A METHOD OF IMPROVING THE MEASUREMENT OF KINEMATIC PARAMETERS ABOVE AND UNDER WATER IN SWIMMING START

Hideki Takagi[1], Takuma Tatsumoto[2] and Shin Sakai[2]

Faculty of Health and Sport Sciences, University of Tsukuba, Tsukuba, Japan[1]
Graduate School of Comprehensive Human Sciences, University of Tsukuba, Tsukuba, Japan[2]

The objectives of this study were to develop an improved method of measuring kinematic parameters of a swimmer at the start of a race from water entry through the initial glide in a seamless manner and to consider deceleration factors with reference to changes in the swimmer's kinematic parameters during the start. Ten elite collegiate male swimmers participated in this study. To obtain accurate displacements of each reference point on a swimmer while avoiding interference from bubbles, waterproofed, super-luminosity LED markers were used. Additionally, a metallic frame (3 m × 2 m) and a nylon belt (6.1 m long with marks at intervals of 0.5 m) were used as calibration control points. Participants were asked to start from a starting block three times with their maximum effort and maintain a streamlined position without any kicking after water entry until they reached the 10-m point. The mean calibration error was 0.0046 m in the horizontal direction and 0.0047 m in the vertical direction across the measurement span (11 m × 6 m). This improved method enabled us to measure successive changes in the velocity and acceleration of the centre of mass both above water and following water entry.

KEYWORDS: track start, LED markers, deceleration rate, 10-m arrival time

INTRODUCTION: In competitive swimming, the start technique can make the difference between winning and losing. Therefore, many studies have focused on efficiency at the start (e.g., Elipot, Dietrich, Hellard, & Houel, 2010; Fischer & Kibele, 2016; Houel, Elipot, André, & Hellard, 2013; Vantorre, Chollet, & Seifert, 2014). However, studies on the phase that includes water entry and gliding in water (hereafter, the entry and glide phase) are less common than those on the starting block technique or propulsion in water. Because a large number of bubbles are generated at the moment when the swimmer passes from air into water, reference points on the body become unrecognisable; therefore, accurate measurements of kinematic parameters such as changes in velocity or acceleration of the centre of mass are very difficult to obtain. Therefore, the objectives of this study were to improve the method of measuring a swimmer's kinematic parameters during the entry and glide phase and to consider deceleration factors occurring around the start.

METHODS: Ten elite collegiate male swimmers participated in this study (mean ± SD: height 1.74 ± 0.05 m; weight 70.21 ± 5.24 kg; age 19.9 ± 1.3 years; swimming experience 13.6 ± 3.2 years). The swimmers were asked to take off three times from the starting block using the kick-start technique exerting their maximum effort until they passed the 10-m point. During this phase, the swimmers maintained a streamlined position without any kicking after water entry, i.e. the one in which the swimmer took the least amount of time to complete 10 m was analysed.
To obtain accurate displacements of each reference point on a swimmer while avoiding interference from bubbles, waterproofed, super-luminosity LED markers were attached to the left side of the body at the following 13 points: vertex, tragus, acromion, superior margin of the sternum, centre of the elbow joint, pisiform, fifth metacarpophalangeal joint, lower end of the thorax, great trochanter, centre of the knee joint, centre of the ankle joint, pterion and toe (Fig. 1). Ae's anthropometric data for Japanese athletes (Ae, Tang, & Yokoi, 1992) were used to calculate the displacement of the centre of mass (CM).
The aerial and underwater area covered by the video cameras ranged from the starting block to the 10-m point. Five cameras were used; two cameras (designated as cameras #1 and #2)

tracked aerial motion and the other three cameras tracked underwater motion. Cameras #1–#3

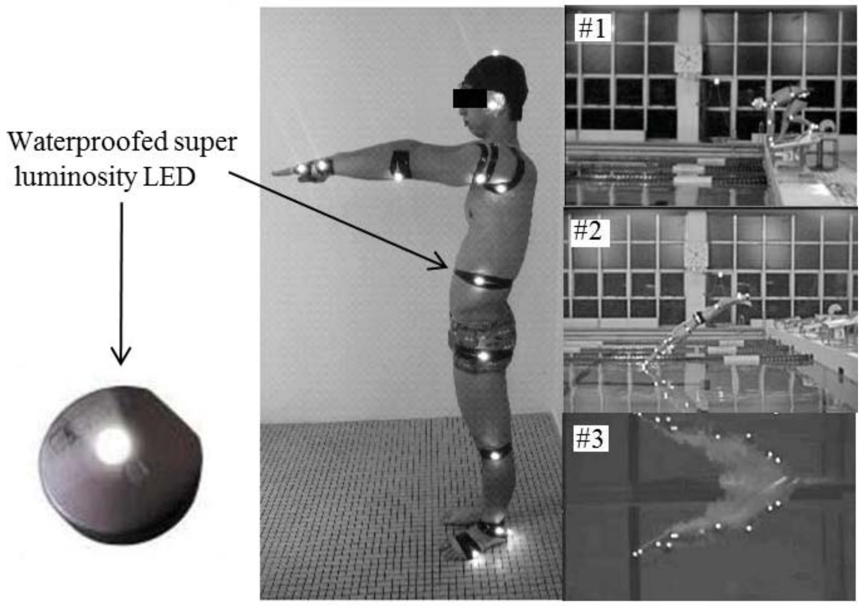

Figure 1: LED markers attached to each reference point and side view images of the aerial and underwater phase in the swimming start.

were high-speed cameras (frame rate 100 fps; exposure time 1/500 s; B-cam system, DKH, Japan). They were connected to a synchronizer (Electronic Start System Model SS2, Colorado Time System, USA) and were used to analyse motions from the starting block through the air–water interface until the swimmer went underwater (see Fig. 1). Cameras #4 and #5 were specially manufactured waterproof cameras (frame rate 60 fps; exposure time 1/500 s; Nihon Jimu Koki, Japan). They were synchronized with LEDs illuminated by the starting signal and were used to analyse motions during the glide phase until the 10-m point (Fig. 2).

The origin of the global reference frame was placed at the intersection between a vertical line passing through the middle of the front edge of the starting block and the water surface. The x-axis and y-axis were defined as the longitudinal and vertical directions, respectively. A metallic frame (3 m × 2 m, 60 control points) and a nylon belt (6.1 m long with marks at intervals of 0.5 m) were used for calibration. The metallic frame was set parallel to the x-axis taking the origin (O in Fig. 2) into consideration and was used mainly to analyse motions on the starting block. The nylon belt was stretched vertically from a suction cup attached to the bottom of the pool and all marks on the belt were used as control points in both the aerial and underwater fields in a seamless manner. To determine the water surface, an extra mark was added on the belt. After we shot footage of the belt at a certain position, the belt was moved to the next point at intervals of 1 m from the origin, parallel to the x-axis, until the 11-m point (Fig. 2)

We assumed that the two sides of the swimmer‘s body were symmetrical and hence only the left-side reference points were manually digitized by using motion analysis software (Frame-DIAS V, DKH, Japan). The 2-D DLT method built into the software was utilized to reconstruct actual 2-D space. Data were filtered with a Butterworth II filter having the cut-off frequencies at 6 Hz. The space reconstruction error was 0.46×10^{-2} m in the x-direction and 0.47×10^{-2} m in the y-direction.

The following key kinematic parameters were obtained: (1) arrival time at the 5-m point ($\mathbf{T_{5m}}$), (2) arrival time at the 10-m point ($\mathbf{T_{10m}}$), (3) horizontal velocity of the CM ($\mathbf{V_{xCM}}$), (4) horizontal acceleration of the CM ($\mathbf{a_{xCM}}$), (5) horizontal velocity of the CM at take-off ($\mathbf{V_{xCM}}$ at take-off), (6) horizontal velocity of the CM at the point when the whole body becomes submerged ($\mathbf{V_{xCM}}$ at submerge), (7) horizontal velocity of the CM at the 5-m point ($\mathbf{V_{xCM}}$ at 5 m), (8) horizontal velocity of the CM at the 10-m point ($\mathbf{V_{xCM}}$ at 10 m) and (9) deceleration rate (**%D**):

(V_{xCM}@take-off– V_{xCM}@5 m)/V_{xCM}@5 m × 100. Moreover, to investigate factors that determine start performance, various kinematic parameters (e.g. changes of joint angles, entry angle and posture) were calculated.
All data are reported as mean ± standard deviation. To evaluate the reliability of this methodology, a time-series coefficient of variance was calculated for the forearm length for all swimmers' trials ($CV_{forearm}$). Pearson's correlation was also calculated with the level of significance set at $p < 0.05$. SPSS Statistics 17.0 (IBM Japan,Tokyo, Japan) was used for statistical analysis.

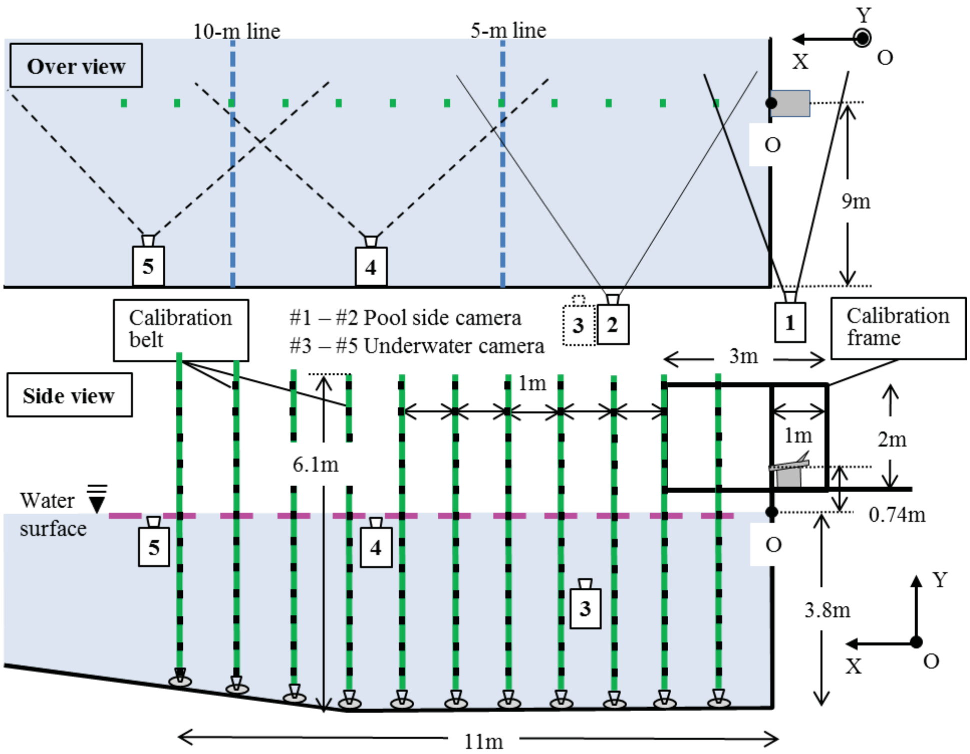

Figure 2: Coverage area for measurements, installation position of cameras and identification of the global reference axes and calibration tools.

RESULTS & DISCUSSION: The $CV_{forearm}$ ranged from a minimum of 2.37% to a maximum of 5.53% with an average of 3.96%. In previous studies, specific body segments could not be identified due to the near-whiteout condition just after the swimmer entered water; however, in this study, the LED markers enabled us to identify the reference points clearly, as shown in Fig. 1. Therefore, we believe that the reliability of the method was confirmed.

Table 1: Mean key kinematic parameters

	$T_{5\,m}$ (s)	$T_{10\,m}$ (s)	V_{xCG} at take-off (m/s)	V_{xCG} at 5 m (m/s)	V_{xCG} at 10 m (m/s)	%D (%)
Mean	1.61	4.88	4.61	3.17	0.95	31.30
SD	0.09	0.52	0.21	0.42	0.13	8.10

Because there was a highly significant correlation between T_{10m} and **%D** ($r = 0.75$, $p = 0.01$), it appears that the **%D** should be considered one of the main performance indexes for the purpose of improving start performance. This correlation seems reasonable, but the factors that determine the **%D** are complex; so, we could not specify a particular explanation for those swimmers with higher **%D**.
In Fig. 2, the time-series changes of V_{xCM} and a_{xCM} are illustrated. Through the use of LED markers and high-speed cameras, a detailed analysis of the velocity and acceleration of the

CM during the start became possible. At first glance, the $\mathbf{V_{xCM}}$ seems to be decreasing monotonically, but focusing on changes in the acceleration of the CM shows that it changed substantially in response to fluid forces. In particular, when the upper body enters the water, a large impact force acts against a swimmer; therefore, a drastic decline in acceleration may be observed. This phenomenon has already been reported by Kiuchi, Nakashima, Cheng, and Hubbard (2010). It is expected that a contributing factor to **%D** could be clarified by investigating the relationship between $\mathbf{a_{xCM}}$ and various body angles or postures.

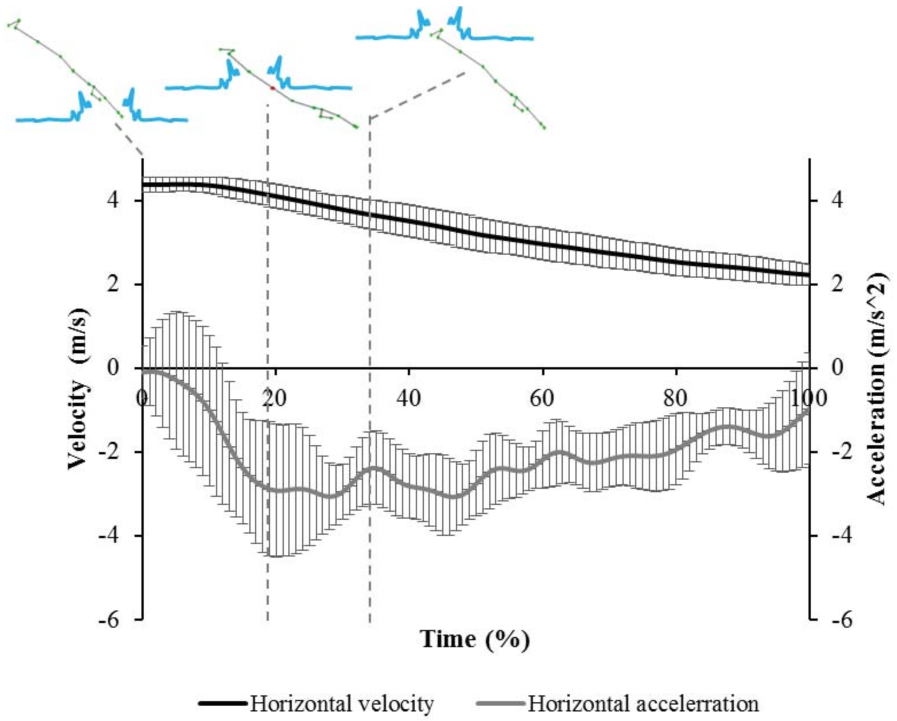

Figure 3: Changes in the mean horizontal velocity and acceleration of the CM from the point of entering water through the glide phase until the 6-m point following the start (n = 10). The horizontal axis indicates normalized time.

CONCLUSION: By improving methods of obtaining kinematic parameters during the start, we were able to identify information that could contribute to improving start performance. Swimmers and coaches should consider more carefully how to minimize the impact force by changing their entry angle into the water or their body alignment. The reliability and usefulness of our new method of identifying a swimmer's kinematic parameters during the entry and glide phase were confirmed

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