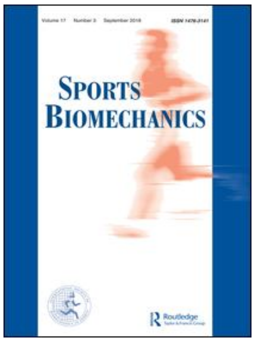

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Key performance indicators and leg positioning for the kick-start in competitive swimmers

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ABSTRACT
The aim of the study was to (1) assess the test–retest reliability of a novel performance analysis system for swimming (KiSwim) including an instrumented starting block and optical motion capture system, (2) identify key performance indicators (KPI) for the kick-start, (3) determine the most beneficial position of the strong leg and (4) investigate the effect of acute reversal of leg positioning. During three sessions, kick-starts of 15 competitive swimmers were investigated. Eighteen kinematic and kinetic parameters showed high reliability (ICC>0.75) from which principal component analysis identified seven KPI (i.e., time to 15 m, time on-block, depth at 7.5 m, horizontal take-off velocity, horizontal impulse back plate, horizontal peak force back plate and vertical peak force front plate). For the preferred start position, the back plate showed a higher horizontal peak force (0.71 vs. 0.96 x body mass; $p < 0.001$) and impulse (0.191 vs. 0.28Ns/BW; $p < 0.001$) compared to front plate. Acute reversal of the leg position reduced performance (i.e., increased time to 15 m and reduced horizontal take-off velocity). However, plate-specific kinetic analysis revealed a larger horizontal peak force ($p < 0.001$) and impulse ($p < 0.001$) for the back compared to the front plate in any start position investigated. Therefore, swimmers are encouraged to position the strong leg in the back.

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Force plate; reliability; swimming; start position; freestyle

Introduction

Very close race outcomes have been seen in the last international swimming events. For instance, during the 2016 Rio Olympic games the men's 50 m freestyle gold medal was won by on a-hundredths of a second only and in the 100 m freestyle final, five-hundredths of a second separated the silver and bronze medal winner. With the marginal differences that distinguish the performance of world-class athletes, the start has gained increasing interest among coaches and scientists. The time to complete the first 15 m of the event, defined as start performance, significantly contributed to the

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final race time and accounted for 11.96 ± 0.26% of 100 m freestyle events (Morais et al., 2019).

Rule changes by the governing swimming federation (Fédération International de Natation, FINA) and the introduction of new technologies have further driven the interest in biomechanical analysis of the swim start (Vantorre et al., 2014). The Omega OSB11 starting block with the adjustable rear foot support, for instance, has introduced the so-called kick-start (Takeda et al., 2017). Compared to the traditional grab-start, which involves the foot and hand placement aligned with the front edge of the block, the kick-start reduced the on-block time, increased the take-off horizontal velocity and the start performance, i.e., time to 5 m and 7.5 m (Biel et al., 2010; Taladriz, 2017). The different functional roles of the front and rear leg in the kick-start derive from the inclined footplate which changes the lever arm and position of the rear leg (Slawson et al., 2013; Takeda et al., 2017). Especially, during the early on-block phase the increased horizontal impulse from the rear leg contributes to the take-off horizontal velocity (Takeda et al., 2017), which has been reported to account for 81% of the variance in start performance during the overwater phase (Tor et al., 2015a). The front leg on the other hand showed the larger vertical impulse contributing to the take-off vertical velocity and adjustment of the take-off angle (Takeda et al., 2017).

Laterality effects have been analysed for the track-start, which also is characterised by the step-like and asymmetric leg positioning similar to the kick-start. Hardt et al. (2009) analysed the track-start performance in 22 competitive age group swimmers and demonstrated that the subjectively preferred compared to the non-preferred leg position led to a shorter 5 m start time. However, footedness, the positioning of the strong leg in the front or the back, was not related to performance (Hardt et al., 2009). The track-start, however, usually is performed on older starting blocks without inclined rear foot support of the Omega OSB11. The missing rear foot support limits the implication of these findings for the modern kick-start and raises the question whether the strong leg should be positioned in the front or back. The rear leg involves the larger horizontal force production during the initial phase of the kick-start (Takeda et al., 2017) while the front leg involves the longer time-under-tension contributing thrust when the rear leg already lost contact to the block in the later on-block phase.

Since there is little evidence on the optimal leg positioning during the kick-start (Ikeda et al., 2016; Takeda et al., 2017), coaches and athletes choose the leg positioning based on subjective preferences and experience rather than objective data. Biomechanical factors underlying the lateralised performance advantage of the leg positioning were not identified so far and science-based start-training guidelines are missing. Recently, a novel Performance Analysis System for Swimming (KiSwim) has been introduced and is commercially available since the year 2015. The KiSwim involves a starting block that is equipped with force plates to measure front leg, rear leg and grab forces. The force plates are synchronised to an optical motion capture system and therefore allows insights into the kinematics and kinetics of the over- and underwater phase of the swim start.

Therefore, the aim of the study was twofold: firstly, to investigate the reliability of the KiSwim with its kinematic and kinetic parameters and to identify the Key Performance Indicators (KPI) for the kick-start using a Principal component analysis (PCA); secondly, to determine whether the most beneficial position of the strong leg is in the front or at the back of the starting block and investigate the effect of an acute reversal of the leg positioning (preferential vs. non-preferential). We hypothesised that fastest starts are achieved with the strong leg in the back of the block. Also, an acute reversal of leg positioning will compromise start performance with the non-preferential leg positioning.

Methods

Participants

Fifteen competitive swimmers (13 males, 2 females, age 20 ± 3 yrs., height 1.85 ± 0.09 m, body mass 74 ± 11 kg) of the National Swimming Training Base (SWTB) participated in the study. The participant characteristics are given in Table 1. FINA points from freestyle events were used to quantify the participant's competitive level. The methodology and test protocol of underlying study were approved by the ethical committee of the ETH Zurich. All participants gave their written informed consent to participate after being informed about the risks and benefits of the study involved.

Table 1. Participant characteristics.

No.	Gender	Age [y]	Height [cm]	Mass [kg]	Best Race [FINA points]	Strong Leg Positioning	CM Positioning
01	M	17.4	185	68.0	808	Front	FW
02	M	20.5	182	74.0	647	Back	FW
03	M	24.9	198	91.0	727	Back	FW
04	M	21.1	188	73.0	801	Front	FW
05	M	19.5	189	77.3	748	Back	FW
06	M	17.5	181	75.0	582	Back	FW
07	M	17.1	186	63.0	723	Back	FW
08	M	18.6	182	68.0	621	Front	FW
09	M	17.0	187	70.5	557	Back	FW
10	M	17.3	189	75.0	739	Front	FW
11	F	16.5	169	54.0	695	Back	FW
12	M	26.3	199	97.0	957	Front	FW
13	M	21.1	195	86.0	768	Front	FW
14	F	19.4	170	56.5	793	Back	FW
15	M	23.0	186	85.0	827	Back	FW
Mean (SD)		19.8 (3.0)	185.7 (8.5)	74.2 (12.0)	733 (103)		
Mean Front (SD)		20.3 (3.4)	189.7 (6.3)	77.8 (11.5)	782 (109)		
Mean Back (SD)		19.5 (2.9)	183.1 (9.1)	71.8 (12.3)	700 (91)		

CM, Centre of mass; FW, Front weighted kick-start.

Procedures

Within a period of three consecutive weeks, three sprint start sessions were performed (Figure 1). During all sessions (#1, #2, and #3) the swimmers performed five freestyle kick-starts with their preferential leg positioning. Additionally, in Session#2 the participants performed five starts with their non-preferential leg positioning which involved the reversal of the front and rear leg. The order of the leg positioning (preferential vs. non-preferential) was randomised in Session#2. The test–retest

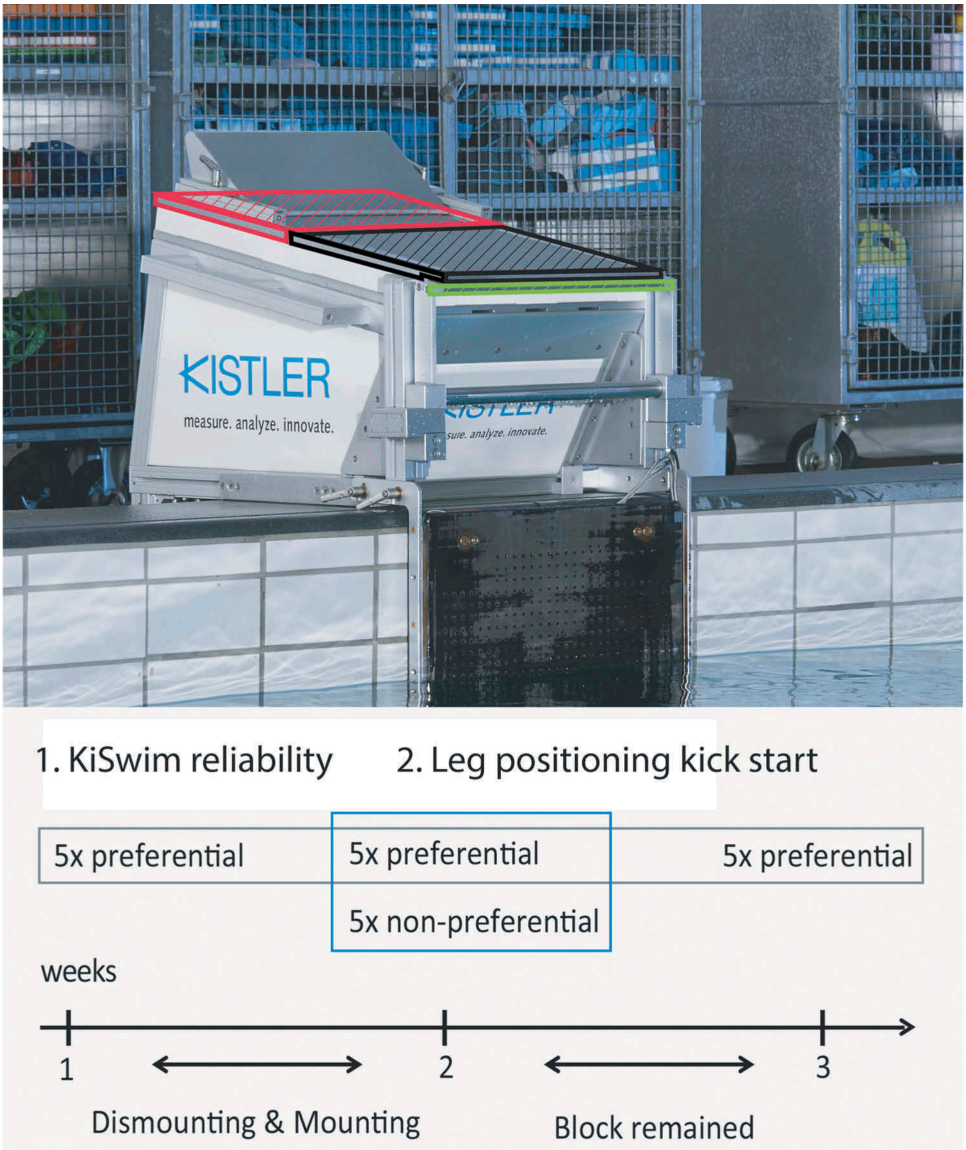

Figure 1. Instrumented starting block with the three force plates (front plate = black, back plate = red and grab bar = green), a detail view of the grab bar and front plate in use, and the study protocol. Three sessions within three consecutive weeks were used to perform the reliability and Principle component analysis of the KiSwim (Sessions#1, #2 and #3, grey). The leg positioning was assessed during Session#2 (blue).

reliability of the kinematic and kinetic data was assessed using the preferential leg positioning data of Session#1, #2, and #3. The performance differences between the preferential and non-preferential leg positioning were determined from Session#2 (Figure 1).

At the beginning of each session, the swimmers performed their standard pre-competition warm-up routine for 15 min. The kick-start trials were performed according to the official swimming regulations SW 4 (Fédération Internationale de Natation, 2017). Swimmers were advised to perform each trial with maximum effort and split times (5, 7.5, 10 and 15 m) were measured and kinematic data collected up to the 15 m mark. To minimise the effect of fatigue on start performance, participants recovered at least 5 min between trials. Apart from the leg positioning, no specific instructions were given to the swimmers with respect to body mass placement or arm movement to allow the most natural start technique. The rear vertical force in the pre-start position was used to assess the kick-start variation: <0.2 body weight is considered as a front-weighted kick-start; >0.2 and <0.5 as neutral-weighted, respectively, and >0.5 as rear-weighted. All participants utilised the kick-start as their routine start position in the competition. Between the three test sessions, athletes followed their routine start practice with about 20 sprint starts per week distributed among 9 training sessions.

Data collection

Kinetic and kinematic data during all kick-start trials were collected using the KiSwim (earlier called PAS-S, Type 9691A, Kistler Group, Winterthur, Switzerland) consisting of an instrumented starting block with three force plates synchronised to an optical motion capture system with four cameras (Prosilica GC660 C, Allied Vision Technologies, Stadtroda, Germany). The starting block was mounted at the third lane from the sidewall. To assure a stable position, the block was fixed with six screws to the concrete pool deck. The dimensions of the block were similar to the Omega OSB 11 with a 10° inclined platform (OSB11: 9°) and a rear foot support with an angle of 30° with respect to the platform (Murrell & Dragunas, 2012). The force plates were positioned to collect the front and rear foot forces separately. The third force plate collected the grab and upper limb pull forces from underneath the front plate. Both, the grab bar and the front foot force plate were separated by a small gap (2 mm) to distinguish arm pull and front foot force production in the best way possible. The underwater cameras were positioned at the 3 m, 10 m and 15 m marks. Additionally, an above-water camera was mounted at the 3 m mark. The cameras were positioned on the sidewall of the pool perpendicular to the swimming direction and collected the video footage at 100 frames per second.

The optical motion capture system was calibrated using a calibration pole with vertically arranged markings at −1.5 m, −1 m, −0.5 m, 0 m, 0.5 m, 1 m, 1.5 m from the water surface. The pole was moved alongside the test lane in one metre intervals from the wall up to the 17 m mark and the exact distance measured using a laser distance measure (Disto D2, Leica Geosystems Inc., Heerbrugg, Switzerland). A two-dimensional matrix was created for the kinematic analysis of the overwater and underwater phase by digitalising the seven markers on the calibration pole and adding the corresponding distance at each spot from the wall. The KiSwim was dismounted, reinstalled and calibrated between Session#1 and #2. A total of 41 kinematic and kinetic parameters (refer to Table 2) were directly available from the KiSwim or were calculated from the measured data using MATLAB (Mathworks Inc., USA). Full descriptions of each parameter are given in the supplementary material.

Table 2. Intra-class correlation coefficient (ICC) for all parameters that were directly available from the KiSwim or calculated using MATLAB*.

Parameter	Inter-Session		Intra-Session	
Peak power on-block	0.93	Excellent	0.94	Excellent
Total horizontal impulse*	0.93	Excellent	0.95	Excellent
Vertical peak force back plate*	0.93	Excellent	0.95	Excellent
Entry distance	0.92	Excellent	0.95	Excellent
Time to 7.5 m	0.91	Excellent	0.94	Excellent
Total horizontal peak force*	0.90	Excellent	0.91	Excellent
Time to 10 m	0.90	Excellent	0.96	Excellent
Horizontal peak force back plate*	0.89	Excellent	0.91	Excellent
Horizontal impulse front plate*	0.88	Excellent	0.90	Excellent
Time to 15 m	0.84	Excellent	0.94	Excellent
Horizontal impulse back plate*	0.82	Excellent	0.83	Excellent
Horizontal peak force front plate*	0.81	Excellent	0.82	Excellent
Time to 5 m	0.81	Excellent	0.88	Excellent
Vertical peak force grab bar*	0.80	Excellent	0.90	Excellent
Horizontal impulse grab bar*	0.80	Excellent	0.84	Excellent
Vertical peak force front plate*	0.79	Excellent	0.79	Excellent
Horizontal take-off velocity	0.78	Excellent	0.85	Excellent
Normalised peak power on-block	0.76	Excellent	0.78	Excellent
Depth at 7.5 m	0.74	Fair to good	0.81	Excellent
Depth at 10 m	0.73	Fair to good	0.83	Excellent
Time total horizontal peak force*	0.70	Fair to good	0.73	Fair to good
Time vertical peak force back plate*	0.69	Fair to good	0.72	Fair to good
Average acceleration on-block	0.69	Fair to good	0.78	Excellent
Breakout distance	0.68	Fair to good	0.81	Excellent
Time vertical peak force front plate*	0.66	Fair to good	0.67	Fair to good
Normalised Work on-block	0.65	Fair to good	0.67	Fair to good
Breakout time	0.63	Fair to good	0.79	Excellent
Time on-block	0.63	Fair to good	0.68	Fair to good
Time horizontal peak force front plate*	0.62	Fair to good	0.62	Fair to good
Distance max depth	0.62	Fair to good	0.77	Excellent
Average power on-block	0.61	Fair to good	0.66	Fair to good
Depth at 5 m	0.55	Fair to good	0.69	Fair to good
Entry angle	0.51	Fair to good	0.62	Fair to good
Max depth	0.50	Fair to good	0.55	Fair to good
Take-off angle	0.41	Fair to good	0.44	Fair to good
Time horizontal peak force back plate*	0.40	Poor	0.59	Fair to good
Time vertical peak force grab bar*	0.40	Poor	0.46	Fair to good
Entry hole	0.38	Poor	0.51	Fair to good
Time max depth	0.37	Poor	0.55	Fair to good
Vertical take-off velocity	0.23	Poor	0.23	Poor
Total entry velocity	0.14	Poor	0.14	Poor

Before Session#1, all athletes performed three single-leg countermovement jumps with the right as well as a left leg on a force plate (Quattro Jump Type 9290BD, Kistler Group, Winterthur, Switzerland). All single leg jumps were performed barefoot and with the hands at the hips to avoid any interference of arm swing or different types of shoes. The best out of three jumps from each leg was used for further analysis and the peak power was used to compare left and right and determine the stronger leg (Hardt et al., 2009).

Statistical procedures

All statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS v. 22, IBM Corp, USA). The inter- and intra-session reliability was assessed with the Intra-class correlation coefficient (ICC) (Eliasziw et al., 1994; Lin et al., 2008). The chosen statistical model allowed '*session*' to be included as a random variable, which was necessary in this study due to the dismounting and reassembling of the KiSwim between Session#1 and #2. The ICC was evaluated for each outcome parameter in the preferential leg positioning to assess the reliability of the measurement set-up. ICC values range from 0 (no reliability) to 1 (perfectly reliable). The ICC values were classified according to Shrout and Fleiss (1979) as poor (<0.4), fair (0.4–0.6), good (0.6–0.75), and excellent (≥0.75).

For the Principal component analysis (PCA), all 41 measures were converted into standardised *z-scores* and factor analysis was performed using the FACTOR procedure in order to preserve the intrinsic features of kick-start performance, as well as to reduce the effective dimensions of the entire dataset. The correlation analysis method was applied to extract the components using the 'VARIMAX' rotation procedure. With the Kaiser criterion (i.e., components that had Eigenvalues greater than one) the appropriate number of components were extracted (Tabachnick & Fidell, 2007). The rotated components were then used to identify key characteristics of swim-start performance and only those parameters of kick-start performance that had the largest weightings with the rotated components were used for further analysis. Following PCA, mixed factors analysis of variances (ANOVA) was performed using a MIXED procedure to analyse the effects of leg positioning on the KPI. Comparisons were made for positioning of the strong leg in the front vs. the back as well as preferential vs. non-preferential leg positioning. The level of significance was set at $p < 0.05$. Cohen's d effect size was calculated to determine the practical relevance of the outcomes (Cohen, 1969). Fourteen athletes successfully completed all three kick-start sessions. One athlete (Nr. 11, Table 1) missed the last session and was therefore excluded from the ICC analysis of KiSwim reliability. The data of athlete Nr. 11 from Session#2 were nevertheless used of the analysis of the leg positioning.

Results

The reliability analysis for the KiSwim is presented in Table 2 for all 41 parameters. Eighteen kinematic and kinetic parameters showed a high reliability (inter- and intra-session ICC>0.75) including all split times (5 m, 7.5 m, 10 m, 15 m), the on-block peak power, entry distance, horizontal take-off velocity as well as the total and plate specific (front and back plate) horizontal peak forces and impulses.

The PCA revealed nine parameter groups that capture the overall kick-start performance with a total variance of 88% (Table 3). The representing parameters for each group were selected by a close correlate with the particular group while at the same time demonstrating good to excellent levels of reliability (all ICC values>0.6). Two of the representing parameters, i.e., vertical take-off velocity and time until maximum depth under water, demonstrated a poor reliability (ICC = 0.226 and 0.367, respectively) and were excluded from any further analysis. Therefore, the PCA identified seven KPI for the kick-start performance including four kinematic, i.e., time on-block, horizontal take-off velocity, depth at 7.5 m and time to 15 m, and three kinetic parameters, i.e., horizontal peak force back plate, vertical peak force front plate and horizontal impulse back plate.

During the kick-start, nine athletes preferred to position their strong leg in the back and the remaining six athletes in the front. No significant differences or performance

Table 3. The Principal Component Analysis (PCA) identifying the key performance indicators and parameter groups of the kick-start with the corresponding Intra-class correlation coefficient (ICC).

Gr. no.	Representing parameter group *Factors identified (Varimax > 0.7)*	Parameter description	ICC Inter-session	ICC Intra-session
1	**Time to 15 m** Time to 5 m Time to 7.5 m Time to 10 m Peak power on-block Total horizontal impulse Entry distance	Time from starting signal to 15 m mark (head) [s].	0.84	0.94
2	**Time on-block** Time total horizontal peak force Time horizontal peak force back plate Time vertical peak force grab bar Time horizontal peak force front plate	Time from the starting signal until take-off [s].	0.63	0.68
3	**Depth at 7.5 m** Depth at 5 m Depth at 10 m Max depth Breakout distance Breakout time	Depth of head at 7.5 m from the wall [m].	0.77	0.81
4	**Horizontal take-off velocity** Entry angle Horizontal impulse front plate	Horizontal velocity at take-off [m/s].	0.78	0.85
5	**Vertical take-off velocity**[a] Take-off angle Total entry velocity	Vertical velocity at take-off [m/s].	0.23	0.23
6	**Horizontal impulse back plate**	Horizontal impulse on the block of back plate normalised by bodyweight [Ns/BW].	0.82	0.83
7	**Horizontal peak force back plate** Total horizontal peak force	Peak force in horizontal direction of the back plate on the block normalised by bodyweight [BW].	0.89	0.91
8	**Vertical peak force front plate**	Peak force in vertical direction of the front plate on the block normalised by bodyweight [BW].	0.79	0.79
9	**Time max depth**[a]	Time from the starting signal until maximum depth of head under water [s].	0.37	0.55

Full description of all parameters provided in Supplementary Material
[a]not considered for further analysis due to poor ICC values (<0.40).
BW, bodyweight.

benefits were found in any of the seven KPI comparing the two groups with the strong leg in the front vs. back (Table 4).

The 15 m start time was shorter with the preferential compared to non-preferential leg positioning. Also, an acute reversal to the non-preferential start positioning had a detrimental effect on five of seven KPI (Table 5). Only depth at 7.5 m and the vertical peak force front plate remained unaffected by the leg positioning.

The additional comparison of the plate-specific kinetic parameters of the back versus front plate, however, showed a higher horizontal peak force and horizontal impulse for the back plate (Table 6). This effect was evident independently on whether the swimmers used the preferential or non-preferential leg position and independent on whether the strong leg was positioned in the front or the back. Figure 2 illustrates the total, horizontal and vertical forces of one representative participant for the front plate, back plate and grab bar.

Table 4. Comparison of key performance indicators with the preferential positioning of the strong leg in the front versus the back. Mean (SD) of five trials for each participant.

Parameter	Strong Front (n = 6)	Strong Back (n = 9)	p	d
Time to 15 m [s]	6.7 (0.2)	7.0 (0.4)	0.052	1.63
Time on-block [s]	0.77 (0.03)	0.75 (0.05)	0.433	0.70
Depth at 7.5 m [m]	−0.89 (0.29)	−0.84 (0.27)	0.654	0.28
Horizontal take-off velocity [m/s]	4.60 (0.22)	4.47 (0.25)	0.292	0.77
Horizontal impulse back plate [Ns/BW]	0.276 (0.011)	0.283 (0.030)	0.579	0.46
Horizontal peak force back plate [BW]	0.93 (0.09)	0.99 (0.14)	0.462	0.64
Vertical peak force front plate [BW]	0.86 (0.13)	0.84 (0.13)	0.821	0.16

The comparison was conducted using the measured data in preferential leg positioning from Session#2.
Abbreviations: BW, bodyweight.

Table 5. Comparison of key performance indicators in preferential versus non-preferential leg positioning. Mean (SD) of five trials for each, the preferential and non-preferential, leg positioning for each participant.

Parameter	Preferential (n = 15)	Non-preferential (n = 15)	p	d
Time to 15 m [s]	6.9 (0.4)	7.1 (0.4)	<0.001	0.80
Time on-block [s]	0.76 (0.05)	0.82 (0.06)	<0.001	1.66
Depth at 7.5 m [m]	−0.86 (0.28)	−0.82 (0.22)	0.050	0.22
Horizontal take-off velocity [m/s]	4.5 (0.2)	4.3 (0.3)	<0.001	1.09
Horizontal impulse back plate [N·s/BW]	0.280 (0.024)	0.275 (0.023)	0.016	0.32
Horizontal peak force back plate [BW]	0.96 (0.12)	0.85 (0.08)	<0.001	1.50
Vertical peak force front plate [BW]	0.85 (0.13)	0.85 (0.17)	0.877	0.03

BW, bodyweight.

Table 6. The plate-specific kinetic analysis for the preferential and non-preferential leg positioning of all participants. For the preferential leg positioning, the data were also compared between the positioning of the strong leg in the front vs. back. Mean (SD), of five trials for each participant.

Parameter	Front plate	Back plate	p	d
Non-preferential leg positioning (n = 15)				
Horizontal peak force [BW]	0.66 (0.08)	0.85 (0.08)	<0.001	3.55
Vertical peak force [BW]	0.85 (0.17)	0.88 (0.14)	0.165	0.27
Horizontal impulse [N·s/BW]	0.176 (0.025)	0.275 (0.023)	<0.001	5.80
Preferential leg position (n = 15)				
Horizontal peak force [BW]	0.71 (0.11)	0.96 (0.12)	<0.001	3.05
Vertical peak force [BW]	0.85 (0.13)	0.97 (0.19)	<0.001	1.10
Horizontal impulse [N·s/BW]	0.191 (0.031)	0.280 (0.024)	<0.001	4.54
Preferential leg positioning: Strong Front (n = 6)				
Horizontal peak force [BW]	0.74 (0.12)	0.93 (0.09)	<0.001	2.57
Vertical peak force [BW]	0.86 (0.13)	0.94 (0.21)	<0.001	0.76
Horizontal impulse [N·s/BW]	0.202 (0.019)	0.276 (0.011)	<0.001	6.73
Preferential leg positioning: Strong Back (n = 9)				
Horizontal peak force [BW]	0.70 (0.09)	0.99 (0.14)	<0.001	3.45
Vertical peak force [BW]	0.84 (0.13)	0.99 (0.18)	<0.001	1.37
Horizontal impulse [N·s/BW]	0.183 (0.035)	0.283 (0.060)	<0.001	0.67

BW, bodyweight.

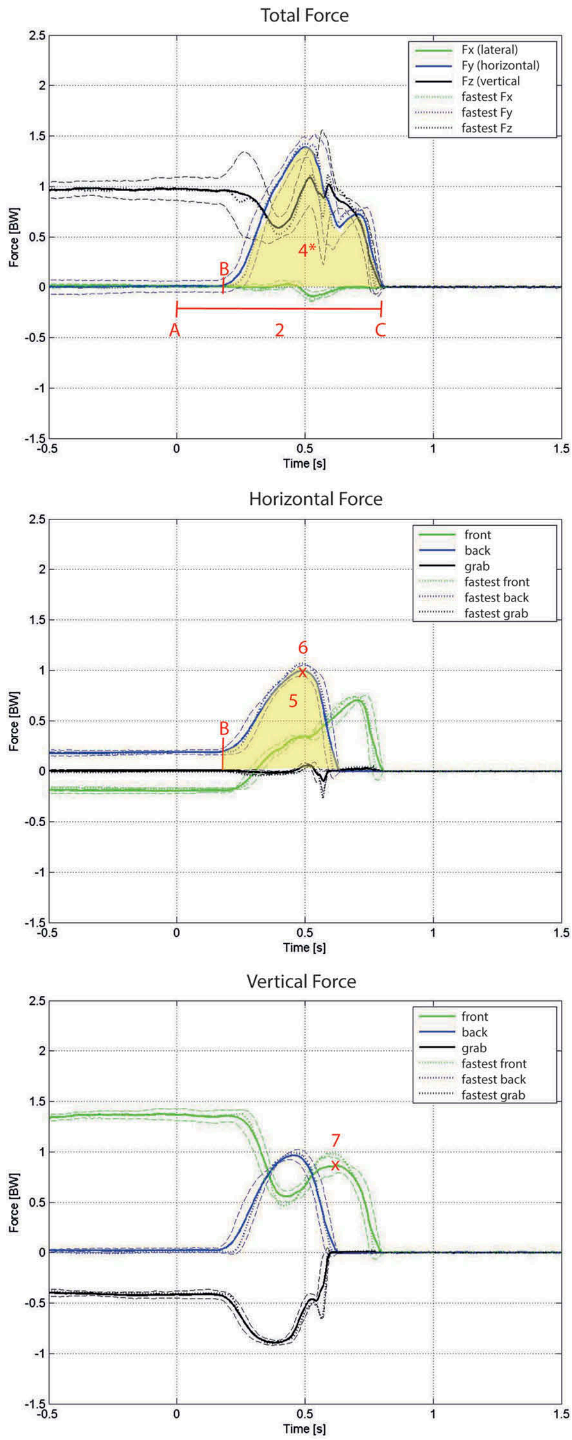

Figure 2. Representative force plots of one representative participant illustrating the front foot, back foot and grab forces. Legend: A = Starting signal. B = point in time where horizontal force is greater than 2% of body weight. C = Take-off time. 2 = time on block. 4 = horizontal take-off velocity derived from integral of horizontal total force divided by body mass. 5 = horizontal impulse of back plate. 6 = horizontal peak force of back plate. 7 = vertical peak force of front plate. Solid lines = mean of 5 trials. Dashed lines = standard deviation of the 5 trials. Dotted line = fastest trial out of the 5 trials. Top: green = Fx (lateral), blue = Fy (horizontal), black = Fz (vertical). Middle and bottom: green = front, blue = back, black = grab.

Discussion and implication

The aim of the study was to investigate the reliability of the KiSwim with its kinematic and kinetic parameters, to identify the KPI for the kick-start using a PCA, to determine whether the most beneficial position of the strong leg is in the front or at the back of the starting block and investigate the effect of an acute reversal of the leg positioning. The PCA identified seven KPI with a high reliability and VARIMAX that are representative for each of the parameter groups, i.e., time to 15 m, time on-block, depth at 7.5 m, horizontal take-off velocity, horizontal impulse back plate, horizontal peak force back plate and vertical peak force front plate. No difference in the start performance was found between the athletes routinely positioning the strong leg in the front versus the back. The acute reversal of the leg positioning reduced the start performance with the non-preferential leg positioning. The plate-specific kinetic analysis, however, revealed a higher horizontal peak force and impulse for the back plate independently from the leg positioning (strong front vs. strong back as well as preferential vs. non-preferential leg positioning).

Different versions and prototypes of instrumented starting blocks for swimming have been evaluated in the recent years. While our main research question aimed to investigate the leg positioning during the kick start, we in addition assessed the reliability of the KiSwim beforehand. The KiSwim is commercially available on the market since the year 2015 but has not been evaluated yet. The reliability analysis revealed an excellent reliability for 18 of the 41 investigated parameters. Fair to good inter-session reliability was shown for 17 parameters. While the KiSwim represents a reliable system for performance analysis in swimming, the findings are in line with previous evaluations of various instrumented starting blocks. Tor and co-workers (Tor et al., 2015b) showed a high reliability for almost all of the investigated kinetic and kinematic parameters by combining the instrumented starting block with three underwater cameras at the 1.6, 5.6 and 12.8 m marks and a separated overwater camera system positioned 1.5 m above the waterline. Recently, Peterson Silveira et al. (2018) showed the importance to analyse the front and rear foot forces individually with the modern kick-start compared to the traditional grab-start. Unfortunately, grab forces at the front edge of the starting block were not reported (Peterson Silveira et al., 2018) although recent research discussed the importance of the arm pull for the kick-start (Takeda et al., 2017). In summary, the KiSwim is generally reliable for the kinetic and kinematic assessment of the start performance in swimming. The individual assessment of the front and rear foot forces combined with the arm pull forces add valuable and practical relevant information for coaches and scientists to better understand the individual components of the kick-start performance. The KPI identified by the PCA help to reduce the number of variables necessary for the assessment of the start performance.

When it comes to the leg positioning, previous research suggested that for the track-start, that the main task of the front leg is to generate thrust, which may be best achieved using the stronger leg in the front (Benjanuvatra et al., 2004; Breed & McElroy, 2000). Especially, the front leg has the longer time on the block to produce force and therefore the strong leg is placed in front in track and field (Vagenas & Hoshizaki, 1986). While both, swim and track start, involve asymmetric foot positions, the movement pattern are quite different still. The more vertically oriented force production in the track start results in a larger take-off angle and increases the importance of the front leg's force production compared to the swim start (Vagenas & Hoshizaki, 1986). In the underlying study, however, there was no significant performance advantage by placing the stronger leg in the front. On the contrary, the plate-specific kinetic analysis showed higher horizontal peak force and impulse for the back plate. This phenomenon was evident with the preferential and non-preferential leg positioning as well as when positioning the strong leg in the front or in the back.

Discrepancies to previous research (Benjanuvatra et al., 2004; Breed & McElroy, 2000) might derive from different start positions investigated on different types of starting blocks. The track-start, that is generally used on older starting blocks, also involves the asymmetric and step-like foot positioning. However, with the introduction of the Omega OSB 11 the inclined rear foot support substantially increased the thrust and force production of the rear leg leading to a task-specific contribution of the front and rear leg to the kick-start performance (Takeda et al., 2017). It has been shown, that the rear leg produces a larger horizontal impulse and contributes therefore substantially to the take-off horizontal velocity (Takeda et al., 2017), which in turn accounts for 81% of the variance in start performance during the overwater phase (Tor et al., 2015a). The front leg, on the other hand, showed the larger vertical impulse (Takeda et al., 2017). Ikeda et al. (2016) modelled the kick-start as an inverted pendulum. Thereby, the front leg creates a pivot point that deviates the rear leg's force production with the counterforce of the arm pull in the optimal horizontally oriented direction and determines the flight phase trajectory. Indeed, before the starting signal, a pre-tension with forces of about 50% body mass is exposed to the grab bar. During the start movement, the arm pull reaches almost 100% body mass to bring the swimmer into an optimal position for force production as quickly as possible (Takeda et al., 2017). The task-specific contribution of the front and rear leg (Takeda et al., 2017) in addition to the plate-specific kinetic analysis of the underlying study suggests an optimal start position with the strong leg in the back. Interestingly, the majority of our athletes ($n = 9$) chose this leg positioning by subjective preferences and experience.

The acute reversal from the preferential to the non-preferential leg positioning had a detrimental effect on the start performance regardless of whether the stronger leg was positioned in the front or the back. Previous research has found similar results for the track-start and showed the advantage of the preferential leg positioning (Hardt et al., 2009). Perfecting the kick-start for optimal performance requires muscular strength to maximise the take-off horizontal velocity (Tor et al., 2015a) and flight distance (Peterson Silveira et al., 2018). Fine control and timing of the force production, however, is also necessary to find the optimal flight phase trajectory and at the same time prepare for a smooth water entry with the least possible resistance. Repetitive training of the movement execution and coordination seems necessary before any increased on-block force production from a reversed leg positioning (strong leg in the back) might transfer to an improved start performance, otherwise the 15 m start time can be longer. From a practical perspective, coaches need to consider that start performance with the non-preferential leg positioning might be impaired initially despite potential long-term benefits. In the long-term talent development, however, choices on foot placement during the swim-start might be based on an early determination of the right and left leg's strength as well as footedness.

In the underlying study, the participant's mean FINA point score of 732.9 ranged from 557 to 957. The results might differ from athletes with a higher mean performance level.

Excluding all participants with ≤750 points or pooling the data retrospectively (> vs. <750 points), however, would have affected the sample size and statistical power. Future research needs to compare the leg preference among different performance levels. Also, a detailed analysis of the timing of the force production would provide valuable insights into an understanding of the swim start. With respect to the rear foot plate adjustment, our participants utilised their routine start position and same adjustment for the preferential and non-preferential leg positioning. Future research needs to investigate the rear foot plate position (position 1–5) in relation to anthropometric data and leg strength. Also, a clear classification of start variations, i.e., front, back, and neutral-weighted, is required. The heterogenic group of participants regarding gender and preferred leg positioning (left vs. right) as well as the missing assessment of the strong leg during the swim start movement limit the implication of the study. Also, the starting block of the KiSwim was designed to imitate the starting position used in competitions in the best way possible. Therefore, the grab bar was positioned right beneath the front foot force plate. While both force plates are separated by 2 mm gap, depending on swimmer's hand positioning, a slight inference effect between the front foot and grab forces cannot be excluded (refer to detailed illustration in Figure 1).

Conclusion

In conclusion, the PCA identified seven KPI with a high reliability and VARIMAX that are representative for each of the parameter groups, i.e., time to 15 m, time on-block, depth at 7.5 m, horizontal take-off velocity, horizontal impulse back plate, horizontal peak force back plate and vertical peak force front plate. While 18 parameters showed excellent and 17 parameters fair to good inter-session reliability, the seven KPI can be used to reduce, if necessary, the number of relevant parameters for the investigation of the swimming kick-start. The leg positioning showed no difference between the athletes routinely positioning their strong leg in the front vs. the back. While the swimming kick-start provides a well-practiced and specific movement pattern, the acute reversal of the leg positioning impaired the start performance. The plate-specific kinetic analysis, however, revealed a higher horizontal peak force and impulse for the back plate independently from the leg positioning: preferential vs. non-preferential leg positioning; strong front vs. strong back. With the findings of the underlying study, coaches and athletes are encouraged to position the strong leg in the back.

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