporal coordination in starting positions

It has been noted that, depending on the starting position, the swimmers' limbs could be used differently (Peterson et al., 2018; Takeda and Nomura, 2006), not only with regard to the influence on ground reaction force vectors, but also owing to the contribution to velocity increase (Benjanuvatra et al., 2004; Breed and Young, 2003; De la Fuente et al., 2003; Ikeda et al., 2016; Mason et al., 2007; Sakai et al., 2016; Slawson et al., 2013) and further flight trajectory (Maglischo, 2003). Therefore, the take-off velocity is mostly a consequence of the initial swimmer's body position, movement organization during push-off, the ground reaction forces exerted on the platform and the body segments position while leaving the platform.

The starting strategy requires some adjustments in the undertaken actions and a certain diversity between these strategies may be compensated for in the sense of the tradeoff between their mutual characteristics (Kruger et al., 2003). So, all the motor decisions must be carefully coordinated with the consideration of the movement patterns in different starting conditions (Vantorre et al., 2014). Therefore, depending on the starting technique, some priority areas and compromises have to be exposed. The relationship between the block phase duration and the magnitude of velocity developed is an example. That knowledge is particularly important to better understand the mechanisms acting between the domains of the swimming start. On this basis, conscious steps concerning the directions of changes and their priorities targeted toward exploiting the athletic performance potential could be undertaken. It becomes even harder as multiple performance determinants have to be taken into account. Here, the interdependence of the parameters has to be cautiously evaluated and a compromise among them should be considered in the context of the special requirements of a given case. While providing feedback, it is therefore crucial to prioritize those parameters that would affect the most relevant aspect of a given starting technique and the evaluation of the starting position performance should be based on the carefully chosen parameters. As stated by Mason and Mackintosh (2020), *continued practice of poor technique, that is not readily identified in training, will be difficult to rectify*. On the basis of those findings, it is justified to search for the specified key factors determining the starting performance of a given technique. Consequently, we wish to highlight the aspects of the technique that potentially might be priorities in the context of prompt improvement.

The knowledge gap and justification of further research

Recently, the new raised incline back plate implementation and its widespread use have become a mile step in starting performance enhancement. As a result, most of the high-level swimmers take advantage of that opportunity and adapt kick-start as their favorite starting technique. However, other techniques are also still in use. The grab-start is mainly applied by developmental-level swimmers, track-start is exercised during training practice (many swimming pools are not equipped with OSB 11 starting blocks) and starts without grip are favorable during relay changeovers. Indeed, the current FINA regulations do not specify where swimmers should locate their upper limbs while starting. Therefore, on the basis of the results presented by Blanksby et al. (2002) and Vint et al. (2009), the use of side handles deserved a reevaluation comprising the FINA rule changes. In this way, a handle-start could become part of the promising future.

As reported by Barlow et al. (2014), the initial position had no effect on velocity measured between 4.5-m and 5.5-m, or between 14.5-m and 15.5-m. In some cases, the descending variability in horizontal velocity might result in no differences found in the 15-m start time (Honda et al., 2012; Vilas-Boas et al., 2003). The presented phenomena have been attributed to the argumentation presented by Kruger et al. (2003), who noted rather small or slightly significant differences between grab- and track-starts and following Allen (1997) whose concluded that there did not seem to exist a general advantage of any of the starts. Thereby, different starting positions ensure similar 15-m start times but employ different strategies to achieve the outcome. One may also say that the results obtained in those comparisons might depend on previous experience, as the preferred technique specialization throughout the swimmer's carrier ensures its better mastery (Kruger et al., 2003). Considering the above findings, it seems valuable to reevaluate available results based on start measurements extended up to 15-m distance from the starting line.

In addition, some methodological limitations demonstrated in the available studies have to be considered, such as small sample sizes, lack of homogeneity of the groups that often merge both genders and the limited number of variables studied. Finally, noting that no research sought to identify the relationships among all three techniques and their possible variants in consistent evaluation conditions, the available advice and insights for performance analyses may not be conclusive, which highlights the need for further research comprising a comparison of a wider range of the possible starting techniques and a search for differences and advantages. That should ensure a better understanding of the behavior in the ventral swimming start and, consequently, reliable guidelines could be provided based on the priority areas. Such an experiment could help clarify the question which of the available starting options is the most advantageous in the context of starting performance enhancement, or which of the starting strategies have to be adopted to ensure better advantage of the individual swimmers' potential.

Concerning the above, in Chapter II, using biomechanical qualitative analyses, we aimed to compare the spatiotemporal structure of performance among ventral swimming start techniques (grab-start, handle-start, and two kick-start variants) performed by national-level male swimmers, referring them to time curves of the ground reaction forces registered during the block phase. Besides, by exposing the advantages and disadvantages of each start technique, we intended to derive the best start technique in terms of performance. The approach undertaken in this assessment will bring more focus to explore factors that determine the performance indicators specified for a particular technique. Moreover, for a wider description of the differences in the swimming starts in the applied scope of evaluating their movement structure, regression analysis models were composed, enabling performance estimation on the basis of selected explanatory variables.

Furthermore, to search for a wider understanding of ventral swimming start and its performance determinants regarding participant diversity, a group composed of international-level female athletes was included in a complementary study (Chapter III). Therefore, Chapter III was intended to expose differences in the spatiotemporal structure of the kick-start between two variants: with a backward and with a forward displacement of the swimmer's center of mass in the initial position.

Starting block back plate and its contribution toward start performance

Selecting the back plate position on the starting block is currently mostly based on the swimmer's subjective personal preferences (Cicenia et al., 2019). Yet, the features of the start – including the starting block construction, initial swimmer's body position, and further movement structure – can have a significant influence on starting performance and, consequently, have to be taken under consideration for training stimuli optimization (Blanco et al., 2017; Pearson et al., 1998; Vantorre et al., 2014). Before, to find the detailed contribution of the given solutions to starting performance output, researchers aimed to evaluate the impact of the swimmer's body placement on the starting platform, the effect of changes in the specific variables values, or the duration of the sub-phase of swimming start (Blanco et al., 2017; Vantorre et al., 2014). Lately, when the back plate is becoming widely implemented and favorably used during competitions, researchers have aimed to expose the importance of foot positioning over the starting platform (Takeda et al., 2012), including the distance between the feet, as well as the impact of angles in lower limb joints on swimming start performance (Kibele et al., 2015; Slawson et al., 2011); some have hypothesized that the change obtained only by adjusting the back plate would significantly affect starting performance (Cicenia et al., 2019, 2020; Honda et al., 2012).

The back plate can be fixed to the main deck in five different locations at a distance of 0.35 cm (in the same inclination angle: 30°). Then, the adjustable back plate advantage arised from the additional, solid fulcrum for the rear foot – forces provided to improve the push-off (Takeda et al., 2012; Tor et al., 2014). Consequently, the kick-start offers benefits over track-start (Beretic et al., 2012; Garcia-Hermoso et al., 2013; Honda et al., 2010; Nomura et al., 2010; Ozeki et al., 2012). Yet, Garcia-Hermoso et al. (2013) observed that the inverse correlation between block time and the final performance occurred only with the new starting block. Indeed, by adjusting the position of the back plate, a swimmer is able to find an optimal body position considering the body dimension.

In detail, only a few studies investigated the advantages and disadvantages of the changes brought about by the back plate shift. Slawson et al. (2011) evaluated the effect of starting block configuration on starting performance in elite athletes (comparing 14 females and 17 males). In individual cases, significant differences were revealed in output and performance variables (peak forces generated off the back plate and horizontal take-off velocity) as a result of changing the back plate position. In turn, group evaluations indicated the effect of varying the width of the swimmer's body position on starting parameters and performance.

Takeda et al. (2012) researched 10 male swimmers who performed trials including three different back plate positions (0.29, 0.44, and 0.59 m from the front edge of the starting block). In that study, significantly longer 5-m time, and lower horizontal and resultant take-off velocities were measured for the narrow longitudinal foot spacing, and the angle and velocity determined at the take-off of the wider back plate positions were significantly lower. The rear foot take-off times differed between the tests in the ascending order: 0.29, 0.44, and 0.59 m. However, the study did not use the officially approved OSB 14 starting block features, but it was based on settings incompatible with official standards.

Honda et al. (2012) tested 18 elite swimmers (nine females and nine males), including three variants which changed the back plate position, one immediately forward and one behind around the swimmers' preferred position. The analysis implied that the adjustment of the back plate position influenced the take-off horizontal velocity, average horizontal force, peak back plate resultant and horizontal forces and peak vertical grab force. The backward back plate shift resulted in an increase in the forces produced and, consequently, in the take-off velocity. Despite this, the swimmers spent similar time swimming up to the 5-m or 7.5-m distance. The authors did not report the time elapsed at a longer distance. However, in that study, tested trials included *nine variations of the kick-start, with three block positions and the three different variations of their weight, along with a track-start*. Therefore, the consequences brought by the adjustments in back plate positions might be also influenced by the changes in the weight distribution between lower limbs.

Kibele et al. (2014) included starts performed by elite swimmers (5 females and 14 males) incorporating back plate displacement (narrow vs. wide stance). They combined a wide number of variations in swimmers' initial body positions, which made it rather difficult to distinguish the direct consequences attributable only to the changes in back plate positioning. In their study, the front weighted stance, decreased foot distance and elevated center of mass position causing an advantage in the shortening of the block time.

The analyses conducted by Cicenia et al. (2019, 2020) were based on the comparison of three back plate positions standardized through the swimmers' shin length. In the data collected among a total of 15 elite adult swimmers (5 females and 10 males), only the reaction time was significantly different (Cicenia et al., 2019). Here, the reaction time was lower when the back plate distance was one-shin long. Furthermore, the same procedure was repeated in a bigger sample size; this time, the shin-length back plate position ensured a significantly shorter block time than the other tested trails (Cicenia et al., 2020). Still, no back plate position effect on the total start time measured at a15-m distance was noted in either study (Cicenia et al., 2019, 2020).

As presented above, most of the available studies included male and female athletes, yet they did not necessarily separate their results in the conducted analyses. Slightly greater differences in the block time between genders were noted when the kick plate was implemented (Garcia-Hermoso et al., 2013). It seems that this element of the starting platform is more beneficial for male swimmers because of the lower limb muscle power that may be reflected in the block phase characteristics (Garcia-Hermoso et al., 2013; West et al., 2011). Additionally, men presented a shorter reaction time to auditory stimuli with lower variability (Garcia-Hermoso et al., 2013; West et al., 2011). Yet, the presented differences in response seem to be related to the type of the employed stimulus (Burnstein et al., 1980; Spierer et al., 2010). Women's superiority in responses to stimuli of a somatic, verbal, or auditory nature was exposed, whereas men favored reaction time tasks that involved spatial or visual stimuli (Lahtela et al., 1985). However, there is no consensus about the association of the observed response differences. Additionally, in swimming, both verbal and visual stimuli are used simultaneously. On the basis of the results obtained by Fischer and Kibele (2014, 2016), it can be noted that, depending on the gender of the athlete, different movement strategies might be favored to perform similar tasks. It seems that an impact of gender is warranted, but the response time, motor abilities, as well as technical proficiency are also associated with athletic performance. As inherent gender differences were demonstrated, not only in athletic performance, but also in motor abilities and response to the stimulus, detailed interpretation including block phase movement organization and its temporal characteristics has to be addressed in association with gender effect.

Most of the presented ventral swimming start studies are focused mainly on the block phase, yet there is a need for analysis including a specific concentration on detailed all-limb movement characteristics during the block phase. Other phases of the swimming start are treated marginally. Moreover, small sample sizes with the lack of gender distinctions could undermine the diagnostic value of the research. Furthermore, in most of the analysis, the results did not refer to the anthropometric characteristics of the swimmers' bodies or their preferences in the optimal starting position with different back plate adjustments. That exposes the need for more holistic approaches to explore this area.

Therefore, in Chapter IV, a question of how the preferential adjustments of the starting block structure would influence start characteristics depending on the swimmers' gender was asked. This study aimed to assess the swimming start performance with different positions of the starting block back plate and to identify if some adaptations would occur in swimmers' movement patterns in association with those position changes. To determine and quantify temporal differences between the trials (incorporating the preferred back plate position, one position forward and one position backward from the preferred one), a particular emphasis was put on the block phase analyses. Besides, the effect of the swimmers' preferences in back plate positioning on overall starting performance was taken into account.

Characteristics of swimming start concerning gender effect

The world leads the way to bring parity in gender equality. In fact, there is no doubt that gender has a significant impact on sports performance. In that context, it appears to be natural that swimming world records and event results are classified depending on the swimmers' genders (FINA rules). The current literature has shown some factors that can interfere with the characteristics of the start. For example, the block time has been reported to differ depending on the athlete's gender (Garcia-Hermoso et al., 2013). However, gender differences in the water may be smaller than those in weight-bearing exercise (Senefeld et al., 2016). Yet still, male swimmers are faster in all indoor-pool competitive swimming events (Morais et al., 2019; Zingg et al., 2014). It is widely known that athletes' anthropometric and physiological features may affect the swimming performance of females and males differently (Rejman et al., 2018; Senefeld et al., 2016). In general, females take advantage of a smaller body size, as well as smaller body density and greater fat percentage (Lavoie et al., 1986; Pendergast et al., 1977; Rudnik et al., 2019). The referred characteristics of the body result in a higher economy of swimming. The performance relationship between genders also depends on the age of the athlete, mainly with regard to the puberty level (Senefeld et al., 2019). Yet, it has been noted by Zingg et al. (2014) that, in comparison to female athletes, men achieve the peak swimming speed earlier in life for the 100-m and 200-m butterfly races, while the opposite occurs in freestyle. Additionally, the diversity between females and males in competitive swimming performance progressively becomes smaller as race distances increase (Tanaka and Seals, 1997; Zingg et al., 2014).

From the available data, the gender differences in swimming start might refer not only to how velocity is developed or how much time swimmers need to effectively push off from the block (Garcia-Hermoso et al., 2013; Tor et al., 2014), but also to the time passing out between the stimulus and the athlete's response (Spierer et al., 2010). Moreover, while starting, male and female swimmers seem to undertake different movement strategies to perform similar tasks (Fisher and Kibele, 2014, 2016). On the other hand, male swimmers are described by a comparatively higher level of maximal and explosive strength (West et al., 2011), as well as maximal power expressed in relation to body weight (Miyashita et al., 1992). In this context, it is interesting that most of the gender-based performance analyses in swimming starts do not meet methodological requirements and the genders are merged together in many analyses (Barlow et al., 2014; Benjanuvatra et al., 2004; Carvalho et al., 2017;

Galbraith et al., 2008; Honda et al., 2012; Ikeda et al., 2016; Lee et al., 2001). According to Blanco et al. (2017), approximately 1/3 of studies taken under consideration in their systematic review included both genders but did not necessarily follow the gender-based performance effect. Here, only a limited number of studies compared the characteristics of swimming starts performed by females and males, or their performance determinants. Furthermore, most research reporting start performance by gender groups did not include direct comparisons between male and female results (Cossor and Mason, 2001; da Silva et al., 2019; Jesus et al., 2011; Mason et al., 2007; Morais et al., 2019) or recruited only a low to moderate number of participants (Ruschel et al., 2007; Sakai et al., 2016; Seifert et al., 2010; Vantorre et al., 2011). Therefore, there is a need for analyses describing the relation between swimming start performance, its structure, and swimmers' body characteristics with regard to gender-based performance effect. Moreover, the influence of swimmers' anthropometric and motor characteristics on the initial starting position as well as further swimmers' actions has to be considered in an objective assessment of swimming start with a distinction between males and females.

Given the above, Chapter V aimed to upgrade the existing knowledge about the gender effect on swimming start characteristics and its key parameters considering the latest FINA rules changes. Consequently, this study explored the gender effect in the spatiotemporal parameters of the kick-start technique executed by international-level swimmers. Besides, the purpose of this research was to determine the effect of gender heterogeneity on the biomechanical characteristics of swimming start by investigating its overall performance determinants. The findings could indicate the parameters that should be considered in an objective assessment of swimming start performed by males and females.

Relationship between dry-land-based tests and swimming start performance

Swimming starts employ a complex movement structure that is highly related not only to motor skills, such as strength or power, but also to the spatiotemporal organization. Therefore, for that kind of activity, it is necessary to search for performance determinants together with the swimmer's motor behavior. One can say that the block phase is based mainly on the one-time extension movement in the lower limb joints, while the butterfly kick exposes rather a cyclic nature of the lower limb motion in the vertical axis. Yet, they still rely primarily on the lower body motor abilities. From this point of view, swimming start performance depends on the efficiency of the transfer of muscular leg forces and power into the forwarding movement of the swimmer's body (De la Fuente et al., 2003; Mason and Mackintosh, 2020; Vantorre et al., 2014). The analysis of transformations referring to a specific motor ability (as the rise in explosive power or strength), described with well-known physical laws extended by an inquiry of specific movement characteristics and cooperation of skeletal and muscular structures, allow for a wider view of the given problem and provides a better understanding of starting performance determinants.

There is no doubt that evaluation is an important component while planning the training process. Therefore, according to Smith et al. (2002), an accurate diagnostic protocol should enable to: *(I) analyze the effects and trends brought about through training; (II) assess the quality, structure, and preparedness for competition; (III) predict future competitive performance; and (IV) provide recommendations for continued directional training*. On the basis of the obtained results, directions of future actions are going to be planned, with further highlights on their importance. Consequently, the significance of distinguishing swimming performance indicators and its key factors has been underlined and attracted the attention of multiple researchers (Blanco et al., 2017; Burtkhard et al., 2020; Peterson et al., 2018; Thng et al., 2019; Tor et al., 2015; Vantorre et al., 2014).

It is important to emphasize that the value of any proposed testing or monitoring protocol should be carefully evaluated (Smith et al., 2002) because of the difficulties and limitations driven by the specificity of the water environment. These challenges still result in constraints in the access to specialized measuring equipment. The limitations arise not only from the necessity to submerge measuring equipment or from its direct contact with the water; also, high humidity can have a significant impact on all electronic devices or plugs which are located in the vicinity of the swimming pool. Owing to these issues, specialized measuring equipment is expensive and difficult to access, particularly for daily-based training usage. Only some scientific laboratories possess high-quality measurement setups, which allow trained coaching staff, laboratory technicians, or scientists to perform complex testing sessions and deliver detailed reports to athletes and their coaches. Indeed, that process is an invaluable tool for knowledge upgrade but from a practical point of view, it could be inaccessible, especially for swimmers and their coaching staff.

One solution, at least partial, might be offered by dry-land standardized tests, which provide information about results obtained in a strictly controlled movement. The reliability, utility, and wide range of the possible practical applications of such tests, as the countermovement jump (CMJ), squat jump (SJ), or standing long jump, have been strongly confirmed in research (Gathercole et al., 2015; Linthorne, 2001; Mizuguchi et al., 2015; Nagano et al., 2005). SJ is a movement that is rarely used in practice. CMJ is a much more natural jumping movement, and most people can jump several centimeters higher than in SJ (Linthorne, 2001). Then, CMJ is favorably applied. Ground reaction force measurements during CMJ allowed reliable examination of athletes' specific motor skills. Consequently, it could be used for specific jumping potential assessment with regard to jump high standards or power developed during a trial (Trzaskoma and Trzaskoma, 2001) as a result of work performed by both lower limbs or by each one independently (Maćkała et al., 2013). Additionally, CMJ and SJ tests could be used for evaluations related to maximal power developed by the knee extensor muscles (Bosco, 1983). As a result, it is important to confirm if there are some analogies between standardized tests based on the well-known movement structures, such as vertical jumps, and the distinguishing movement structures specific for swimming kick-start. In this way, it would be possible to develop a tool to predict changes in the performance motor skills or movement structures specific for the kick-start.

Regarding the starting position used, the characteristics of a starting jump from the block are similar to those of a vertical jump also in the coherence of the propelling force, resulting mainly from the lower limbs (Breed and McElroy, 2000; Guimarães and Hay, 1985; Vilas-Boas et al., 2003). Cossor et al. (2011) indicated a strong positive correlation between peak forces measured during kick-start and those reported in the CMJ test. Here, the swimmers who generate peak force higher than average tend to show better overall starting performance (Slawson et al., 2013). On the other hand, the set posture (including smaller hip angle) and the direction of the movement, make swimming start a more complex movement structure (Arellano et al., 2005; Lee et al., 2001). Indeed, during vertical jumps, the athlete has to exceed the gravitational force, while in the case of starting, the desirable direction of the take-off force is significant (Arellano et al., 2005). Finally, as the block phase includes a complex movement structure, it engages the whole body coordination and, thus, the association between lower body motor abilities and starting performance seems to be multifactorial (West et al., 2011). The importance of technical proficiency has often been brought into the discussion on this topic (Breed and Young, 2003; Carvalho et al., 2017; De la Fuente et al., 2003).

Athletes' strength and power abilities could be evaluated with several dry-land tests (Beretić et al., 2013; Bishop et al., 2013; García-Ramos et al., 2016; Rebutini et al., 2016; Thng et al., 2019). Therefore, over the years, researchers have attempted to establish the interrelation between dry-land-based tests results and performance in different starting techniques (Arellano et al., 2005; Benjanuvatra et al., 2007; Breed and Young, 2003; Carvalho et al., 2017; Cossor et al., 2011; West et al., 2010). A lack of or a low relationship for the starting mechanism has been presented in the majority of previous analyses comprising out-of-date starting features (Arellano et al., 2005; Benjanuvatra et al., 2007; Breed and Young, 2003; De la Fuente et al., 2003; Lee et al., 2001). The latest reports present more promising results.

The findings of cross-sectional studies by Thng et al. (2019) revealed swimming start as more related to SJ or CMJ than to the tests incorporating maximal muscle strength measurements. Furthermore, body weight-bearing vertical jumps presented higher accuracy than their loaded counterparts. In contrast, García-Ramos et al. (2016) demonstrated jumps with additional resistance equivalent to a given percentage (varying from 25% to 100%) of swimmers' body weight as more correlated with swimming start performance. In their study, the highest correlation was noted for weighted SJ tests, followed by body weighted CMJ, and then SJ. Moreover, the further from the starting line (from 5-m, through 10-m, up to 15-m), the lower correlation with CMJ and SJ parameters was observed. All in all, a vertical jump is still admitted as the exercise most related to swimming start (Bishop et al., 2013; García-Ramos et al., 2016; Zatsiorsky et al., 1979). West et al. (2011) also followed this trend and recruited 11 male international-level sprinters to perform CMJ and three repetitions of maximum strength squat. In their study, the peak vertical and horizontal forces developed during the block phase as well as the total (15-m) start time correlated significantly with parameters evaluated during dry-land tests (putting rate of force development aside). Then, in a group of 10 elite swimmers, Carvalho et al. (2017) noted an inverse correlation between the total (15-m) start time and the CMJ height, peak vertical force, and peak power. Additionally, on the basis of the CMJ height and peak vertical force, those authors composed a regression model to predict the total (15-m) start time. A strong inverse relationship between CMJ height and 15-m freestyle start time was also shown by Keiner et al. (2015) in a group of non-skilled swimmers (12 males and 9 females). On the other hand, García-Ramos et al. (2016) did not find the 15-m start time as significantly correlated with any CMJ or SJ parameters. Finally, Thng et al. (2019) concluded that measuring performance with jump height provided more reliability than other kinetic or kinematic evaluations. Yet, it was postulated by Kibele (1998) that the measurements of jump height should be complemented by more specific parameters provided in standard testing routines. Furthermore, the change in the shape of the vertical jump force-time curve can further provide the understanding of adaptation in specific motor skills (McMahon et al., 2018; Cormie et al., 2009). A controversy also arose concerning the correlation between start performance and lower body isometric muscle force characteristics. Here, Beretić et al. (2013), on the basis of leg extensors maximum voluntary force (also relative to body mass) noted a significant correlation with 10-m kick-start time. Moreover, data registered in the isometric contraction exercise allowed to develop a model able to significantly explain the start time (Beretić et al., 2013). In contrast, no correlations between isometric variables (leg extension and leg flexion maximal voluntary isometric contractions) and start times measured at the 5-m, 10-m, or 15-m distances were obtained by García-Ramos et al. (2016).

As the majority of the available studies involved a low number of parameters, the exposure of jump height as a predominant parameter to predict swimming start performance seems to be an exaggeration. Thus, research based on a wider collection of variables would be beneficial for the objective interpretation of this issue. A profound understanding of the kick-start mechanism and the importance of lower body power and strength for optimizing swim start performance have to be further confirmed. From that perspective, it seems that the starting performance enhancement is underpinned mainly by improving jumping ability, strength and lower limb power with various dry-land training methods (Bishop et al., 2009; Breed and Young, 2003; Rebutini et al., 2016; Rejman et al., 2017; Thng et al., 2019). However, in addition to increasing the long-term swimming performance, a susceptibility to change the variables measured during take-off as a result of applying the post-activation potentiation protocol has been shown (Cuenca-Fernandez et al., 2015). Therefore, as there are no doubts that the enhancement of lower limb motor abilities through extensive training practice or targeted warm-up strategies has a significant effect on starting performance, there is a need to further understand this relationship mechanism and evaluate dry-land-based exercises in the context of their utility for the kick-start performance prediction purpose.

Modeling performance of the swimming start

Any testing, by supplying a basis for future recommendations and by improving the planning of methods implemented throughout the consecutive training period, is intended to support a better understanding of the relevant areas of the athlete's performance. Therefore, equations allowing to predict a particular variable on the basis of the swimmer's motor potential, provide direct objective feedback, indicating the necessities specifically focused on a given swimmer. Those dedicated and detailed tools imply future actions concerning the targeted weakness which needs to be improved in the studied case and, consequently, enhance sports performance. In this way, the priority areas can be highlighted and recommendations for wider assessment and monitoring are provided. Moreover, the model based on statistical methods could be further improved as more data collected during testing sessions bring opportunities to raise the confidence of the implemented equations. Models based on statistical methods could also be an invaluable tool to evaluate the current and cumulative effects in the motor and technical training of swimming start.

Indeed, researchers are interested in examining the key factors contributing to starting performance by using statistical modeling methods (de Jesus et al., 2018; Nguyen et al., 2014; Peterson et al., 2018; Tor et al., 2015). Nguyen et al. (2014), on the basis of regression modeling, identified the strongest predictors of backstroke total (15-m) start time. Furthermore, in that study, separate equations for the two backstroke start techniques were presented. Also Peterson et al. (2018) composed separate regression models for each of the ventral starts included in their analyses, which allowed to predict time measured at 5-m after the breaststroke start. In turn, Tor et al. (2015) focused on distinguishing equations based on the variables predicting total (15-m) start time which belong to the given phase and presented multiple regression outputs separately, revealing an equation based only on block phase variables and another one based on underwater variables. Here, correlation analyses combined with other statistical methods allowed for a wider understanding of mechanisms contributing toward the best starting performance.

Furthermore, with the objective estimation of the crucial variables of starting performance, the interpretation of the actual athlete's potential estimated, for example, on the basis of motor abilities, became easier to be performed in a daily routine. To give an example, the shape of the force-time curve exhibits changes in specific motor skills efficiency (Peterson, 2006), so statistical models may also allow to predict directions of changes in swimmer performance. Here, scientists focus rather on predicting overall starting performance than its specific elements. Carvalho et al. (2017), using multiple regression, obtained a model in which, with variables measured during the CMJ test, the total (15-m) start time could be predicted. Also, Beretić et al. (2013) applied multiple regression analysis to expose the associations of time at 10-m with significant predictor variables collected during a standing leg extensor isometric muscle force test. In this way, practical tools were revealed which are intended to control and improve start performance. Moreover, as some swimming start variables have been shown to relay more on lower limb motor abilities, it seems interesting to indicate equations that allow to predict those swimming start variables and, consequently, contribute to a better understanding of the interrelation between CMJ measures and swimming start performance determining factors.

The previous review showed the lack of studies analyzing correlations between specific variables of kick-start and CMJ characteristics. There are also no studies concerning the association between the temporal structure of the swimming start in relation to the percentage share of the start duration and the characteristics of dry-land tests. Therefore, there is a lack of studies that would search for the interrelation between detailed characteristics of the vertical jump and variables describing changes in the key factors used for swimming start performance assessment. Moreover, as the water environment imposes some methodological disadvantages, the exposure of the validity of a simple, cheap, and easily available CMJ test as a tool to assess and predict swimming start performance may upgrade the monitoring and evaluation of swimmers' potential performance. That confirms the legitimacy of searching for more available testing options. Additionally, collecting data from swimmers of various profiles would help reveal the contribution of given dry-land-based exercises to a successful start. Finally, the obtained findings will further improve the understanding of swimming start performance behavior and factors adding to its enhancement.

Concerning the above, to provide an opportunity to better recognize swimmer efficiency and identify areas for improvement in ventral swimming start, Chapter VI was intended to determine the relationship between selected variables characterizing the CMJ structure and key biomechanical features in the assessment of the kick-start performance in high-level swimmers. With those variables, we aimed to compose and validate a regression model that would reveal the data usefulness to assess and predict kick-start performance on the basis of athletes' motor potential.

The rationale of the proposed research

In the general introduction concerning the theoretical framework and brief review of the available literature on the topic, some gaps were identified that allow to develop dedicated avenues of original studies encompassing this thesis. Firstly, it could be found that many analyses evaluating swimming start performance might not be relevant to what is currently employed by swimmers. That is mainly a result of swimming start evolution, but also of the improvement in measurement quality and artificial intelligence advancement. Moreover, there is still too much diversity between in preferred variables and their range. In that case, it seems important to reevaluate some of the previous findings. The process of changes raised new argumentation in swimming start analysis and assessment. It highlights the relevance of studies focused on available knowledge verification due to the optimal starting conditions based on currently used techniques (Benjanuwatra et al., 2004; Biel et al., 2010; Blanksby et al., 2002; Galbraith et al., 2008; Vilas-Boas et al., 2003). Therefore, the information gained through detailed swimming start analyses with more holistic approaches seems to be valuable in understanding how swimmers can improve their start performance. Here, to enhance athletic performance by providing an accurate training program, at least the most relevant performance-related factors (pool- and dry-land-based) have to be systematically evaluated with tests from reliable sources. Specific screening tests are playing an increasingly important role in competitive swimming and evaluations employing standardized tests ensure a high level of comparability between measurements. Finally, their relevance is becoming crucial while individual pathways are implemented to expert performance.

RESEARCH PROBLEMS AND AIMS

In the light of the above-mentioned observations, the overarching objective of this dissertation was to upgrade the knowledge about ventral swimming start and the potential of its future enhancement. Furthermore, this thesis aims to describe, examine, and understand the swimmers' motor characteristics when starting and the directions of their changes with regard to various conditions. It is hoped that this will provide a comprehensive insight into athletes' physical and technical development and, consequently, improve the ventral swimming start through conscious motor decision-making. Considering the general purpose of the thesis, the following specific objectives were established:

1. To describe and compare the spatiotemporal structure of four swimming start positions (grab-start, handle-start, kick-start forward, and kick-start backward) and determine the most beneficial one in terms of overall start performance.
2. To expose the advantages and disadvantages of the two kick-start variants and indicate the more beneficial one for international-level female swimmers.
3. To examine the impact of back plate position on movement pattern and total starting performance.
4. To compare the spatiotemporal structure of both kick-start variants exposure differences brought about by gender effect.
5. To examine the relationship between CMJ test results and ventral swimming start in order to verify the utility of CMJ as a tool for swimming start performance prediction.

THE FORMAL STRUCTURE OF THE THESIS

The present dissertation was written in conformity with the requirements and presentation guidelines of the Faculty of Sport, University of Porto, Portugal, and the Wroclaw University of Health and Sport Sciences, Poland.

The main aim of this thesis was to describe and interpret the complex intertwined relationships among multiple relevant performance-related factors (e.g. starting position, starting block features, gender of the swimmer, swimming technique, and motor abilities) of ventral swimming start performance. Therefore, this thesis aimed to upgrade the current knowledge about ventral swimming starts with the consideration of the current FINA facility rules. To achieve this purpose, six studies were conducted (Chapters II–VI). Additionally, Chapter VII is dedicated to the general discussion and final thoughts on the main findings, and Chapter VII comprises conclusions, practical applications and future research directions, which were elaborated upon the results obtained in each empirical study (Chapters II - VI) and supported by the specialist literature (Chapter I). The main conclusions, limitations, suggestions for future research, recommendations for practice and references regarding each study are presented in Chapters II - VI. A summary of the thesis formal outline is presented in Table 1.

Table 1. Synopsis of the structure, contents, and studies included in the present dissertation.

Chapter I	**GENERAL INTRODUCTION, PURPOSE AND FORMAL STRUCTURE OF THE THESIS** Presents the theoretical framework and a brief review of the available literature on the topic, the pertinence of the investigation, research questions and aims, as well as the formal structure of the dissertation.
Chapter II	**EMPIRICAL STUDY I** **The spatiotemporal structure and performance in ventral swimming starts** Aim: To describe and compare the spatiotemporal structure of four swimming start positions (grab-start, handle-start, kick-start forward, and kick-start backward) and reveal which one is the best in terms of overall start performance. Authors: Daria Rudnik, Karla de Jesus, Luis Mourão, Susana Soares, Ricardo Jorge Fernandes, Marek Rejman, and João Paulo Vilas Boas
Chapter III	**EMPIRICAL STUDY II** **Backward or forward kick-start: which variant of the initial position ensures better starting performance?** Aim: To expose the advantages and disadvantages of two kick-start variants and reveal which of them is more beneficial for international-level female swimmers. Authors: Daria Rudnik, Ricardo Jorge Fernandes, João Paulo Vilas Boas, and Marek Rejman

Table 1. Synopsis of the structure, contents, and studies included in the present dissertation (continuation).

Chapter IV	**EMPIRICAL STUDY III** **Does back plate position influence the temporal characteristics of the swimming start?** Aim: To examine the impact of back plate position on movement pattern and total starting performance. Authors: Daria Rudnik, Leandro Machado, Ricardo Jorge Fernandes, Marek Rejman, and João Paulo Vilas Boas
Chapter V	**EMPIRICAL STUDY IV** **Kinematic profile of ventral swimming start: gender effect** Aim: To compare the spatiotemporal structure of the kick-start toward exposure of differences brought by gender diversity. Authors: Daria Rudnik, Marek Rejman, and João Paulo Vilas Boas
Chapter VI	**EMPIRICAL STUDY V** **Countermovement jump test as a tool for ventral swimming start performance prediction** Aim: To examine the relation between CMJ test results and ventral swimming start, to verify the utility of CMJ as a tool for swimming start performance prediction. Authors: Daria Rudnik, Pedro Fonseca, Ricardo Jorge Fernandes, João Paulo Vilas Boas, and Marek Rejman
Chapter VII	**GENERAL DISSCUSION**
Chapter VIII	**CONCLUSIONS, PRACTICAL APPLICATIONS AND FUTURE RESEARCH DIRECTIONS**

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CHAPTER II

THE SPATIOTEMPORAL STRUCTURE AND PERFORMANCE IN VENTRAL SWIMMING STARTS

Daria Rudnik, Karla de Jesus, Luis Mourão, Susana Soares, Ricardo Jorge Fernandes, Marek Rejman, and João Paulo Vilas Boas

Abstract

In case of swimming competitions, only final race time is considered as a performance measure. Yet the event can be divided into four contributing phases, and the start always initiates rivalry. The characteristics of starting phases highly dependent on the initial starting position. Using biomechanical analyses, the study aimed to compare the spatiotemporal structure and performance among ventral swimming start techniques. Ten male national-level swimmers were tested performing swimming starts with each of four positions: kick-start backward, kick-start forward, grab-start, and handle-start. Qualisys system, video camera, and instrumented starting block were used for data acquisition. To explore whether differences among four positions exist, the key spatiotemporal parameters were identified and evaluated throughout statistical procedures comprising Kendall's coefficient of concordance test, Spearman correlation, and multiple regression analyses. Obtained results allowed to determine the sets of data composed for each position which differ significantly from each other, as well as reveal variables determining the starting performance of a given starting position. Front weighted kick-start was described by the shortest movement time, block time,5m time, and 15m time. The highest take-off velocity was measured for the grab-start, yet it was also described by the highest decrease in horizontal velocity from the take-off to the 5-m marker. The shape of ground reaction forces of the lower limb located at the front of the block was similar for all starts. In turn, different GRF profiles of staggered stance were noted for the rear lower limb. For all positions, the highest positive correlation value for 5-m instantaneous horizontal velocity was observed with velocities measured at the instant of take-off and those at the first water contact. Equations enabling the prediction of the 5-m and 15-m times were computed for each starting position independently. This way the analyses revealed a group of variables that have to be selected deliberately to examine the swimming start performance of the chosen position. It could be concluded that kick-start forward, seems to be the most beneficial starting position for swimmers while striving for temporal performance improvement. Crucial areas for improvement in ventral swimming start were identified and depending on the starting position separate expectations concerning specific elements of start have to be considered. Obtained findings refer to the starting technique selection and optimization on the basis of conscious decisions supported by evidence from accurate and reliable research.

Key words: ventral swimming start, starting position, performance determinants.

Introduction

In swimming, only the final race time is a decisive factor in athletes' ranking positions. Nevertheless, this outcome is determined by many factors (Morais et al., 2013) and, in order to succeed, it is necessary to optimize the efficacy and efficiency of all parts of the race (Bishop et al., 2009). A swimming race can be divided into four contributing phases: the starting, stroking, turning and finishing phases (Mason and Cossor, 2000). In sprint events, the 15-m start time can take approximately a quarter of the total race time (Cossor and Mason, 2001) and it determines the actions undertaken in the consecutive phases of the race. Assuming that a very small time interval may be critical for a competition classification, an effective start is widely recognized as crucial for success in swimming. The time that a swimmer spends starting depends on their individual abilities, starting conditions, starting platform and starting technique (Vantorre et al., 2014). This area of swimming performance is attracting attention mainly to determine whether there are differences between starting techniques and to reveal which position or its parameters are predominant to achieve the best starting performance (Mason and Mackintosh, 2020; Mason et al., 2007; Peterson et al., 2018; Tor et al., 2015).

As a consequence of specific foot and hand placement on the starting block, both upper and lower limbs play a different role in each starting technique (Peterson et al., 2018; Takeda and Nomura, 2006). Accordingly, each starting technique is described by a different ground reaction force (GRF) profile, as well as foot contribution to velocity growth (Benjanuvatra et al., 2004; Breed and Young, 2003; De la Fuente et al., 2003; Ikeda et al., 2016; Mason et al., 2007; Sakai et al., 2016; Slawson et al., 2013; Takeda et al., 2017). The block phase has a strong influence on the flight phase by imposing a compromise between flight trajectory (Maglischo, 2003) and further swimmers' actions performed in the water. Each of these phases could occupy around 11%, 5% and 84% of the time dedicated for starting (Tor et al., 2014a). Yet, as a swimmer should start the propulsive movements while gliding in an estimated 6.5-m distance from the wall (Elipot et al., 2009), the time exposed for 5-m distance is rather used for block and fly phases evaluation, while the time measured in longer distances contains more of consecutive phases (Cossor and Mason, 2001; Ruschel et al., 2007; Tor et al., 2014a). On the basis of those findings, it is an important issue to reveal the key factors determining the starting performance specified for a given technique.

Throughout the years, the swimming start technique has evolved, and many starting techniques have been in use. In the middle of the 20th century, the grab-start (parallel foot placement with hands grabbing the front edge of the starting block) was introduced in swimming (Hanauer, 1967) and in the 1970s, the track-start position was applied from the track and field (Ayalon et al., 1975). Consequently, early analyses were mainly focused on the comparison of those two techniques (Benjanuvatra et al., 2004; Blanksby et al., 2002; Counsilman et al., 1988; Issurin and Vertebitsky, 2003; Krüger et al., 2003; Takeda and Nomura, 2006; Vilas-Boas et al., 2003; Vantorre et al., 2010b, 2011, Zatsiorsky et al., 1979). Some studies presented the disadvantage of the grab-start consisting in a longer block time (Benjanuvatra et al., 2004; Issurin and Vertebsky, 2003; Mason et al., 2007; Takeda and Nomura, 2006), while others pointed out that the grab-start ensured increased take-off horizontal velocity (Blanksby et al., 2002; Kruger et al., 2003). In the track-start, athletes can move their bodies on the starting block forward (front-weighted) or backward (rear-weighted) from the neutral position (Vilas-Boas et al., 2000, 2003). Here, studies have shown that the backward position has a greater impulse over the starting block, increased horizontal take-off velocity and allowing for longer flight distance, but consequently extends the block time as compared with the forward position (Barlow et al., 2014; Honda et al., 2012; Vilas-Boas et al., 2000; Vilas-Boas et al., 2003; Welcher et al., 2008). Finally, Vilas-Boas et al. (2003) suggested that despite the several biomechanical differences indicated, those techniques seemed to be equally valuable considering the relevance of the underwater subsequent phase. Yet, research has been inconclusive as to which position is more useful regarding the overall start performance.

The swimming start techniques have evolved also in close relation to the modifications in swimming rules and technologies. Here, one of the latest changes was the authorization by Fédération Internationale de Natation (FINA) of the additional rear foot support in the starting block construction. Its implementation has resulted in a modification of the track-start technique toward the kick-start. Since then, this start technique has attracted scientific attention. The mentioned starting block adds solid support for the rear foot and, accordingly, ensures better conditions for the push-off (Takeda et al., 2012; Ozeki et al., 2012), which results in a significant improvement of starting performance (Beretić et al., 2012; Biel et al., 2010; Honda et al., 2010, 2012; Nomura et al., 2010; Ozeki et al., 2012; Takeda et al., 2017). Meanwhile, the Anti Wave Company introduced a SuperBlock with grips placed on the sides of the block, which allows to lean the center of mass forward by holding the grips with the hands, thus reducing the block time (Pearson et al., 1998). According to Blanksby et al. (2002), after the implementation of a specific training program, this start technique, named handle-start, exceeds grab-start and track-start over 10-m starting performance (for 0.06 s and 0.11 s). Furthermore, Vint et al. (2009), on the sole basis of the minimal instruction and practice provided in their study, reported substantial advantages offered by the side handles during the track-start.

The new raised incline back plate implementation and its widespread use have become a mile step for starting performance and most of the high-level swimmers take advantage of that opportunity. However, other techniques are still in use. Moreover, the current FINA regulations do not specify where swimmers should locate their upper limbs while starting, although the handgrips placed on both sides of a starting block are still not validated by FINA. Then, on the basis of the results presented by Blanksby et al. (2002) and Vint et al. (2009), the use of side handles deserves a second thought and reevaluation in the context of the latest FINA rule changes. Furthermore, to the best of our knowledge, our study is the only one that includes a direct comparison of the grab-start (as a reference), handle-start, and two kick-start variants (forward and backward) considering the applicable FINA rules. Here, handle-start (requiring specific side-placed handles) was used as a reference of the guidance for future advancement. Meanwhile, by including past and present preferences, as well as prospects in technique utilization, it would expose the consequences of technology implementation (expressed as changes in the starting block structure).

The latest literature review involves 16 studies reporting the comparison between starting techniques and aiming to imply which starting position (on the starting block) is predominant to achieve better starting performance (Blanco et al., 2017). Yet, most of them included small sample groups, composed mainly of elite swimmers. Additionally, only two starting techniques were compared in these studies and their evaluation was mostly based on the same criterion variables. Meanwhile, it has been shown that different solutions undertaken by swimmers could lead to a successful start (Seifert et al., 2010). Although there are no doubts that the starting position can significantly influence the subsequent phases of the swimming start, investigating the key factors affecting start performance in the specific starting techniques seems to be interesting.

Using biomechanical qualitative analyses, we aimed to compare the spatiotemporal structure of performance among ventral swimming start techniques (grab-start, handle-start, and two kick-start variants), referring them to the GRF time curves registered during the block phase. Besides, by exposing the advantages and disadvantages of each start technique, we intended to derive the best start technique in terms of its performance. The approach undertaken in the performed assessment will bring more focus to explore factors that determine the performance indicators specified for a particular technique. Moreover, for a wider decryption of the differences in the swimming starts in the applied scope of assessing their movement structure, regression analysis models were composed, enabling performance estimation on the basis of selected explanatory variables.

It was expected that, depending on the starting position, different criteria for the successful start measured with several commonly used parameters would have to be considered. Thus, specific priorities should be imposed in the performance assessment. Here, the applied approach should support the utility of the exposed sufficient advice for starting technique optimization, its settings, and the directions of its future development trends.

Material and methods

The sample was composed of 10 healthy male national-level competitive freestyle swimmers. They were characterized by the following mean values (± standard deviation): 23.3 ± 2.5 years of age, 176.2 ± 7.11 cm of body height, and 72.27 ± 8.15 kg of body mass. All swimmers had been rested from strenuous exercise for a minimum of 24 hours and were free from any injury or illness. They had previous experience with all starting positions that were tested. Nevertheless, they preferred kick-start over grab-start and handle-start and it was kick-start that they mainly used during the training process. Despite this, before the testing session, the participants were acquainted with the specifications of the investigated starts. For each swimmer, all trials were completed over a one-day testing session. Data were acquired at a swimming pool at the University of Porto with the assistance of the LABIOMEP, Porto Biomechanics Laboratory. The procedures were in compliance with recognized ethical standards and the principles of the international law required in human research.

After being introduced to the purpose of the study and the testing procedure, by signing a written informed consent, the participants volunteered to take part in the study. Then, their body height, body mass, age, as well as training and competition experience data were collected. During a standard warm-up based on the athletes' prerace routine, they had time to become familiar with the instrumented starting block used.

The swimmers were instructed to perform all starts until a distance further than 20 m from the starting line was reached to ensure representative values of the 15-m start time. After the gliding phase, they were to continue freestyle swimming. While kick-start positions were recorded, the athletes were free to choose their preferred back plate position as well as the foot located at the front of the starting block (yet those settings had to be constant for all trials). Each trial was organized to simulate the starting conditions which secured the achievement of the highest possible performance during the start. In order to avoid any fatigue or learning effect between the trials, at least 3-minute recovery time was arranged, and the techniques execution order was randomized. The swimmers performed three repetitions of each out of the four tested swimming start positions: grab-start, kick-start backward, kick-start forward, and handle-start (Figure 1). A standardized starting procedure compliant with the FINA rules was applied. It was presumed that if some trouble occurred during a trial, then that trial would be repeated after all starts planned for the swimmer were finished.

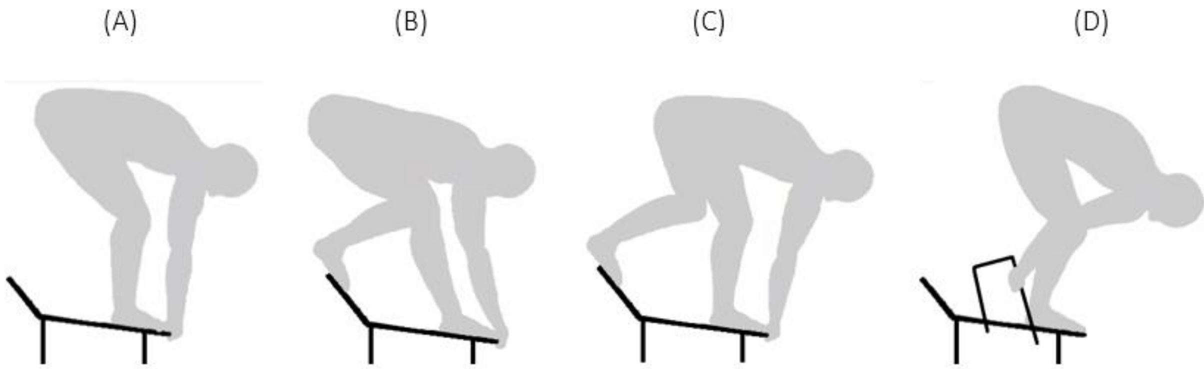


Figure 1. Illustration of the grab-start (A), kick-start backward (B), kick-start forward (C), and handle-start (D) positions.

To collect GRF data, an instrumented starting block – 3D dynamometric central 3D-6DoF (Vilas-Boas et al., 2014) – was employed (Figure 2). This device used together with the Visio software (LabVIEW 2013 System Design Software, SP1 NITM, USA) allows the measurement of the forces exerted on the starting block by each limb independently (with a sampling frequency of 2000 Hz). It is compliant with the FINA facilities and starting rules (the construction of 3D-6DoF corresponds with that of OMEGA OSB 14). Temporal variables evaluated during on-block actions were derived from kinetic data, which ensures more accurate measurements than the ones that could be obtained from video recordings.

Figure 2. A swimmer dressed up with a full-body marker set, positioned in the starting platform used for data collection.

The Qualisys 3D Motion Capture System, composed of 10 overwater and 6 underwater Qualisys Oqus cameras (Figure 3) with a sampling frequency of 100 Hz (Oqus, Qualisys AB, Sweden), and two personal computers with the Qualisys Track Manager software (QTM, Qualisys AB, Sweden) were used to collect three-dimensional kinematic data. The calibration was performed before each testing session. Each swimmer was equipped with a Fastskin (Speedo) textile swimsuit, which allowed the attachment of 48 passive markers (based on the anatomical anthropometric model of Istituto Ortopedico Rizzoli, Bologna, Italy – IOR Gait Full-Body Model) (Figure 4). By using that system for the on-block, aerial, transition, and underwater phase up to 5-m, the kinematic data represented by the swimmer's center of mass displacement were obtained.

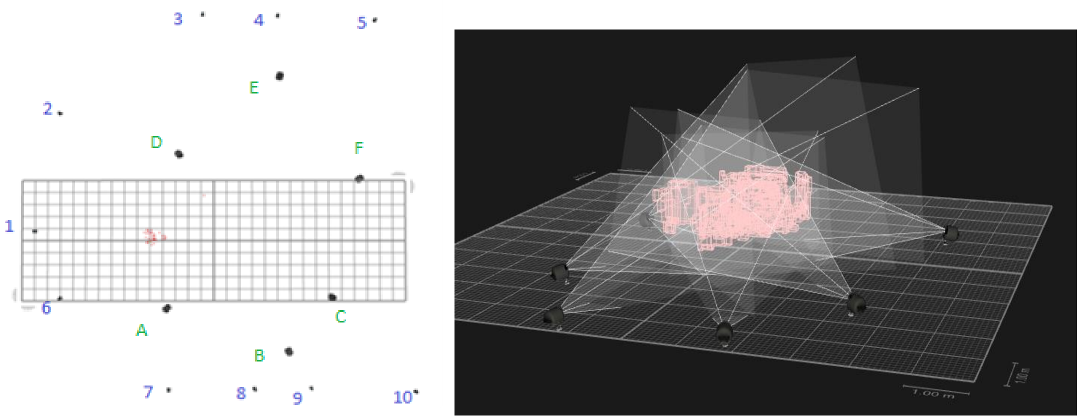


Figure 3. Qualisys cameras set up (numbers are related to overwater cameras, letters are related to underwater cameras).

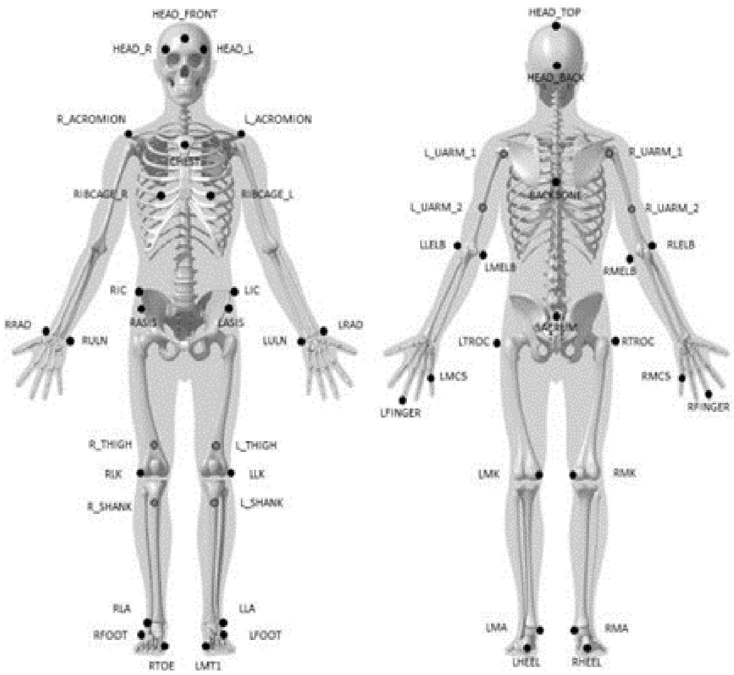


Figure 4. Markers' placement in accordance with the IOR Gait Full-Body Model.

In the initial phase, a three-dimensional Automatic Identification of Markers (AIM) model (Figure 5) was composed for each swimmer independently in the Qualisys Track Manager software (version 2.17, Qualisys AB, Sweden). The values of the spatiotemporal variables were derived from analyses based on those models. To obtain the continuity of the variable tracking along the timeline, a gap-fill trajectory with a preview based on polynomial behavior was determined.

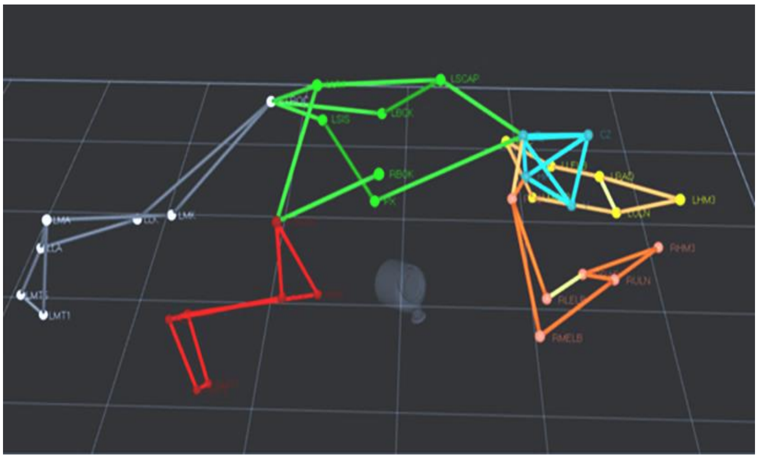


Figure 5. AIM model composed in the Qualisys Track Manager software on the basis of the IOR Gait Full-Body Model.

One surface video camera (50 frames per second) was used to record the view of the swimmer’s actions at a 15-m distance from the edge of the starting platform. It was fixed on a tripod on one side of the pool, so that its optical axis was perpendicular to the direction of swimming. Markers and light-emitting diodes (LED light associated with a trigger that gives a visual stimulus when the start signal appears) were located in the visual frame of the camera, allowing a measurement of the 15-m time. During postproduction, the first frame in which the LED light was visible determined the triggering time for the trial. The kinematic and kinetic data were collected simultaneously and synchronized with the starting signal with a professional starting device (Onda TTL, 0–5 V) (Figure 6).

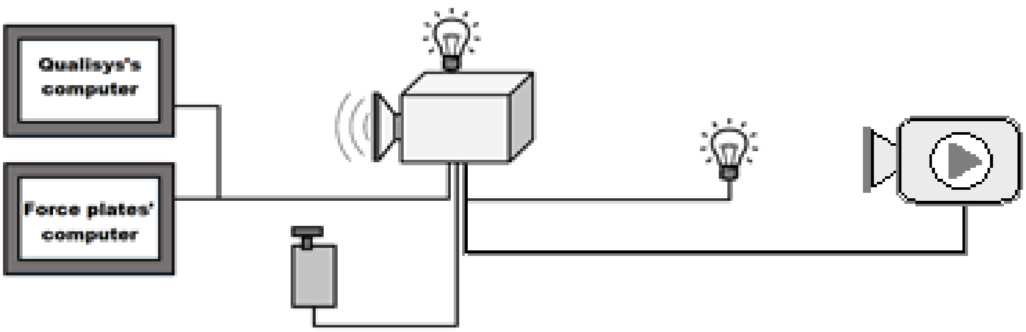


Figure 6. Setup used for data collection synchronization.

Kinetic data were processed with the MATLAB software (MathWorks Inc., USA) by using a specially designed routine. The database was filled with all data collected during the testing sessions, which allowed calculation and selection of specific variables. It was assumed that the shorter the 5-m and 15-m times and the higher the instantaneous velocity measured at the 5-m distance from the starting line, the better the starting performance was. The variables selected for further analysis are described in Table 1. They are also consistently included in other studies evaluating swimming starts (Blanco et al., 2017; Colyer et al., 2019; Vantorre et al., 2014).

The mean values of each variable calculated from the three trials completed in each starting position by the individual participants were chosen for further analysis. Then, means and standard deviations were computed for each variable to represent the group results. The results were scrutinized for significant differences between the starting positions. One set of individuals was tested four times, with the starting position as the category of variables. Common descriptive statistics were used for primary data analysis. As the sample was reduced and the studied variables were not normally distributed, nonparametric statistical procedures were conducted. Kendall's coefficient of concordance was used to determine if the sets of data composed for each position significantly differed from one another. Next, the analysis of variance for repeated measures test was run, allowing the computation of post-hoc tests to confirm the obtained statistically significant differences for each pair of starting techniques. However, it was assumed that, if in a given case no significant starting position effect is exposed, but yet the values obtained bring certain attention, then to further search for significant differences among parameters, the Wilcoxon signed-rank test will be conducted in between the variables measured for two starting techniques. To reveal variables that were highly related to the overall starting performance, Spearman correlation coefficient was determined between the given starting position performance indicators and variables describing its spatiotemporal structure.

Table 1. Definitions of the specific variables used to characterize the structure of the swimming start.

Phase		Variable	Symbol	Definition
Temporal	Block	Reaction time (s, %)	RT	The time interval between the starting signal and change in starting block reaction force curve as a result of the initial movement (absolute duration expressed in seconds and relative duration expressed in percentage of the block time)
		Hands take-off (s)	Hoff	The time interval between the starting signal and the last contact of the hands with the starting block
		Rear foot take-off (s)	RFoff	The time interval between the starting signal and the last contact of the rear foot with the starting block
		Front foot support (s)	FF	The time interval between the last contact of the rear foot with the starting block and the moment when total vertical force fell to zero
		Block time (s)	BT	The time interval between the starting signal and the moment when total vertical force fell to zero
		Movement time (s, %)	MT	The time interval between the first visible change in starting block reaction force curve and the instant when total vertical force fell to zero (absolute duration expressed in seconds and relative duration expressed in percentage of the block time)
	Flight	Flight time hip (s)	FT	The time interval between the last contact of the toes with the block and the moment of the first contact of the hips with the water
		Water time (s)	WT	The time interval between the first contact of the hips with the water and the instant when the hips crossed the 5-m mark
	Water	5-m time (s)	T5	The time interval between the starting signal and the moment when the head crossed the 5-m mark
		5–15-m time (s)	T5–15	The time interval between the instant when the head crossed the 5-m mark and the moment when the head crossed the 15-m mark
		15-m time (s)	T15	The time interval between the starting signal and the moment when the head crossed the 15-m mark
Spatiotemporal	Block	Take-off resultant velocity (m/s)	Off_v	The instantaneous resultant velocity of the swimmer's center of mass measured at the instant of take-off
		Take-off horizontal velocity (m/s)	Off_hv	The instantaneous horizontal velocity of the swimmer's center of mass measured at the instant of take-off
		Average resultant velocity at block phase (m/s)	B_v	The average resultant velocity of the swimmer's center of mass in the block phase
		Average horizontal velocity at block phase (m/s)	B_hv	The average horizontal velocity of the swimmer's center of mass in the block phase
		Average vertical velocity at block phase (m/s)	B_vv	The average vertical velocity of the swimmer's center of mass in the block phase

Table 1. Definitions of the specific variables used to characterize the structure of the swimming start (continuation).

Phase		Variable	Symbol	Definition
Spatiotemporal	Flight	Average resultant velocity at flight phase (m/s)	F_v	The average resultant velocity of the swimmer's center of mass in the flight phase (from take-off to full immersion)
		Average horizontal velocity at flight phase (m/s)	F_hv	The average horizontal velocity of the swimmer's center of mass in the flight phase
		Average vertical velocity at flight phase (m/s)	F_vv	The average vertical velocity of the swimmer's center of mass in the flight phase
	Entry	Water contact horizontal velocity (m/s)	Wc_hv	The instantaneous horizontal velocity of the swimmer measured at the instant of the first contact of the hands with the water
		Entering horizontal velocity (m/s)	E_hv	The instantaneous horizontal velocity of the swimmer measured at the instant when the hips entered the water
	Water	Horizontal velocity at 5-m (m/s)	5_v	The instantaneous horizontal velocity of the swimmer measured at the moment when the head crossed the 5-m mark
		Dec off_5m (m/s)	Dec1	Decrease in horizontal velocity between the take-off and the moment when the head crossed the 5-m mark
		Dec 5m_15m (m/s)	Dec2	Decrease in horizontal velocity between the moment when the head crossed the 5-m mark and the instant when the head crossed the 15-m mark
Spatial	Flight	Take-off angle (°)	offA	The angle between the horizontal axis, the block edge, and the hip joint at take-off
		Entry angle (°)	EA	The angle between the horizontal axis, the fingertips, and the hip joint when hands entered the water
		Flight distance (m)	FD	The horizontal distance measured between the point where the hip entered the water and the starting wall

Besides, separate multiple linear regression models were calculated for each position exposing equations based on the received variable values. The estimation of the 5-m and 15-m start times, based on the linear regression equation, created a model containing selected variables. Finally, the assessment and verification of the model were performed, confronting the calculated and directly measured values of given start performance indicators. Here, to analyze each model output accuracy, the percentage of the standard error of estimation was calculated; the obtained mean value of the predicted variables, p-value, and the values of the coefficient of determination (partial R-squared) were taken into consideration. All statistical analyses were run by using the Statistica 13.1 software (StatSoft, USA), with the statistical significance level set at $\alpha = 0.05$.

Results

Spatiotemporal analyses

In the first part of the analyses, the arithmetical mean and standard deviation values of variables were extracted for each start (Table 2). The results of time measured at 5-m and 15-m expose the superiority of kick-start forward (1.78 ± 0.15 s, 7.73 ± 0.55 s, respectively) over kick-start backward (1.86 ± 0.11 s, 8.00 ± 0.72 s, respectively), handle-start (1.86 ± 0.16 s, 8.07 ± 0.78 s, respectively) and grab-start (1.91 ± 0.12 s, 8.05 ± 0.80 s, respectively).

It has to be emphasized that, in our study, 8 out of 10 subjects displayed either superior or almost equal 5-m time while using kick-start forward in comparison with other techniques. Even more swimmers exposed that trend for the 15-m time measurement. Consequently, not only group mean values, but also intra-subject analyses revealed similar conclusions. That position resulted in a shortening of the block phase duration (0.793 ± 0.075 s), which was achieved mainly by reduced movement time (0.591 ± 0.067 s). However, other positions, by extending the time of impulse generation, enabled swimmers to achieve higher values of take-off horizontal velocity. Here, the highest take-off horizontal velocity was measured for the grab-start (4.69 ± 0.35 m/s), even though the longest block time (0.90 ± 0.076 s), the shortest flight distance (2.80 ± 0.17 m) and the highest decrease in horizontal velocity during entering the water (2.18 ± 0.30 m/s) resulted in weaker overall starting performance as compared with other positions. Moreover, grab-start was followed by the greatest decrease in horizontal velocity from take-off to the 5-m distance (2.18 ± 0.30 m/s). The lowest average vertical velocity measured during the block phase (–0.03 ± 0.23 m/s), the longest flight distance (2.90 ± 0.11 m) and 33.41 ± 1.90° take-off angle were determined during kick-start backward. In handle-start, a decrease in horizontal velocity in the subsequent phases of the sprint race was the highest (0.99 ± 0.18 m/s).

Table 2. Descriptive statistics of spatiotemporal variables describing swimming start, presented for each starting position.

Phase		Variable	KF	KB	H	G	
			Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
Temporal	Block	Reaction time	0.202 ± 0.023	0.177 ± 0.023	0.199 ± 0.066	0.179 ± 0.019	
		Hands take-off	0.496 ± 0.084	0.524 ± 0.095	0.516 ± 0.135	0.558 ± 0.093	
		Rear foot take-off	0.666 ± 0.084	0.73 ± 0.071	0.755 ± 0.092	–	
		Block time	0.793 ± 0.075	0.873 ± 0.062	0.883 ± 0.104	0.900 ± 0.076	*
		Movement time	0.591 ± 0.067	0.696 ± 0.048	0.685 ± 0.085	0.721 ± 0.080	*
		Reaction time %	25.6 ± 2.88	20.3 ± 2.08	22.3 ± 5.58	20.0 ± 2.57	*
		Movement time %	74.4 ± 2.88	79.7 ± 2.08	77.7 ± 5.58	80.0 ± 2.57	*
	Flight	Flight time hip	0.44 ± 0.03	0.45 ± 0.03	0.46 ± 0.06	0.47 ± 0.04	
		Water time	0.56 ± 0.10	0.52 ± 0.07	0.56 ± 0.09	0.54 ± 0.08	*
	Water	5-m time	1.78 ± 0.15	1.86 ± 0.11	1.86 ± 0.16	1.91 ± 0.12	*
		5–15-m time	5.95 ± 0.50	6.14 ± 0.64	6.21 ± 0.68	6.14 ± 0.73	
		15-m time	7.73 ± 0.55	8.00 ± 0.72	8.07 ± 0.78	8.05 ± 0.80	
Spatiotemporal	Block	Take-off resultant velocity	4.61 ± 0.30	4.71 ± 0.27	4.69 ± 0.33	4.85 ± 0.40	
		Take-off horizontal velocity	4.45 ± 0.26	4.57 ± 0.24	4.55 ± 0.29	4.69 ± 0.35	
		B_v (m/s)	2.16 ± 0.24	2.24 ± 0.33	1.79 ± 0.33	1.62 ± 0.14	*
		B_hv (m/s)	2.11 ± 0.22	2.21 ± 0.33	1.72 ± 0.32	1.56 ± 0.15	*
		B_vv (m/s)	–0.29 ± 0.19	–0.03 ± 0.23	–0.26 ± 0.23	–0.23 ± 0.16	*
	Flight	F_v (m/s)	5.05 ± 0.26	5.06 ± 0.28	4.93 ± 0.32	4.92 ± 0.32	
		F_hv (m/s)	4.13 ± 0.26	4.17 ± 0.31	4.06 ± 0.34	4.01 ± 0.36	
		F_vv	–2.59 ± 0.19	–2.22 ± 0.94	–2.46 ± 0.25	–2.47 ± 0.22	
	Entry	Water contact horizontal velocity	4.10 ± 0.28	4.15 ± 0.35	4.09 ± 0.35	4.03 ± 0.39	
		Entering horizontal velocity	3.60 ± 0.32	3.66 ± 0.27	3.53 ± 0.35	3.59 ± 0.42	
	Water	Horizontal velocity at 5-m	2.51 ± 0.45	2.59 ± 0.48	2.46 ± 0.39	2.51 ± 0.40	
		Dec off_5m	1.94 ± 0.37	1.98 ± 0.32	2.09 ± 0.23	2.18 ± 0.30	
		Dec 5m_15m	1.14 ± 0.27	1.06 ± 0.15	1.07 ± 0.20	0.99 ± 0.18	
Spatial	Flight	Take-off angl	34.60 ± 4.06	33.41 ± 1.90	32.90 ± 5.74	30.89 ± 3.90	
		Entry angle	36.20 ± 5.29	33.12 ± 3.35	34.35 ± 4.46	34.56 ± 5.21	
		Flight distance	2.85 ± 0.09	2.90 ± 0.11	2.84 ± 0.14	2.80 ± 0.17	

KF: kick-start forward; KB: kick-start backward; H: handle-start; G: grab-start; B_v: average resultant velocity at block phase; B_hv: average horizontal velocity at block phase; B_vv: average vertical velocity at block phase; F_v: average resultant velocity at flight phase; F_hv: average horizontal velocity at flight phase; F_vv: average vertical velocity at flight phase; Dec off_5m: decrease in horizontal velocity between the take-off and the moment when the head crossed the 5-m mark; Dec 5m_15m: decrease in horizontal velocity between the the 5-m mark and the 15-m mark.
*Significant position effect at exact $p \leq 0.05$.

Kendall's coefficient of concordance test was employed to reveal significant differences among all variables describing the evaluated starting positions. The results included in Table 2 imply that the diversity of the values describing particular starting positions clearly decreased in each subsequent phase. Significant differences were estimated for the following variables: block time (0.004), absolute and relative movement time (0.001, 0.002), relative reaction time (0.002), water time (0.017), 5-m time (0.023), mean velocities in the block phase (< 0.010). The flight time (0.065) and the decrease in horizontal velocity between take-off and the 5-m distance marker (0.069) did not meet the set significance level. None of the differences reported in spatial variables were significant ($p > 0.200$).

In order to further investigate the specific differences and justify the findings of the nonparametric procedure, all swimming start positions were compared with one another with the post-hoc test. The p-values calculated for each pair of positions are presented in Table 3. The results indicate that kick-start forward significantly differed from the other starting positions. Only average resultant and horizontal velocities measured during the block phase differed between almost all positions. The exception is the result obtained for kick-start forward and kick-start backward, which did not show any significant difference. The lowest number of significant differences refers to the relation of grab-start and handle-start. In general, no stroke effect was revealed for the main performance measure. Yet, as our curiosity had been driven by the high time gap between the kick-start and other positions tested, to further investigate this issue, the kick-start 15-m start time was compared separately with 15-m time results measured during each of the tested starting positions. Indeed, the undertaken procedure exposed the distinction regarding the 15-m start time between kick-start and the other positions tested.

Table 3. Post-hoc and paired analysis results. Only variables displaying substantial diversity are shown.

Variable	KF-KB	KF-G	KF-H	KB-G	KB-H	H-G
BT	0.002*	0.000*	0.001*	0.260	0.653	0.452
MT	0.000*	0.000*	0.000*	0.189	0.565	0.078
RT%	0.001*	0.001*	0.031*	0.873	0.163	0.142
MT%	0.001*	0.001*	0.031*	0.873	0.163	0.142
B_v	0.215	0.000*	0.000*	0.000*	0.000*	0.013*
B_hv	0.112	0.000*	0.000*	0.000*	0.000*	0.017*
B_vv	0.000*	0.372	0.723	0.005*	0.001*	0.588
WT	0.049*	0.189	0.892	0.428	0.057	0.209
T5	0.043*	0.003*	0.039*	0.233	0.883	0.263
T15	0.020*	0.008*	0.006*	–	–	–
Dec1	–	0.012*	–	0.031*	–	–

KF: kick-start forward; KB: kick-start backward; G: grab-start; H: handle-start; BT: block time; MT: movement time; RT: reaction time; B_v: average resultant velocity at block phase; B_hv: average horizontal velocity at block phase; B_vv: average vertical velocity at block phase; WT: water time; T5: 5-m time; T15: 5–15-m time; Dec1: decrease in horizontal velocity between the take-off and the moment when the head crossed the 5-m mark.
*Significant at exact $p \leq 0.05$.

Ground reaction force

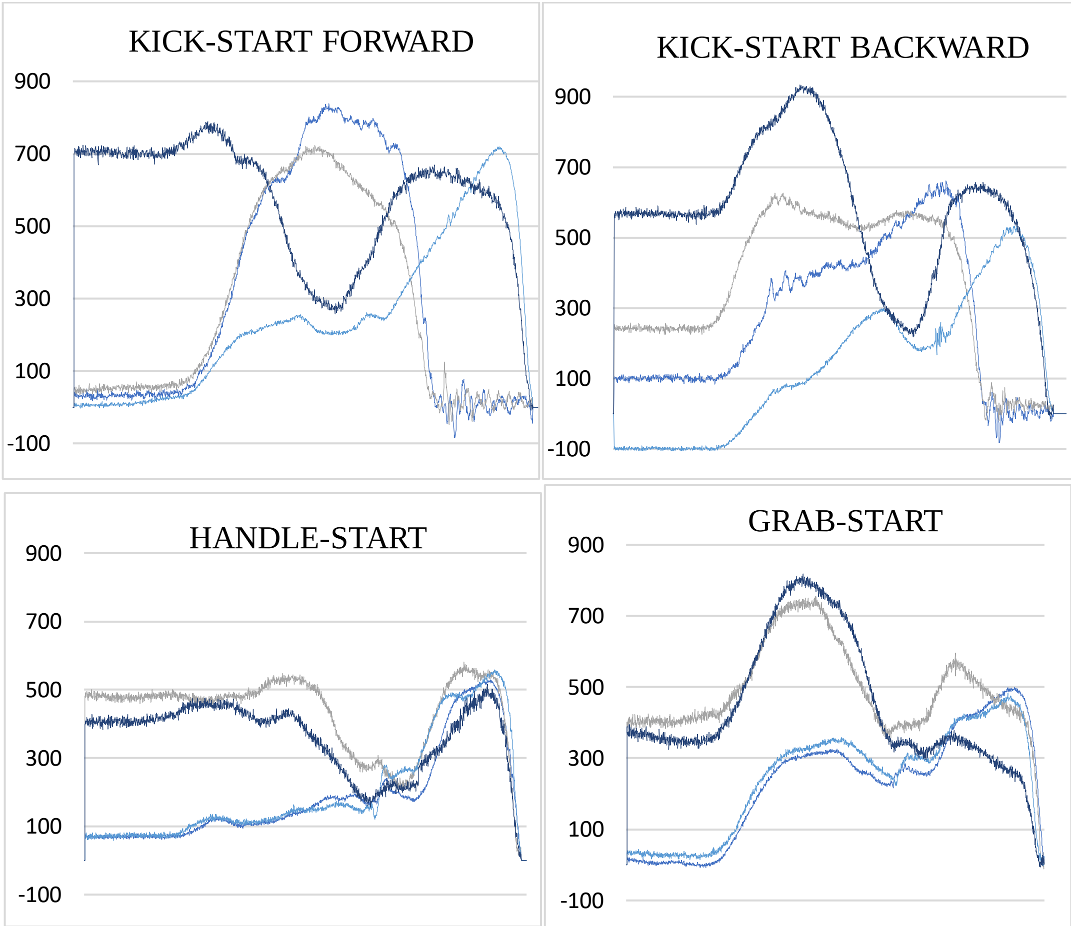
The profiles of GRF components derived separately for each lower limb were exposed (Figure 7). Consequently, biomechanical qualitative analyses of spatiotemporal structure among the ventral swimming start techniques were performed with reference to the GRF time curves registered during the block phase. Parallel foot placement displayed a rather symmetrical nature in the force development profile. Therefore, almost the same profile was valid for both lower limbs (as they were both supported on the front edge of the starting platform). In turn, for asymmetrical foot placement, different GRF profiles were noted for each lower limb.

The shapes of vertical and horizontal components of force production in the time estimated for the front lower limb during all starts show some similarities. Here, horizontal force produced by the limb gradually increased during the movement time, to achieve its peak just before the take-off from the starting block. Besides, in all positions, during the block phase, the vertical force decreased, achieving a value lower than the swimmer’s body mass, and increased again before returning to the scale. Moreover, considering the grab-start and kick-start backward, the vertical force produced by the foot located at the front of the starting block rose to its maximum value before the described drop.

However, some differences between GRF time-force curves are visible. Only in kick-start forward, to support the body in the initial phase of the start, did the swimmers displace most of their body mass toward one lower limb. In turn, in the initial phase of kick-start backward, as a result of displacing the center of gravity toward the backward direction, the front lower limb generated a horizontal (posterior-anterior) reaction force that exposed negative values. This pre-tension pattern was specific only for the mentioned starting position. Furthermore, in kick-start backward, the horizontal force produced by the front lower limb dropped a little when the force of the rear lower limb was reaching its maximum value and the swimmer was taking contribution from the incline back plate. While considering grab-start, the drop was a result of rotational movement regarding the front edge of the starting block, when a swimmer could take advantage of the passive force (gravity) acting on their body.

In handle-start and grab-start, the evaluation of any asymmetry in force production was easily achievable, as the upper and lower body movements were considered simultaneous and symmetrical. As those specific movement structures aimed to displace the swimmer’s body as far as possible in the forward direction, any mediolateral forces or disproportions in symmetrical force production would result in rotations. Therefore, a swimmer would be required to complement the arisen deficit to reach an appropriate trajectory and would spend extra energy cost on the consequences of the unsymmetrical movements.

For the other two starting positions, the measurement of the mediolateral component of GRF is required for that hypothesis verification.



Rear foot horizontal component of force (blue), rear foot vertical component of force (grey), front foot horizontal component of force (light blue), front foot vertical component of force (dark blue).

Figure 7. Typical time-force GRF curves (vertical and horizontal components) produced during the block phase of the swimming start, presented for each starting position.

Correlation analyses

Secondly, the focus of attention was moved toward identifying variables that could affect the minimization of the start time measured at 5-m and 15-m. The Spearman correlation results evidence that, for the majority of tested starting positions, the velocity value seems to be crucial (Table 4). For all positions, the highest positive correlation values for 5-m instantaneous horizontal velocity were observed with velocities measured at the instant of take-off (horizontal velocity: kick-start forward, r = 0.66; kick-start backward, r = 0.90; handle-start, r = 0.89; grab-start, r = 0.76) and those at the first water contact (kick-start forward, r = 0.78; kick-start backward, r = 0.83; handle-start, r = 0.90; grab-start, r = 0.79). Additionally, all starting performance indicators revealed for kick-start backward and handle-start also presented significant correlations with them. Movement time was significantly associated with the 5-m time measured during kick-start backward, handle-start and grab-start (r = 0.60, r = 0.76, r = 0.66). Excluding kick-start forward, the higher the average resultant velocity in the block phase was, the higher the swimmer's instantaneous velocity at the 5-m marker was noted (kick-start backward, r = 0.58; handle-start, r = 0.70; grab-start, r = 0.50). Surprisingly, the flight distance (preferably used for starting analyses and assessment) correlated significantly only with the 5-m time measured during kick-start forward (r = 0.59) and with all starting performance indicators in grab-start (r > 0.50). The take-off angle did not show any significant correlation only with grab-start, while the correlations calculated for the entry angle did not reach the significance level at any position. Except for the kick-start backward trials, a high correlation was presented between water time and 5-m start time (kick-start forward, r = 0.92; handle-start, r = 0.74; grab-start, r = 0.84). Interestingly, in kick-start forward, the swimmers' instantaneous velocity at the 5-m marker was not significantly related to the 5-m start time (r = –0.42). Yet, it highly determined the 15-m start times in all tested starts (kick-start forward, r = –0.88; kick-start backward, r = –0.80; handle-start, r = –0.79; grab-start, r = –0.89). The frequency analyses considering correlation significance suggest that the indicator of handle-start overall starting performance was the highest related to the velocity values obtained during the test.

Table 4. Spearman correlation coefficients between given starting position performance indicators and variables describing its spatiotemporal structure. Only variables displaying statistical significance are presented.

Variable	KF			KB			H			G		
	5_v	T5	T15	5_v	T5	T15	5_v	T5	T15	5_v	T5	T15
MT	–0.19	0.13	0.15	–0.47	0.60*	0.32	–0.16	0.76*	0.05	–0.27	0.66*	0.30
BT	–0.04	0.19	–0.03	–0.43	0.55*	0.25	–0.12	0.54*	0.14	–0.27	0.66*	0.30
FT	–0.49	–0.21	0.67*	–0.15	0.22	0.41	–0.55*	0.17	0.67*	–0.14	0.02	0.06
WT	–0.33	0.92*	0.09	–0.48	0.46	0.25	–0.23	0.74*	0.33	–0.47	0.84*	0.50*
B_v	0.41	–0.16	–0.30	0.58*	–0.48	–0.26	0.70*	–0.65*	–0.77*	0.50*	–0.30	–0.39
B_hv	0.41	–0.16	–0.30	0.58*	–0.42	–0.21	0.61*	–0.68*	–0.68*	0.48	–0.36	–0.41
B_vv	–0.53*	0.35	0.43	–0.31	0.33	0.41	–0.59*	0.22	0.60*	–0.47	–0.04	0.43
Off_v	0.61*	–0.45	–0.48	0.75*	–0.78*	–0.68*	0.82*	–0.84*	–0.73*	0.79*	–0.48	–0.82*
Off_hv	0.66*	–0.38	–0.59*	0.90*	–0.84*	–0.86*	0.89*	–0.68*	–0.83*	0.76*	–0.33	–0.73*
F_v	0.54*	–0.65*	–0.48	0.81*	–0.71*	–0.72*	0.85*	–0.66*	–0.92*	0.70*	–0.22	–0.76*
Wc_hv	0.78*	–0.49	–0.69*	0.83*	–0.70*	–0.77*	0.90*	–0.64*	–0.79*	0.79*	–0.30	–0.82*
E_hv	0.57*	–0.40	–0.45	0.37	–0.28	–0.63*	0.60*	–0.33	–0.52*	0.53*	–0.16	–0.59*
5_v	–	–0.42	–0.88*	–	–0.84*	–0.80*	–	–0.64*	–0.79*	–	–0.68*	–0.89*
offA	–0.62*	–0.07	0.66*	–0.48	0.59*	0.48	–0.77*	0.33	0.62*	–0.41	–0.02	0.23
FD	0.33	–0.59*	–0.31	0.36	–0.03	–0.36	–0.16	0.05	0.02	0.50*	–0.52*	–0.75*

KF: kick-start forward; KB: kick-start backward; H: handle-start; G: grab-start; 5_v: horizontal velocity at 5-m; T5: 5-m time; T15: 5–15-m time; MT: movement time; BT: block time; FT: flight time hip; WT: water time; B_v: average resultant velocity at block phase; B_hv: average horizontal velocity at block phase; B_vv: average vertical velocity at block phase; Off_v: take-off resultant velocity; Off_hv: take-off horizontal velocity; F_v: average resultant velocity at flight phase; Wc_hv: water contact horizontal velocity; E_hv: entering horizontal velocity; offA: take-off angle; FD: flight distance.
*Significant at exact $p \leq 0.05$.

Regression analyses

Finally, for each starting position, separate regression equations were successfully revealed, providing results matching our assumptions. The obtained equations enabling the prediction of the given swimming start performance indicators described as 5-m and 15-m times and meeting significance level requirements are presented in Table 5. The residual error obtained from the equations (presented as percentage values of the arithmetical mean of the dependent variable) evidenced that the models were considered as satisfying. To reveal how much of the variation in the 15-m start time was explained by each of the chosen explanatory variables, the partial R^2 was presented. Through the values of the coefficient of determination, the evidence of statistically high closeness of the measured data to the fitted regression line was obtained. The coefficient of determination for multiple regression indicated that the models explained 83–99% of the variability of the response data around its means. On this basis, the regression equations composed for grab-start seem to outperform other models in terms of accuracy.

Table 5. Results of using multiple regression methods for modeling and predicting swimming start performance exposed as 5-m and 15-m time based on specific spatiotemporal variables describing the movement structure of a given starting position, composed for each tested starting position.

	Equation	F	R^2	p	Error (%)
KICK-START FORWARD					
5-m time	= WT × 1.2064 + RFoff × 0.6372 + 0.6743 ± 0.0657	20.98	0.857	0.001*	3.7
15-m time	= 20.495 – FD × 1.4203 – EA × 0.0993 – E_hv × 1.4359 ± 0.1466	40.33	0.960	< 0.001*	1.9
KICK-START BACKWARD					
5-m time	= 3.792 – Off_hv × 0.445 – F_vv × 0.043 ± 0.0428	26.43	0.883	0.001*	2.3
15-m time	= Off_hv × 2.5949 – Off_v × 4.6127 – FF × 2.1043 + 18.1377 ± 0.1812	45.11	0.964	< 0.001*	2.2
GRAB-START					
5-m time	= WT × 0.9907 + BT × 0.8055 + 0.6504 ± 0.0381	43.29	0.925	< 0.001*	1.9
15-m time	= RT × 13.7884 – FD × 2.8222 – Off_hv × 1.0689 + 18.4279 ± 0.1585	32.86	0.952	< 0.001*	1.9
HANDLE-START					
5-m time	= WT × 0.8356 – Off_hv × 0.3213 + 2.8565 ± 0.0735	16.56	0.826	0.002*	3.9
15-m time	= RT × 2.021 – F_v × 2.618 – EA × 0.0533 + 22.4428 ± 0.172	58.26	0.972	< 0.001*	2.1

WT: water time; RFoff: rear foot take-off; FD: flight distance; EA: entry angle; E_hv: entering horizontal velocity; Off_v: take-off resultant velocity; F_vv: average vertical velocity at flight phase; Off_hv: take-off horizontal velocity; FF: front foot support; BT: block time; RT: reaction time; F_v: average resultant velocity at flight phase.
*Significant at exact p ≤ 0.05.

Discussion

Overall starting performance

The most remarkable result of this analysis indicates that the foot placement in the staggered position seems to be more beneficial for swimming start performance than the parallel placement at the front of the platform. As can be seen in Tables 2 and 3, the kick-start forward considerably exposed the shortest 5-m start time (considering the inter-subject variability and group mean value). Additionally, the kick-start forward was described by the greatest number of parameters recognized as distinct from those for other techniques. Finally, it was revealed as advantageous over the other techniques not only in terms of overall starting performance but also regarding block and movement times or the 5-m start time. Indeed, currently, there is a conviction that the kick-start outstands other swimming start techniques (Beretić et al., 2012; Honda et al., 2010; Nomura et al., 2010; Ozeki et al., 2012; Peterson et al., 2018). Interestingly, there is no consensus about which projection of the swimmer's body during an asymmetrical stance (forward or backward) is more beneficial (Barlow et al., 2014; Kibele et al., 2014, 2015; Honda et al., 2012; Peterson et al., 2018; Vilas-Boas et al., 2000; Welcher et al., 2008). Our results provide support for a number of studies presenting a slightly shorter 5-m start time for the forward variant (Honda et al., 2012; Kibele et al., 2015; Welcher et al., 2008). Yet, a contrasting finding was shown by Barlow et al. (2014), who determined shorter start times for both 5-m and 15-m distance during the kick-start backward as compared with kick-start forward. While concerning only temporal analysis, the kick-start forward seems to outstand the other techniques; thus, the instantaneous swimmer's velocity has also been indicated as a key factor in performance assessment. Here, our findings were coherent with the results where instantaneous velocity measured at 5-m was higher for kick-start or track-start backward (Honda et al., 2012; Vilas-Boas et al., 2000). The better performance of a staggered start position probably takes advantage of a more stable body position on the starting platform. According to Barlow et al. (2014), no significant differences exist between horizontal velocities measured around the 5-m and 15-m markers for the kick-start variants. Those diversified observations might result from the subjects' extended practice or preferences toward one starting technique. Considering the lack of studies extending the analyses up to 15-m, it is reasonable to assume that, despite the inconsistency about the 5-m starting performance, the additional distance of up to 15-m from the starting line contributes to the superiority of kick-start forward. Additionally, the time gap between the 15-m start time of kick-start forward and the other included techniques is significant not only from the statistical point of view – it also corresponds to the time often deciding about losing or winning in high-level competitions.

Interestingly, our results do not confirm previous findings presented by Blanksby et al. (2002) and Vint et al. (2009), who noted temporal advantage of the handle-start. In the study by Blanksby et al. (2002), as a consequence of a specific way of training, the block phase of the handle-start was reported to cover 81% of the block time without side grip. Peterson et al. (2018) provided data where incline back plate implementation reduced the block time by 4% with asymmetrical stance. This is in line with observations by Vint et al. (2009), who suggested that the use of side handles had a more substantial effect than the employment of the incline back plate on block time and take-off horizontal velocity. Here, they presented significant advantage toward take-off velocity development resulting from the side handles usage. On the other hand, our findings confirmed significant extension of propulsion time as a consequence of side handles usage presented by Vint et al. (2009). It has also been reported as the technique in which the swimmer who has the most experience tends to be the best (Blanksby et al., 2002; Vantorre et al., 2010b; Welcher et al., 2008). This reasoning confirms the results obtained by Blanksby et al. (2002), implying that after a few weeks of practice, the crucial parameters of start performance were improved. Consequently, during the post-intervention evaluation, handle-start demonstrated time advantage superiority over grab- and track-starts at the 10-m distance (Blanksby et al., 2002). Indeed, the non-preferential technique was found to be less stabilized and described by higher inter-trial variability, which could explain its lower efficacy (Vantorre et al., 2010).

While the opposite was exposed for the preferential technique, it was highly stabilized and reproducible by the swimmers.

Until now, studies describing the handle-start effect are scarce. Then, the comparatively higher standard deviation values calculated for the variables describing the handle-start imply a need for further analyses exposing the strengths and weakness of the technique. These would allow to formulate accurate and reliable approaches to guide athletes throughout the starting technique selection and development process. Meanwhile, the conflicting results regarding the best solution to achieve the shortest start time require deeper exploration.

Spatiotemporal characteristics

The take-off characteristics were in the range of the results provided by other studies: Blanksby et al. (2000) (BT ≈ 0.86 s); Kibele et al. (2014) (Off_hv ≈ 4.4 m/s, BT ≈ 0.82 s); Takeda and Nomura et al. (2006) (Off_v ≈ 4.3 m/s, BT ≈ 0.74 s); Peterson et al. (2018) (BT ≈ 0.82 s). The kick-start forward ensures a significant reduction of time that would not be possible while using the other techniques (Table 2). Furthermore, the average velocities of the block phase were differentiated among the tested positions (Table 4). Here, the kick-start backward exposed the highest average forward velocity calculated for the block phase; according to Guimaraes and Hay (1985), its higher values lead to a faster start. In this technique, however, a backward stretch requires time to displace the body from the further back until the take-off (Blanksby et al., 2002). Therefore, during the block phase, in order to produce a higher impulse value and a higher center of mass velocity, extended time is needed (Tanaka et al., 2016; Vilas-Boas et al., 2003; Welcher et al., 2008). Then, according to Blanksby et al. (2002), it might be beneficial to move the center of mass forward, consequently shortening the movement time. The handle-start enables the center of mass to be positioned further forward – even outside the block base; then, a comparatively shorter distance that has to be covered until the body is placed at an appropriate angle to leave the starting block is needed (Blanksby et al., 2002). Meanwhile, in line with our findings, the available results reported longer block time describing grab-start trials in comparison not only with kick-start (Peterson et al., 2018; Taladriz et al., 2015) but also with track-start (Benjanuvatra et al., 2004; Fisher and Kibele, 2016; Takeda and Nomura, 2006; Vantorre et al., 2010b) and handle-start (Blanksby et al., 2002; Vint et al., 2009). This solution provided enough time to achieve the highest forward velocity at take-off. Indeed, a larger take-off velocity seems to be beneficial, but in the case of grab-start, owing to the short flight distance, it was not preserved for long. Additionally, in a study by Taladriz et al. (2015), the horizontal velocity measured in the flight was lower for the grab-start than for the kick-start (4.06 ± 0.21 m/s and 4.12 ± 0.30 m/s, respectively; $p = 0.004$). Our results are in agreement with a study previously published by Vilas-Boas et al. (2003), in which the grab-start provided a faster reaction time than other techniques. Yet, as indicated in the available literature, the reaction time was not significantly influenced by the starting position (Blanksby et al., 2002). Still, regardless of the lower take-off velocity, the kick-start forward seems to expose an optimal compromise between the block phase duration and the amount of force exerted in the horizontal direction (Honda et al., 2010; Kibele et al., 2014; Peterson et al., 2018) in order to shorten the start time.

The main differences between the starting techniques were revealed in the block phase, and their influence decreased in the subsequent phases of start (Table 2). It is widely known that the block phase characteristics are highly dependent on the starting position type (Blanco et al., 2017; Honda et al., 2010; Kibele et al., 2014, 2015; Peterson et al., 2018; Takeda and Nomura, 2006; Takeda et al., 2012; Vilas-Boas et al., 2003; Welcher et al., 2008). Yet, as the take-off characteristics have a significant impact on the subsequent phases of the swimming start, as mentioned before, that phase needs to last long enough to exert enough force for the swimmer to leave the starting block with the highest possible velocity (Breed and Young, 2003; Hubert et al., 2006; Vantorre et al., 2014). Therefore, a compromise between high impulse generation and time reduction is needed. Indeed, swimmers have to leave the starting block as fast as possible to prevent the time deficits that could arise during the push-off actions (Lyttle et al., 1999; Vantorre et al., 2014). In this context, for better understanding, the specification of the swimming start enhancement and strategies undertaken to make use of the potential of the athletic performance and consequently to explore the future directions for its improvement, as well as multiple performance determinants and their significance for overall starting performance have to be considered. Their interdependence has to be cautiously evaluated to reveal a compromise among them that will meet the specific expectations of a given case.

No significant differences were noted in the flight distance between the tested positions (Table 2). These results were coherent with the findings from previous studies involving not only kick-start but also track-start (Blanksby et al., 2002; Jorgic et al., 2010; Kruger et al., 2003; Takeda et al., 2006; Taladriz et al., 2015; Thanopoulus et al., 2012; Vantorre et al., 2010a, 2010b). One reasonable explanation for this could come from the conclusion drawn by Seifert et al. (2010). These authors analyzed the flight phase following the grab-start position and distinguished four profiles of the flight trajectory. They advised to consider the intra-subject variability and provide support for the theory that the best start solution is the one detected for each swimmer with regard to their personal characteristics.

The decrease in the horizontal velocity between the take-off and the 5-m marker calculated for the grab-start differed significantly from that for both variants of kick-start (Table 4). Seifert et al. (2010) evidenced that the profile of the flight trajectory could significantly impact on the velocity values. The mentioned variability could also result from differences in the angular momentum, which influences the body orientation during water entry and contributes to the size of the “entry hole” (McLean et al., 2000; Taladriz et al., 2015; Vantorre et al., 2014). Here, the smaller the hydrodynamic drag when a swimmer passes the water line at the immersion, the lower velocity reduction will be observed (Maglischo, 2003; Mason and Mackintosh, 2020; Vantorre et al., 2014; Vilas-Boas et al., 2003). Therefore, reaching the appropriate entry angle during the descent phase of the flight and maintaining a streamline position while entering the water would result in better performance in this part of the swimming start (Mason and Mackintosh, 2020; Seifert et al., 2010).

The missing significant differences in water phases among the start techniques (Table 3) could be explained by a statement by Barlow et al. (2014) and Vilas-Boas et al. (2000). According to these authors, during the underwater phase, all differences noticed between techniques tend to disappear, which confirms the lack of significant diversity describing water phase characteristics in our study. To maximize the contribution to overall starting performance, each element of the start has to be carefully coordinated; therefore, the starting strategy requires some compromise between them (Vantorre et al., 2014).

Limb contribution to the velocity grown

The results of the GRF time series (Figure 7) demonstrated four distinct motor strategies in the considered start techniques. Then, as a consequence of the specific feet and hand placement over the starting block, the limbs were used in a different manner. The asymmetrical techniques exposed bimodal horizontal force profiles, while symmetrical limb placement exhibited a single peak force at the end of the push-off. These results are coherent with the observations in previous studies, in which each starting technique was described by different force-time curve profiles, as well as foot contribution to the velocity of the swimmers' center of mass (Benjanuvatra et al., 2004; Breed and Young, 2003; De la Fuente et al., 2003; Ikeda et al., 2016; Sakai et al., 2016; Slawson et al., 2013; Takeda et al., 2017). Positions implementing parallel foot position displayed a rather symmetrical nature, and a higher extensional component resolved from the take-off velocity in the starting movement described with the pendulum model (Takeda and Nomura, 2006). Here, any asymmetries in force generation between limbs could result in body rotation (Benjanuvatra et al., 2004), but have not been confirmed as a factor contributing to starting performance in ventral start (de Jesus et al., 2018; Hardt et al., 2009).

Interestingly, regardless of the body position, the percentage part contributing to push-off duration stays rather similar (Table 2). The group of participants who utilized staggered foot placement during handle-start spent 79% of the movement time on push-off from the incline element. In kick-start forward, 78% of the block time was devoted for rear foot take-off, while for 0.13 s all force was exerted only by the front lower limb. As a consequence, during the rear projection of the swimmer's body, the described association in force generation equaled approximately 79% and 0.15 s, respectively. A slightly higher percentage share of rear foot support time was presented by Benjanuvatra et al. (2004). They found some inconsistencies in impulse generation, exposing the diversity in force development strategies. Although in all track-start cases the front foot exerts force for longer, there were still a number of subjects with rear foot dominance (Benjanuvatra et al., 2004). The rear foot, especially important for horizontal impulse (Ikeda et al., 2016; Takeda et al., 2017) and the main contributor of the rotational component (Takeda and Nomura, 2006), has been reported as the main determinant of 5-m track- and kick-start time (Peterson et al., 2018). In grab-start and handle-start, both lower extremities follow a symmetrical movement pattern. Yet, in grab-start, rapid knee flexion followed by rapid extension is performed (Lee et al., 2001), while in handle-start, the knees are already flexed and, by performing only concentric contraction, a smaller amount of elastic energy can be utilized (Bartlett, 2014; Blanksby et al., 2002). Moreover, regarding the high contribution of the rear foot in horizontal velocity development (Ikeda et al., 2016; Slawson et al., 2013; Takeda et al., 2017), it has been stated that a more backward projection of a swimmer's body allows them to generate higher take-off horizontal velocity (Honda et al., 2012; Kibele et al., 2014; Tanaka et al., 2016; Welcher et al., 2008). Indeed, according to Taladriz et al. (2015), owing to back foot support, swimmers are able to produce a greater horizontal force before the starting signal appears and, consequently, obtain a huge acceleration in a short time.

One noted exception case resulted from shifting of an athlete's center of mass more into the back direction and an increase in pre-tension (during kick-start backward, the horizontal component of force obtained negative values for the initial position), which were indicated as beneficial for velocity development (Lee et al., 2001). For this reason, to maintain a stable position until the starting signal appeared, the swimmers had to compensate by exerting additional force by hand grip. Interestingly, as in handle-start, the center of mass is placed outside the swimmer's base of support; then, the upper extremities avoid overbalancing

(Blanksby et al., 2002; Pearson et al., 1998). Moreover, the length of the upper limbs would determine the position of the swimmer's center of mass (Blanksby et al., 2002). Therefore, the contact time, as well as the function of the upper limbs differ in that position from those in other techniques. Here, other positions that were behind the front edge of the starting block held pre-tension of the lower limbs by employing arm tension. Moreover, during grab-start by pulling upward, arms initiate the forward movement of the swimmer's body (Maglischo, 2003). Despite the above, our results revealed upper limb movement organization during the block phase as incorporating unique characteristics of the specific athlete rather than being attributed to the starting position. In contrast, Taladriz et al. (2015), while searching for differences between the grab-start and the kick-start regarding the initial position, observed significant differences in the upper limbs contact time with the starting platform. Accordingly, those findings were confirmed in their further work, focusing mainly on the analysis of the angular momentum describing both techniques (Taladriz et al., 2017).

The contribution of each limb to swimmers' center of mass velocity development is an interesting area to be further explored by characterizing different starting techniques and their performance enhancement. Shedding more light on that matter, we recommend to pay attention not only to the importance of the lower limbs, but also to the upper limbs placement over the starting block in the initial phase of the ventral swimming start as an initiation of consecutive swimmer's actions.

Correlation analyses

Movement time and block time expose high positive correlations with the 5-m starting time (Table 4). Nevertheless, the described relation seems to disappear while the starting distance extends as the overall starting performance demonstrates little or weak correlation with it, and the horizontal velocity gains significance. Block time prolongation provides the capacity to generate a larger impulse over the starting block and leave it with higher velocity (Breed and Young, 2003; Vantorre et al., 2014). Here, those two variables show correlations with the 5-m time, but with opposite signs. Therefore, in our study, that pattern was not followed by kick-start forward, in which a significantly shorter block time was observed, but simultaneously the swimmers attained lower take-off horizontal velocities. Meanwhile, for all starting positions, the velocity at 5-m was significantly associated with take-off horizontal velocity (Table 5); then, it demonstrated significant inverse correlations with the 5-m and 15-m start times, except for kick-start forward. These results supported the observations by Blanksby et al. (2002), who found significant correlations of both movement and block times with the 10-m time ($r = 0.53$, $r = 0.58$, respectively) obtained in a comparison involving grab-start, track-start, and handle-start. Those two variables were also associated with the center of mass position established prior to the starting signal (–0.67, –0.71) (Blanksby et al., 2002). In a study evaluating kick-start backward (in accordance with the presented GRF profile), an inverse correlation (–0.68) was revealed between the 5-m time and horizontal velocity at the front foot take-off (Ikeda et al., 2016). Moreover, those authors support the view that block time is not significantly correlated with the 15-m start time. The presented results might suggest that the increase in horizontal velocity is more important than the shortening of block time for improving overall start time. In fact, an optimal combination of those two parameters is required for best individualized swimming start performance. Indeed, on the basis of the kick-start forward case, the block time could become a main advantage ensuring the most successful start. Yet, different priorities have to be taken under consideration depending on the starting technique.

A high influence of the take-off angle on the velocity at 5-m was observed for kick-start forward and handle-start (Table 4). Indeed, the higher the take-off angle for these starting positions was, the lower decrease in take-off velocity was observed. This confirms that an increase in the take-off angle could help raise flight distance (Breed and Young, 2003) and maintain high horizontal velocity for a longer time or distance. Moreover, in a study by Peterson et al. (2018), the take-off angle was pointed out as one of the variables that influenced the 5-m starting performance the most, yet depending on the starting position, a different method of the take-off angle measurement was exposed as significantly associated with it.

A strong correlation between flight distance and 5-m time was also noted for grab-start and kick-start forward (Table 4). That is in line with the studies by Peterson et al. (2018) and Ikeda et al. (2016), in which negative Pearson correlation coefficients for flight distance and start times were reported. In contrast, Blanksby et al. (2002) found no significant correlation between flight distance or flight time and the 10-m start time. It seems important to underline that it is the only available study including handle-start in the interrelation of swimming start variables. Those results could therefore suggest that handle-start performance exhibits a low association with flight distance or flight time, confirming our observation of a decrease in flight distance importance with an extension of starting distance.

A highly significant positive correlation was revealed between water time and the 5-m time, excluding kick-start backward (Table 4). It could be a consequence of the shorter time from the water entry to the 5-m marker, which results from a longer flight and relatively higher velocity for a longer distance from the starting block (Maglischo, 2003; Peterson et al., 2018; Vilas-Boas et al., 2000). In our study, the instantaneous horizontal velocity at 5-m was one of the most important factors for shortening the 15-m start time. Indeed, the high contribution of the water phase to the total start time was widely emphasized by other researchers (Cossor and Mason, 2001; Peterson et al., 2018; Tor et al., 2014, 2015; Vilas-Boas et al., 2000, 2003).

These results suggest that the effectiveness of the considered techniques is determined by different variables of their spatiotemporal structure. Each of these is recognized as a certain measure in the assessment of starting performance. Therefore, depending on the starting position, different requirements for a successful start have to be addressed, and specific priorities should be considered.

Regression models

For a wider decryption of the differences in the swimming starts in the applied scope of their movement structure assessment, regression analysis models were composed (Table 5). With the selected explanatory variables, these analyses exposed equations derived from multiple linear regression methods that allowed to predict overall swimming start performance measured over the 5-m and 15-m distances. The multiple regression equations enabled performance prediction based on the values and configuration of selected variables, with the coefficient of determination explaining 86–99% of the variability of the response data around its means. Following Peterson et al. (2018), we paid special attention to the prediction of start parameters at the 5-m distance from the starting platform. The reasoning arose from the fact that an elongation of the analyzed distance (to 15-m, including subsequent water phases) would include more variables that were less related to the initial starting technique itself or its direct consequences (Barlow et al., 2014; Garcia-Ramos et al., 2015; Tor et al., 2015; Vilas-Boas et al., 2000).

The accuracy of our prediction models is in line with results published earlier (Peterson et al., 2018; Tor et al., 2015). According to those previous authors, the relevance of selected parameters describing the swimming start changes depending on the modeled technique. Moreover, it is rather unlikely that one aspect of the movement would act in isolation to determine the overall performance (Magloscho, 2003; Peterson et al., 2018; Tor et al., 2015). Here, as a swimming start includes complex specific motor skills, the performance is a result of multiple components (that could be described as a number of degrees of freedom) that complement one another. Despite this, multiple regression analyses have also been successfully used to derive feasible model equations providing the objective predictors of starting performance on the basis ofcountermovement jump test results (Carvalho et al., 2017; Durović et al., 2015).

Generally, the multiple linear regression model may be successfully employed as a valuable tool to predict and monitor start performance. Consequently, it contributes to the area of ventral start performance monitoring and enhancement. Coaches should pay attention to the parameters that would significantly impact on the most crucial elements of particular starting techniques. Finally, the added advantage of the proposed solution enables a wider view and detailed interpretation of changes in the starting performance in relation to its specific parameters.

Limitations

Notwithstanding the relevance of the obtained results, some procedural limitations should be considered in this study. Because of a small sample size, the results do have a limited source of interpretation. In fact, concerning the number of participants, the independent variables included in the equations may be further reduced. Yet, the inclusion of more independent variables ensures higher accuracy of the obtained multiple linear regression model. Generally, much larger samples (retrospective trials) might be desired, enabling to employ parametric statistical procedures that would allow for more valuable analyses of the tested hypotheses and increase the research inferential robustness in terms of achieving statistical significance. However, similar numbers of participants were also involved in congruous analyses conducted in experimental settings (e.g. Blanksby et al., 2000; Peterson, 2018; Taladriz et al., 2015).

The influence of the swimmers' preference and experience background might also become one of the limitations and should be considered. It seems that the level of proficiency in the starting technique preferred (kick-start) in the research group influenced the results of its comparison with other techniques. In our study, during warm-up and familiarization sessions, detailed demonstrations and feedback were provided; besides, the athletes were allowed to practice more starts if desired, but no specified training program was implemented. However, concerning the findings presented by Kibele et al. (2014), the preferred stance could be substantially improved while implying a different stance alternation. A longer process of "new techniques" learning or practicing should be therefore ensured before the next stage of research. Nevertheless, the level of starting technique development prior to the commencement of the experimental trials was not a formal consideration in the previous research (Blanksby et al., 2000). Finally, the obtained results should be confirmed in a procedure engaging swimmers representing different levels of swimming proficiency.

Conclusions

In general, the spatiotemporal analysis assessing starting performance demonstrated starting techniques that incorporated staggered foot position to be more beneficial than those that included parallel foot placement. Owing to the asymmetrical positions implementation, the swimmers took advantage of a shorter block time, 5-m and 15-m times, and lower decrease of velocity. The kinematic analysis evaluating starting performance demonstrated the superiority of kick-start forward concerning the above-mentioned variables, while the backward variant ensured the highest instantaneous horizontal velocity measured in a 5-m distance from the starting block. The fact that kick-start was the technique preferred by the investigated swimmers probably accounted for this technique results being the best. Nevertheless, it seems that with the indicated advantages, kick-start can be recommended as a model technique for swimmers beginning their sports training.

Significant differences were revealed in all temporal variables for kick-start forward, except for reaction time and flight time. The highest take-off velocity was measured for the grab-start. Also, a significantly higher decrease in horizontal velocity from the take-off to the 5-m marker was determined for that technique. It seems that despite the start technique, a compromise between the block phase duration and the magnitude of velocity is crucial for a successful start. Therefore, the different expectations concerning specific elements of movement structure have to be considered.

The analyses revealed a group of variables that have to be selected deliberately to examine the swimming start performance of the chosen technique. In general, the Spearman correlation values were higher for velocity than for temporal parameters. The crucial areas for improvement in ventral swimming start were identified in accordance with the multiple regression models implemented for each starting position. The model equations enabled the prediction of selected swimming start performance indicators while providing feedback, which could be important to identify priorities in combinations of parameters mostly affecting the starting performance. In this way, in the future, a guideline for athletes and their coaching staff should be prepared; it should refer to the starting technique selection and optimization on the basis of conscious decisions supported by evidence from accurate and reliable research.

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CHAPTER III

BACKWARD OR FORWARD KICK-START: WHICH VARIANT OF INITIAL POSITION ENSURES BETTER STARTING PERFORMANCE?

Daria Rudnik, Ricardo Jorge Fernandes, João Paulo Vilas Boas,
and Marek Rejman

Abstract

The start is commonly divided into distinct phases, but the starting strategy requires consideration of interconnections between them. The block phase executes an acceleration profile and, consequently, influences further swimmers' actions. Thus, to understand its contribution to overall starting performance, one has to carefully analyze the subsequent phases of the start. This study was intended to expose differences in the spatiotemporal structure of two kick-start variants: backward (KB) and forward (FB), to finally reveal a more beneficial position in terms of its overall performance. The sample included eight females – members of the national junior team. Six kick-starts were randomly performed by each swimmer, constituting three repetitions of each variant. Five stationary video cameras were used to record a lateral view of the swimmers' movements over the 15-m distance from the starting block. To explore the differences between the two variants of kick-start under consideration, key spatiotemporal variables were identified and compared with the Wilcoxon signed-rank test. Then, correlation coefficients estimated between the selected spatiotemporal variables of swimming start were calculated for each starting variant and its main performance measures. Finally, regression analyses served to compose formulas predicting chosen performance indicators. The hip height, its length, and rear knee joint angle at the initial position differentiated the tested variants. The KF not only ensured temporal advantage with regard to the total start time but also reduced the duration registered for movement, block, overwater, and 10-m distance times. The correlation analyses exposed a number of variables significantly related with start performance indicators, yet only the 5–10-m time correlated with the 15-m time in both start variants. The univariate linear regression results revealed a relationship between 5-m and 15-m start times with chosen start variables, and equations composed with different combinations of predictors with the multivariate regression procedure were formulated to model swimming start under the two starting conditions separately. It can be concluded that swimmers aiming to reduce total start time should consider using KF over KB. It is important to differentiate the parameters employed to evaluate the swimming start performance with the consideration of its variants. Yet, to improve the starting performance optimization process, a conscious decision has to be made concerning individual characteristics of each swimmer with objective measures.

Key words: swimming start, kick-start variants, center of mass projection, performance, modeling.

Introduction

The swimming start is the first of three distinct technical domains of a swimming race. Regardless of the starting variant, from the instant when the starting signal is given, the start is commonly divided into four components: block phase, flight phase, water phase, and swim phase (Blanco et al., 2017). Here, to maximize the contribution to overall starting performance, each phase of the start must be carefully coordinated (Vantorre et al., 2014). The block phase and take-off parameters strongly influence the flight phase by determining the swimmers' flight trajectory (Maglischo, 2003) and, consequently, the features of the distance covered during the water phase (Nomura et al., 2010; Vantorre et al., 2010b). Concerning the Fédération Internationale de Natation (FINA) rules, after the start, the swimmer's head must emerge before reaching 15-m from the starting wall. But still, a low number of studies concerning kick-start variants extend their evaluations to the 15-m distance.

Over time, the swimming start technique has evolved; thus, many starting solutions have been used in competition. Therefore, researchers have tried to identify which technique is the best among those practiced by swimmers. Major differences regarding movement organization, performance enhancement, and the determining factors of different starting positions have been widely analyzed (Blanco et al., 2017; Rudnik et al., 2021; Vantorre et al., 2014). Some years ago, the main discussion concerned the advantages of the grab-start vs. track-start, the latter initially proposed as similar to a track and field start (Ayalon et al., 1975). Both techniques coexisted for more than 40 years (Blanco et al., 2017), but regardless the high number of studies aiming to reveal the more advantageous technique through comparison analyses, that issue has not been resolved (Benjanuvatra et al., 2004; Blanksby et al., 2002; Issurin and Vertebsky, 2002; Kruger et al., 2003; Takeda and Nomura, 2006; Vantorre et al., 2010b).

Lately, since the new back plate (OMEGA OSB 11) was approved by FINA introduced it has been shown that the kick-start is faster than the track-start – the same technique performed without the incline support for the rear-foot (Biel et al., 2010; Honda et al., 2010; Vint et al., 2009). Furthermore, despite the fact that various studies have been inconclusive about the superiority of track-start over grab-start, since the introduction of the new incline back plate, the kick-start has outstood its previous version mostly by shortening the block time (Beretic et al., 2012; Biel et al., 2010; Garcia-Hermoso et al., 2013; Honda et al., 2010; Ozeki et al., 2012) and improving take-off velocity (Biel et al., 2010; Honda et al., 2010; Ozeki et al., 2012). Indeed, on the basis of recent swimmers' preferences, the lead of the one toward staggered feet placement on the starting block could be exposed (Vint et al., 2009).

In these years, a controversy was also roused between two possible variants of the staggered position of kick start: forward and backward. While establishing the initial position, swimmers could project their center of mass more toward the rear (backward or rear-weighted start) or closer to the front (forward or front-weighted rear-weighted) of the starting block (Vilas-Boas et al., 2000). The backward variant of the track-start was exposed as taking advantage of higher impulse generation and longer flight distance, while implementing the second variant allowed swimmers to shortening the block phase duration (Breed and McElroy, 2000; Vilas-Boas et al., 2000; Welcher et al., 2008). Hence, while evaluating the adequacy of different technical solutions, a conscious decision has to be made to consider and prioritize those starting elements that highly contribute to the final performance. Furthermore, it remains unclear whether parameters should lead the evaluation process of the given variant or if performance indicators differ between them. Thus, there has been no consensus on the advantage of either variant (Bingul et al., 2015; Sabaghi et al., 2018; Vilas-Boas et al., 2000, 2003; Welcher et al., 2008).

The possibility of supporting the rear-foot supply swimmers with more opportunities, which have to be considered before the final start decision. As a result, the current scientific reports are eager to focus more on detailed analyses in order to reveal the best possible option. Consequently, the new advantages for swimming start performance have been further revealed. The use of the back plate leads to performance enhancement. The introduced changes have made it necessary to reevaluate the current knowledge with the consideration of up-to-date starting conditions and have raised new argumentations for swimming start analysis. The exposure has highlighted the relevance of studies focused on the available knowledge verification due to the new starting opportunities. Recently, several studies have compared the mentioned kick-start variants. However, the existing results are still scarce. Besides, these findings are inconclusive as to which of the kick-starts is best from the point of view of overall starting performance. Moreover, the majority of the studies were based on a low number of participants and often combined both genders, which makes it rather difficult to distinguish the recommendations for a precisely selected population of swimmers. Finally, there is a need for studies that would search for parameters that highly determine the starting performance.

Considering the above, this study was intended to expose differences in the spatiotemporal structure of the kick-start in two variants: with backward and with forward displacement of the swimmer's center of mass in the initial position. Furthermore, analyses were conducted to disclose the advantages and disadvantages of each of the two kick-start variants and reveal which one was more beneficial for international level female swimmers. Finally, attention was paid to whether parameters describing the spatiotemporal structure of the swimming start should be considered as key performance determinants and highlighted in the process of monitoring the selected kick-start variant. It was hypothesized that, owing to a shorter distance covered during the block phase, the kick-start forward would ensure a reduction of block time, and, in consequence, result in a shorter total start time (at a 15-m distance). On the other hand, with a longer block phase, the kick-start backward may allow to obtain higher take-off velocity, which could be maintained for longer.

Material and methods

The sample included eight female junior swimmers; all of them were freestyle specialists with a high level of swimming proficiency (members of a national junior team). The general characteristics of the sample were as follows: 15.9 ± 0.4 years of age, 1.68 ± 0.05 m of body height, and 59.5 ± 4 kg of body mass; the best freestyle personal record mean value was of 741 ± 32 FINA points. The swimmers volunteered to participate in all the testing procedures. They (and their coaches) were informed of the benefits, any potential risks, and the purpose of the experiment. Written informed consent was obtained from participants and their parents or legal guardians. The study was performed in accordance with the Declaration of Helsinki regarding human research and was approved by the local ethics committee.

All swimmers had previous experience with the kick-start performed in starting blocks with a back plate. However, before the testing session, they were acquainted with the description of the kick-start variants to be tested. Moreover, they had an opportunity to familiarize themselves with the starting platform during the warm-up. The subjects were asked to avoid strenuous exercise and to keep their normal daily routine for at least two days before the data acquisition. The testing session was conducted on one day for all participants and organized to ensure a sufficient three-minute resting interval before each repetition. The experimental session was carried out at the University of Porto, with the assistance of Porto Biomechanics Laboratory – LABIOMEP-UP. The 25-m indoor swimming pool was compliant with the FINA rules, with water temperature of 27°C.

All participants completed a standard warm-up at the beginning of the testing session. In order to simulate race conditions, each swimmer was asked to perform all the starts with a maximum effort, swimming freestyle at maximal speed for 20 m. That ensured the preservation of the highest possible velocity at least over 15 m from the starting block and provided representative values of the targeted time recorded over the 15-m distance (Barlow et al., 2014). Six kick-starts were randomly performed by each swimmer, constituting three repetitions of each variant: kick-start backward (KB) and kick-start forward (KF) (represented in Figure 1). The swimmers were asked to position their bodies (center of mass) as far as possible in selected directions (on the basis of their perception of the weight bearing), without displacing their feet or the back plate.

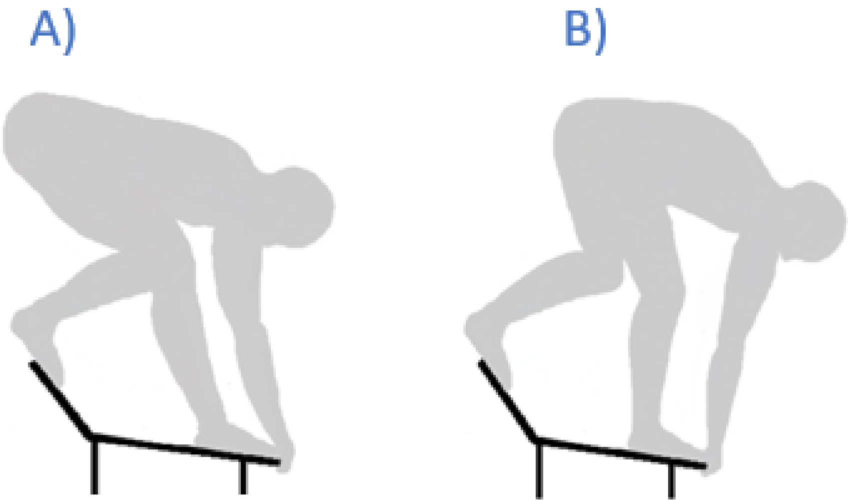


Figure 1. Illustration of the kick-start backward (A) and kick-start forward (B).

A total of 22 anatomical marks were painted on the swimmer's body at the locations described by Juergens (1994): proximal end of lateral fifth and first metatarsals (foot), lateral and medial malleolus of fibula (ankle), proximal portion of lateral and medial condyle of femur (knee), lateral greater trochanter of the femur (hip), lateral greater tubercle of humerus (shoulder), lateral and medial epicondyles (elbow), center of lateral wrist joint (wrist). These were used to digitize a link segment model and determine the position of body segments (while processing the collected video recordings). Moreover, for the sake of simplicity, the hip joint marker (identified as the greater trochanter of the femur) was used as a reference point while determining the position of swimmers' center of mass during the initial position (Barlow et al., 2014; Figueiredo et al., 2008; Kibele et al., 2014).

As shown in Figure 2, five stationary video cameras were used to record the swimmers' movements (with a frequency of 50 frames per second and the optical axis positioned perpendicularly to the stsrting/swimming direction). Two cameras (HDR CX160E, Sony Electronics Inc., Japan) were fixed on the surface, 0.5 m from the front edge of the starting block. They were located on both sides of the pool in order to track the swimmers' movements from the starting signal until full immersion of the body. Another camera was fixed on a tripod to record the swimmers at the 15-m distance from the starting block.

Two underwater cameras (GoPro Hero 4, GoPro, San Mateo, CA, USA) were fixed on the sidewall of the pool at a 5-m and 10-m distance from the starting block. They were dedicated to record the participants' underwater movement (from the first contact with water until the moment when the swimmer had disappeared from the optical view of the camera. A laterally positioned 2 × 2 m calibration frame was recorded and used to determine the pixel/meter calibration factor. An instrumented starting block (3D dynamometric central; 3D-6DoF, corresponding with starting block OMEGA OSB 14) was employed to derive the exact values of the temporal parameters describing the block phase (Mourão et al., 2016; Vilas-Baoas et al., 2014). It was composed of five independent force plates, allowing the acquisition over time of ground reaction forces generated by each lower and upper limb independently, with a sampling frequency of 2000 Hz.

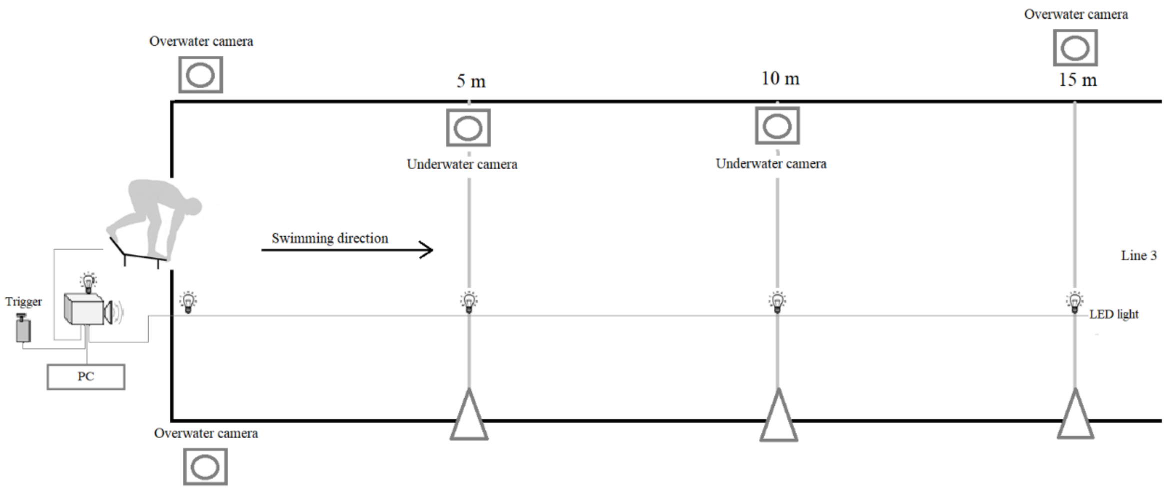


Figure 2. Graphical presentation of the measurement equipment setup used for data collection.

The 5-m, 10-m, and 15-m distances from the starting line were marked (above the water on the side of the pool and under the water on the bottom of the pool). Additionally, light-emitting diodes (LED light connected with a trigger giving an optical stimulus simultaneous to the acoustic start signal) were placed to be visible by each camera. Harmonized sound, visual, and electrical signals were produced by the starting device (consistently with the FINA rules), which was used as a trigger for synchronizing all parts of the measuring setup (Vitor et al., 2016). It was assumed that the shorter the start times (5-m, 10-m, and 15-m) and the higher the values of swimmer's velocity, the better the starting performance was (Blanco et al., 2017). To explore the differences between the two variants of kick-start under consideration, key spatiotemporal variables were identified (Table 1).

A dedicated processing routine created in the MATLAB R2016a software (MathWorks Inc., USA) was used to derive the temporal characteristics of the block phase collected from the instrumented starting block. To measure the parameters based on the collected video footage, the SIMI Motion System (SIMI Reality Motion Systems GmbH, Germany) was applied. When the video recordings were processed, the first frame in which the LED light was activated was used to determine the starting signal for a given trial. Mean values were calculated for all parameters (on the basis of the three repetitions performed by each swimmer in a given variant) and employed in further analysis. The descriptive statistical parameters (mean and standard deviation) were calculated for each variable in both starting variants. Then, the results were thoroughly examined to explore the significant differences between the two starting variants. As the sample size was reduced and the studied variables did not exhibit normal distribution (Shapiro-Wilk test), non-parametric statistical procedures were used to compare the two kick-start variants. To determine whether significant differences between the variants represented by the two sets of data occurred, the Wilcoxon signed-rank test was implemented. The effect size was calculated in accordance with the criteria established by Cohen (1988) (trivial if $r < 0.1$; small if $0.1 \le r < 0.3$; medium if $0.3 \le r < 0.5$; large if $0.5 \le r < 0.7$; very large if $r \ge 0.7$).

Table 1. Definition of the specific variables used for characterizing the structure of the swimming start.

Phase		Variable	Definition
Spatiotemporal structure	Block	Reaction time (s)	The time interval between the starting signal and the first observable change in the starting block reaction force to time curve as a result of the initial swimmer's movement
		Hands take-off (s)	The time interval between the starting signal and the last contact of the hands with the starting block
		Rear foot take-off (s)	The time interval between the starting signal and the last contact of the rear foot with the starting block
		Front foot stand (s)	The time interval between the last contact of the rear foot with the starting block and the instant of take-off
		Block time (s)	The time interval between the starting signal and the instant of take-off
		Movement time (s)	The time interval between the first observable change in the starting block reaction force to time curve as a result of the initial swimmer's movement and the instant of take-off
		Take-off horizontal velocity (m/s)	The instantaneous horizontal velocity of the swimmer measured at the instant of take-off
	Flight	Time from start to water touch (s)	The time interval between the starting signal and the moment of the first contact of the hands with the water
		Flight time (s)	The time interval between the instant of take-off and the moment of the first contact of the hands with the water
	Water	Time from start to hips water entry (s)	The time interval between the starting signal and the moment of the first contact of the hips with the water
		Time from start to full water entry (s)	The time interval between the starting signal and the moment of full body immersion in the water
		Entry time (s)	The time interval between the first contact of the hands with the water to the moment of full immersion of the swimmer's body
		5-m time (s)	The time interval between the starting signal and the moment the head crossed the 5-m mark
		10-m time (s)	The time interval between the starting signal and the moment the head crossed the 10-m mark
		15-m time (s)	The time interval between the starting signal and the moment the head crossed the 15-m mark
		0–5-m average velocity (m/s)	The average swimmer's velocity between the starting wall and the 5-m marker
		5–10-m average velocity (m/s)	The average swimmer's velocity between the 5-m and 10-m markers
		10–15-m average velocity (m/s)	The average swimmer's velocity between the 10-m and 15-m markers

Table 1. Definition of the specific variables used for characterizing the structure of the swimming start (continuation).

	Phase	Variable	Definition
Spatial structure	Initial starting position	Initial rear knee joint angle (°)	The angle between the hip, knee, and ankle markers in the rear lower limb at the set position
		Initial front knee joint angle (°)	The angle between the hip, knee, and ankle markers in the front lower limb at the set position
		Initial hip height (m)	The vertical distance from the hip and water surface at the starting signal
		Initial hip length (m)	The horizontal distance from the hip to the front edge of the starting block at the starting signal
	Block	Horizontal displacement of hip during block phase (m)	Horizontal displacement of the hip during block phase
		Hip height at take-off (m)	The vertical distance from the hip to the water surface at take-off
		Hip length at take-off (m)	The horizontal distance from the hip to the front edge of the starting block at take-off
		Take-off angle (°)	The angle between the horizontal axis, the block edge, and the hip joint at take-off
	Flight	Entry angle (°)	The angle between the horizontal axis, the fingertips, and the hip joint when hands entered the water
		Flight distance (m)	The horizontal distance between the point where the hip entered the water and the starting wall
		Hip displacement during flight phase (m)	The horizontal displacement of the hip between the instants of take-off and first hands contact with the water
		Hip height at the water contact (m)	The vertical distance from the hip to the water surface at hand's contacting the water
		Hip length at the water contact (m)	The horizontal distance from the hip to the water surface at hand's contacting the water
		Entry hole diameter (m)	The horizontal distance between the point where the hands contacted the water and the point where the toes disappeared in the water

Finally, the focus of attention was moved toward the search for parameters determining the 5-m and 15-m start times. Therefore, to find the variables which were associated with starting performance in each of the variants, as well as to determine which set of variables better explained the main performance indicators, the correlation and regression analyses were performed. The correlation describing associations between each variable and main performance measures was calculated separately for each starting variant implemented in the study. Spearman correlation coefficients were evaluated by using the following criteria scale for correlations: little for the range of 0–0.25;

weak for 0.26–0.49; moderate for 0.50–0.69; strong for 0.70–0.89; and very strong for 0.90–1.0 (Blikman et al., 2013). The study involved numerous parameters but only the variables that reached at least moderate correlation with one of the start variants were presented as the results. To further understand the exposed interrelations between the variables, a linear regression between pairs of variables (for which at least moderate correlation with the main performance measure was noted) was implemented. Moreover, the stepwise multiple regression procedure was run, revealing a number of equations with different combinations of predicting variables (predictors). The regression analyses of the variables measured under the two starting conditions were conducted for the 5-m and 15-m start times separately. To analyze each model output accuracy, the p-value ($\alpha = 0.05$) and the values of the coefficient of determination (R-squared) were taken into consideration. The regression equation was included in the results when the created model (containing a selected set of variables) was able to explain at least 60% of variances in the 5-m or 15-m start performance. All statistical analyses were carried out with the Statistica 13.1 software (StatSoft, USA).

Results

Comparative analyses

Descriptive statistics and the Wilcoxon test results are presented in Table 2. Differences in the body initial position, the block phase, and the flight phase of the swimming start were noted between the variants. The horizontal and vertical displacements of the hip (center of mass) in relation to the front edge of the starting block were higher in the kick-start backward (KB) than in the kick-start forward (KF) ($p = 0.012$). Then, in the backward variant, the swimmers' hips were positioned 0.19 m further back (in the horizontal line) and 0.05 m lower than in the kick-start forward. Consequently, a change was also found at the rear knee joint angle (KF: 99 ± 16°; KB: 77 ± 13°; $p = 0.012$). However, the front knee joint angle did not differ between the two variants (KF: 147 ± 10°; KB: 148 ± 10°; $p = 0.834$).

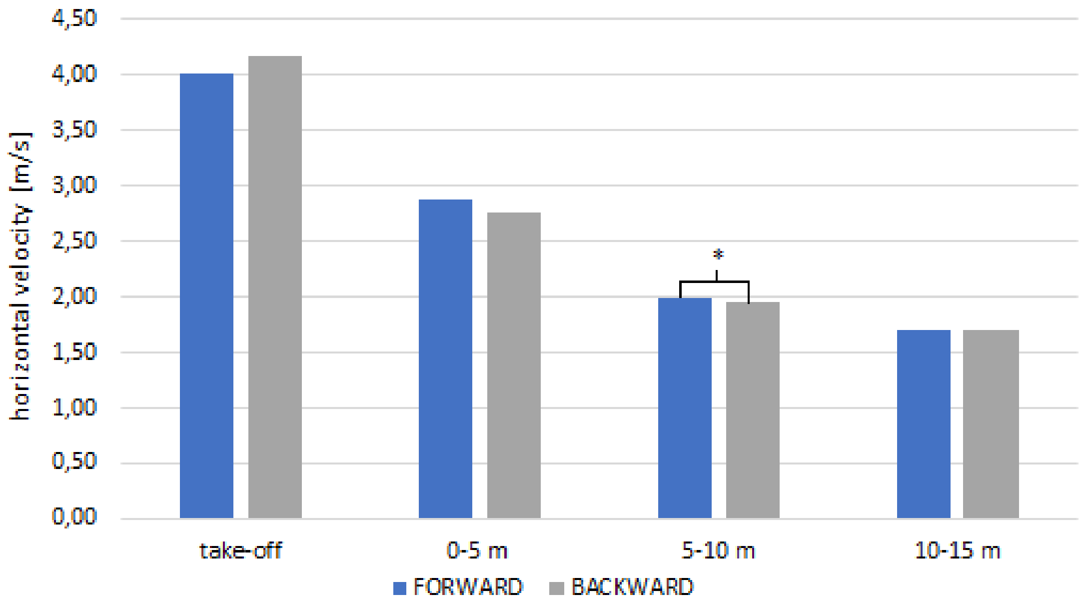
The mean values of the temporal parameters assumed as the crucial for staring performance assessment showed that the forward start position gave the swimmer advantage over the backward variant by shortening the 5-m time (KF: 1.74 ± 0.12 s; KB: 1.81 ± 0.09 s; $p = 0.123$), the 10-m time (KF: 4.27 ± 0.27 s; KB: 4.39 ± 0.24 s; $p = 0.036$), and the 15-m time (KF: 7.22 ± 0.31 s; KB: 7.35 ± 0.26 s; $p = 0.012$). The duration of the sub-phases of the block phase (excluding reaction time) were also different between the two kick-start variants. The hands take-off time (KF: 0.398 ± 0.05 s; KB: 0.446 ± 0.05 s; $p = 0.012$), rear foot take-off time (KF: 0.63 ± 0.03 s; KB: 0.70 ± 0.04 s; $p = 0.012$), and movement time (KF: 0.60 ± 0.02 s; KB: 0.67 ± 0.02 s; $p = 0.012$) were shorter for the kick-start forward variant. In contrast, no differences were observed for the majority of flight phase spatial variables (hip height and length at entry, flight distance, entry hole diameter) ($p > 0.100$). Additionally, the starting position had no effect on flight time ($p > 0.100$) or flight duration (KF: 0.42 ± 0.08 s; KB: 0.43 ± 0.09 s; $p = 0.499$). No differences were determined when analyzing angles measured during take-off and water entering ($p > 0.100$).

The results representing horizontal velocity measurements throughout the swimming start are depicted in Figure 3. Only the average horizontal velocity calculated for the intermediate 5-m share part of the 15-m start time differed significantly between the two kick-start variants compared. Here, higher 5–10-m average velocity was noted for the forward variant (KF: 1.99 ± 0.13 m/s; KB: 1.95 ± 0.13 m/s; $p = 0.05$). The obtained results exposed a near-significant take-off velocity advantage for kick-start backward (KF: 4.02 ± 0.23 m/s; KB: 4.18 ± 0.26 m/s; $p = 0.069$). For both start variants, the average horizontal velocity measured between the 10-m and 15-m marks equaled 1.7 m/s.

Table 2. Descriptive statistics results and statistical differences evaluated with the Wilcoxon test for the swimming start variables measured during the two kick-start variants.

Phase		Variable	Forward (mean ± SD)	Backward (mean ± SD)	Wilcoxon test Z	Wilcoxon test p	Effect size
Spatiotemporal	Block	Reaction time	0.178 ± 0.02	0.167 ± 0.02	1.68	0.093	0.60
		Hands take-off	0.398 ± 0.05	0.446 ± 0.05	2.52	0.012*	0.89
		Rear foot take-off	0.632 ± 0.03	0.700 ± 0.04	2.52	0.012*	0.89
		Front foot stand	0.144 ± 0.01	0.134 ± 0.02	2.10	0.036*	0.74
		Block time	0.776 ± 0.02	0.834 ± 0.03	2.52	0.012*	0.89
		Movement time	0.597 ± 0.02	0.667 ± 0.03	2.52	0.012*	0.89
		Take-off horizontal velocity	4.02 ± 0.23	4.18 ± 0.26	1.80	0.069	0.64
	Flight	Flight time	0.26 ± 0.08	0.26 ± 0.09	0.17	0.866	0.06
		T start to water touch	1.01 ± 0.08	1.07 ± 0.08	2.52	0.012*	0.89
	Water	T start to hips water entry	1.18 ± 0.07	1.25 ± 0.08	2.37	0.018*	0.84
		T start to full water entry	1.31 ± 0.07	1.38 ± 0.09	2.52	0.012*	0.89
		5-m time	1.74 ± 0.12	1.81 ± 0.09	1.54	0.123	0.55
		10-m time	4.27 ± 0.27	4.39 ± 0.24	2.10	0.036*	0.74
		15-m time	7.22 ± 0.31	7.35 ± 0.26	2.52	0.012*	0.89
Spatial	Initial position	Initial hip height	1.62 ± 0.08	1.57 ± 0.08	2.52	0.012*	0.89
		Initial hip length	0.23 ± 0.05	0.41 ± 0.05	2.52	0.012*	0.89
		Initial rear knee joint angle	99 ± 16	77 ± 13	2.52	0.012*	0.89
		Initial front knee joint angle	147 ± 10	148 ± 10	0.21	0.834	0.07
	Block	Hip height at take-off	1.29 ± 0.13	1.32 ± 0.14	1.40	0.161	0.50
		Hip length at take-off	0.88 ± 0.11	0.86 ± 0.09	1.19	0.234	0.08
		Take-off angle	32.5 ± 9.3	33.4 ± 10.1	0.56	0.575	0.20
	Flight	Hip height at entry	0.77 ± 0.08	0.80 ± 0.07	2.24	0.025*	0.79
		Hip length at entry	1.90 ± 0.26	1.92 ± 0.26	0.98	0.327	0.35
		Flight distance	2.55 ± 0.21	2.59 ± 0.24	1.54	0.123	0.55
		Entry angle	37.5 ± 4.3	39.1 ± 3.1	1.54	0.123	0.55
		Hip displacement	1.02 ± 0.30	1.05 ± 0.31	1.26	0.208	0.45
		Entry hole diameter	0.63 ± 0.19	0.61 ± 0.22	0.42	0.674	0.15

Forward: kick-start forward; backward: kick-start backward; T start to water touch: time from start to water touch; T start to hips water entry: time from start to hips water entry; T start to full water entry: time from start to full water entry; hip displacement: hip displacement during flight phase. *Significant at exact $p \leq 0.05$.



Forward: kick-start forward; backward: kick-start backward; take-off: instantaneous take-off horizontal velocity; 0–5 m: 0–5-m average velocity; 5–10 m: 5–10-m average velocity; 10–15 m: 10–15-m average velocity.
*Significant at exact p ≤ 0.05.

Figure 3. Comparison of horizontal velocity measured throughout the swimming start between kick-start forward and kick-start backward.

Correlation analyses

The statistical analyses involving correlation and regression methods were implemented to identify variables that could affect the minimization of the start times measured at the 5-m and 15-m marks. Firstly, the correlation analyses were conducted exposing variables highly related with the total start time measured at the 15-m distance (Table 3). For both starting variants implemented in the study, strong positive correlations with the time measured between the 5-m and 10-m marks were noted (KF: 0.79; KB: 0.83). The longer the 5-m start time, the longer the total start time of the forward variant was (0.71). Besides, the initial hip height strongly inversely correlated with the main performance measure of kick-start forward (–0.83) and moderately inversely correlated with the main performance measure of kick-start backward (–0.69). The initial front knee angle strongly inversely correlated with the total time of kick-start backward (–0.79) and moderately inversely correlated with the 15-m time measured for kick-start backward (–0.67). In short, the higher the hip position and the wider the front knee joint angle at the initial position, the better the starting performance was.

Table 3. Spearman correlation coefficients estimated between the main swimming start performance measure (15-m start time) and its selected spatiotemporal variables, with a distinction for kick-start variants.

	Variable	KF 15-m time	KB 15-m time
Temporal	5-m time	0.71*	0.57
	5–10-m time	0.79*	0.83*
Spatial	Initial hip height	–0.83*	–0.69
	Initial rear knee joint angle	–0.55	–0.21
	Initial front knee joint angle	–0.67	–0.79*
	Take-off angle at hip joint	–0.48	–0.24
	Entry angle	0.64	0.10
	Flight distance	–0.52	–0.60
	Entry hole diameter	–0.76*	–0.17

KF: kick-start forward; KB: kick-start backward.
*Significant at exact $p \leq 0.05$.

The results presenting Spearman correlation coefficients estimated between the 5-m start time and its selected spatiotemporal variables are presented in Table 4. A strong positive correlation was noted between rear foot take-off and the 5-m time of kick-start backward (0.71). The flight distance correlated inversely with the above-mentioned performance indicator (–0.71). For kick-start forward, a strong inverse correlation was obtained with the following variables: initial hip height (–0.83), initial hip length (–0.71), initial rear knee joint angle (–0.76), take-off angle at hip joint (–0.76). Interestingly, a moderate correlation was presented between take-off horizontal velocity and the 5-m start time for both start variants. Yet, for the forward variant, an inverse correlation was presented (–0.69), while for the backward variant, a positive value of correlation coefficient was noted (0.50).

Table 4. Spearman correlation coefficients estimated between the 5-m start time and its selected spatiotemporal variables, with a distinction for kick-start variants, with a distinction for kick-start variants.

	Variable	KF 5-m time	KB 5-m time
Spatiotemporal	Hands take-off	0.14	–0.53
	Rear foot take-off	0.45	0.71*
	Block time	0.64	0.40
	Take-off horizontal velocity	–0.69	0.50
Spatial	Initial hip height	–0.83*	–0.43
	Initial hip length	0.71*	0.12
	Initial rear knee joint angle	–0.76*	0.05
	Hip length at take-off	–0.55	–0.52
	Take-off angle at hip joint	–0.76*	0.00
	Flight distance	–0.43	–0.71*

KF: kick-start forward; KB: kick-start backward.
*Significant at exact $p \leq 0.05$.

Regression analyses

To supplement the correlation analyses results with univariate linear regression, the focus was shifted towards determining the relationship between one explanatory variable and the 15-m start time (dependent variable). To reveal how much of the variation in the 15-m start time was explained by each of the chosen explanatory variables, R^2 was calculated (Table 5). From among the temporal variables included in the analyses, the 5–10-m time explained 70% of variance in the 15-m time of kick-start forward ($p = 0.009$) and 62% of variance in total start time measured for the backward variant ($p = 0.021$). Besides, in kick-start forward, the 5-m time was able to explain 58% of variance in total start time ($p = 0.028$). The initial hip height and initial front knee joint angle were the only spatial variables that reached the significance level for both start variants ($p < 0.05$). Here, R^2 was higher for kick-start forward ($R^2 = 0.66$; $p = 0.014$) than for kick-start backward ($R^2 = 0.62$; $p = 0.020$). For the initial front knee joint angle, R^2 was approximately 0.56 for both kick-start variants evaluated ($p = 0.032$). Finally, the entry hole diameter explained 55% of variance in the 15-m kick-start time ($p = 0.036$).

Table 5. Univariate linear regression results exposing relationships between the 15-m start time and chosen swimming start variables, calculated separately for each kick-start variant.

	Variable	KF 15-m time	KB 15-m time
Temporal	5-m time	0.58*	0.18
	5–10-m time	0.70*	0.62*
Spatial	Initial hip height	0.66*	0.62*
	Initial rear knee joint angle	0.43	0.17
	Initial front knee joint angle	0.56*	0.56*
	Take-off angle at hip joint	0.17	0.04
	Entry angle	0.32	0.06
	Flight distance	0.15	0.18
	Entry hole diameter	0.55*	0.01

KF: kick-start forward; KB: kick-start backward.
*Significant at exact $p \leq 0.05$.

To explore which set of variables was associated with the starting performance in each of the variants, a number of models were implemented (Table 6). For each starting variant, separate regression models were successfully revealed, providing results matching our assumptions. A total of six equations for kick-start forward and five equations for kick-start backward were composed predicting indicators of the 15-m start performance and meeting significance level requirements. The best equation enabling the prediction of the 15-m kick-start forward performance was based on the initial front knee joint angle and the 5–10-m time (adjusted $R^2 = 0.79$). For the backward variant, the initial front knee joint angle and flight distance were included in the best equation, explaining 92% of the 15-m start time variance (adjusted $R^2 = 0.92$). The following common predicting variables for both start variants were included in some models exposed: initial hip height, initial front knee joint angle, 5-10-m time.

Table 6. The best equations composed with different combinations of predictors with multivariate regression procedures, calculated separately for each kick-start variant.

KF 15-m time		**Explanatory variables**				
R^2	Adjusted R^2	Initial hip height	Initial front knee joint angle	Entry hole diameter	5-m time	5–10-m time
0.85	0.79		x			x
0.84	0.78	x		x		
0.83	0.76			x	x	
0.8	0.72	x				x
0.76	0.67		x		x	
0.74	0.63				x	x

KB 15-m time		**Explanatory variables**				
R^2	Adjusted R^2	Initial hip height	Initial front knee joint angle	Take-off horizontal velocity	Flight distance	5–10-m time
0.95	0.92		x		x	
0.78	0.69	x			x	
0.75	0.65		x			x
0.7	0.58	x		x		
0.65	0.51				x	x

KF: kick-start forward; KB: kick-start backward.

To estimate the relationships between the dependent variable (5-m start time) and one independent variable, the models exposed through statistical procedures were obtained (Table 7). For kick-start forward, the outcome variable was significantly related with the initial hip height (R^2 = 0.74; p = 0.006) and the initial rear knee joint angle (R^2 = 0.60; p = 0.025). For the backward variant of the kick-start, a significant association with the starting performance was noted for one predictor only: the rear foot take-off (R^2 = 0.64; p = 0.017).

Table 7. Univariate linear regression results exposing relationships between one explanatory variable and the 5-m start time (dependent variable), presented separately for each kick-start variant.

	Variable	KF 5-m time	KB 5-m time
Spatiotemporal	Hands take-off	0.02	0.13
	Rear foot take-off	0.12	0.64*
	Block time	0.11	0.41
	Take-off horizontal velocity	0.29	0.20
Spatial	Initial hip height	0.74*	0.18
	Initial hip length	0.49	0.10
	Initial rear knee joint angle	0.60*	0.17
	Hip length at take-off	0.31	0.07
	Take-off angle at hip joint	0.38	0.02
	Flight distance	0.16	0.34

KF: kick-start forward; KB: kick-start backward.
*Significant at exact $p \leq 0.05$.

A number of equations that allow prediction of the 5-m start time with different combinations of predicting variables were obtained for each kick-start variant separately (Table 8). A total of five models for kick-start forward and three models for kick-start backward were composed and met significance level requirements. For the kick-start forward, two models reached the highest exact adjusted R^2 at 0.92. The first model included the following predictors: initial rear knee joint angle, block time, and flight distance. The second model involved initial hip height, block time, and flight distance. Furthermore, the adjusted R^2 at 0.80 was obtained for the model containing only two predictors (initial rear knee joint angle and flight distance). With the stepwise multiple regression procedures, the best model predicting the 5-m time of kick-start backward was obtained on the basis of the following covariates: rear foot take-off, block time, and flight distance (adjusted R^2 = 0.86). The second-best model included two covariates: rear foot take-off and flight distance (adjusted R^2 = 0.72).

Table 8. The best equations predicting 5-m start times for each kick-start variant, composed of different combinations of predictors.

KF 5-m time		Explanatory variables			
R^2	Adjusted R^2	Initial hip height	Initial rear knee joint angle	Block time	Flight distance
0.92	0.86		x	x	x
0.92	0.86	x		x	x
0.86	0.8		x		x
0.84	0.78	x			x
0.76	0.66	x		x	

KB 5-m time		Explanatory variables			
R^2	Adjusted R^2	Initial hip height	Rear foot take-off	Block time	Flight distance
0.9	0.82		x	x	x
0.8	0.72		x		x
0.7	0.59	x			x

KF: kick-start forward; KB: kick-start backward.

Discussion

Overall starting performance

In the current study (Table 2), each swimmer obtained a significantly shorter total start time at 10 m and 15 m when using kick-start forward compared with kick-start backward (0.12 s and 0.13 s, respectively). As success in a swimming race is determined by thousandths of second margins (especially in the short distances and in the highest competitive level), the difference examined between the two starting variants (0.13 s) may determine the final score. This trend was also presented in previous studies evaluating the kick-start over shorter distances (Honda et al., 2012; Kibele et al., 2014, 2015). The majority of the available findings suggest a slightly shorter 5-m time for kick-start forward (Honda et al., 2012; Kibele et al., 2015; Welcher et al., 2008). Honda (2012) showed a temporal advantage in the 5-m start time of kick-start forward (1.62 ± 0.02 s) over the backward variant (1.64 ± 0.01 s), and a non-significant difference between the start variants was noted in their study for the 7.5-m time (2.73 ± 0.02 s and 2.71 ± 0.02 s, respectively). Yet, none of the above-quoted studies took into consideration data obtained at a distance further than 7.5 m, which makes it difficult to directly compare their results with those of our study. Only Barlow et al. (2014) compared the temporal parameters at 5 m and 15 m from the starting wall. Contrary to our findings, those authors reported lower time values for the kick-start backward variant as compared with kick-start forward (0.09 s and 0.18 s, respectively). However, it is important to note that these results were obtained in a group of 10 participants, of whom only two regularly used kick-start forward. Many authors suggested that the most practiced swimming starts tended to be the best in terms of success (Blanksby et al., 2002; Vantorre et al., 2010b). The performance of the swimming start is a sum of specific phases and so the starting strategy requires a consideration of some compromises between the particular elements. To maximize the contribution to overall starting performance, each phase of the start must be carefully coordinated (Vantorre et al., 2014).

Initial starting position

The initial angular hip position differed between the two tested kick-start variants (p = 0.012) (Table 2). This significantly higher horizontal distance between the hip and front edge of the starting block when the forward and backward kick-start variants was also reported in previous studies, both with and without the back plate use (Barlow et al., 2014; Honda et al., 2012; Kibele et al., 2014, 2015; Vilas-Boas et al., 2000, 2003; Welcher et al., 2008). In our study, the knee angle of the front lower limb was almost constant, while the knee joint angle in the rear lower limb was significantly smaller when the swimmers' hips were positioned more in a backward direction (99° and 77°, respectively). Additionally, in the kick-start forward trials, the initial rear knee joint angle was revealed to significantly influence the performance measured at 5 m (Tables 6-8). According to Slawinski et al. (2010), these two distinct conditions differ in the values of knee joint angle measured at the initial body position on the block. It has been declared that the inclined back plate provides beneficial features and allows swimmers to push off with a rear lower limb knee joint angle of 90° (Slawson et al., 2012). This statement was also explored by Nomura et al. (2010). They evaluated the back plate effect and exposed a reduction in the rear lower limb knee joint angle from 97° to 84°, but with no significant change in take-off velocity or flight distance. The knee angle of 80–90° while producing the highest vertical force and 100–110° at the highest horizontal force were shown as beneficial for starting performance (Slawson et al., 2012). This affects the acceleration profile of the swimmer's body during the block phase. As a consequence of changing the swimmer's position on the starting block, the temporal characteristics of the start also change (Barlow et al., 2014; Honda et al., 2012; Kibele et al., 2014, 2015; Vilas-Boas et al., 2000, 2003; Welcher et al., 2008).

Block phase

In current study (Table 2), the kick-start backward seems to be advantageous when horizontal take-off velocity was compared, while kick-start forward allowed swimmers to leave the starting block in a significantly shorter time (the time gap between the two variants was 0.058 s). To the best of our knowledge, no published study obtained a shorter block time for the backward set position of the swimmer's body, which might result from the longer distance covered during the block phase while using this variant (Vilas-Boas et al., 2003; Welcher et al., 2008). In this study, during kick-start backward, the displacement of hips until the moment when the feet left the starting block was 0.15 m longer than in the forward variant. Vilas-Boas et al. (2000) found a similar difference between the mean values of the total displacement of center of mass during the block phase between the two compared variants of the track-start. A longer forward excursion of the center of mass or the hip during the block phase is expected to impose a longer block time duration. In general, the block time differences between the two starting variants obtained in this study were also reported in several previous studies. Peterson et al. (2018) presented differences of 0.01 s, Honda et al. (2012) of 0.04 s, Barlow et al. (2014) of 0.07 s, and an even higher gap was obtained by Kibele et al. (2014): an approximately 0.12-s difference between low-front wide (0.76 ± 0.04 s) and low-back wide (0.88 ± 0.05 s) positions.

Reaction time did not differ significantly (p = 0.093), but movement time did (Table 2). The estimated movement time (0.597 s and 0.669 s for kick-start forward and kick-start backward, respectively) was in line with the results obtained by different authors. Barlow et al. (2014) found lower mean values for the forward variant (0.50 ± 0.06 s) than for the backward position (0.56 ± 0.05 s). Honda et al. (2012) presented quite comparable results (0.59 ± 0.01 s and 0.66 ± 0.01 s, respectively). Therefore, similar trends were presented in the quoted studies.

The (Table 2) results point out that the impulse time for each lower limb differs significantly between the variants. This made expectable that the total impulse would be affected, resulting in different take-off velocities. Here, the rear foot was in contact with the back plate for 0.07 s more, which is related to an near-significant improvement in take-off horizontal velocity while using kick-start backward. Recent studies of kick-start emphasized an important contribution of the rear lower limb to take-off horizontal velocity development (Ikeda et al., 2016; Takeda et al., 2017). The results observed in this study (KF: 4.02 m/s; KB: 4.18 m/s) were slightly lower than in other studies – respectively 4.30–4.42 m/s (Kibele et al., 2014) and 4.45–4.55 m/s (Honda et al., 2012). Despite these differences, all the previous studies clearly expose higher take-off velocity values for kick-start backward. With the aforementioned arguments concerning temporal evaluation of the block phase, kick-start forward seems to be more beneficial for swimmers. On the other hand, because of the longer block time in kick-start backward, swimmers are able to develop higher horizontal take-off velocity, which may reduce the time deficit arisen during the block phase.

Overwater actions

The results obtained for the time from start to water touch, the time from start to the hips water entry, and the time from start to the full water entry were higher for the backward variant (Table 2). This was partially expected given the block time differences, but possibly attenuated by the higher take-off velocity of the backward variant. However, the flight time or flight distance obtained for kick-start forward and kick-start backward did not differ, as was expected owing to differences in take-off velocity, although the flight distance showed a slight tendency to be longer for the backward variant. According to Ruschel et al. (2007), flight time is less relevant than flight distance as a determinant of starting performance. Once the block phase and take-off characteristics have a strong influence on the swimmers' flight trajectory (Arellano et al., 1996; Maglischo, 2003; Nomura et al., 2010; Vantorre et al., 2010b,2010c), our observation might be explained by reciprocally compensatory differences in the take-off angle and/or the take-off height of the center of mass. Nevertheless, these variables also did not differ between the variants in this study. Similar findings were presented in previous studies but in some cases differences between flight distances reached the significance level (Barlow et al., 2014; Honda et al., 2012; Kibele et al., 2014, 2015; Welcher et al., 2008).

Meanwhile, in the present study, a greater entry angle for kick-start backward was found. Consequently, the hydrodynamic drag may probably be reduced during water entry when that variant is used (Barlow et al., 2014). It is worthy to note that this effect of the entry angle on drag may be counterbalanced by a higher vertical velocity at entry due to a higher elevation of the center of mass during flight if the higher take-off velocity and the similar flight distance are taken into account. Mclean et al. (2000) and Vantorre et al. (2010d) showed that swimmers had to generate a proper angular momentum to fulfil the necessary conditions for obtaining a "clear" entry into the water. Therefore, sufficient time is needed to rotate the body for it. The aforementioned analyses should lead to the conclusion that the back projection of the swimmers' body during kick-start implies better performance during the flight phase.

Water phase

With reference to the sole water phase, the results did not reveal clear differences between kick-start forward and kick-start backward (Table 2). In kick-start forward, a shorter time from start to full water entry (0.07 s) could be expected to imply also a reduced time of the water phase. Vilas-Boas et al. (2000) observed that the primary advantage of the backward variant – higher take-off velocity – vanished during the entry and water phases owing to the presumably higher hydrodynamic drag arisen in the water. As stated before, this is not incoherent with the greater entry angle if entry velocity is taken into account. Finally, we could observe an almost equal 10–15-m average velocity for both starting variants, reinforcing the loss of the take-off velocity advantage during flight and water entry for the backward variant. Interestingly, all differences between the two kick-start variants bring about conditions demonstrating no significant differences in horizontal velocities measured in the water phase around the 5-m and 15-m distances from the starting block (Barlow et al., 2014). Vilas-Boas et al. (2000) suggested that during the water phase, all the differences noticed between similar track-start variants tended to disappear. Our results are not in complete agreement but also emphasize the importance of the water phase. Finally, regardless of the initial body position (forward or backward), the swimmer can reach equal instantaneous horizontal velocity in water, at the end of the start. Yet, the kick-start forward ensures the achievement of a shorter start time. Therefore, kick-start forward seems to be more beneficial and promising, considering demonstrated temporal advantage.

Key factors determining the starting performance

The conducted analyses revealed the 5-m time measured during kick-start forward as significantly related with initial body position (rear knee joint angle, hip height, and hip length) and take-off angle measured at hip joint (Table 4). Besides, a moderate correlation was also noted between 5-m time and block time (0.64). Indeed, the regression models composed for these performance indicators included a combination of the above-mentioned variables, supplemented by flight distance (Table 7). In kick-start backward, the shorter the rear foot take-off time and the longer the flight distance, the better the 5-m starting performance is (Table 4). Furthermore, with the stepwise multiple regression procedures, the best models predicting the 5-m time of kick-start backward were obtained on the basis of the following covariates: initial hip height, rear foot take-off, block time, and flight time (Table 8). The quality of our models estimating the 5-m start time follows the results presented by Peterson et al. (2018), who composed separate regression models to predict the 5-m time in different breaststroke starts. In that study, flight distance was one of the most relevant parameters and was included in the LASSO models composed for all tested start techniques. During the overwater phase, a swimmer can take advantage of comparatively lower resistance, thus flight distance is one of the parameters commonly exposed as key factors affecting starting performance. The flight distance revealed by Peterson et al. (2018) as an example of key variable influencing the 5-m start time might be optimized by proper flexion in the hip joint angle (Alptekin, 2014). Meanwhile, Slawson et al. (2012) discussed the effect of knee angle evaluated during the block phase on the overall start performance. Those authors highlighted the importance of lower body segments position while starting and brought attention toward swimmers' tendency to adapt to the provided position. Furthermore, the rear knee angle was positively correlated with the produced peak force (0.7). The relatively high hip position may also impact on flight distance at take-off (Guimaraes and Hay, 1985). Yet, depending on the starting position, different methods of the take-off angle measurement expose significant associations with the total start time (Peterson et al., 2018). In a study by Ikeda et al. (2016), an inverse correlation (-0.68) was revealed between the 5-m time and horizontal velocity at the take-off of the kick-start. Another parameter widely used in research is block time, which has been reported by Blanksby et al. (2002) as significantly related with starting performance measured at the 10-m distance (0.58). Furthermore, also in the results obtained by Tor et al. (2015), the block phase duration and flight distance were chosen as the set of variables describing 83% of the variance in total start time. The presented findings confirm the high importance of the swimmer's initial position, as well as their overwater actions performed while starting for the 5-m time optimization.

A strong positive correlation was shown for intermediate 5-m start time (5-10-m time) and total start time calculated for both kick-start variants (Table 3). The results reveal that the higher the swimmer's hip and the wider the rear knee angle at the initial phase, the shorter the 15-m start time was (Table 3). Additionally, for the above-mentioned variables, unilateral regression models describing variance in total kick-start time were successfully composed (Table 5). From the variables included in the stepwise regression analyses, the hip height and front knee joint angle recorded for the initial phase of the start, as well as the 5–10-m time were common for the two kick-start variants. Additionally, the entry hole diameter and the 5-m start time were included in the models composed for the forward variant, and take-off velocity and flight distance were involved for the backward variant (Table 6). Despite using different parameters, the quality of our prediction models is in line with those presented in other studies (Tor et al., 2015). On the basis of the data collected during kick-start, Tor et al. (2015) aimed to determine which parameters affected the 15-m start performance the most. Similarly, to the current study, those authors composed models based on a number of predictor combinations. Successfully formulated were the equations containing block parameters only, as well as ones based solely on predicting variables derived from the group of underwater parameters. In contrast, Peterson et al. (2018) stated that the starting technique was more likely to determine start performance measured over a 5-m distance. Indeed, the water phase can account for more than 80% of the 15-m start time (Slawson et al., 2013; Tor et al., 2015). In the model obtained by Tor et al. (2015), 81% of the variance in start performance was accounted for by the take-off horizontal velocity, while a larger amount of variance in the 15-m start time was associated with underwater phases and time measured to the 10-m mark.

In general, from among multiple commonly used parameters, the short block time, great jumping power, high take-off velocity, long fly distance, low resistance during the gliding phase, and powerful underwater kicking were revealed as the most relevant for start performance improvement (Arellano et al., 2000, 2005; Mason and Mackintosh, 2020; Slawson et al., 2013; Tor et al., 2014). Swimming start mechanics seems to be multifunctional in its nature (West et al., 2011), and each element has to be cautiously analyzed. Indeed, numerous researchers are interested in analyses exposing the best parameters determining starting performance by using not only correlation analyses but also statistical modeling methods (Beretić et al., 2013; Carvalho et al., 2017; Cossor et al., 2011; de Jesus et al., 2018; Nguyen et al., 2014; Peterson et al., 2018; Tor et al., 2015). It has to be underlined that the characteristics of swimming start, as well as its performance might be influenced by multiple factors, e.g. the athlete's gender (Garcia-Hermoso et al., 2013; Jesus et al., 2011; Morais et al., 2019; Thanopoulos et al., 2012; Tor et al., 2014). Those insights underline the requirement of gender effect inclusion in various approaches undertaken in swimming start analyses. To our knowledge, none of the studies evaluating similar issues regarding the kick-start meets those requirements. That makes it difficult to directly compare the regression analyses results obtained with investigations that were based on mixed gender groups. By deeply examining the links between various individual contributing parameters, we disclosed the predicting variables constituting the core of swimming start performance monitoring.

Limitations

The findings presented in this study need to be interpreted in light of some limitations. The first of them is related to the low number of participants (eight), including only female varsity swimmers. However, that number of subjects seems to be reasonable as the population of elite swimmers is already reduced by highly competitive level requirements. Consequently, a small number of participants is prevalent in this type of research. Furthermore, the back plate position was held constant for both variants, then the impact of its positioning was not considered in these analyses. Yet, all swimmers freely chosen their preferred back plate position on the basis of their previous experience. As implied in Chapter IV, swimmers' preferred back plate positions tend to be the most beneficial in terms of overall starting performance. Finally, this study evaluated high level junior competitive female swimmers. Therefore, the results obtained in other studies could vary depending on the swimmers' level and age. Yet, the relationships between the assessed parameters indicate similar patterns.

Conclusions

It can be concluded that swimmers aiming to reduce the start time should consider using kick-start forward rather than the backward variant. The findings presented in this study suggest that the initial position of a swimmer's hip during kick-start leads to advantageous differences in specific parameters describing the performance level of this element of the swimming race. In comparison with kick-start backward, kick-start forward is characterized by shorter block time, which was shown as being enough to consequently enable kick-start forward to maintain time dominance over the whole start distance (15 m). On the other hand, in kick-start backward, by spending more time on the block, swimmers can develop near-significantly higher horizontal velocity and achieve better performance in the flight phase. However, the advantages of the backward variant are lost after immersion to the water, probably owing to higher hydrodynamic drag, despite the bigger entry angle; finally, almost equal 10–15-m average velocity was measured for both start variants.

For a wider description of the differences in the swimming starts in the applied scope of movement structure assessment, correlation analyses were conducted, and regression models were composed. The conducted analysis successfully produced a number of models with different combinations of predicting variables explaining the variance in the 5-m and 15-m start time for the two kick-start variants included. Depending on the kick-start variant used, different expectations concerning the specific elements of movement structure have to be considered. Therefore, the performance determinants presented separately for each kick-start variant should be chosen deliberately as priority areas in swimming start performance monitoring. Finally, to improve the starting performance optimization process, a conscious decision has to be made considering individual characteristics of each swimmer and the objective measures dedicated to a given starting condition.

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CHAPTER IV

DOES BACK PLATE POSITION INFLUENCE TEMPORAL CHARACTERISTICS OF THE SWIMMING START?

Daria Rudnik, Leandro Machado, Ricardo Jorge Fernandes, Marek Rejman, and João Paulo Vilas Boas

Abstract

The currently used starting block is equipped with an incline back plate which can be fixed to the main deck in different positions. Here, the contribution of each lower limb and its placement is reflected in the take-off features, which further determine the flighting trajectory profile. Thus, by adjusting the back plate, a swimmer should be able to reach an optimal body position before starting signal. The purpose of this study was to evaluate starting performance following different positions of the back plate and to identify if some adaptations occurred in swimmers' movement patterns in association with those changes. A total of 38 international level competitive swimmers performed trials with changing back plate position (preferred back plate position [PP], one position forward [FP], and one position backward [BP] from PP). The 15-m start time was obtained from recording collected with one surface video camera, and temporal parameters describing movement organization of block phase were derived from data collected with the 3D dynamometric central. To identify and quantify temporal differences between the trials, ANOVA and t-test for repeated measures was implemented to check if two pairs from back plate configurations differed from each other. Only in the male group the 15-m start time was significantly shorter for PP in comparison with BP. Regardless of the back plate positioning, swimmers tend to spend similar time on the starting block, but a significant difference between the tested positions was observed for the duration of each lower limb contact time. For both genders, the back plate position effect was mostly exposed for lower limb contact times (rear foot take-off and front foot stand). The back plate position effect was revealed for the rear foot take-off and front foot stand times in males with a large effect size. In females, in turn, a change of about two positions (from FP to BP) was needed to reach a significance level in those variables. A more forward back plate position ensures postponing the rear foot take-off and consequently reduces the front foot stand. Both genders responded similarly in the temporal structure of block phase to the directions of changes from PP. Yet, as more impact of changes introduced in back plate position was noted for males, probably the various adjustments of back plate position might affect more males than females. Finally, searching for optimal conditions for the efficiency of the musculoskeletal system in the starting position can be used to reinforce the effect of personal preference in back plate positioning.

Key words: swimming start, kick-start, back plate, preference effect, movement organization

Introduction

To excel in any sport, it is necessary to optimize the performance of all its components. A competitive swimming event can be divided into distinct phases, such as the start, swimming, turns, and finish (Marinho et al., 2020; Mason and Cossor, 2000). In accordance with the swimming rules, the start phase can be extended up to the 15-m distance from the starting block; then, while starting, swimmers have to perform actions in both terrestrial and water environments. To propel themselves from the starting block, they have to involve whole body. While the majority of the force is generated by the lower body (Breed and McElroy, 2000; Mourão et al., 2016), the role that each limb plays in the start is highly dependent on its relative positioning. Indeed, the initial starting position significantly determines swimming start performance (Blanco et al., 2017; Honda et al., 2010; Peterson et al., 2018; Vilas-Boas et al., 2003; Welcher et al., 2008).

The currently used starting block is equipped with adjustable incline part. The back plate can be fixed to the main deck of starting block in five locations, while its inclination stays constant at 30°. Any change in these positioning influences not only both lover limb joint angles, but also the initial center of mass position (Nomura et al., 2010). That opportunity of placing the foot upon a back plate has made the kick-start more advantageous comparing with previously used track-start. Accordingly, a reduction of block time, increase in horizontal impulse and horizontal take-off velocity, as well as shortening of overall start time were revealed (Biel et al., 2010; Honda et al., 2010; Ozeki et al., 2012; Takeda et al., 2017). The importance of the rear lower limb in horizontal velocity production has been shown (Ikeda et al., 2016; Nomura et al., 2010; Ozeki et al., 2017; Takeda et al., 2017; Takeda and Nomura, 2006), while the foot placed ahead contributes more to the vertical velocity and acts mainly as a support of body weight (Ozeki et al., 2017). Moreover, in the kick-start, each lower limb plays a different role in the inverted pendulum approached as the model of kick-start by Ikeda et al. (2016). In short, the contribution of each lower limb and its placement is reflected in the take-off velocity components and modifies the take-off angle, which determines the profile of further starting actions.

Slawson et al. (2011) analyzed the trials where a back plate was placed at three from the available five positions. Honda et al. (2012), Kibele et al. (2014), and Slawson et al. (2011) combined back plate displacement with a different swimmers' initial body positions. Despite of these some studies were based on block settings incompatible with official standards or included multiple factors acting on the measured output, their findings provide valuable sources of data that not only make a background for discussions, but also expose the directions for further research.

There is no doubt that the improvement of starting performance requires more comprehensive research, once, until now, the positioning of the back plate has been mostly based on a swimmer's comfort – their subjective feelings (Cicenia et al., 2019). It has also been mentioned that the movement output could be significantly affected by the experience gained throughout previous practice (Rodacki and Fowler, 2001); thus, swimmers tend to follow their well known movement patterns, e.g. adjusting the body position to the provided starting block features (Slawson et al., 2012). Despite the availability of findings exposing positions other than preferential as equal or even more advantageous (Kibele et al., 2014), still the most frequently practiced technique has been very often qualified as the best (Blanksby, 2002; Vantorre et al., 2010b). Here, as each athlete has their own motor potential and practical experiences, the individuality of swimmers also has to be considered. More attention should be also focused on whether the swimmer's preferred back plate position could be described as optimal while considering their bodyvantor dimensions. In fact, a starting position other than the swimmer's preferred one may provide further improvements to performance after extensive practice (Blanksby et al., 2002). The same effect can be attained after the controlled change in the starting block features (Kibele et al., 2014). Therefore, the decisions involved in the optimization of training process in swimming start should be supported by multidirectional research and findings implied by reliable sources of information. As the knowledge focusing on the effects of different back plate positions is still not sufficiently reported, it might be interesting to examine how the preferential adjustments of the back plate would influence starting performance of swimmers representing different genders.

The aim of this study was to evaluate starting performance following different positions of the back plate and to identify if some adaptations occurred in swimmers' movement patterns in association with those changes. To verify and quantify the temporal differences between trials (incorporating preferred back plate position [PP], one position forward [FP], and one position backward [BP] from PP), particular emphasis was put on the block phase analyses. Finally, the obtained results were analyzed in distinctions for the genders.

Material and methods

A total of 38 members of a national swimming team (junior and senior), all international level swimmers (with the best competitive performance of at least 750 points (Fédération Internationale de Natation [FINA]), voluntarily participated in the study. This group was composed of 19 females (16.6 ± 2.2 years of age, 169.7 ± 4 cm of body height, and 59.9 ± 4.5 kg of body mass) and 19 males (20.8 ± 4.2 years of age, 179.1 ± 6.4 cm of body height, and 73.4 ± 9.0 kg of body mass). Before the testing sessions, the swimmers and their coaches were informed about the purpose of the study and the experimental procedures. During the data acquisition, all participants were healthy, without any injuries, and rested from any fatiguing exercises. The research protocol, consistent with the Declaration of Helsinki, was approved by the local Ethics Committee. All swimmers or, if under 18 years old, their legal guardians signed written informed consent forms.

Firstly, the following data were collected: the swimmers' body height, body mass, years of age, competitive experience, and the starting block back plate individually preferred position. Then, a standard warm-up based on the athletes' pre-race routine was implemented. All participants were already accustomed to the swimming kick-start technique Each swimmer performed three series of repetitions of the kick-start variants. At the beginning, on the basis of the previous individual experience, the preferred position of the back plate was selected independently for each person. Then, to obtain a full set of back plate positions considered, the positions other than the preferred ones were revealed comprising FP and BP. Finally, with the collected trial options, each swimmer had all their trials arranged in a randomized order. It is worth underlining that the participants were free to choose their preferred movement pattern while starting. Between the trials, the athletes had at least three minutes of break to recover from fatigue. The testing sessions were performed in an indoor 25-m swimming pool, and the FINA rules and facilities regulations were followed.

The starting procedure complied with the FINA rules and was organized under simulated race conditions to ensure the best possible starting performance. The participants were asked to accomplish each repetition in the shortest possible time. Time was measured from the starting signal to the moment when the swimmer's head reached the 15-m mark. After starting, the athletes were requested to swim front crawl for at least 20 m. The starting signal (acoustic and optical) was given to the swimmer with a dedicated device (described below), which additionally allowed to simultaneously initiate and synchronize the video recordings and dynamometrical data collection.

One surface video camera (GoPro Hero 4, GoPro, USA) configured to record 50 frames per second was used to measure the 15-m start time. The camera was fixed to a tripod (Hama Star 63, Hama Ltd., UK) at a height of 0.75 m, perpendicular to the trajectory of the swimmers' body during the start. A light-emitting diode (LED light connected with a trigger) was used to synchronize the camera with the starting signal. A 3D dynamometric central (3D-6DoF, corresponding with starting block OMEGA OSB 14) with the Visio software (LabVIEW 2013 System Design Software, SP1 NITM, USA) was used to accurately measure the temporal parameters of ground reaction forces in the successive sub-phases of the block phase of ventral starts (Mourão et al., 2016; Vilas-Boas et al., 2014). The description of the measured variables is presented in Table 1. The variables and their definitions were selected on the basis of previous publications (Blanco et al., 2017; Carvalho et al., 2017; Colyer et al., 2019).

Table 1. Definitions of the parameters used for swimming start analyses.

Variable	Abbreviation	Definition
Reaction time (s)	RT	The time interval between the starting signal and the first observable change in the starting block reaction force to time curve as a result of the initial swimmer's movement
Hands take-off (s)	Hoff	The time interval between the starting signal and the last contact of the hands with the starting block
Hands take-off – RT (s)	Hoff-RT	The time interval between the starting signal and the last contact of the hands with the starting block, reduced by the reaction time
Rear foot take-off (s)	RFoff	The time interval between the starting signal and the last contact of the rear foot with the starting block
Rear foot take-off – RT (s)	RFoff-RT	The time interval between the starting signal and the last contact of the rear foot with the starting block, reduced by the reaction time
Front foot stand (s)	FFoff	The time interval between the last contact of the rear foot with the starting block and the moment when total vertical force fell to zero
Block time (s)	BT	The time interval between the starting signal and the moment when total vertical force fell to zero
Movement time (s)	MT	The time interval between the first visible change in starting block reaction force to time curve and the instant when total vertical force fell to zero
15-m time (s)	T15	The time interval between the starting signal and the moment when the head crossed the 15-m mark

The best trial was selected for further analysis on the basis of the 15-m time. It was taken for granted that the shorter the 15-m time, the better the starting performance was (Vantorre et al., 2010b. Firstly, key biomechanical parameters were selected; then, their values were measured from the collected data with the use of dedicated software. The video recordings were treated with the DaVinci Resolve software (Blackmagic Design Ltd., USA); the first frame with visible LED light was used to determine the starting signal for a given trial. A processing routine created in the MATLAB R2016a software (MathWorks Inc., USA) was employed to derive the temporal characteristics of the block sub-phases on the basis of the data collected with the 3D dynamometric central. Before examining our research questions with statistical tests, we evaluated the collected data regarding the parametric test assumptions (to verify normal distribution and homogeneity of variance, as well as to look for extraneous or confounding variables) by using descriptive statistics, the Shapiro-Wilk test, and Levene's test. To describe the group with representative values of the obtained results, means and standard deviations were computed for all the parameters. Repeated analysis of variance was run to compare variables extracted from the repeated observations of three different swimming start variants defined by the position of the back plate (PP, FP, and BP). Here, in cases revealed as significant through ANOVA, the Duncan post-hoc test was used to verify significance for three dependent pairs of measurements. Moreover, as some differences among the parameters values brought special attention, a further aim was to consider in greater depth the possible consequences of changes applied in the back plate position for a given direction. To better understand if shifting the back plate in two positions would significantly determine more from the obtained differences between measures, additional analyses were conducted. Here, to investigate the interaction between the changed back plate positions, the t-test for repeated measures was performed for the parameters measured in every two pairs from the block configurations tested. To augment significance test results, the effect size was reported, which describes the proportion of the variability attributed to a given factor. The effect size was based on the criteria established by Cohen (1988). The gender effect was included, as it was confirmed to occur in the statistical interpretation process. Statistical procedures were conducted by using the Statistica 13.1 software (StatSoft, USA), with the level of statistical significance established at $\alpha = 0.05$.

Results

The descriptive characteristics of the swimming start temporal variables in different back plate positions complemented with significant differences between trials exposed through statistical procedures incorporating back plate effect and its size, as well as repeated measurement analyses results are presented in Table 2 for female and in Table 3 for male participants.

As can be seen, for both groups tested, the back plate position effect was mostly exhibited for lower limb contact times (rear foot take-off and front foot stand). The comparatively high value of standard deviation in hands take-off time suggests a high intragroup variability as a vast majority of the participants managed the movement of their upper limbs in an individually specified (probably preferred) pattern. Additionally, the non-significantly shortest mean 15-m time was reached with the preferred positioning of the back plate.

Only in the male group was the total (15-m) start time significantly shorter for the preferred back plate position in comparison with the backward one. Also in the male group, a back plate position effect was noted for the front foot stand, rear foot take-off, and rear foot take-off time reduced by the reaction time ($p < 0.001$). Besides, the rear foot take-off and front foot stand times significantly differentiated FP, PP, and BP in males (0.615 ± 0.05 s, 0.609 ± 0.04 s, 0.589 ± 0.05 s, $p < 0.001$; and 0.109 ± 0.02 s, 0.118 ± 0.02 s, 0.130 ± 0.02 s, $p < 0.001$, respectively). Here, none of the variables describing temporal organization regarding lower-limb push-off time distribution shows the lowest time for the preferred position.

In females, the most remarkable effect of lower limb movement organization during the block phase was brought about by shifting the back plate for two positions. A change in the back plate position from FP to BP resulted in a near-significant shortening of time spent for front lower limb stand (PP: 0.140 ± 0.02 s, FP: 0.131 ± 0.02 s, BP: 0.144 ± 0.02 s; $p = 0.073$) and extended the rear foot take-off time (PP: 0.630 ± 0.03 s, FP: 0.641 ± 0.05 s, BP: 0.618 ± 0.05 s; $p = 0.072$). Here, only the preferred and backward back plate positions differ from each other. Therefore, a similar tendency was observed in the female group, but without statistical significance in most cases. Indeed, the conducted tests reveal that only FP and BP showed different mean values.

The average values of the 15-m time for the PP, FP, and BP variants in the female group were higher (7.28 ± 0.33 s, 7.35 ± 0.32 s, 7.31 ± 0.37 s, respectively) than in the male group (6.41 ± 0.47 s, 6.33 ± 0.55 s, 6.43 ± 0.49 s, respectively). Following our expectations, male participants needed less time to cover the 15-m distance after start than their female counterparts ($p < 0.000$) in all of the variants considered.

Table 2. Descriptive statistics of temporal variables of swimming start performed by female swimmers, presented separately for each starting position, complemented with significant differences between trials incorporating the tested back plate positions, exposed through statistical procedures.

Variable	**FP** (mean ± SD)	**PP** (mean ± SD)	**BP** (mean ± SD)
15-m start time (s)	7.351 ± 0.32	7.282 ± 0.33	7.306 ± 0.37
Reaction time (s)	0.165 ± 0.03	0.167 ± 0.03	0.158 ± 0.03
Hands take-off (s)	0.457 ± 0.09	0.441 ± 0.08	0.449 ± 0.08
Hands take-off – RT (s)	0.287 ± 0.08	0.269 ± 0.06	0.283 ± 0.08
Rear foot take-off (s)	0.641 ± 0.04[b]	0.630 ± 0.03	0.618 ± 0.05[f]
Rear foot take-off – RT (s)	0.475 ± 0.04	0.463 ± 0.03	0.460 ± 0.03
Front foot stand (s)	0.131 ± 0.02[b]	0.140 ± 0.02	0.144 ± 0.02[f]
Block time (s)	0.772 ± 0.03	0.769 ± 0.03	0.761 ± 0.05
Movement time (s)	0.607 ± 0.04	0.602 ± 0.03	0.603 ± 0.04

FP: forward position of back plate; PP: preferred position of back plate; BP: backward position of back plate.
[f]Differs significantly from FP at exact $p \leq 0.05$.
[b]Differs significantly from BP at exact $p \leq 0.05$.

Table 3. Descriptive statistics of temporal variables of swimming start performed by male swimmers, presented separately for each starting position, complemented with significant differences between trials incorporating the tested back plate positions, exposed through statistical procedures.

Variable	FP (mean ± SD)	PP (mean ± SD)	BP (mean ± SD)
15-m start time (s)	6.411 ± 0.47	6.331 ± 0.55[b]	6.434 ± 0.49[p]
Reaction time (s)	0.168 ± 0.04	0.175 ± 0.03	0.171 ± 0.03
Hands take-off (s)	0.452 ± 0.07	0.463 ± 0.08	0.445 ± 0.07
Hands take-off – RT (s)	0.279 ± 0.07	0.288 ± 0.08	0.276 ± 0.07
Rear foot take-off (s)	0.609 ± 0.04[p,b]	0.615 ± 0.05[b,f]	0.589 ± 0.05[p,f,*]
Rear foot take-off – RT (s)	0.448 ± 0.05[b]	0.440 ± 0.05[b]	0.424 ± 0.04[p,f,*]
Front foot stand (s)	0.109 ± 0.02[p,b]	0.118 ± 0.02[b,f]	0.130 ± 0.02[p,f,*]
Block time (s)	0.718 ± 0.04	0.734 ± 0.05	0.719 ± 0.04
Movement time (s)	0.557 ± 0.05	0.558 ± 0.04	0.554 ± 0.05

FP: forward position of back plate; PP: preferred position of back plate; BP: backward position of back plate.
*Significant ANOVA results for BP effect at exact p ≤ 0.05.
[p]Differs significantly from PP at exact p ≤ 0.05.
[f]Differs significantly from FP at exact p ≤ 0.05.
[b]Differs significantly from BP at exact p ≤ 0.05.

Discussion

Overall starting performance

In the assessment of the swimming start performance with different positions of the back plate, the total (15-m) start time was selected as the main indicator of the impact of the different tested conditions. For both genders in general, no back plate positioning effect was noted for the mean 15-m start time. However, in males, the 15-m start time differed significantly between PP and BP, with lower values observed for the former (Table 3). Interestingly, concerning the female group, adjusting the back plate position did not impose any differences in the overall start performance (Table 2). Despite this lack of significance, considering the competitive level of the participants and the minuscule difference that could decide about the final race score, especially during Olympic Games, the advantage in the total starting time of 0.1 s for males and 0.07 s for females measured in the current study might become significant for coaches and swimmers. This supports the view of Maglischo (1999), who stated that a change in the starting technique could reduce the event total time by at least 0.1 s. As far as we know, there is only one study that examined the impact of back plate adjustment with a distance further than 7.5-m (Cicenia et al., 2019). These authors observed that the 15-m start times were not significantly different among the tested back plate positions. Unfortunately, the mentioned study did not consider the participants' preferred starting block setup (the back plate position changes were based on the swimmer's shin length) and both genders were combined in the analyses. Then, a direct comparison of the current results with those obtained by Cicenia et al. (2019) is rather difficult. There are also inconsistent findings on whether a change in back plate position would affect overall starting performance on shorter distances. Only Honda et al. (2012) tested swimmers in comparable conditions and presented some suggestions concerning no significant effect of the back plate position on the 7.5-m start time. According to those authors, the limited availability of the new starting block during daily practice might be important for the level of success. It is widely known that motor performance is a result of several interactive factors, especially in the case in study, as the swimming start encompasses many specific movement patterns, taking advantage of various motor skills.

Effect of preference in back plate positioning

In our study, while searching for the effect of preference in back plate positioning on the swimming start performance, it was found that males obtained a shorter mean 15-m start time using their preferred positioning. Then, in terms of swimming start performance, the preferred back plate position was considered as better than or at least equal to the adjusted position studied (BP). Also, the rear foot and front foot stand times differed significantly between the tested back plate positions (Table 3). It was mentioned by Kruger et al. (2003) that the starting technique specialized throughout the swimmer's carrier ensured better mastery.

Indeed, the most practiced technique often guarantees the best starting performance (Blanksby, 2002; Vantorre et al., 2010b). Meanwhile, in a study evaluating differences in the preferred back plate position with the consideration of anthropometrical characteristics, only 1/3 of the participants displayed decline in the 15-m start time resulting from changes in their preferred position (Kibele et al., 2014). It has to be highlighted that the movement output is also influenced by the past experience of an athlete as a tendency toward selecting a strategy congruent with the previously mastered one was exposed (Rodacki and Fowler, 2001). Thus, swimmers, searching for comfortable, established, and stable circumstances, tend to adjust the implemented position to obtain starting conditions possibly similar to their well known ones (Slawson et al., 2012).

Before data acquisition, all participants were allowed to perform a few practice starts, but no intentional training was provided. Also, the preferred back plate position was defined by each subject on the basis of their previous experience. It has been demonstrated by many authors that the higher the level of experience in swimming starts, the better the results of its performance (Blanksby et al., 2002; Vantorre et al., 2010b). Using correlation analysis, Welcher et al. (2008) clarified the relationship between swimmers' experience, preferences, and start performance. They concluded that the greatest instantaneous horizontal velocity at the starting distance of 5 m presented the highest correlation with the starting position which the swimmer mostly preferred ($r = 0.53$). This reasoning could explain the results obtained, suggesting the superiority of the start employing the preferential starting block settings. Interestingly, Vantorre et al. (2010b) showed a higher intertrial variability of flight phase characteristics for non-preferential start techniques, which indicated their lower efficiency. As implied by Cicenia et al. (2019), the positioning of the back plate is mostly determined by the swimmer's comfort and "natural feeling". Furthermore, Slawson et al. (2012) concluded that in some swimmers, the preferred starting position was so well-established that they tended to control the accommodation of their position in an unpreferred setup of the starting block by lifting or lowering their foot over the inclined back plate. As a consequence, the specific foot placement can also imply relevant biomechanical effects (e.g. change the direction of ground reaction forces).

The presented findings confirmed that the temporal parameters of the block phase did not reveal any significant differences resulting from the back plate positioning (Tables 2 and 3). However, in most of the above-mentioned studies, temporal movement patterns of the start changed significantly with the back plate position changes, which corresponds to the profile of exerted forces and their consequences for the performance of further phases. When swimmers adjust the back plate toward the back, the optimal position enhancing an increase in take-off velocity development together with a decrease in back foot stand time might be obtained. Similarly, in sprint track and field starts, elongation of the feet position in the starting block allows generating greater take-off forces (Guissard et al., 1992; Harland and Steele, 1997). Therefore, searching for optimal conditions for the efficiency of the musculoskeletal system in the starting position can help reinforce the effect of personal preference in back plate positioning.

Adaptation in the movement organization pattern

The symptoms of adaptation that occurred in swimmers' movement patterns in association with the implemented back plate positioning were illustrated in some significant differences in temporal parameters of the take-off phase, but they did not influence the total duration of the block phase (Tables 2 and 3). Consequently, the swimmers spent a similar amount of time on the starting block (in the range of 0.76–0.77 ± 0.03 s and 0.72–0.73 ± 0.04 s for the female and the male group, respectively). Honda et al. (2012) observed comparable results, with a mean block time of 0.77 ± 0.01 s ($p = 0.089$) for all tested kick plate positions. Likewise, in a study by Slawson et al. (2011), the block time did not vary significantly depending on the back plate position. Although it was referred that the reaction time significantly decreased when the back plate was placed at a distance equal to swimmers' shin length from the front foot, this exerted no effect on the block time (0.69–0.72 s) (Cicenia et al., 2019). Interestingly, a study evaluating a wide number of alternatives to the preferred back plate position did not show differences in the block time only between high-front center of mass position combined with a narrow stance and low-front center of mass position combined with a wide stance (Kibele et al., 2014).

Meanwhile, in the current study, the temporal characteristics of each lower limb action differed significantly between trials, which could have affected the resultant take-off velocity and its vertical and horizontal components, even though the magnitude of those differences was larger in male subjects. The time that elapsed from the starting signal to the rear foot take-off decreased while the back plate position was changed from the front further toward the back (Tables 2 and 3). Simultaneously, an increase in front foot contact time was observed (Tables 2 and 3). The decrease, in percentage values, of the time spent only for front foot contact resulting from back plate forward position was also reported by Takeda et al. (2012). Furthermore, that change affected the acceleration profile of the swimmer's body (Takeda et al., 2012), which was a consequence of a modification in the distance between the swimmers' hips and the edge of the back plate. The rear knee and ankle joints angles do not differ significantly in the three back plate positions (Cicenia et al., 2020), but the length of the limb might determine the contact time with the starting block. The length of the lower limb muscle-tendon units might change in those conditions, which, in turn, might impact on the efficiency of force production (Bobbert et al., 2008). On this basis, when timing transition between lower limb stands takes place on the starting block and its segments positioning is slightly changed, the transfer between the magnitudes of velocity vector components would also be reflected (Takeda et al., 2006). Indeed, during the swimming start action, each lower limb contributes differently to velocity production (Ozeki et al., 2017; Takeda et al., 2017), once impulse is the integral of force applied during a given time interval. Consequently, it has been demonstrated that a more backward position of back plate results in significantly higher horizontal take-off velocity (Honda et al., 2012; Slawson et al., 2011; Takeda et al., 2012). As Colyer et al. (2019) indicated, also in sprint start, to enhance performance, the priority should be to maximize anteroposterior bilateral force production rather than subsequent unilateral force. Furthermore, in sprint start, lower center of mass projection angles at the end of each sub-phases of the block phase are associated with better performance

(Colyer et al., 2019). It therefore becomes difficult to distinguish the response to the change of back plate position from that to the take-off angle, as both conditions were included in the study by Takeda et al. (2012). In short, the contribution of each lower limb and its placement impact on the take-off velocity components and modify the take-off angle, which further determines the profile of the flight phase of the swimming start. While leaving the block, a swimmer needs to find a proper take-off angle combined with the forward rotation of the body to generate sufficient angular momentum and make a proper entry into the water (Arellano et al., 2005; Blanco et al., 2017; Taladriz et al., 2016; Vantorre et al., 2010a). Additionally, the flight distance (in relation to the body height) has been exposed as significantly correlated with the average vertical force exerted during the front foot stand (r = 0.783) (Ikeda et al., 2016).

As it was mentioned above, while searching for optimal conditions to improve starting performance, swimmers tend to adjust their setup body position (Slawson et al., 2012). This might be a consequence of incorporating unique physical attributes of the subject, or rather a habituation effect. Indeed, it could be a psychological effect arisen from the swimmer's own comfort, skill stability, or fear of making a mistake. On the other hand, it has been demonstrated that starts other than preferred may provide further improvements to starting performance after extensive practice (Blanksby et al., 2002). Therefore, the adaptation as a result of searching for an optimal movement pattern (technique) of the swimming start on the basis of biomechanical criteria should be recommended for coaches and swimmers.

Gender-effect impact on the start

The results of this study pointed out a lower mean 15-m start time (0.921 s) obtained by male swimmers as compared with their female counterparts. In males (with the effect size $\eta_p^2 = 0.14$), the longest total start time (15-m) was observed for the trials with backward back plate position, accounting for 101.6% of the shortest 15-m start time, obtained with the preferred back plate position. A medium effect size was reported for females, with the longest total start time for the forward back plate position. It constituted 100.1% of the shortest 15-m start time, performed with the preferred back plate position. These results are consistent with those achieved in the majority of studies presenting a shorter start time for males than for female swimmers (Jesus et al., 2011; Morais et al., 2019; Tor et al., 2014). Here, as swimming performance depends on many factors (Morais et al., 2013), the physical, strength, and technical diversity between genders was also reported as a factor influencing the start (Tor et al., 2014). Calculated after McClelland and Weyand (2020), the percentage difference in male and female total start time was 14.4%, while for the whole swimming race, that value is much lower (7–11%) (Kenney et al., 2015). This suggests that gender-effect differences influence more the starting performance than the total event time. Findings from other sports also show a diversity in the gender skill gap depending on the event. Mean male/female differences across jumping events were greater (17.8 ± 2.7%) than the respective mean differences for running events (11.2 ± 1.4%) (McClelland and Weyand, 2020).

The characteristics of the temporal variables for each lower limb differed significantly between trials, revealing higher variability with regard to back plate position in the male group ($p < 0.001$, with the effect size $\eta_p^2 = 0.55$) as compared with females ($p > 0.05$, with the effect size $\eta_p^2 = 0.14$). A higher effect size was observed for males not only for the overall starting performance, but also for the temporal profile of the lower limb movement organization during the block phase. On the basis of the reaction time measured with the Cybex Reactor, Spierer et al. (2010) exposed a gender effect while auditory stimuli were provided. Besides, body dimension can influence not only the body position, but also the time of limb contact with the starting block. Moreover, if each lower limb contributes differently to the profile of velocity development (Ozeki et al., 2017; Takeda et al., 2017), the presented temporal structure variability may affect take off velocity and take-off angle of each gender differently. Additionally, the change in back plate position has not been shown to influence flexion values in lower limb joints, but it impacts the block time (Cicenia et al., 2020), which consequently should modify the ability to generate the take-off forces (Bobbert et al., 2008; Gheller et al., 2015). The higher muscle power leads to an improvement in the start impulse among male swimmers (Jesus et al., 2011), and the peak forces produced by females on the block have been shown as significantly lower compared with those in males (Slawson et al., 2013). Then, the various adjustments of back plate position might probably affect males more than females. This generalization is in line with the results presented in Chapter V, where the parameters describing the block phase (block time and take-off horizontal velocity) were significantly correlated with the start time (5-m, 10-m, and 15-m start time) in males, while the correlation among females lacked significance.

Limitations

Notwithstanding the pertinence and originality of the study, some limitations and future research directions should be addressed. Firstly, the present study explored only three of the five available back plate positions (the swimmers' preferred position, one above, and one below). Yet, the majority of research that evaluated corresponding issues typically focused on the same starting block setups (Cicenia et al., 2019, 2020; Honda et al., 2012; Slavson et al., 2011, 2012; Takeda et al., 2012). Moreover, the starting block used in our study emulated the OSB 14 and the swimmers choose their own preferred positions (individuality inclusion) on the basis of their previous experience. Finally, to ensure that the habits or psychological effects were not the main factors that influenced the obtained results, the upcoming study should include an extended period of adaptative training with non-preferential variants of back plate positioning. We are also aware that only selected biomechanical parameters of block phase have been taken under consideration, but the most relevant of them were presented and discussed in the wide context of findings provided by other studies.

Conclusions

This study showed the superiority of the preferential back plate adjustment for the ventral start performance, comparing it to the backward back plate positioning. Therefore, searching for optimal conditions for the efficient functioning of the musculoskeletal system during the initial starting position and subsequent block actions, the effect of the subjective preference in back plate position should be taken into consideration.

In general, regardless of the back plate positioning, swimmers of both genders tend to spend similar time on the starting block. When the athlete's preferred back plate position is implemented, male swimmers need less time to cover the 15-m distance than when the back plate is adjusted backwards. Moreover, a diversity in block sub-phases duration depending on the back plate position. It seems that the various adjustments of back plate position might probably affect males more than females.

A variability among the tested positions was observed with reference to the duration of each lower limb stand time. A more backward back plate position ensures a shortening of the rear foot stand time and, consequently, an extension of the front foot stand. The trials including a back plate replacement toward the front exposed inverse temporal consequences. Therefore, adaptation as a result of searching for an optimal movement pattern (technique) of the swimming start based on biomechanical criteria should be recommended for coaches and swimmers. The findings should thus support swimmers in their more conscious decisions concerning their individual motor strategy, focusing on the best starting performance. Consequently, the exposure of strengths and weaknesses of the back plate positioning variants provides utility knowledge, which should lead coaches and swimmers in the optimization process to exceed current performance.

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CHAPTER V

KINEMATIC PROFILE OF VENTRAL SWIMMING START: GENDER EFFECT

Daria Rudnik, Marek Rejman, and João Paulo Vilas Boas

Abstract

It is widely known that sex has a significant impact on sport performance, as physical features appear to be the determints in swimming. However, gender-based performance dependency has not been taken into consideration by all the researchers who evaluated swimming start performance. Therefore, the purpose of this research was to determine the effect of gender heterogeneity on the biomechanical characteristics of swimming start by investigating the determinants of its performance. A total of fifty-two international level athletes, comprising thirty females and twenty-two males volunteered to participate in the study. All participants performed three repetitions of kick-start up to 15-m. During trials, spatiotemporal data was collected using dual media video cameras and instrumented starting block. To search for evidence of a difference between two unrelated groups, the one-way analysis of variance for independent samples was conducted, and Pearson correlation coefficients were calculated between several temporal measurements and some parameters of swimming start. A gender effect was exposed for the following temporal parameters: duration of block and flight phases, 5-m, 5-10 m, 10-m, 10-15 m, and 15-m times. Additionally, take-off horizontal velocity and flight distance have been shown to differ between the groups. Male swimmers, by spending less time in the block phase, reaching higher take-off velocity, jumping further overwater, and swimming faster while in the water, take a starting advantage over their female counterparts. Consequently, such performance variables as 5-m, 10-m, and 15-m start times indicate that male participants were faster than females. A gender effect was also observed for some parameters selected toward exposure of starting performance determinant factors (block phase duration, take-off horizontal velocity, and flight distance). Here for those variables significant correlation with 5-m, 10-m, and 15-m start times was noted only in the group composed of male swimmers. Considering, the study of swimming start confirms that the spatiotemporal parameters of swimming start, the relation between them as well as its the start overall starting performance differ among genders. Moreover, as parameters commonly used for swimming start performance assessment, correlated significantly with start performance only in the group of male athletes, thus while evaluating swimming start performance and selecting its key factors, depending on the gender of the swimmer different expectations must be addressed. Finally, presented findings highlighted the need to split analyses while the study group encompasses representants of both genders.

Key words: gender effect, swimming start, performance determinants, spatiotemporal analyses.

Introduction

Competitive swimming predominantly involves athletes competing to be the fastest over a given distance. In swimming, success is determined by many factors. It is widely known that gender has a significant impact on sports performance, as physical demands appear to be among the decisive elements in swimming. Yet, the gender variance in the timing of competitive swimming performance became progressively smaller as race distance increased, which could be related to greater reliance on oxygen metabolism (Tanaka and Seals, 1997). That has been attributed to the higher swimming economy of women, as characterized by a smaller body size and shorter legs, as well as smaller body density and greater fat percentage (Lavoie et al., 1986; Pendergast et al., 1977; Rudnik et al., 2019). However, as presented by Senefeld et al. (2019), the performance relation between genders depends also on the age of the athlete, especially prior to the performance-enhancing effects of puberty. Knechtle et al. (2020) showed that female swimmers outscored their male counterparts in the case of 10-year-old or younger and older age groups (75 years or more). Meanwhile, considering other age groups, male swimmers have better overall results in all indoor-pool swimming Olympic events (Miller et al., 1984; Morais et al., 2019).

However, gender-based performance dependency has not been taken under consideration by all the researchers who evaluated swimming start performance. Many previous studies evaluating swimming start included mixed-gender groups in their analyses (Barlow et al., 2014; Benjanuvatra et al., 2004; Carvalho et al., 2017; Galbraith et al., 2008; Honda et al., 2012; Ikeda et al., 2016; Lee et al., 2001). In those publications, the lack of significant diversity between the measured parameters describing each gender was used as argumentation confirming the methodological approaches chosen by the authors. Other studies reporting start performance within gender groups did not involve direct comparisons of results between males and females (Cossor and Mason, 2001; Da Silva et al., 2019; Jesus et al., 2011; Mason et al., 2007; Morais et al., 2019) or recruited a small number of participants (Ruschel et al., 2007; Sakai et al., 2016; Seifert et al., 2010; Vantorre et al., 2011). Furthermore, in their systematic review of the ventral swimming start, Blanco et al. (2017) took under consideration almost 50 studies, from among which 18 included both genders but did not necessarily make a gender division, 18evaluated males, and only 3 encompassed females. In 10 of those publications, the gender of the participants was not clearly exposed. Then, there is limited research comparing swimming start characteristics in females and males, which confirms the need to search for the gender effect on starting performance.

It is widely known that the anthropometrics and physiological characteristics of the athletes may differently affect the swimming performance of females and males (Rejman et al., 2018; Senefeld et al., 2016). However, gender differences in water activities may be less visible than those during weight-bearing exercise (Senefeld et al., 2016). The data reported by Fischer and Kibele (2014, 2016) provide evidence that while starting, male and female swimmers undertake different movement patterns to perform similar tasks. Moreover, concerning gender diversity, differences might exist in how velocity is developed, and thus combining both genders in one group may not be appropriate (Tor et al., 2014). Regardless of the participants' gender, such parameters as block time, take-off horizontal velocity, and flight distance have been widely used by many authors as starting performance indicators (Honda et al., 2012; Ikeda et al., 2016; Morais et al., 2019; Slawson et al., 2013). That methodologically controversial approach probably arose as a result of analyses including mainly male swimmers or even, in some cases, studies combining both genders regardless of their potential diversity. Moreover, as simple analyses were based on limited numbers of parameters, in specific instances, the mentioned differentiation might not be exposed, especially when the sample size was also reduced. It is important to underline that swimming performance depends on many biomechanical determinant factors (e.g. anthropometrics, kinematics, hydrodynamics, and efficiency) and relations between them (Morais et al., 2013). Concluding, in the context of the current knowledge review, separate analyses describing kick-start performed by swimmers of both genders seem to be needed.

Consequently, this study aimed to explore gender diversity in the variation of the spatiotemporal parameters of the kick-start technique executed by international-level swimmers. Besides, the purpose of this research was to determine the effect of gender heterogeneity on the biomechanical characteristics of swimming start by investigating the determinants of its performance. The findings could indicate the parameters that should be considered in an objective assessment of swimming start performed by males and females.

Material and methods

A total of 52 swimmers, comprising 30 females (16.9 ± 2.2 years of age, 168.9 ± 4.4 cm of body height, and 59.3 ± 4.7 kg of body mass) and 22 males (18.3 ± 1.8 years of age, 178.9 ± 5.3 cm of body height, and 69.9 ± 5.9 kg of body mass) volunteered to participate in the study. A swimmer was considered as one of international level when they were a member of the national swimming team and held a personal record at the level of at least 800 Fédération Internationale de Natation (FINA) points (in accordance with the FINA point scoring system for a given year). Before signing an institutionally established informed consent, all swimmers and their coaches were informed about the purpose of the study and the testing protocol (for athletes under 18 years of age, their legal guardians signed the consent). The study followed the tenets of the Declaration of Helsinki and was approved by the local Ethical Board.

In the initial part of the experimental session, the athletes performed their conventional pre-race warm-up routine and had time to familiarize themselves with the instrumented starting block equipped with measurement devices (Vilas-Boas et al, 2014; Vitor et al., 2016). The swimmers were asked to simulate a 20-m sprint race after the kick-start. They were encouraged to simulate the race behavior, i.e. to achieve the shortest possible time measured between the starting signal and the instant when the swimmer's head reached 15-m from the starting wall. In order to keep the highest possible performance for the next trial, at least three minutes of passive resting break was provided between all repetitions. Each swimmer performed three kick-starts (a change in their body position on the starting block during the steady phase or repositioning of the backplate were allowed). The best trial – considering the 15-m time as a performance predictor – was chosen for further analyses. All data were acquired in approximately the same environmental conditions in accordance with the FINA facility regulations (a 25-m indoor swimming pool with water temperature of 27°C). To ensure standardization of the data collection protocol, the same equipment was used for the measurements and equipment calibration (by using dedicated tools), which took place before each series of trials.

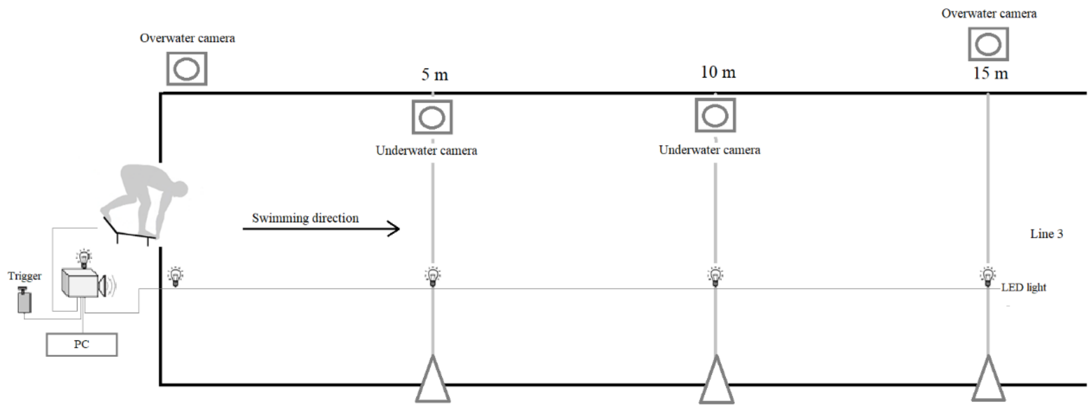


Figure 1. Graphical presentation of the measurement equipment setup.

Figure 1 illustrates the equipment setup used during the experiment. The 2D kinematic setup consisted of four video cameras (HDR CX160E, Sony Electronics Inc., Japan, and GoPro Hero 4, GoPro, USA), placed on the side of the swimmer, with their optical axis perpendicular to the swimming start trajectory. The videotaping frequency was adjusted at 50 frames per second, with a resolution of 1920 × 1080. The two surface video cameras were fixed to tripods (Hama Star 63, Hama Ltd., UK) at a height of 0.75 m. The first one was dedicated to capturing the swimmers' movements from the starting signal until total immersion of the swimmer's body; the other one was used for 15-m start time measurement. The two underwater video cameras, located on the sidewall of the pool, were applied to record the swimmers at 5-m and 10-m from the starting platform. All the cameras were calibrated with a 2 × 2 m frame and synchronized with the LED light, visible in each of the cameras. The starting signal was given by the starting device (Onda TTL wave, 0–5 V), which acted as a trigger providing simultaneous verbal, visual, and electrical signals, supporting synchronization of all equipment used for data acquisition (Vitor et al., 2016). To obtain a higher sensibility of temporal data during the block phase, a self-made 3D-6DoF instrumented starting block compliant with the current FINA regulations and replicating OMEGA OSB 14 (Vilas-Boas et al., 2014) was used. The athletes were dressed in textile swimsuits and had 32 landmark points marked on their bodies (Juergens, 1994), which allowed to define their body parts displacement in a two-dimensional plane.

The raw data were synchronized with the starting signal and processed with the use of dedicated software. In order to expose the spatiotemporal characteristics of the start, the SIMI Motion System (SIMI Reality Motion Systems GmbH, Germany) was applied for video image data treatment. Independently, a processing routine created in the MATLAB R2016a software (MathWorks Incorporated, USA) was employed to derive the temporal characteristics of the block phase on the basis of data collected with the instrumented starting block. The parameters selected for further analysis are described in Table 1. These parameters are also included on a regular basis in studies evaluating swimming starts (Blanco et al., 2017; Colyer et al., 2019; Tor et al., 2014).

The particular parameters describing spatiotemporal movement characteristics were used for further analyses, and results were scrutinized to expose any significant differences among values representing different genders. Furthermore, to screen if sets of data did not include any extraneous or confounding variables, as well as represented normal distributions and homogeneity of variance, the Shapiro-Wilk test, Levene’s test, and descriptive statistics were calculated for each parameter. Concerning the above, the assumptions of the parametric tests were confirmed, and values of the variables were presented as means and standard deviations. Accordingly, a one-way analysis of variance for independent samples was conducted, allowing statistical inference whether there was statistically significant evidence of a difference between two unrelated groups. To argument the significance of the tests, the effect size was calculated and reported. Theeffect size was exposed by using partial eta squared (η_p^2). The Statistica 13.1 software (StatSoft, USA) was applied for all statistical computations ($\alpha = 0.05$).

Table 1. Definitions of the specific parameters used to characterize the structure of the swimming start.

Variable	Definition
Reaction time (s)	The time interval between the starting signal and change in starting block reaction force curve as a result of the initial movement
Hands take-off (s)	The time interval between the starting signal and the last contact of the hands with the starting block
Rear foot take-off (s)	The time interval between the starting signal and the last contact of the rear foot with the starting block
Front foot support (s)	The time interval between the last contact of the rear foot with the starting block and the moment when total vertical force fell to zero
Block time (s)	The time interval from the starting signal and the moment when total vertical force fell to zero
Movement time (s)	The time interval from the first visible change in starting block reaction force curve and the instant when total vertical force fell to zero
Flight time (s)	The time interval between the last contact of the toes with the block and the moment of the first contact of the hands with the water
Flight time hip (s)	The time interval between the last contact of the toes with the block and the moment when the hips crossed the water surface
Water time	The time interval measured between the first water contact and the moment when the head crossed the 5-m mark
5-m time (s)	The time interval between the starting signal and the moment when the head crossed the 5-m mark
10-m time (s)	The time interval between the starting signal and the moment when the head crossed the 10-m mark
15-m time (s)	The time interval between the starting signal and the moment when the head crossed the 15-m mark
5–10-m time (s)	The time interval between the moment when the head crossed the 5-m mark and the moment when the head reached the 10 m distance from the starting line
10–15-m time (s)	The time interval between the moment when head crossed the 10-m mark and the moment when the head reached the 15-m distance from the starting line
Take-off horizontal velocity (m/s)	The instantaneous horizontal velocity of the swimmer measured at the moment of take-off
5–15-m average velocity (m/s)	The average swimmer's velocity the between the 5-m and 15-m marks
Take-off angle (°)	The angle between the horizontal axis, the block edge, and the hip joint at take-off
Entry angle (°)	The angle between the horizontal axis, the fingertips, and the hip joint when hands entered the water
Flight distance (m)	The horizontal distance measured between the point where the hip entered the water and the starting line

Results

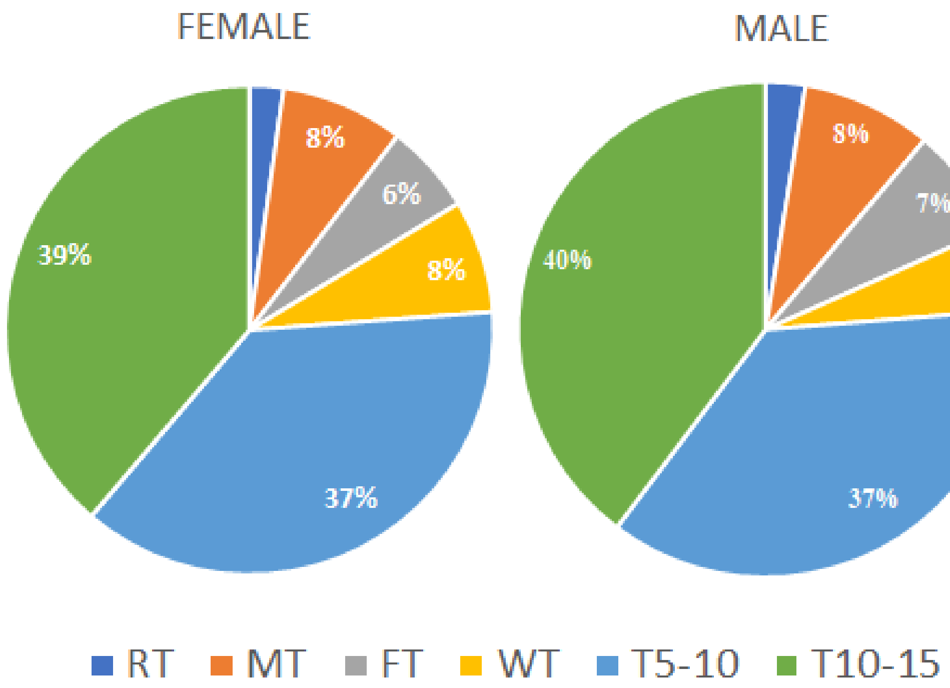
The values of the selected spatiotemporal parameters taken under consideration are described as means and standard deviations (Table 2). They are organized in order to expose the consequences of subsequent phases of the swimming start (Hay, 1986). Generally, the male group achieved relatively better results than females. This advantage was demonstrated not only by a shorter total start time (at 15-m and 5-m) or block time, but also by higher values of take-off horizontal velocity. Neither the reaction time (0.161 ± 0.03 s, 0.167 ± 0.03 s, $p = 0.453$ for females and males, respectively) nor the front foot support time (0.131 ± 0.02 s, 0.127 ± 0.02 s, $p = 0.552$ for females and males, respectively) differed between the two groups. Yet, the time measured from the first visible movement to rear foot take-off (excluding the reaction time) was significantly higher in females than in males (0.459 ± 0.03 s, 0.431 ± 0.05 s, $p = 0.020$, respectively). Finally, male swimmers spent less time overall on the block (by about 0.029 s, $p = 0.015$). It can be noticed that the groups did not differ in take-off or entry angles. Nevertheless, the standard deviation is quite high in both groups, which suggests that the athletes adopted different solutions during the flight phase. Moreover, male participants covered a longer distance over water during a longer flight phase ($p < 0.05$). Males also achieved significantly shorter times for 5-m (less by 0.18 s), 10-m (less by 0.51 s), and 15-m (less by 0.72 s) distances. Looking at the gender differences in the time results for each 5-m segment from the start, the highest diversity in the time of the 5–10-m distance should be underlined. The difference in gap time between the male and female participants increased continuously with the starting distance.

Table 2. Descriptive statistics for spatiotemporal variables of the swimming start, presented by gender, and between-gender comparisons obtained with one-way ANOVA.

		FEMALE	MALE	ANOVA		
Phase	**Variable**	**Mean ± SD**	**Mean ± SD**	**F**	**p**	**Eta-sqr partial**
Block	Reaction time	0.161 ± 0.03	0.167 ± 0.03	0.57	.453	0.01
	Hands take-off	0.440 ± 0.11	0.453 ± 0.08	0.23	.631	0.00
	Rear foot take-off	0.620 ± 0.04	0.599 ± 0.05	2.90	.095	0.05
	Front foot support	0.131 ± 0.02	0.127 ± 0.02	0.36	.552	0.01
	Block time	0.745 ± 0.04	0.716 ± 0.05	6.30	.015*	0.11
	Movement time	0.584 ± 0.03	0.548 ± 0.05	10.62	.002*	0.18
	Take-off horizontal velocity	4.096 ± 0.21	4.372 ± 0.23	19.81	.000*	0.29
Flight	Flight time	0.253 ± 0.05	0.288 ± 0.04	6.91	.011*	0.12
	Flight time hip	0.426 ± 0.05	0.464 ± 0.05	7.21	.010*	0.13
	Flight distance hip	2.533 ± 0.17	2.834 ± 0.20	33.59	.000*	0.40
	Take-off angle	32.3 ± 4.7	33.8 ± 4.4	1.35	.251	0.03
	Entry angle	38.9 ± 3.8	37.3 ± 4.0	2.44	.125	0.05
Water	5-m time	1.705 ± 0.09	1.529 ± 0.12	33.76	.000*	0.43
	5-10 m time	2.681 ± 0.22	2.352 ± 0.18	29.51	.000*	0.40
	10-15 m time	2.780 ± 0.24	2.557 ± 0.23	10.19	.003*	0.19
	15-m time	7.128 ± 0.34	6.410 ± 0.45	42.95	.000*	0.46
	Vx 5-15 m	1.837 ± 0.11	2.048 ± 0.16	29.50	.000*	0.40

Vx 5-15 m (average horizontal velocity calculated using the formula distance over time during 5-15-m.
*Significant at exact p ≤ 0.05.

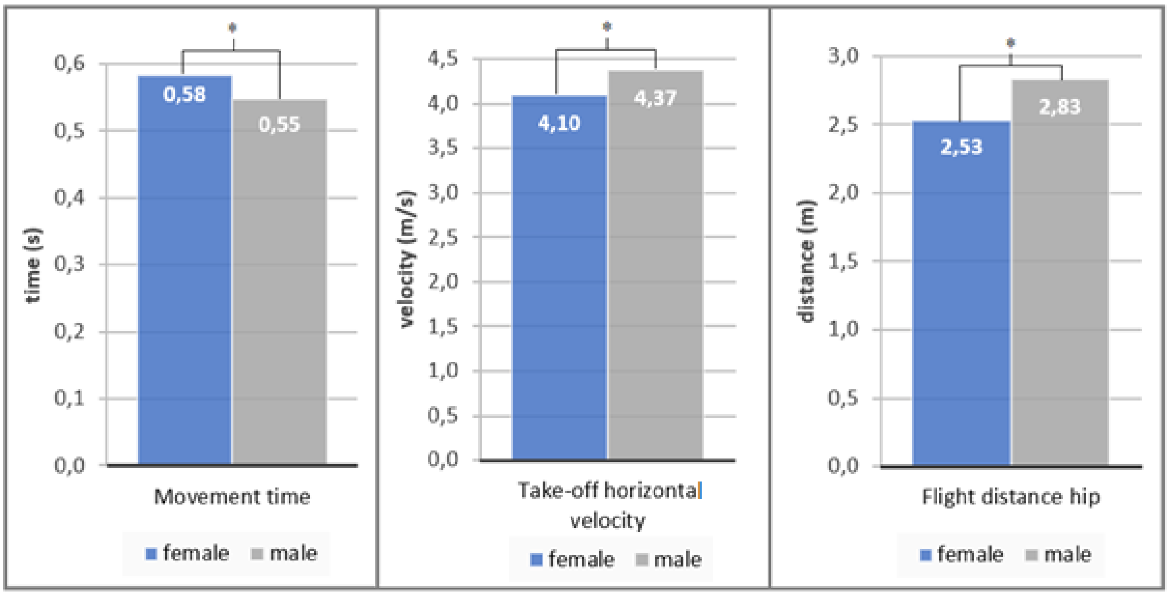
As presented in Figure 2, the first 5-m of start distance took almost a quarter of the total start time (measured at 15-m). Moreover, excluding the reaction time, the mentioned time decreased to 22% in the female group and 20% in the male group. Generally, the participants spent 10% and 11%, respectively, of the total start time in contact with the starting block and 16% and 18%, respectively, in the flight phase. Females spent 8% and males 5% of the total start time submerged in water (gliding and undulatory movements phases). More than a third of the total start time (39% for females, 40% for males, and 37% for both genders) was spent for the intermediate 5-m start (the underwater segment). It is worth highlighting that all the swimmers who participated in this study needed 2–3% of the total start time to produce a movement response to the acoustic stimulus generated by the starting signal. In both genders, the highest percentage of the starting time was spent on water phases.



RT: reaction time; MT: movement time; FT: flight time; WT: water time; T5-10: 5–10-m time; T10-15: 10–15-m time.

Figure 2. Diagrams representing the time intervals (in percentages) of each swimming start phase by gender.

Male athletes needed a shorter time to propel themselves from the starting block, even though they reached higher values of the take-off horizontal velocity and displaced their bodies further overwater in forward directions (Figure 3). The time gap between the two groups increased while starting and equaled 0.718 s at 15-m. Meanwhile, the movement patterns during push-off as well as technical elements like take-off and entry angles did not reveal a significant impact of gender diversity (Table 2). The results imply that gender had a significant effect on the measured spatiotemporal parameters that describe the kick-start structure and its consequences up to 15-m distance from the starting line (Table 2, Figure 3).



*Significant at exact $p \leq 0.05$

Figure 3. Movement time, take-off horizontal velocity, and flight distance hip measured from the starting line to the place where swimmers' hip crossed the water surface, by gender.

Pearson correlation coefficients calculated for males and females between several time periods of the swimming start and its selected spatiotemporal parameters are presented in Table 3. In the male group, higher values of the time determinants of swimming start performance were significantly correlated with take-off horizontal velocity ($r < –0.48$), flight distance ($r < –0.50$), and block phase duration ($r > 0.41$). A gender effect was also observed for selected parameters of starting performance determinants (block phase duration, take-off horizontal velocity, and flight distance). A general overview of the aforementioned correlation analysis shows that starting performance measured in a wide range of distances exposed gender diversity in relation to most evaluated variables.

Table 3. Pearson correlation coefficients estimated between several time intervals of swimming start and its selected spatiotemporal parameters, by gender.

	5-m time		**5–10-m time**		**10-m time**		**10–15-m time**		**15-m time**	
	M	F	M	F	M	F	M	F	M	F
Take-off horizontal velocity	–0.69*	–0.27	–0.48*	–0.18	–0.65*	–0.26	–0.50*	–0.20	–0.66*	–0.34
Flight distance hip	–0.55*	–0.16	–0.64*	–0.16	–0.69*	–0.20	–0.50*	–0.03	–0.69*	–0.17
Block time	0.52*	0.36	0.41	–0.35	0.52*	–0.18	0.45	–0.02	0.56*	–0.15
Flight time	–0.17	0.09	–0.29	0.04	–0.28	0.07	–0.25	0.05	–0.30	0.09

M: males; F: females.
*Significant at exact $p \leq 0.05$.

Discussion

General trends

To determine whether gender diversity resulted in the variation of the spatiotemporal parameters of the kick-start movement pattern, the ANOVA analysis was conducted, demonstrating some significant and strong effects of the gender factor. The results pointed out multiple differences in swimming start characteristics and performance between female and male swimmers (Table 2). In general, the obtained results were in line with several studies assessing swimming start performance. According to Newton (2014), there is a clear presence of differences in strength, performance, and technical characteristics between male and female swimmers. Here, as Senefeld et al. (2019) imply gender distinctions in physiology (e.g. more subcutaneous fat, body size, limb length, and body density) may affect the swimming performance of each gender differently. Despite this, a number of studies still include mixed-gender groups in their analyses, bringing statistical procedures in argumentation (Barlow et al., 2014; Benjanuvatra et al., 2004; Carvalho et al., 2017; Galbraith et al., 2008; Honda et al., 2012; Ikeda et al., 2016; Lee et al., 2001). However, in those cases, the sample groups might not expose the right trends for all the population researched, especially when the sample size is extremely reduced. In addition, swimmers may adopt similar biomechanical, motor control, and tactical strategies regardless of the group (e.g. gender) they belong to (Jesus et al., 2011). It is also important to highlight that swimmers' performance depends on many factors, as well as on relationships between them (Morais et al., 2013). Hence, as widely known, physical, strength, performance, and technical characteristics differentiate male and female athletes, especially in sports events based on the maximal velocity effect**,** which implies that combining both genders in the same analysis may not be appropriate (Rudnik et al., 2019; Tor et al., 2014). Consequently, the requirement of gender factor and its heterogeneity effect should be included not only in the detailed characteristics of separate variables but also in all approaches undertaken.

Comparison of swimming start characteristics and parameter structure

In the present study, the total start time (15-m), its shares (5-m, 10-m), and time of each starting phase were shorter for the male group ($p < 0.05$), except for the flight time, which was shorter in the female group owing to lower velocity and shorter flight distance (Table 2). This is in line with the majority of studies presenting less block time (not significantly) and start time (statistically significant) for male than female swimmers (Garcia-Hermoso et al., 2013; Jesus et al., 2011; Morais et al., 2019; Thanopoulos et al., 2012; Tor et al., 2014). In contrast, Fischer and Kibele (2016) showed equal grab-start block time and shorter track-start block time for female swimmers. A shorter flight time for females was also measured in a study by Thanopoulos et al. (2012) (0.41 ± 0.07 s vs. 0.38 ± 0.06 s), which was a result of a significantly longer flight distance obtained by males (3.14 ± 0.20 m vs. 2.73 ± 0.21 m). That pattern was also observed in a study by Morais et al. (2019), showing a flight time longer by 0.04 s for males (whose flight distance was longer by 0.38 m than that of females) in a freestyle event. Yet, according to Ruschel et al. (2007), flight time is less significant than flight distance as a starting performance determining factor.

No significant differences between genders were noted in reaction time. Despites, the female swimmers spent 0.029 s more on the block than their male counterparts, who needed 0.716 s to push off from the starting platform. Slawson et al. (2013) found block time values in the range of 0.735–0.865 s for 19 females and 0.726–0.856 s for 27 males. Da Silva et al. (2019) presented a new perspective of block time patterns in high-level swimmers. In that study, a comparison of block time and the final results of world championships events exposed similar trends in both genders. The results obtained among 45 females and 57 males presented mean block time values of 0.64–0.71 s and 0.62–0.71 s, respectively. In general, however, male swimmers seem to need less time to push off from the block. Based on data obtained with the Cybex Reactor from the group of college athletes, Spierer et al. (2010) exposed gender effect on reaction time only while auditory stimuli was provided. While regardless of the stimuli, in men movement time was reduced as compared to woman. According to those authors gender differences seen in their study *may be influenced by the amount of muscle fiber needed to create movement*. If any gender differences in reaction time exists, still they are attributed largely to inherent as related to information processing speed (Adam, 1999).

Male swimmers obtained a higher take-off velocity and displaced their hips further during the flight phase (Figure 3), which is also consistent with the findings by Slawson et al. (2013). According to those authors, the block time, take-off horizontal velocity, and flight distance were among the main indicators of swimming start performance. In the quoted study, a methodology for categorizing swimming start performance was based on the peak force data analyses. The peak forces produced by females were significantly lower than those in male athletes. In general, it is reasoned by the higher muscle power leading to an improvement in the block start impulse in male swimmers (Jesus et al., 2011). Similar results were obtained by Tor et al. (2014), who characterized the start of elite swimmers, including a comparison of start parameters and their diversity between the genders. From all parameters considered in the evaluation of swimmers' overwater actions, only take-off vertical velocity and flight time did not differ between genders (Tor et al., 2014).

Data reported by Fischer and Kibele et al. (2014) provide evidence that male and female swimmers undertake different movement patterns to perform similar tasks during starts. As a result, the parameters describing movement structures of the entry phase (average horizontal velocity, the angular displacement of the hip joint, and the duration of the entry phase) vary significantly between genders. Therefore, the same authors, focusing mainly on grab-start and track-start comparison, showed that gender diversity was expressed for even more specific variables, including vertical take-off velocity and relative height at take-off (Fischer and Kibele, 2016), which determine flight and water entry profiles. Also, in the referred study, the flight and water phases were different between males and females. These results are coherent with those suggesting different technical underwater strategies undertaken by swimmers of each gender (Tor et al., 2014). Here, males swam longer and deeper underwater. Besides, timing and velocity values measured from 5 up to 15-m in that study corroborate our findings. Unfortunately, the current study did not put much focus on the underwater phase, in which the main temporal similarities among genders were presented by Tor et al. (2014). Regardless of the higher level (in terms of the mean time values) of swimmers evaluated by Tor et al. (2014), the quoted results revealed a profile of diversity similar to our observations. Considering that male swimmers benefit from their shorter block time, higher take-off velocity, and longer flight distance, they are able to successfully transfer the energy included in those phases into underwater gliding.

Factors determining starting performance

In the current analyses, significant correlation values (Table 3) confirmed that specific anthropometric profiles of athletes might have a significant influence on swimming performance (Rejman et al., 2018). Similar conclusions can be drawn when assessing starting performance, but here, gender-related anthropometrics would determine the results in a different way. Male swimmers would take advantage of body mass, body height, muscle strength, and power, which are crucial in the push-off phase and its consequences. On the other hand, females would compensate for their lower profile in these variables through the more hydrodynamic body shape and body density, which gain special relevance during the water phase. Moreover, during the flight phase, females seem to rely more on body height than males (Table 2). Vantorre et al. (2010) suggested that better gliding performance was attributed to a slimmer body, as taking advantage of better hydrodynamics. However, while looking at the undulatory propulsion phase, the power of propulsion movements overtakes the benefits of the body shape. Indeed, following Tor et al. (2014), the temporal description of underwater movements did not show significant differences between groups. In short, not only overall race performance but also the starting phases are related to the anthropometrical gap based on gender diversity (Jesus et al., 2011). Findings from other sports confirm the gender skill gap existence; mean male/female differences across jumping events (17.8 ± 2.7%) were 1.5 times greater than those for running events (11.2 ± 1.4%) (McClelland and Weyand, 2020)

Generally, there is a trend that males present a shorter block time and total start time, and, consequently, longer flight distance overwater with higher horizontal velocities. At the same time, depending on the gender of the swimmer, those parameters relate differently to the total start time (Table 2). Besides, a significant correlation was found between overall starting performance and block time, take-off horizontal velocity, and flight distance in the male group. On the contrary, the Pearson product-momentum correlation coefficients expose low values for women participants. Meanwhile, those parameters have been widely used as starting performance indicators (Honda et al., 2012; Ikeda et al., 2016; Morais et al., 2019; Slawson et al., 2013). Yet, the correlations between the same parameters observed previously by Garcia-Ramos et al. (2015) did not confirm the results obtained for the female group (Table 2). The current findings thus demonstrate the need for gender separation in the assessment of start performance based on factors selected as significantly relating to it. The presented findings could contribute to future practice, clarifying which parameters should be considered while objectively evaluating start performance in male and female swimmers.

Limitations

Notwithstanding the relevance of the undertaken approach, some limitations resulting from the methodology of this research should be addressed. The first one concerns the free choice of the starting technique applied by the participants, which was based on their previous experience and specified for each subject independently. Consequently, the starting position could have influenced the structural and temporal characteristics of the start. As swimming performance is determined by many factors (Morais et al., 2013), no general trend for an optimal kick-start stance was revealed (Kibele et al., 2014). Therefore, as an individualized starting position seems to be the best, the study aimed to observe differences among swimmers using their own natural patterns of kick-start, avoiding simulation of artificial movements. Secondly, not enough focus was probably provided on underwater actions. Indeed, the water phase has been exposed as an important performance determinant by many scientists. Yet, the results describing other phases of the swimming start match with the findings previously presented by other authors; thus, in the context of the presented conclusions, more detailed analysis of underwater actions should shed more light on the gender effect while starting. Further research is needed to explore such specific factors as biomechanical demands, anthropometrics, specific motor abilities, and relationships between them, in order to exhaustively describe the crucial variables determining the swimming start performance per gender.

Conclusions

The study confirms that the spatiotemporal parameters of the swimming start, the relationships between them, as well as the overall starting performance differ between genders. Here, such performance variables as 5-m, 10-m, and 15-m start times indicate that male participants were faster than females. They also obtained significantly higher horizontal velocities. In general, temporal movement organization during the block phase did not differ between the two groups. Yet, male swimmers, by spending less time in the block phase, reaching higher take-off velocity, jumping further overwater, and swimming faster while in the water, take a starting advantage over their female counterparts.

Aside from issues related to gender diversity exposed between the individual variables, the correlations between separate variables and main parameters in the assessment of overall swimming start performance were also presented as varying between the two groups. Parameters commonly used for swimming start performance assessment, such as take-off velocity, flight distance, or time needed to propel from the starting block, correlated significantly with overall start performance only in the group of male athletes. In light of this finding, it is important to differentiate parameters employed to evaluate the swimming start performance considering the athlete's gender.

The applied approach to swimming performance measurement in regard to the gender of the swimmer was accurate and reliable. The findings play a crucial role in swimming start gender evaluation in post-pubertal age groups of swimmers. Therefore, as we aim to contribute to knowledge development and, consequently, to support swimmers and their coaching staff in the starting performance enhancement, the study outcome should attract considerable attention among practitioners. The findings regarding key factors in the assessment of swimming start performance can be directly applied to training practice.

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CHAPTER VI

COUNTERMOVEMENT JUMP TEST AS A TOOL FOR VENTRAL SWIMMING START PERFORMANCE PREDICTION

Daria Rudnik, Pedro Fonseca, Ricardo J. Fernandes, Joao Paulo Vilas-Boas, and Marek Rejman

Abstract

Many factors could determine starting performance, from them the lower limbs motor abilities have been brought into discussions. Indeed, it seems that the start is a part of the swimming event, which is the most influenced by lower body motor abilities Here, difficulties and limitations driven by the specification of the water environment moved attention toward the land-based test. The main objective of the study was to determine the relationship between results of countermovement jump (CMJ) test and the characteristics of the kick-start. Thirty-one, male international-level swimmers participated in the study. Each participant performed two tests comprising of the CMJ that took place at the biomechanics laboratory, and ventral swimming start completed at the swimming pool. During the land-based test, two force platforms (Bertec FP4060-15) were used to collect ground reaction force data from which all parameters were calculated using the MATLAB routine. To collect the spatiotemporal data, the kick-start data acquisition set up comprising three video cameras and instrumented starting block was implemented. Collected data were analyzed using SIMI Motion software. To distinguish a relationship between CMJ and swimming start Pearson's correlation and multiple regression analyses were used. the 15-m start time chosen for the swimming start performance description was recognized as highly correlated with the dry-land CMJ test. The inverse relationships indicate that the lower the start time measured over 5-m, 10-m, or 15-m, the higher CMJ variables are: jump height, flight time, maximum velocity, total CMJ impulse, net impulse, absolute and normalized peak power, absolute and normalized mean power. A moderate positive correlation was found between jump high, max velocity, total impulse, and power of CMJ and both relative block and flight phase durations. In contrast, those CMJ variables corresponded inversely to water phase duration relative duration. Furthermore, a high correlation between take-off horizontal velocity, flight distance, or 5-10 m time, and many distinctive parameters of CMJ confirmed the significance of lower limbs' motor abilities while starting. Finally, regression analyses derived the model equations providing the premises for predictions of individual starting performance based on results of the CMJ test. The results of the current study provide evidence of an important correlation between variables of CMJ and the kick-start. We justified the utility of composed equations allowing quantification of the potential transfer of motor abilities registered in the CMJ test to kick-start performance. By further exploring the issue of the ventral start performance determinants, we hope to provide insights for swimmers and their coaching staff into conscious and reliable monitoring, assessment, and improvement of starting performance.

Key words: swimming start, countermovement jump, performance prediction, motor abilities

Introduction

Success in competitive swimming is affected by many factors (Morais et al., 2013). Thus, it is important to distinguish the key determinants of overall swimming performance, including the swimming start. As the first part of each competitive swimming event, swimming start could count up to 25% of overall sprint race time (Cossor and Mason, 2001). It has been widely accepted that the shorter the start time, the higher the swimming performance might be (Cossor and Mason, 2001). The start as an element of a swimming race is commonly divided into the block, flight, and water phases, all contributing to the overall starting performance (Hay, 1986). Moreover, it seems that the start is a part of the swimming event which is the most influenced by lower body motor abilities (Bishop et al., 2013). From this point of view, swimming start proficiency depends on the efficiency of the transfer of muscular leg forces and power into the forwarding movement of the swimmer's body (De la Fuente et al., 2003; Mason and Mackintosh, 2020; Vantorre et al., 2014). The block phase requires an explosive muscular response resulting mainly from the extension of the lower limb joints (Breed and McElroy, 2000; Guimaraes and Hay, 1985; Robertson and Stewart, 1998; Vilas-Boas et al., 2003). However, considering the requirements of the complicated movement structure involving whole-body coordination in a very limited time period, the mechanism describing the dependencies between lower body motor abilities and the swimming start performance seems to obey to a multifactorial nature (West et al., 2011). Indeed, the importance of technical proficiency in start has been widely underlined (Breed and Young, 2003; Carvalho et al., 2017; De la Fuente et al., 2003).

Starting performance development enhancement was mostly underpinned by improving jumping ability, strength, and power of lower limbs with various dry-land training methods (Bishop et al., 2009; Breed and Young, 2003; Rebutini et al., 2016; Rejman et al., 2017; Thng et al., 2019). Several dry-land tests were implemented while searching for tools to monitor or improve the start performance. Therefore, previous studies attempted to establish the interrelation between dry-land-based tests results and performance in different starting techniques (Arellano et al., 2005; Benjanuvatra et al., 2007; Breed and Young, 2003; Carvalho et al., 2017; Cossor et al., 2011; West et al., 2011). To search for any similarities between lower body characteristics (muscular strength and explosive power) and starting performance, ballistic movements such as countermovement jump (CMJ) or squat jump (SJ) have been widely taken into consideration (Garcia-Ramos et al., 2015; Keiner et al., 2015; Sammound et al., 2019; Thng et al., 2019, 2020). In CMJ, the rising concentric phase is preceded by a lowering eccentric phase, which stores elastic energy in the eccentrically contracting (lengthening) muscles and makes it more advantageous over SJ (Bartlett, 2014). Thus, it appears that lower limbs movements describing the swimming start expose some similarities with CMJ (Breed and Young, 2003; Garcia-Ramos et al., 2016b; Lee et al., 2001; Pearson et al., 1998; Robertson and Stewart, 1998) (Figure 1). In those jumps, the knee and ankle moments are recruited simultaneously rather than sequentially (Robertson and Stewart, 1998). Moreover, both activities require the athletes' ability to rapidly and effectively move through the stretch-shortening cycle (Lee et al., 2001).

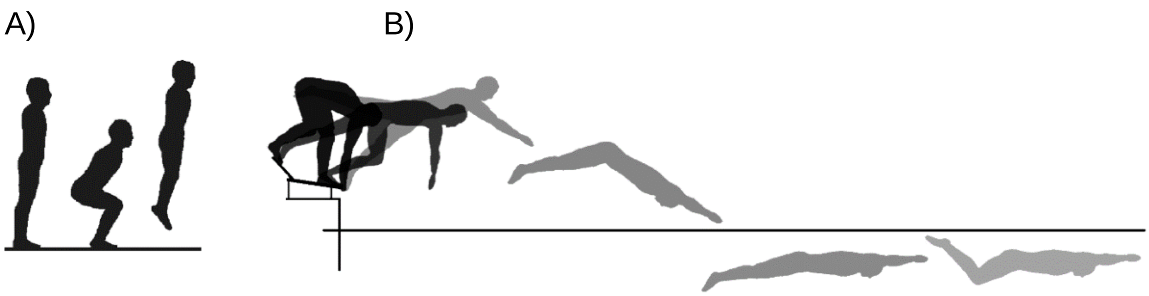


Figure 1. The movement structure of a countermovement jump (A) and a kick-start (B).

Over the years, researchers have tried to identify which one from swimming start techniques is the most advantageous among those practiced by swimmers. Some years ago, the grab-start and the track-start (initially proposed as similar to the track and field start) were two techniques the most scientifically explored. Yet, owing to the new construction of the OSB11 starting block, with the possibility to support the rear foot, crucial biomechanical consequences of the starting block configuration have occurred and led to modifications in the starting technique. Here, the kick-start, by reducing slippage changes through the rear foot support, results in performance enhancement by shortening the block time and increasing the horizontal impulse of the body (Honda et al., 2010; Takeda et al., 2017).

Although most of the research shows no interrelation between grab-start performance and jumping ability, muscular leg force, or power (Arellano et al., 2005; Benjanuvatra et al., 2007; Breed and Young, 2003; Lee et al., 2001), some similarities have been exposed, including matching profiles of vertical force-time curves recorded for grab-start and CMJ (De la Fuente et al., 2003). Yet, Breed and Young (2003) did not find any significant differences between the grab and swing starts for any temporal, kinematic, or kinetic variables due to the application of a dry-land resistance training program, while, in contrast, the track-start was significantly improved. The available findings revealing the lack of relationship between the results of CMJ and swimming start parameters have to be reconsidered on the basis of up-to-date starting techniques. Consequently, given the practical importance of swimming start to the final race result, most of the available observations have limited applications to the current context. Indeed, as noted by Peterson et al. (2018), lower limbs play a different role in take-off performance depending on the starting technique.

Moreover, the latest analyses presented more similarities between movement structures describing CMJ and kick-start, which further drives the interest to resolve the presented issue (Carvalho et al., 2017; Keiner et al., 2015). Cossor et al. (2011) exposed a strong positive correlation between peak forces measured during swimming start and those reported in the CMJ test. In a group of 10-mixed-gender elite swimmers, Carvalho et al. (2017) established an inverse correlation between the total start time (to 15-m) and such CMJ variables as jump height, peak force, and peak power. A strong inverse relationship between CMJ height and 15-m start time has been also shown in a group of non-skilled swimmers composed of 12 males and 9 females (Keiner et al., 2015). On the other hand, Garcia-Ramos et al. (2016a) did not find a significant correlation between any CMJ variables and 15-m start time performed by 20 females. However, in their study, the relative peak power and take-off velocity recorded during CMJ were associated with both 5-m and 10-m start time. These contrasting findings could be attributed to the variability among the studied groups. Besides, some differences visible in the mentioned references have to be considered, such as small sample sizes or heterogeneity of the participants merging both genders. Therefore, there are a limited number of studies that sought to identify the relationship between CMJ and the kick-start, and no research has examined the link between key factors in the assessment of the kick-start performance and CMJ force-time curve shape. Then, further evaluations have to be performed to explore the presented issues.

Moreover, difficulties and limitations concerning direct data acquisition in water require specific and not fully accessible measuring equipment. An assessment of the CMJ quality commonly provides simple to measure and coach-friendly data, which allows its inclusion in daily practice. However, the shape of the CMJ force-time curve can exhibit adaptations in specific motor skills (McMahon et al., 2018; Cormie et al., 2009). Thus, receiving and relating more variables seems to be beneficial for the interpretation process. As almost all sports laboratories are equipped with at least one force platform, and various valid portable devices used to measure variables derived from CMJ have become widely available (Rago et al., 2018), the prediction of starting performance based on land tests results seems to be a solution targeted to coaches and swimmers.

Nowadays, the kick-start is used by most of the elite swimmers; thus, the need for multidimensional research in its improvement is still justified. The exposure of a simple, cheap, and easily available tool for swimming start performance prediction such as the CMJ test may upgrade the process of performance evaluation in swimmers. Additionally, a model based on statistical methods could be an invaluable tool that allows choosing the test that causes fewer difficulties and offers alternative assessment options for swimmers and their coaching staff.

The main objective of this investigation was to determine the relationship between selected variables characterizing the CMJ structure and key biomechanical parameters in the assessment of the kick-start performance in high-level swimmers. On the basis of those variables, which potentially correlate with one another, it will be possible to compose and validate a regression model that would reveal the useful data for kick-start performance assessment and improvement prediction. Finally, we wish to provide an opportunity to better understand swimmer efficiency and identify areas for improvement in ventral swimming start.

In their previous studies, Bishop et al. (2009), Breed and Young (2003), Rebutini et al. (2016), Rejman et al. (2017), and Thng et al. (2019) emphasized the crucial role of muscle forces (torque) generated by lower extremities while starting, as well as revealed a high influence of the targeted training focused on leg strength and power improvement. Therefore, it has been hypothesized that CMJ test results would exhibit a significant correlation with the deliberately selected variables to assess swimming start performance.

Material and methods

Thirty-one male international level competitive swimmers participated in the testing sessions. They were members of the national swimming teams for the Olympic Games or World or European Championships. The group was characterized by the mean (± SD) age of 20.7 ± 4.1 years, body height of 179.8 ± 4.9 cm, body mass of 72.3 ± 5.5 kg, and the best personal record at least at the level of 750 FINA points. The study was approved by the local ethics committee and was conducted in accordance with recognized ethical standards and the international principles of the Declaration of Helsinki regarding human research. All participants and their coaches were informed about the purpose of the study and the procedure which would be used and decided to voluntarily participate in the data acquisition. Moreover, the swimmers had been asked to stay refrained from strenuous load exercises for a minimum of 48 hours before the study commencement. Written informed consent was obtained from all participants and, if needed, from their parents or legal guardians.

Data acquisition was carried out at the University of Porto, with the assistance of the LABIOMEP Porto Biomechanics Laboratory. All the measurements were administered, and all equipment was calibrated in a standardized manner to minimize differences between the testing sessions. All swimmers had been trained and had previous experience with the equipment and testing protocols that were implemented. In the laboratory, a dry-land test session of CMJ was performed. Meanwhile, in a 25-m indoor swimming pool, swimming start data were collected. To complete the testing protocol, the athletes were required to participate in both testing sessions (in random order, by division into groups) during one day.

Countermovement jump test

A standard warm-up for the jumping test was applied. Next, the subjects were asked to perform three maximal weight-bearing CMJs without arm swing. *In a countermovement jump, the jumper starts from an upright standing position, makes a preliminary downward movement by flexing at the knees and hips, then immediately and vigorously extends the knees and hips again to jump vertically up off the ground* (Linthorne, 2001) (Figure 2).

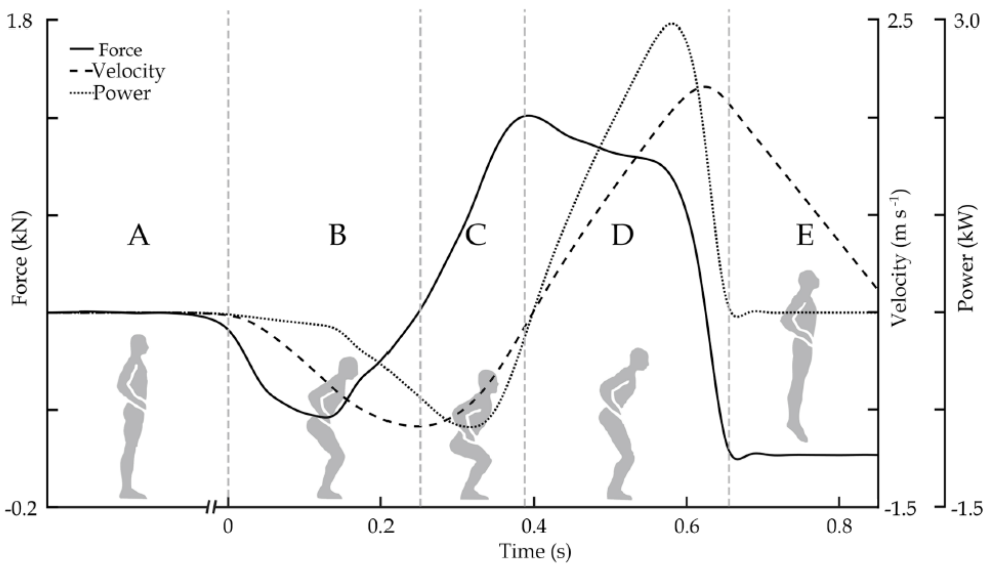
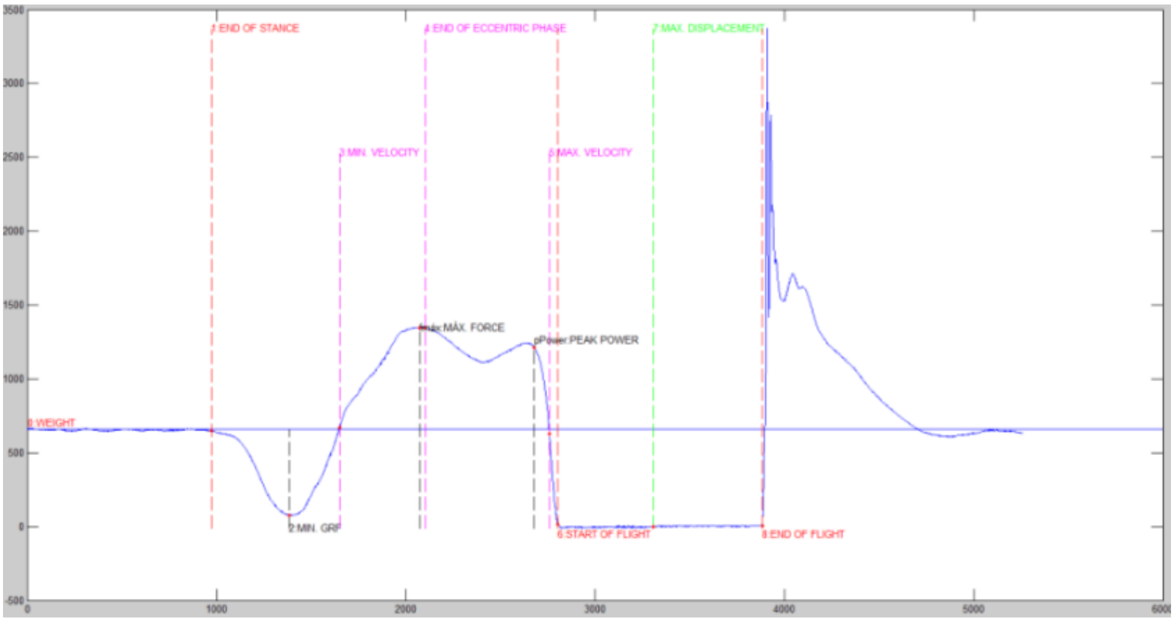


Figure 2. Countermovement jump phases: stable (A); eccentric: unweighting (B) and braking (C); concentric-propulsive (D); flight (E) (Souza et al., 2020).

The target was to rapidly displace the center of mass up as much as possible in the vertical axis. To exclude the effect of shoe differences, the CMJ test was performed with bare feet. In the initial position (before the sound starting signal was given), the swimmers had to stand stable, upright, with their feet placed in a parallel position on the two separated force platforms. To eliminate the arm action, hands were placed on the hips. The participants were instructed to ensure that the knee joint angle reached a value close to 90 degrees of flexion, avoid pause between the eccentric and concentric phases, and maintain extension in the lower limb joints during the flight phase (to avoid the registration of any additional flight time being a result of bending their legs in the landing phase).

The values of all parameters were calculated through the ground reaction forces (GRF) time series (Figure 3) collected by using two Bertec FP4060-15 force plates (Bertec Inc., Columbus, OH, USA) operating at 2000 Hz. The Qualisys Motion Capture System software (Qualisys AB, Sweden) was employed to operate the force plates.



GRF: ground reaction forces.

Figure 3. Countermovement jump force-time curve pattern with all the remaining jump events presented.

In line with the current references (Gathercole et al., 2015a, 2015b, 2015c; Laffaye et al., 2014; Linthorne, 2001; Mizuguchi et al., 2015; Rago et al., 2018; Thomas et al., 2017), selected CMJ variables (Table 1) were taken into consideration. The force and power variables are expressed as absolute and normalized (relative to body mass) values.

Table 1. Definitions of variables used to describe the countermovement jump test.

	Variable	Definition
Spatial	Jump height (m)	Vertical displacement measured with the flight-time method modified to the velocity calculated from the force platform
Temporal	Total duration (s)	Time between the beginning of the downward movement and the moment of take-off
	Flight time (s)	Time of zero force, corresponding to the period of flight when there is no contact with the floor
	Eccentric phase (s)	Time of the eccentric phase
	Concentric phase (s)	Time of the concentric phase
	FC ratio	Ratio between the flight time and the contraction time
	Time to peak power (s)	Time between the beginning of the downward movement and the instant of peak force
Velocity	Maximum velocity (m/s)	Value of maximum positive velocity
	Velocity at peak power (m/s)	Velocity value measured at the instant of peak power
Force	Peak force (N, N/kg)	Maximum force value of the CMJ
	Mean force (N, N/kg)	Average force value during the entire CMJ
	RFD (N/s)	Maximum value of the rate of force development: force increase within the 30-ms window during the eccentric phase
Impulse	CMJ impulse (N · s)	Total impulse: the product of average force (a result of the sum of both the positive and negative force productions) and specified time calculated for the entire CMJ
	Positive impulse (N · s)	Impulse calculated for the portion of force above the weight of the participant
	Net impulse (N · s)	Impulse between the beginning of the concentric phase and the moment when force reaches weight level, minus the impulse equivalent to that of the propulsion-deceleration phase
Power	Peak power (W, W/kg)	Maximum value of power during the concentric phase
	Mean power (W, W/kg)	Average power production during the CMJ concentric phase
	RPD (W/s)	Maximum rate of power development: largest power increase within the 30-ms window during the CMJ

CMJ: countermovement jump.

Swimming start

A standardized starting procedure was used (conforming to the FINA swimming rules), with a visual and sound starting signal given to the swimmers. The participants performed three repetitions of the swimming start applying the kick-start technique and continued swimming at maximal effort until the end of the 25-m pool. It was assumed that the shorter the total start time (at a 15-m distance), the better the starting performance was. Each trial was organized to ensure the achievement of optimal conditions for the highest performance. Between the repetitions, the athletes had at least three minutes of rest time to compensate for the energy loss.

In all the kick-start trials, kinematic and kinetic data were collected by using a setup consisting of the following equipment (Figure 4). All the data were registered simultaneously, and all equipment was synchronized with the starting device (Onda TTL wave, 0–5 V), which acted as a trigger initiating data collection. To record the swimmers' actions from the starting signal until the 15-m from the starting platform, a dual media setup was applied. Two underwater (Hero 4, GoPro, USA) and two over water video-cameras (HDR CX160E, Sony Electronics Inc., Japan) were placed on the side of the swimming pool parallel to the direction of the swimmers' movement during the kick-start. Two cameras were fixed on a tripod at a height of 0.70 m (Hama Star 63, Hama Ltd., UK), at a distance of 0.50 m and 15-m from the starting block. Two underwater cameras were fixed to the sidewall of the pool (0.30 m deep), at 5-m and 10-m distances from the starting block. All cameras were configured to record 50 frames per second. To obtain a higher sensibility of temporal data during the block phase, a self-made dynamometric starting block device (Mourão et al., 2016; Vilas-Boas et al., 2014) compliant with the current FINA regulations for OMEGA OSB 14 (Swiss Timing Ltd., Switzerland) was employed.

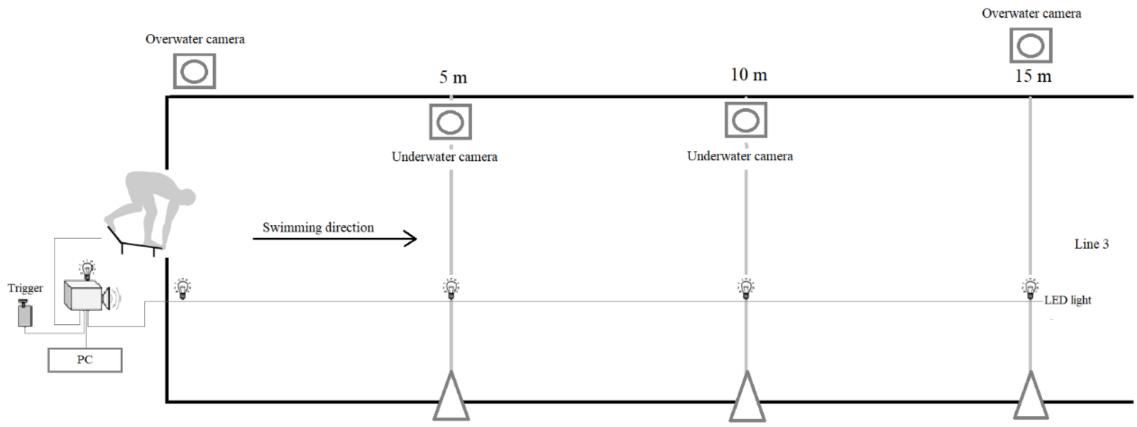


Figure 4. Graphical presentation of the measurement equipment setup.

Variables measured during the swimming are presented in Table 2. These parameters are often reported in the current references (Blanco et al., 2017; Carvalho et al., 2017; Colyer et al., 2019). The absolute duration of each temporal variable is expressed in seconds, while the phases relative duration is expressed in percentage of the 15-m start time (Seifert et al., 2010).

In order to assess the variables describing the spatiotemporal structure of the swimming start on the basis of video footage analyses, the SIMI Motion System (SIMI Reality Motion Systems GmbH, Germany) was employed. In the video recording processing, the first frame in which the LED light was lightened was used to determine the starting signal for each trial. The camera recordings were calibrated with the video footage of the calibration frame, which was placed above and under water in the sagittal plane of the swimmer's displacement.

Table 2. Definitions of variables used to describe the swimming start structure.

	Variable	Definition
Start times	5-m time (s)	The time interval between the starting signal and the moment the head crosses the 5-m mark
	10-m time (s)	The time interval between the starting signal and the moment the head crosses the 10-m mark
	15-m time (s)	The time interval between the starting signal and the moment the head crosses the 15-m mark
Phase duration	Block time (s, %)	The time interval from the starting signal until the instant of take-off
	Flight time (s, %)	The time interval from the instant of take-off until the moment of the first contact of the hands with the water
	Water time (s, %)	The time interval between the first contact of the hands with the water and the moment the head crosses the 15-m mark
Start parameters	Take-off horizontal velocity (m/s)	The instantaneous horizontal velocity of the swimmer measured at the instant of take-off
	Flight distance (m)	The horizontal distance measured between the point where the hip enters the water and the starting wall
	5–10-m time (s)	The time interval between the moment the head crosses the 5-m mark and the moment the head crosses the 10-m mark

Data analysis

A specially designed processing routine was created in the MATLAB R2016a software (MathWorks Inc., USA) and used to provide GRF parameters of the CMJ test (Rago et al., 2018). Special attention was paid to the GRF vertical component of CMJ. For normalization purposes, the vertical component of the GRF during the CMJ tests was used in conjunction with the subject's body mass.

A database was built with values collected during both tests, allowing calculation and selection of specific variables. The best results of each swimmer in both tests were selected for further analyses. The Pearson product momentum correlation coefficient and multiple regression analysis were computed to examine if a relationship between CMJ and swimming start existed. Firstly, it was assessed if parametric statistical test assumptions were not violated. Mean and standard deviation were estimated for each variable, distribution formalities for sets of data were tested. As it was assumed that continuous variables were normally distributed, Pearson's correlation coefficients were calculated to explore whether a statistically significant relationship between start performance and CMJ variables existed.

In order to explain swimming start as a complex human body movement, multiple linear regression methods were used. This approach was based on obtained values of all variables and allowed to estimate the regression equations explaining selected swimming start performance indicators depending upon measured values of CMJ parameters. To ensure the best fitting of the regression residuals in the obtained regression models forecasting given swimming start variables, different regression methods were used. These included a stepwise regression method conducted to fit the regression models based on an automatic procedure while choosing the predictive variables from the group of CMJ variables primary selected with the consideration of the obtained correlation analyses results. Among the set of candidates (designed) models, the most suitable (with reference to the selection criteria) equation determined the inclusion of the relevant variables. They were implemented to obtain predicted values and their equivalents measured during the testing sessions. It was assumed that for an equation to be considered as relevant and valuable, its coefficient of determination should suggest that the equation revealed the estimated values for the trendline corresponding at least to 70% of the actual data, p-value allowed to reject the zero hypotheses, and the standard error of estimate met practical expectations. Then the equation would be included in the presentation of the study results and introduced as a tool for swimming start performance prediction. As a repeated-measures t-test assesses whether the mean scores for two experimental conditions are statistically different from each other, it was used to verify the obtained model usefulness. For this reason, two sets of data were composed, including one for values measured in real conditions (observed) and the other one for predicted values based on the composed equation. The level of statistical significance was set at α = 0.05. All statistical analyses were carried out with the Statistica 13.1 software (StatSoft, USA).

Results

The mean and standard deviation values calculated for each of the CMJ parameters taken under consideration are presented in Table 3. The total time of CMJ was 0.86 ± 0.10 s, from which 0.57 ± 0.09 s constituted the eccentric phase and 0.29 ± 0.03 s stood for the concentric phase. In the flight phase, the participants spent 0.55 ± 0.05 s, displacing the body at a height of 0.35 ± 0.06 m in the vertical direction. The FC ratio equaled 0.64 ± 0.09. The entire CMJ impulse was 191.1 ± 24.4 Ns, with a positive impulse of 283.9 ± 34.1 Ns. The absolute and relative maximum values of vertical forces were 1629 ± 198 N and 22.19 ± 1.75 N/kg. The measured maximum rate of force development equaled 6807 ±2181 N/s. The relative peak power of 50.6 ± 6.4 W/kg was obtained at a time of 0.80 ± 0.1 s from the start of the jump, with the 2.51 ± 0.18 m/s velocity noted at this instant. While jumping, the subjects reached 2.76 ± 0.2 m/s maximum velocity.

Table 3. Means and standard deviations of parameters describing the countermovement jump structure.

	Variable	Mean ± SD
Spatial	Jump height (m)	0.35 ± 0.06
Temporal	Total duration (s)	0.86 ± 0.10
	Flight time (s)	0.55 ± 0.05
	Eccentric phase (s)	0.57 ± 0.09
	Concentric phase (s)	0.29 ± 0.03
	FC ratio	0.64 ± 0.09
	Time to peak power (s)	0.80 ± 0.1
Velocity	Maximum velocity (m/s)	2.76 ± 0.2
	Velocity at peak power (m/s)	2.51 ± 0.18
Force	Peak force (N)	1629 ± 198
	Peak force normalized (N/kg)	22.19 ± 1.75
	Mean force (N)	941 ± 79
	Mean force normalized (N/kg)	12.83 ± 0.45
	RFD (N/s)	6807 ± 2181
Impulse	Total CMJ impulse (N · s)	191.1 ± 24.4
	Positive impulse (N · s)	283.9 ± 34.1
	Net impulse (N · s)	191.7 ± 24.3
Power	Peak power (W)	3723 ± 627
	Peak power normalized (W/kg)	50.6 ± 6.4
	Mean power (W)	1993 ± 320
	Mean power normalized (W/kg)	27.09 ± 3.1
	RPD (W/s)	21749 ± 5087

FC: ratio between the flight time and the contraction time; RFD: rate of force development; CMJ: countermovement jump; RPD: rate of power development.

The mean and standard deviation values estimated for each spatiotemporal variable describing the swimming start are presented in Table 4. The total 15-m start time was divided into shorter distances from the starting wall: 5-m (1.501 ± 0.11 s) and 10-m (3.793 ± 0.25 s). From the total start time, measured over the 15-m distance (6.203 ± 0.43 s), 11.6 ± 1.0% was for the block phase (0.719 ± 0.05 s), 4.6 ± 0.9% for the flight phase (0.286 ± 0.05 s), and 83.7 ± 1.4% for the water phase (5.184 ± 0.34 s). Additional key factors in the assessment of the swimming start performance depending highly on the muscular forces (torque) generated by lower extremities were selected. This included take-off horizontal velocity (4.463 ± 0.27 m/s), flight distance (2.874 ± 0.20 m), and time of underwater swimming between the 5th and the 10th m (2.291 ± 0.19 s).

Table 4. Descriptive statistics of parameters measured during the swimming start testing session.

	Variable	**Mean ± SD**
Start times	5-m time (s)	1.501 ± 0.11
	10-m time (s)	3.793 ± 0.25
	15-m time (s)	6.203 ± 0.43
Phase duration	Block time (s)	0.719 ± 0.05
	Block time (%)	11.6 ± 1.0
	Flight time (s)	0.286 ± 0.05
	Flight time (%)	4.6 ± 0.9
	Water time (s)	5.184 ± 0.34
	Water time (%)	83.7 ± 1.4
Start variables	Take-off horizontal velocity (m/s)	4.463 ± 0.27
	Flight distance (m)	2.874 ± 0.20
	5–10-m time (s)	2.291 ± 0.19

Using Pearson production momentum correlation, CMJ variables were compared with temporal start performance measurement (15-m start time), as well as with start performance measured over the 5-m and 10-m distances (Table 5). In general, significant negative correlation values were obtained. The inverse relationships indicate that the lower the start time measured over 5-m, 10-m, or 15-m, the higher CMJ variables: jump height (r = –0.53, r = –0.72, r = 0.72), flight time (r = –0.53, r = –0.75, r = –0.78), maximum velocity (r = - 0.50, r = –0.74, r = –0.75), total CMJ impulse (r = –0.47, r = –0.72, r = –0.76), net impulse (r = -0.49, r = –0.74, r = –0.77), peak power (r = –0.49, r = –0.76, r = –0.82), peak power normalized (r = –0.51, r = –0.75, r = –0.79), mean power (r = –0.53, r = –0.74, r = –0.74), and mean power normalized (r = –0.57, r = -0.73, r = –0.69). Besides, for the 10-m and 15-m start times, larger correlations were obtained for absolute values of the force and power CMJ parameters than for the values normalized to swimmers' body mass.

Table 5. Pearson's coefficient correlation results describing relationships between temporal variables of swimming start and selected countermovement jump variables.

	Variable	**5-m time**	**10-m time**	**15-m time**
Spatial	Jump height	–0.53	–0.72*	–0.72*
Temporal	Total duration	–0.08	0.13	–0.07
	Flight time	–0.53*	–0.75*	–0.78*
	Eccentric phase	–0.18	0.09	0.13
	Concentric phase	0.23	0.15	0.12
	FC ratio	–0.29	–0.60*	–0.44
	Time to peak power	–0.08	0.12	–0.07
Velocity	Maximum velocity	–0.50*	–0.74*	–0.75*
	Velocity at peak power	–0.44	–0.68*	–0.67*
Force	Peak force	–0.37	–0.57*	–0.61*
	Peak force normalized	–0.32	–0.44	–0.42
	Mean force	–0.35	–0.64*	–0.64*
	Mean force normalized	–0.25	–0.54*	–0.36
	RFD	–0.01	–0.19	–0.15
Impulse	Total CMJ impulse	–0.47*	–0.72*	–0.76*
	Positive impulse	–0.36	–0.67*	–0.69*
	Net impulse	–0.49*	–0.74*	–0.77*
Power	Peak power	–0.49*	–0.76*	–0.82*
	Peak power normalized	–0.51*	–0.75*	–0.79*
	Mean power	–0.53*	–0.74*	–0.74*
	Mean power normalized	–0.57*	–0.73*	–0.69*
	RPD	–0.38	–0.55*	–0.63*

FC: ratio between the flight time and the contraction time; RFD: rate of force development; CMJ: countermovement jump; RPD: rate of power development.
*Significant at exact $p \leq 0.05$.

Pearson's coefficient correlation results describing relationships between absolute and relative values of time in swimming start phases and CMJ variables are presented in Table 6. Block time duration was negatively correlated with positive impulse generated in CMJ (r = –0.52). Despite this, a moderate positive correlation was found between some CMJ variables and both relative block and flight phase durations. Higher values of most CMJ variables corresponded to shorter water phase duration, as well as to its lower percentage share in the total start time. Besides, the recorded absolute force and power demonstrated a higher correlation with water phase duration than their values normalized to body mass. Jump height, flight time, maximum velocity, total CMJ impulse, net impulse, peak and mean power, as well as RPD correlated significantly with all start phases relative duration, expressed in percentage of the 15-m start time.

Table 6. Pearson's coefficient correlation results describing relationships between absolute and relative duration of swimming start phases and CMJ variables.

	Variable	BT	BT%	FT	FT%	WT	WT%
Spatial	Jump height	–0.30	0.47*	0.18	0.41	–0.76*	–0.60*
Temporal	Total duration	–0.09	0.24	–0.26	–0.10	–0.21	–0.11
	Flight time	–0.34	0.42*	0.16	0.43*	–0.77*	–0.58*
	Eccentric phase	–0.04	0.33	–0.28	–0.07	–0.28	–0.18
	Concentric phase	–0.15	0.15	–0.05	–0.14	0.12	0.20
	FC ratio	–0.13	0.05	0.28	0.36	–0.29	–0.26
	Time to peak power	–0.11	0.24	–0.25	–0.09	–0.22	–0.11
Velocity	Maximum velocity	–0.3	0.47*	0.15	0.41*	–0.77*	–0.60*
	Velocity at peak power	–0.38	0.37	0.18	0.38*	–0.70*	–0.50*
Force	Peak force	–0.27	0.31	0.18	0.41*	–0.60*	–0.48*
	Peak force normalized	0.01	0.27	0.23	0.36	–0.42*	–0.43*
	Mean force	–0.42	0.21	0.16	0.41*	–0.58*	–0.41*
	Mean force normalized	–0.1	0.05	0.30	0.36	–0.26	–0.26
	RFD	–0.05	0.08	0.39	0.39*	–0.22	–0.31
Impulse	Total CMJ impulse	–0.43	0.40*	0.39	0.46*	–0.78*	–0.58*
	Positive impulse	–0.52*	0.21	0.24	0.46*	–0.65*	–0.45*
	Net impulse	–0.42	0.43*	0.14	0.44*	–0.79*	–0.59*
Power	Peak power	–0.29	0.54*	0.07	0.43*	–0.85*	–0.67*
	Peak power normalized	–0.15	0.59*	0.06	0.39*	–0.83*	–0.68*
	Mean power	–0.35	0.43*	0.16	0.47*	–0.77*	–0.60*
	Mean power normalized	–0.23	0.45*	0.19	0.46*	–0.74*	–0.61*
	RPD	–0.08	0.44*	0.13	0.40*	–0.64*	–0.57*

FC: ratio between the flight time and the contraction time; RFD: rate of force development; CMJ: countermovement jump; RPD: rate of power development; BT: block phase duration; BT%: relative block phase duration; FT: flight phase duration; FT%: relative flight phase duration; WT: water phase duration; WT%: relative water phase duration.
*Significant at $p \leq 0.05$.

For the relationship analysis, selected CMJ variables were also compared with key factors in the assessment of the swimming start performance (chosen deliberately as highly depending on motor abilities of lower limbs). The results are presented in Table 7. Results obtained from the Pearson product momentum correlation revealed that most of the variables describing CMJ structure were significantly related to key factors in the assessment of the swimming start performance. In general, positive correlation values were noted for take-off horizontal velocity and flight distance, while the 5–10-m time was inversely related with CMJ results. The obtained results suggest moderate to strong dependence of all start variables with jump height, flight time, and peak power. High positive correlations between impulse variables and take-off horizontal velocity ($r = 0.72$, $r = 0.67$, $r = 0.73$) and flight distance ($r = 0.62$, $r = 0.66$, $r = 0.63$) were achieved, while inverse relationships with the 5–10-m time ($r = –0.70$, $r = –0.70$, $r = –0.71$) were noted. Moreover, excluding RFD, all peak and mean force variables recorded during CMJ were significantly related to take-off horizontal velocity and flight distance. Furthermore, all CMJ variables describing power measurement highly correlated with all swimming start variables taken under consideration. Higher power recorded during the concentric phase of CMJ corresponded to higher take-off velocity, longer flight distance, and shorter duration of the temporal variables. Besides, considering the 5–10-m start time, weaker correlations were found for normalized force and power variables than for their absolute values. In short, the higher power and force generated during the dry-land test, the better the results of swimming start performance indicators were.

Table 7. Pearson's coefficient correlation results describing relationships between key factors in the assessment of the swimming start performance and countermovement jump variables.

	Variable	**Take-off velocity**	**Flight distance**	**5–10-m time**
Spatial	Jump height	0.65*	0.68*	–0.67*
Temporal	Total duration	–0.14	–0.39	0.22
	Flight time	0.65*	0.68*	–0.70*
	Eccentric phase	–0.08	–0.37	0.23
	Concentric phase	–0.20	–0.22	0.08
	FC ratio	0.54*	0.75*	–0.64*
	Time to peak power	–0.14	–0.38	0.22
Velocity	Maximum velocity	0.68*	0.68*	–0.71*
	Velocity at peak power	0.61*	0.63*	–0.67*
Force	Peak force	0.66*	0.58*	–0.56*
	Peak force normalized	0.50*	0.57*	–0.41
	Mean force	0.69*	0.58*	–0.66*
	Mean force normalized	0.50*	0.70*	–0.58*
	RFD	0.31	0.51*	–0.25
Impulse	Total CMJ impulse	0.72*	0.62*	–0.70*
	Positive impulse	0.67*	0.66*	–0.70*
	Net impulse	0.73*	0.63*	–0.71*
Power	Peak power	0.78*	0.65*	–0.75*
	Peak power normalized	0.72*	0.67*	–0.72*
	Mean power	0.76*	0.68*	–0.69*
	Mean power normalized	0.71*	0.73*	–0.66*
	RPD	0.66*	0.58*	–0.52*

FC: ratio between the flight time and the contraction time; RFD: rate of force development; CMJ: countermovement jump; RPD: rate of power development.
*Significant at $p \leq 0.05$.

Our findings suggest an interdependence between the results obtained in the two tests. The outcomes reveal the existence of some significant correlations between the CMJ test results and swimming start performance indicators such as take-off horizontal velocity, flight distance, and 5–10-m time. On the other hand, the results did not show a highly significant correlation between the CMJ test and block or flight phase durations. Indeed, also swimming start performance measured over the 5-m distance demonstrated a lower association with CMJ results than the 10-m or 15-m start times. Additionally, temporal variables describing CMJ were rather exposed as not related to swimming start performance.

Further analyses were conducted to verify if the CMJ test was a usable tool to indirectly assess the actual motor potential of the swimmer to perform the swimming start. The multiple regression method was employed for this. The regression analyses provided equations enabling prediction of quantitative dependent variables, including given swimming start performance indicators. The composed set of independent variables was based on data collected during the CMJ testing session. From the primarily selected set of 22 variables describing CMJ characteristics, 18 correlated with the majority of given swimming start variables (Tables 5–7) and, consequently, were selected for further regression analyses as potential predictors in equations. Finally, only 10 of them were identified as raw elements for regression models composed. Out of these, only positive impulse was included in all three prediction models, and the variables of mean force normalized, total CMJ impulse, flight time, velocity at peak power, and maximum velocity were selected for two equations. The equations based on CMJ test results are presented in Table 8.

This suggests that the estimated models make it possible to predict not only 15-m start performance but also some of the key factors in the assessment of the swimming start performance. As so, regression analyses offered feasible model equations providing valid predictions of starting performance and allowing modeling of start variables on the basis of the CMJ test results.

Table 8. Results of the multiple regression analyses used for modeling and predicting selected swimming start variables on the basis of countermovement jump results.

Variable	Equation	F	R^2	p	Eror (%)
15-m time	= 1.549 + mean force normalized × 0.532 + total CMJ impulse × 0.014 – positive impulse × 0.015 – peak power normalized × 0.078 – flight time × 10.682 + velocity at peak power × 3.663 ± 0.18	13.6	0.84	< 0.001	2.9
15-m time	= 5.165 + mean force normalized × 0.350 – peak power normalized × 0.067 ± 0.23	35.5	0.73	< 0.001	3.7
5–10-m time	= mean force normalized × 1.126 – peak force normalized × 0.263 – net impulse × 0.037 + mean power normalized × 0.201 + RPD × 0.00008 + time to peak power × 6.009 – maximum velocity × 3.278 + positive impulse × 0.015 – 6.598 ± 0.1	8.34	0.83	< 0.001	4.4
Take-off velocity	= 2.063 total CMJ impulse × 0.015 + positive impulse × 0.020 – flight time × 15.247 + maximum velocity × 8.360 – velocity at peak power × 5.605 ± 0.18	7.12	0.65	< 0.001	4

CMJ: countermovement jump; RPD: rate of power development

Discussion

The CMJ force-time curves profiles reported in our study (Figure 2) followed the general pattern prevalently described by Linthome (2001). In most studies, CMJ performance is assessed mainly by the jump height or peak power values (Arellano et al., 2005; Benjanuvatra et al., 2007; Breed and Young, 2003; Garcia-Ramos et al., 2016b; Keiner et al., 2015; West et al., 2011). For those values, the CMJ results obtained were in the ranges reported in the literature. Besides, the particular start times registered were similar to or shorter than those previously reported in studies conducted in experimental settings (Arellano et al., 2005; Carvalho et al., 2017; De la Fuente et al., 2003; Durović et al., 2015; Garcia-Ramos et al., 2015; Keiner et al., 2015; West et al., 2011). Yet, the diversity in available results could be explained by the level of participants, their gender, or even differences in the implemented starting techniques.

The relationship between countermovement jump test results and overall starting performance

The results of Pearson's correlations showed that the majority of parameters related to force, power, velocity, and jump height were inversely correlated with starting performance (Table 5). The presented outcome is in line with previous studies reporting that the better performance of the dry-land test, the shorter the start time registered at 5-m, 10-m, or 15-m distances from the starting platform (Benjanuvatra et al., 2007; Carvalho et al., 2017; Garcia-Ramos et al., 2016a, 2016b; Keiner et al., 2015; West et al., 2011). West et al. (2011) identified CMJ performance (jump height, peak power, and relative peak power) as significantly related to start time at 15-m for international sprint swimmers ($r = –0.69$, $r = –0.85$, $r = –0.66$, respectively) and confirmed the importance of power proficiency for starting performance. Then, on evaluating mid-level athletes, Keiner et al. (2015) obtained an even stronger correlation between the 15-m start time and CMJ jump height ($r = –0.92$). Regardless of the low number of participants included by Carvalho et al. (2017), also in that analysis a significant inverse correlation was observed between CMJ jump variables (such as CMJ height, peak vertical force, peak power) and the 15-m start time. Interestingly, neither in our study nor in the research by West et al. (2011), was RFD (obtained from a measurement conducted in dynamic conditions) found as significantly related to start time.

The current study represents a corroborative contribution to previously reported findings by confirming the existence of an inverse relationship between the CMJ test results and overall starting performance in high-level male swimmers (Table 5). Even though there are no doubts about the importance of lower body contribution while starting and jumping, there are still some differences between the motor tasks undertaken in the two tests. Then, no direct transfer from changes in lower body muscular strength and power to starting performance could be expected. Here, for conscious and targeted movements, an optimal combination of the swimmers' strength and power potential and their technical proficiency is still required, as direct consequences of improving specific skills are impossible without controlling the adaptation of neuromuscular properties for changing conditions (Van Soest, 1994; Breed and Young, 2003; Carvalho et al., 2017; De la Fuente et al., 2003).

The relationship between countermovement jump test results and selected parameters of swimming start

Our data support the hypothesis that CMJ test results are linked with the swimming start variables that particularly rely on the movements performed by the lower limbs. In general, the results from Pearson's product-moment correlation revealed most of CMJ related variables (peak and mean force, impulse, jump height, peak and mean power in the concentric phase, rate of power development, FC ratio, peak velocity) as being moderately to strongly correlated with starting studied variables (take-off horizontal velocity, flight distance, 5–10-m time) (Table 7).

Breed and Young (2003) concluded that the improvement in leg extensor power and jumping ability should increase the velocity of take-off and flight distance. Indeed, while aiming to attain its high value, leg extension force became especially important (Miyashita et al., 1992; Ozeki et al., 2017). Cossor et al. (2011) identified a strong positive correlation between peak vertical forces measured during the CMJ test and peak vertical forces recorded over the main (front) and back plates while starting from an instrumented starting block. Furthermore, the swimmers who generate higher than average peak forces during the block phase tend to achieve better overall start performance (Slawson et al., 2013), although in swimming, contrary to CMJ (in which the vertical component of GRF is emphasized), after the eccentric phase, horizontal impulse gains significance (Figure 1) (Arellano et al., 2005). Consequently, it appears that the interrelation between CMJ results, and the take-off horizontal velocity was not clearly revealed in scientific studies. However, more recent publications state that the swimming start requires an explosive muscular response to effectively push-off from the starting block (Thng et al., 2019). Indeed, improvements in take-off velocity were reported after plyometric training intervention (Bishop et al., 2009; Rebutini et al., 2016; Rejman et al., 2017).

Our results (Table 6) are also in line with the pioneer studies conducted by Zatsiorsky et al. (1979), where standing vertical jump was related with the flight and water phases rather than with block actions of swimming start. Surprisingly, few studies take into consideration the parameters of those phases in order to directly evaluate the relationship with dry-land tests for the currently used kick-start. Yet, some analyses showed an association among numerous land-based tests results, including leg extension power, jump height, peak vertical force, and flight distance measured for various tested starting techniques (Breed and Young, 2003; Cossor et al., 2011; Miyashita et al., 1992). In addition, according to Breed and Young (2003), there might be similarities between vertical jump and start, as both tested CMJs (with and without arm swing) correlated significantly with the flight distance of the starts. Besides, the extension of the flight phase relative duration (percentage of the 15-m start time) correlated with jump height and power developed by the swimmer during CMJ ($r = 0.44$) (Seifert et al., 2010). A significant improvement to flight distance has been also found after plyometric long jump training (Rebutini et al., 2016).

Moreover, Seifert et al. (2010) exposed variables of CMJ as significantly differentiating four clusters used to classify different profiles of the flight phase in front crawl start. Besides, the take-off angle was also positively associated with several parameters of CMJ (jump height: r = 0.39; power: r = 0.4) (Seifert et al., 2010).

In our study, the absolute power and force measured during CMJ tend to exhibit a higher correlation for the water phase of start than its relative equivalent (Table 2). Indeed, following the reasoning provided by Carvalho et al. (2017), based on findings presented by Taylor et al. (2003), the absolute value of CMJ vertical force is more reliable as while emerged in the water environment, the importance of body weight of the swimmer decreases. In a study by Garcia-Ramos et al. (2016a), the results normalized to swimmers' body weight in the dry-land tests were less correlated while the starting distance increased, yet an inverse pattern was observed for absolute values of those parameters. However, even that the correlations between start times and relative peak power and take-off velocity of CMJ decrease from 5-m to 10-m start time measurements, they still preserve importance for both distances (Garcia-Ramos et al., 2016a). The desirable shortening of glide time has been observed due to plyometric training results (Rejman et al., 2017), which seems to confirm the important dependence of that phase on lower extremities power abilities.

As swimming start can be recognized as an explosive pattern of movement (Prins et al., 2006), it has been stated that strength and power training could enhance the ability to exert force against the starting block and, consequently, as also during the underwater propulsive actions (Bishop et al., 2009; Rebutini et al., 2016; Rejman et al., 2017). Indeed, in the examined group of swimmers, better overall CMJ performance presented a high positive correlation with take-off horizontal velocity and flight distance, while the inverse relationship was exposed with the time measured between 5-m and 10-m from the starting wall (Table 7). Consequently, athletes who attained higher take-off horizontal velocity were able to keep it for a longer time and displace their body faster until the 10-m distance. Meanwhile, push-off from the starting block was shown as of more explosive nature than CMJ and required greater muscle coordination in time to leave the block with targeted velocity angle and angular momentum (Breed and Young, 2003; De La Fuente et al., 2003; Lee et al., 2001). Therefore, in swimming start, more complicated motor patterns than in CMJ are performed. Then, an optimal model arising from the mutual dependences between the principles of movement patterns and motor abilities is needed to control the process of swimming start improvement.

Prediction models

On the basis of the variables registered during the CMJ test and kick-start trials, we computed multiple regression equations. They allowed to compose the models predicting the 15-m start time**,** 5**–**10-m time, and take-off velocity. Then, by providing relevant results that confirm the relationships between CMJ measurements and the variables of start performance, this study allows to assess the adequateness of the tested prediction procedure toward its diagnostic power and provides a marker set/tool to evaluate start performance and, consequently, its training progress. Our findings follow the results previously presented by Carvalho et al. (2017), where the regression model explaining the 15-m start time was successfully designed on the basis of CMJ height and peak vertical force. They are also consistent with the observations by Cossor et al. (2011), indicating that dry-land tests could be successfully used to assess starting performance as an alternative to pool-based tests. The aforementioned findings provide promising output toward the validity of that simple, practical, and reliable method to monitor and assess swimming start performance through the indirect measure of power variables, linked also to explosive strength and maximal speed. Consequently, in the context of the results of a test containing different motor tasks (De la Fuente et al., 2003) but performed in more accessible conditions, and of the previous outcomes obtained from start variables collected with the more expensive and less accessible devices dedicated for water environment usage (Peterson et al., 2018), the quality of our prediction model could be assessed as a high.

The mechanisms explaining all the relations between lower body motor abilities and starting performance seem to expose a multifactorial nature (West et al., 2011). Therefore, swimming start does not depend solely on strength and explosive abilities (Benjanuvatra et al., 2007). The predicted starting performance based on CMJ results depends also on the quality of the starting technique. Yet, the importance of motor abilities of the lower body to enhance the development of starting performance has been confirmed by many researchers, which established the usefulness of various dry-land training programs and verified not only their consequences for jumping ability measured in dry-land tests but also the application for starting improvement (Bishop et al., 2009; Breed and Young, 2003; Rebutini et al., 2016; Rejman et al., 2017; Thng et al., 2019). Therefore, the discussed results imply the validity of CMJ as a simple, valuable, and reliable testing method for the assessment of the potential starting motor abilities. Nevertheless, the proposed solution, which concerns modeling the prediction effect of the lower body power dry-land test, allows a wide view and detailed interpretation of principles that play a crucial role in the improvement of starting performance.

Limitations

Notwithstanding the relevance and utility of this study, we recognize some limitations. Considering only the correlation approach, it is rather difficult to critically appraise if there is a direct link among the CMJ movement structure and phases of swimming start related to them. Consequently, their direct interpretation in terms of change in swimmers' individual technique of swimming start also raises scientific doubts. Therefore, for a wider assessment, correlation analyses were performed in conjunction with multiple regression analyses. Furthermore, the dry-land training programs based on the explosive power development were demonstrated to significantly affect swimming start performance enhancement (Bishop et al., 2009; Breed and Young, 2003; Rebutini et al., 2016; Rejman et al., 2017; Thng et al., 2019). These independent statements seem to constitute an objective support of the interpretation of our results and reduce counter-arguments arising from the confounding effects of technical differences between CMJ and swimming start. Generally, to prevent those constrains, larger samples are recommended for further research. With adequate statistical procedures, wider analyses of the tested hypotheses will be possible, and the research inferential robustness will increase. Finally, further research should consider the implementation of analyses based on non-linear approaches or artificial intelligence techniques.

Conclusions

The results of the current study provide evidence of an important correlation between specific variables of CMJ and swimming kick-start. In line with our expectations, the 15-m start time chosen for the swimming start performance description was recognized as highly correlated with the dry-land CMJ test. Moreover, a high correlation between take-off horizontal velocity, flight distance, or the 5–10-m time and many distinctive parameters of CMJ confirmed the significance of lower limb motor abilities while starting the block phase. Regression analyses offered the model equations providing the premises to predict individual starting performance on the basis of the CMJ test results. We justified the utility of composed equations allowing quantification of the potential transfer of motor abilities registered in the CMJ test to kick-start performance. Finally, we determined normative kinetic and kinematics reference values for CMJ, supplemented by kick-start kinematics among high-level male swimmers.

Therefore, an optimal combination of training focused on swimmers' strength and power improvement with starting technical proficiency is necessary to reach athletes' full potential. Indeed, ventral start does not depend solely on strength or power abilities. Moreover, it exhibits more complicated motor patterns than the CMJ test, which stands as a measure of lower-body explosive abilities. Yet, a verification of mutual dependences between the principles of movement patterns and motor abilities becomes a valuable step for the understanding of the swimming start improvement process and its control.

The obtained results illustrate the validity of CMJ as a simple, valuable, and reliable testing method to assess the potential ventral starting motor abilities. Besides, the proposed solution that predicts starting performance indicators on the basis of the CMJ force-time curve shape allows a wide view and detailed interpretation of principles that play a crucial role in the enhancement of swimming start performance.

Moreover, by further exploring the issue of the ventral start performance determinants, we hope to provide insights for swimmers and their coaching staff into conscious and reliable monitoring, assessment, and improvement of starting performance. As we speculated, a swimmer who does not reach the predicted parameters values could attribute it to the quality of their starting technique. Consequently, the outcome could be interpreted toward a display of the starting motor abilities potential and its exposure to the improvement of the training process. Synthesizing, the prediction of starting performance on the basis of dry-land test results (causing fewer difficulties and offering alternative assessment options) offers a simple yet valuable tool to indirectly assess the actual motor potential of the swimmer to perform the swimming start, as well as a useful monitoring technique that seems to be a solution targeted to practitioners.

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CHAPTER VII

GENERAL DISSCUSION

GENERAL DISCUSSION

Over the years, researchers have been interested in swimming start analyses allowing them to better understand its mechanisms and provide insights for performance excellence (Blanco et al., 2017; Thing et al., 2019; Vantorre et al., 2014). One of the pioneer studies on the topic was conducted by Heusner (1959). Throughout all time passed out, the swimming start technique has been changing within a close relationship with technologies available to support its analyses (Vantorre et al., 2014). Therefore, each newly proposed starting position led to fresh inquiries and, consequently, was favorably examined by researchers. Indeed, the importance of distinguishing swimming performance determinants and their key factors has been displayed by many researchers. Moreover, one of the latest significant Fédération Internationale de Natation (FINA) rule changes, concerning authorization of the new construction of starting block (Omega OSB 11), put into practice a back plate exploited during ventral starts (Vantorre et al., 2014). The added advantages arising from the back plate resulted in a situation when most of the scientific studies in kick-start may not be relevant to what is currently favored by competitive swimmers and their coaches. Consequently, updating the existing findings on the basis of the limitations exposed through the critical review of previous academic achievements has become advisable (Chapter I). That emphasizes a rationale of the general purpose of this thesis to actualize the current knowledge concerning ventral start characteristics and reevaluate the role of its determining factors, in order to provide up-to-date starting scenarios, based on the results of various representative groups of swimmers.

The main findings of this thesis pointed out that: (i) in comparison with kick-start backward, grab-start and handle-start, the kick-start forward is characterized by the shortest block time, which has been shown to be enough to maintain the shortest time until the 15-m distance; (ii) the kick-start forward demonstrated a temporal advantage in a group of international level female junior swimmers as well as male national level swimmers; (iii) depending on the starting position, a different strategy regarding movement structure has to be addressed with reference to overall start time performance enhancement; (iv) regardless of the back plate adjustment, swimmers tend to spend a similar time on the starting block, but at the same time, a significant back plate position effect was observed for lower limb movement characteristics measured as duration of rear foot take-off and front foot stand; (v) male swimmers need less time to cover the 15-m distance when they employ preferred back plate position in comparison with excess backward back plate position; (vi) spatiotemporal parameters of the swimming start, the relationships between them, as well as the overall starting performance differ significantly between genders; (vii) male international level swimmers, by spending less time in the block phase, reaching a higher take-off velocity, extending flight distance, and swimming faster in the water phase, take a starting advantage over their female counterparts; (ix) the countermovement jump (CMJ) test results are significantly correlated with the overall kick-start performance, as well as variables of the start that particularly rely on the movements performed by the lower limbs; (xi) the CMJ test can be used as a simple, valuable, and reliable testing method to assess the potential of lower body motor abilities toward the prediction of ventral swimming start performance.

As already mentioned above, over the years, the knowledge about the spatiotemporal structure and performance in ventral swimming starts has attracted researchers' attention. Yet, following the conclusion of Chapter I, the available findings concerning what is currently favored by the swimming community, as well as its expected future directions, seem to be ambiguous (Blanco et al., 2017; Rudnik et al., 2021; Vantorre et al., 2014). It is widely known that the block phase characteristics are highly dependent on the starting position (Honda et al., 2010; Issurin and Vertebsky, 2003; Kibele et al., 2014, 2015; Takeda and Nomura, 2006; Takeda et al., 2012; Taladriz et al., 2015; Vilas-Boas et al., 2003; Welcher et al., 2008). Despite this, as far as our knowledge goes, there are no available studies that sought to directly compare grab-start with handle-start and the two variants of kick-start. Therefore, to better understand the performance of ventral swimming starts, the analyses included in Chapter II comprised a wide comparison of those starting techniques. In our study, the instantaneous horizontal velocity at 5-m was one of the most important factors for shortening the total (15-m) start time. Furthermore, our results exposed the temporal advantage of kick-start forward over the 5-m and 15-m time parameters. Yet, the time gaps between different starting techniques progressively decreased with increasing the reference distance. Finally, such an experiment helped to clarify the starting techniques with staggered foot position on the block as being advantageous than those including parallel foot position. Issurin and Vertebsky (2003), Taladriz et al. (2015) and Welcher et al. (2008) also referred the superiority of asymmetrical positions. Besides, in line with our findings, most of the studies reported longer block time while the grab-start was used (Benjanuvatra et al., 2004; Fisher and Kibele, 2016; Peterson et al., 2018; Takeda and Nomura, 2006; Taladriz et al., 2015; Vantorre et al., 2010). A significant extension of movement time, as a consequence of side handles usage, presented by Vint et al. (2009), was further supported in the current study. Interestingly, the results obtained did not confirm previous findings concerning the overall temporal advantage of the handle-start (Blanksby et al., 2002; Vint et al., 2009). In Chapter II, it was shown that kick-start forward incorporated shorter block phase duration and reduced total start time in comparison with its backward variant, which provided additional support for the discussed findings. Here, also a number of studies presenting a slightly shorter 5-m start time for the forward variant while staggered foot positions further supported the current findings (Honda et al., 2012; Kibele et al., 2015; Welcher et al., 2008). Profile of force production over the starting block specified for a given technique, as well as lower limbs role in velocity achievement of the swimmers, have been widely demonstrated by other authors (Benjanuvatra et al., 2004; Breed and Young, 2003; De la Fuente et al., 2003; Ikeda et al., 2016; Sakai et al., 2016; Slawson et al., 2013; Takeda et al., 2017). These observations partially agree with the previously stated conclusion that in order to optimize take-off features, a compromise between the possibly highest impulse generated on the starting block or take-off velocity and reduction of push-off time is needed

(Tanaka et al., 2016; Vilas-Boas et al., 2003; Welcher et al., 2008). Yet, the high contribution of the water phase to the 15 m start time has been widely emphasized by other researchers (Cossor and Mason, 2001; Peterson et al., 2018; Tor et al., 2014, 2015; Vilas-Boas et al., 2000, 2003). Therefore, different strategies concerning specific elements of the movement structure have to be considered and their interdependence has to be cautiously evaluated with regard to each specific case. Considering that the race time is the only event performance indicator, the kick-start forward seems to be the most advantageous starting technique.

The results presented in Chapter II show that owing to the implementation of the asymmetrical position, male national level swimmers took advantage of a shorter block time and a lower decrease of velocity between the take-off and the 5-m mark, what in consequence ensures reduced start times measured at 5-m and 15-m marks. Yet, it was noted in Chapter I that there was no consensus among researchers about which body position variant during an asymmetrical stance is more beneficial (Barlow et al., 2014; Honda et al., 2012; Kibele et al., 2014, 2015; Peterson et al., 2018; Vilas-Boas et al., 2000; Welcher et al., 2008). Here, the starting strategies undertaken by swimmers presenting different genders (Chapter V) or sport proficiency (Benjanuvatra et al., 2007; Rudnik, 2017; Veiga et al., 2016) were different. Thus, the assessment of the kick-start technique and its key parameters included in Chapter II was reinterpreted and validated for a group of swimmers presenting higher sport level and different genders. To better understand the presented issue and validate goals pursued for larger samples, in Chapter III we critically examined the knowledge about swimmers' initial position effect on the spatiotemporal structure of the kick-start in two variants: with a backward and with a forward displacement of swimmer's center of mass. The analyses showed that, with a shorter center of mass distance covered during the block phase, the kick-start forward ensured a reduction of block time. That temporal advantage also led to the shorter total (15-m) start time. However, it has been confirmed that the time determined over the 15-m distance as the main measure of swimming start performance is a rather weak predictor of the consequences of the initial (forward or backward) body displacement. The extended block time, characteristic of the backward variant, followed our previous assumptions based on conclusions from Chapter II, and further supported the findings of the studies incorporating track-start or kick-start trials (Blanksby et al., 2002; Honda et al., 2012; Vilas-Boas et al., 2000; Welcher et al., 2008). On the other hand, a longer block time in the kick-start backward allows to obtain high take-off velocity (Dragunas et al., 2014; Honda et al., 2012; Tanaka et al., 2016; Vilas-Boas et al., 2000, 2003; Welcher et al., 2008) which can be maintained during the water phase (Honda et al., 2012). Furthermore, in line with our data, Barlow et al. (2014) showed that the main differences between the kick-start variants were mostly observed in the block phase. Yet, according to those authors, its variability seems to decrease in the subsequent phases of the start, with an almost equal horizontal velocity for both start variants. Indeed, most researchers aiming to resolve similar issues focused rather on indicators describing shorter distances (Bingul et al., 2015; Honda et al., 2012; Peterson et al., 2018; Vilas-Boas et al., 2000; Welcher et al., 2008). Therefore, to improve the starting performance optimization process with regard to the starting position effect, different expectations, mainly toward block phase duration and take-off velocity, have to be addressed and necessary compromises between those priority areas of the start have to be considered. In this context, coaches must make conscious decisions with the consideration of the individual characteristics of each swimmer and support them with objective measures. Considering, the results obtained in chapters II and III indicated that the kick-start forward most probably offers a temporal advantage independently of the proficiency level.

It has been extensively emphasized that the back plate usage provides significant advantages for swimmers (Beretić et al., 2012; Garcia-Hermoso et al., 2013; Honda et al., 2010; Nomura et al., 2010; Ozeki et al., 2012). Furthermore, the inclined support can be adjusted in different positions, offering swimmers a wide range of possible initial body positions on the starting block. Besides, while the back plate was in use, slightly greater differences in the block phase characteristics were noted between male and female swimmers (Garcia-Hermoso et al., 2013). As presented in Chapter I, there is a need for studies that would search for back plate position effect, as the small sample sizes and the lack of gender differences shown in the available literature, could undermine the diagnostic value of the existing research. Therefore, the aim undertaken in Chapter IV was to analyze the back plate position effect on the temporal structure of the kick-start, also with regard to the swimmers' gender. The effect of swimmers' preferences in back plate positioning was also taken into consideration.

The symptoms of adaptation to the changed back plate position that occurred in swimmers' movement patterns were depicted in some significant differences in the temporal structure of the block sub-phases, but they did not influence the total duration of the block phase. A more backward back plate position ensured a shortening of the rear-foot take-off time and, consequently, an extension of the front foot stand. Here, both genders responded similarly to the change in the block configuration. Only in male athletes a lower total start time was measured for the preferred position in comparison with its backward variant. Similarly, in most of the available studies, no back plate position effect was noted for the block time duration (Cicenia et al., 2019; Honda et al., 2012; Slawson et al., 2011). Furthermore, the presented differences in feet contact time with the starting block (Takeda et al., 2012) and the effect of back plate position on lower limb joint angles (Cicenia et al., 2020), together with the fact that each lower limb is represented by different profiles of force production (Ikeda et al., 2016; Sakai et al., 2016; Slawson et al., 2013) and, consequently, the velocity developed (Ozeki et al., 2017; Takeda et al., 2017), imply that the ability to generate force and its direction (Bobbert et al., 2008; Gheller et al., 2015) should be affected not only by the gender of the swimmer (Jesus et al., 2011; Slawson et al., 2013), but also by the back plate position (Takeda et al., 2012). While searching for optimal conditions, scientists tended to perform multi-condition analyses including numerous variants of initial body position (Honda et al., 2010; Kibele et al., 2014; Takeda et al., 2012). Unfortunately, in most circumstances, no lasting advantages after the swimmer's leaving the block were confirmed. Here, no back plate positioning effect was noted for the total start time in the existing studies (Cicenia et al., 2019, 2020; Honda et al., 2012). The findings presented in Chapter IV allow suggesting a temporal advantage of the preferential back plate position for the overall ventral start performance in male swimmers. Furthermore, as more significant differences were noted for male participants, the various adjustments of back plate position might probably affect males more than females. The exposure of strengths and weaknesses of changes in the back plate positioning variants could provide useful knowledge, which should lead coaches and swimmers in the starting optimization process by exceeding athletes' performance.

It has been suggested that gender distinctions in physiology may affect the swimming performance of each gender differently (Senefeld et al., 2019). Interestingly, in swimming start research, male and female swimmers were usually merged in the samples (Barlow et al., 2014; Benjanuvatra et al., 2004; Carvalho et al., 2017; Galbraith et al., 2008; Honda et al., 2012; Ikeda et al., 2016; Lee et al., 2001). Therefore, the findings presented in Chapter I reinforced the need for a methodological update of analyses that include both genders' groups, treating them differently. Consequently, an exploration of the differences between male and female swimmers in the variation of the spatiotemporal parameters of the kick-start was the objective of the research described in Chapter V. Furthermore, the effect of gender heterogeneity was investigated with the consideration of the crucial parameters of swimming start performance. The obtained findings supported the existence of gender effect, not only for the total start time, but also for the specific variables commonly used to evaluate swimming start performance. Indeed, for male swimmers, shorter block time, higher take-off velocity, longer flight distance, and faster swimming while in the water were noticed, what resulted in overall starting advantage over their female counterparts. It was also observed that, depending on the athlete's gender, different variables have to be employed as key factors determining swimming start performance. A shorter start time in male than in female swimmers has been confirmed in several studies conducted not only in competition settings (Garcia-Hermoso et al., 2013; Jesus et al., 2011; Morais et al., 2019; Thanopoulos et al., 2012), but also in experimental conditions (Tor et al., 2014). There is evidence that, during starts, male and female swimmers undertake different movement patterns to perform similar tasks (Fischer and Kibele, 2014). The differences might also refer to how velocity is developed (Tor et al., 2014), or how much time is needed to effectively push off from the starting block (Garcia-Hermoso et al., 2013; Tor et al., 2014). Those findings are further supported by the statements that. in general, male swimmers take advantage of their comparatively higher strength and power abilities (Miyashita et al., 1992; West et al., 2011). In Chapter IV, it was observed that the effect of changes in the back plate position was more evident in the male group of swimmers. Consequently, gender heterogeneity effect should be included not only in the detailed characteristics of different variables but also in other approaches undertaken in swimming start analyses.

The kick-start, being a consequence of the new starting block implementation, has been employed by most competitive swimmers. Besides, it has been revealed as the most advantageous technique with reference to starting performance (Chapter II). Therefore, the majority of previously published studies seeking for a relationship between starting performance and athletes' strength and power abilities have to be verified on the basis of up-to-date starting features. Here, as specifications attributed to the water environment result in some constraints, authors have often searched for solutions by implementing standardized dry-land tests (Thng et al., 2019). The investigation reported in Chapter VI was therefore to determine the relationship between selected variables characterizing the CMJ structure and key biomechanical parameters used to assess the kick-start performance in high-level swimmers. The analyses demonstrated that CMJ could be used as a reliable testing method to evaluate the potential motor abilities of ventral starting. It was, thus, shown as a valid tool for swimming start prediction. Besides, such CMJ test measures as peak and mean force, impulse, jump height, peak and mean power in the concentric phase, the rate of power development, the ratio between the flight time and the contraction time, and peak velocity were related with the swimming start variables that particularly rely on the movements performed by the lower limbs (take-off velocity, flight distance and 5-10 m time). Moreover, the absolute power and force measured during CMJ tended to exhibit a higher correlation with the start water phase than their equivalent relative to bodyweight. Indeed, the parameters measured during land-based tests correlated not only with key performance factors of the take-off from the starting block (Carvalho et al., 2017; Cossor et al., 2011; West et al., 2011), or with variables of the flight phase (Breed and Young, 2003; Seifert et al., 2010) and also with actions undertaken by swimmers in the water phase of the start (Morouço et al., 2011). Congruously, previous studies reported that the better performance of the dry-land test, the shorter the start time registered (Benjanuvatra et al., 2007; Carvalho et al., 2017; Garcia-Ramos et al., 2016a, 2016b; Keiner et al., 2015; West et al., 2011). Indeed, it has been observed that dry-land tests could be successfully used to predict starting performance as an alternative to pool-based tests (Beretić et al., 2013; Carvalho et al., 2017; Cossor et al., 2011). This also corroborates studies including a training intervention where dry-land training programs based on the muscular force and explosive power development were demonstrated to significantly enhance swimming start performance (Bishop et al., 2009; Breed and Young, 2003; Rebutini et al., 2016; Rejman et al., 2017; Thng et al., 2019). Those independent statements seem to support the interpretation of our results. In the light of the observed outcomes, those findings serve to create objective criteria for performance prediction in a ventral start based on CMJ test results. Furthermore, the conclusions have delivered relevant information for performance monitoring, providing solid indications to be implemented by coaching staff during training routines.

Numerous researchers are interested in examining the key factors that contribute to starting performance by using statistical modeling methods (Beretić et al., 2013; Carvalho et al., 2017; Cossor et al., 2011; de Jesus et al., 2018; Nguyen et al., 2014; Peterson et al., 2018; Tor et al., 2015). Here, a challenge for scientists is to align the obtained insights with swimmers' and coaches' needs. The target is to bridge the gap between research and practice in sport and produce practical and usable tools providing information about athletes' performance enhancement. The presented approach should upgrade coaches' knowledge and support their attempts to better understand starting mechanisms, further allowing for more conscious solutions undertaken in individualized pathways to improve starting performance. Searching for the understanding of how swimmers' motor abilities, or the initial body position and its consequences, affect the starting performance, correlation analyses and multiple regression analyses were applied in the current thesis. In general, the aim here was to expose swimming start determining factors among variables used to evaluate the spatiotemporal structure of ventral start (Chapters II, III, and V) and measurements taken in the land-based CMJ test (Chapter VI). The conducted analyses revealed a group of variables that had to be selected deliberately to monitor the swimming start performance of the chosen starting technique. Furthermore, to adequately control the swimming start performance and provide insights into its key factors, multiple regression models were applied and validated (the comparison of the values computed with the data estimated directly from the experimental trials and the existing formulas). For each starting position researched in Chapter II, separate regression models predicting 5-m and 15-m start times were successfully revealed, explaining 83–99% of the variability of the response data around the means. From the variables included in the equations, the reaction time, take-off velocities, flight distance, entry angle and water time were included in at least two of the equations obtained. Variables describing the initial position, take-off spatiotemporal characteristics and flight distance were some of the ones included in most of the equations describing 5-m and 15-m start times measured for both kick-start variants (forward and backward) researched in Chapter III. Peterson et al. (2018) composed separate regression models for the prediction of 5-m time in different breaststroke starts, while Tor et al. (2015) focused more on distinguishing equations based on variables belonging to the specified phases of the swimming start. As stated by Peterson et al. (2018), the starting position is more likely to determine start indicators measured over a 5-m distance. The reasoning arose from the fact that elongation of the analyzed distance up to 15-m would include more variables that were less related to the initial starting technique itself or its direct consequences (Barlow et al., 2014; Garcia-Ramos et al., 2015; Tor et al., 2015; Vilas-Boas et al., 2000). Therefore, while 15-m start time measurements reveal more impact from the water phase, the water phase can account for more than 80% of the 15-m start time (Slawson et al., 2013; Tor et al., 2015). By examining the link between various individual contributing variables, we disclosed the predicting variables constituting key factors in swimming start performance assessment and development.

In Chapter VI, CMJ parameters were shown as linked with start elements that take the contribution of lower body motor abilities as muscular strength and power. From the measured variables, equations composed of CMJ variables (mainly positive impulse, mean force normalized, total CMJ impulse, flight time, velocity at peak power and maximum velocity) were presented. Therefore, the models describing not only the total (15-m) start time, but also some start variables that take in considerations the contribution of lower body motor abilities were obtained. Those variables were revealed as key start performance indicators in the existing literature (Blanco et al., 2017; Thing et al., 2019; Vantorre et al., 2014) and in Chapters II, III, and V as priority areas toward shortening the total start time and highly involving the lower body. Carvalho et al. (2017) presented a regression equation explaining the 15-m start time on the basis of height and peak vertical force measured for CMJ. Also, Beretić et al. (2013) used multiple-regression analysis to successfully compose an equation predicting the 10-m start time from variables collected in a test of the standing leg extensor isometric muscle force test. Cossor et al. (2011) mentioned that dry-land tests could be successfully used to assess starting performance as an alternative to pool-based tests. Furthermore, the association between CMJ relative peak power and take-off velocity and both 5-m or 10-m start times was presented by Garcia-Ramos et al. (2016a). Also a strong inverse relationship between CMJ height and the 15-m start time was reported by Keiner et al. (2015). Finally, the land-based training programs focusing on explosive power development have been proven to significantly affect swimming start performance enhancement (Bishop et al., 2009; Breed and Young, 2003; Rebutini et al., 2016; Rejman et al., 2017; Thng et al., 2019). These independent statements seem to constitute objective support for the interpretation of our results. Therefore, equations allowing to predict overall, as well as given swimming start variables on the basis of the athlete's motor potential, provide direct objective feedback bringing attention toward specific necessities.

Generally, it should be recommended that, depending on the starting distance measured or starting technique implemented, different expectations for the commonly used variables have to be addressed (Peterson et al., 2018; Thing et al., 2019; Tor et al., 2015). In this way, the priority areas can be exposed and recommendations for wider assessment delivered. From among diverse commonly used parameters, the short block time, great jumping power, high take-off velocity, great fly distance, low resistance during the gliding phase and powerful underwater kicking were revealed as the ones relevant for start performance enhancement (Arellano et al., 2000, 2005; Maglischo, 1993; Mason and Mackintosh, 2020; Slawson et al., 2013; Tor et al., 2014). Furthermore, as a change in one parameter would affect another and, consequently, for the complete swimmers' actions, some compromises in the expectations of the results of the start have to be taken into consideration (Vantorre et al., 2014). Indeed, swimming start mechanics seems to be multifunctional in their nature (West et al., 2011) and each element has to be cautiously analyzed and depicted with reference to the potential of a given swimmer. What is more, prediction models could also constitute an invaluable tool to examine the current and cumulative effects of technical or motor training targeted toward swimming start improvement.

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CHAPTER VIII

CONCLUSIONS, PRACTICAL APPLICATIONS, AND FUTURE RESEARCH DIRECTIONS

GENERAL CONCLUSIONS

This final chapter summarizes what has been revealed throughout the dissertation. The main goal of the investigations included in the thesis was to upgrade knowledge about ventral swimming start and to search for the potential of its future enhancement. Furthermore, the overall purpose of this thesis was to describe, examine, and objectively explain the swimmer's motor behavior when starting in regard to various conditions. Besides the cognitive aim was to provide comprehensive knowledge and tools for monitoring the swimmers' motor and technical training in the ventral swimming starts. The effort in responding to the assumed purposes was provided in the previous chapters. Based on the outcomes revealed in each of the above-mentioned studies, as the response on the specific objectives stated, it is pertinent to outline the following major conclusions.

Chapter II The spatiotemporal structure and performance in ventral swimming starts

- The different limb combinations used at the initial position exposed biomechanical advantages when swimmers placed their feet in a staggered position.
- Start time measured at 5-m and 15-m demonstrated the superiority of kick-start forward over kick-start backward, followed by handle-start and grab-start.
- Despite the start technique used, a compromise between the block phase duration and the magnitude of velocity is crucial for a successful start.
- For each starting feature, specific crucial areas have to be measured in accordance with the multiple regression models implemented.

Chapter III Backward or forward kick-start: which variant of the initial position ensures better starting performance?

- In comparison with kick-start backward, kick-start forward is characterized by shorter block time, which was shown to be sufficient to consequently enable kick-start forward to maintain time dominance until the total (15-m) start distance.
- Depending on the kick-start variant used, different expectations concerning the specific elements of movement structure have to be considered.
- The kick-start forward probably offers a temporal advantage, independently of the technique level, provided that the technique constitutes a motor habit.

Chapter IV Does back plate position influence the temporal characteristics of the swimming start?

- A more backward back plate position ensures a shortening of the rear foot push-off time and, consequently, an extension of the front foot stand.
- Comparing the backward variant of back plate positioning with its preferred placement, the superiority of the preferential back plate position for male swimmers was exposed.
- It seems that the various adjustments of back plate position might affect males more than females.

Chapter V Kinematic profile of ventral swimming start: gender effect

- The spatiotemporal parameters of the swimming start, the relationships between them, as well as the overall starting performance, differ between genders.

- Male swimmers, by spending less time in the block phase, reaching higher take-off velocity, jumping further over the water, and swimming faster while in the water, take a starting advantage over their female counterparts.
- It is important to differentiate the parameters employed to evaluate the swimming start performance considering the athlete's gender.

Chapter VI Countermovement jump test as a tool for ventral swimming start performance prediction

- The total 15-m start time, chosen as the main swimming start performance indicator, was recognized as highly correlated with the dry-land CMJ test results.
- The high correlation revealed between take-off horizontal velocity, flight distance, time measured between 5-m and 10-m marks during ventral swimming start and many distinctive parameters of CMJ confirms the significance of lower limb motor abilities while starting.
- The equations allowing quantification of the potential transfer of motor abilities registered in the CMJ test to kick-start performance can be successfully applied for prediction purposes.
- The solution that predicts starting performance indicators on the basis of the variables derived from the CMJ force-time curve shape allows a wide view and detailed interpretation of principles that play a crucial role in the enhancement of swimming start performance.

PRACTICAL APPLICATIONS

Time that swimmers spend starting depends on many factors (swimmers' capacities and abilities, starting conditions, and starting technique etc.). Nevertheless, it seems to be worth to emphasise that, a simple change in positioning swimmer’s centre of mass toward the front direction could offer a substantial change in the race time - the only benchmark of event performance. Therefore, swimmers should search their reserves in starting performance in the more advantageous forward variant of the kick-start than in other starting position alternatives. Additionally, as extensive practice can improve starting performance thus, it has to be emphasized that the dedicated technical training should be included for daily practice. Yet still, different strategies concerning specific elements of the movement structure have to be considered, and their interdependence has to be cautiously evaluated with regard to the specific case.

The large amount from considered parameters: the short block time, great jumping power, high take-off velocity, great fly distance, were commonly revealed as the most relevant parameters for start performance enhancement. The predicting models’ variables disclosed on their basis were used to constitute the key factors in swimming start performance assessment. Those tools might be directly implemented for starts techniques monitoring and provide improvement of the performance evaluation process.

To improve the starting performance optimization with regard to the starting position effect, different expectations mainly toward block phase duration and take-off velocity have to be addressed, and necessary compromises between those priority areas of the start have to be considered. In this context, coaches must make conscious decisions with the consideration of the individual characteristics of each swimmer and support them with reliable, adequate measures.

The exposure of strengths and weaknesses of changes in the back plate positioning variants provide utility knowledge, which should lead coaches and swimmers to the starting optimization for performance exceeding. Here, the findings presented suggest the temporal advantage of the preferential back plate position for the overall ventral start performance in male swimmers. It was also observed that the effect of changes in the back plate position was more evident in the male group of swimmers. Thus, the requirement of gender heterogeneity should be considered not only in the detailed characteristics of separate parameters, but also in the approaches undertaken in swimming start analyses. Moreover, coaches should be aware that the various adjustments of back plate position might probably affect more males than their female counterparts.

It has been shown that numerous independent statements seem to support the observed outcomes confirming the link between results of land based CMJ test and biomechanical structure of swimming start as well as its total start time. Those findings serve to create objective criteria for performance prediction in a ventral start based on CMJ test results. Furthermore, the correlation analyses and regression models presented have delivered relevant information for performance monitoring, providing solid indications to be implemented by coaching staff during training routines. Here the attention was brought for key parameters of the CMJ which could be measured by coaches and swimmers with easily accessible devices. What is more, prediction models could also constitute an invaluable tool to examine the current and cumulative effects of technical or motor training targeted toward swimming start improvement.

FUTURE RESEACH DIRECTIONS

Future studies should take into consideration longitudinal data collection performed toward monitoring the effect of implementation the results obtained. A longer process of “detailed elements of the starting techniques improvement” learning should be therefore also recommended before the next stage of research. That way the preferential effect might be reduced, and the level of motor behaviour adjustment done by swimmers to the provided starting features should be much more comparable. It might allow for deeper understanding about factors affecting structure and performance of the swimming start.

Depending on the gender of the swimmer, starting technique, or distance and stroke of competitive swimming even, different expectations toward commonly used key performance indicators and its determinants have to be addressed. Therefore, obtained results should be further confirmed in a procedures engaging swimmers representing different levels of swimming proficiency. Furthermore, to provide wider view on the evaluation issues, the data have to be collected in various conditions considering for example different stages of training process. Additionally, there are some fields which have not been evaluated extensively, as for example the impact of the swimmers' anthropometrics profile on their motor behaviour on the initial, block, take-off, flight and glide phases of the start. That way, by including more factors that might potentially expand knowledge in swimming start, a more holistic approach in this element of swimming race might be provided.

Generally, much larger samples (e.g., retrospective trials) should be expected, enabling to employ parametric statistical procedures that would allow for more valuable analyses of the tested hypotheses and increase the research inferential robustness in terms of achieving statistical significance. Finally, the data obtained from many athletes performed their starting in various conditions, would make an opportunity for implementation of analyses based on non-linear approaches or artificial intelligence techniques.