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Upper body kinematic differences between maximum front crawl and backstroke swimming [Original Article]

Tomohiro Gonjo[1,2], Ricardo J. Fernandes[3], João Paulo Vilas-Boas[3], and Ross Sanders[4]

1: Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway

2: Institute for Sport, Physical Education & Health Sciences, The University of Edinburgh, Edinburgh, Scotland, UK

3: Faculty of Sport, CIFI2D, and LABIOMEP, University of Porto, Porto, Portugal

4: Faculty of Health Sciences, The University of Sydney, Sydney, New South Wales, Australia

Corresponding author

Tomohiro Gonjo, Ph.D.

Department of Physical Performance,

Norwegian School of Sport Sciences

Postboks 4014 Ullevål Stadion, 0806 Oslo, Norway

Phone: +47 23 26 23 13

e-mail: tomohiro.gonjo@nih.no

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Abstract: The purpose of this study was to investigate why front crawl is faster than backstroke from a kinematic perspective. Three-dimensional kinematics were obtained from one upper-limb cycle of ten male competitive swimmers performing 50 m front crawl and backstroke trials at maximum speed. Swimmers achieved faster centre of mass velocity in front crawl than backstroke (1.70±0.04 vs 1.54±0.06 m·s^{-1}; $p<0.01$) with no difference in stroke length (2.00±0.25 vs 2.07±0.17 m·cycle^{-1}), while stroke frequency in front crawl was higher than that in backstroke (51.67±6.38 vs 44.81±4.68 cycles·min^{-1}; $p<0.01$). Maximum shoulder roll angle in front crawl was larger than that in backstroke (52.88±4.89 vs 49.73±5.73°; $p<0.05$), while swimmers had smaller maximum hip roll in front crawl than backstroke (33.79±6.07 vs 39.83±7.25°; $p<0.05$). Absolute duration of the release phase (from the last backward movement to the exit from the water of the wrist) and relative duration of the recovery phase were shorter in front crawl than backstroke (0.07±0.03 vs 0.26±0.08 s; $p<0.01$, and 28.69±2.50 vs 33.21±1.43%; $p<0.01$, respectively). In conclusion, front crawl is faster than backstroke because of its higher stroke frequency due to the shorter absolute release phase and relative recovery phase durations. (191 words)

Keywords: alternating strokes, performance, aquatic locomotion, stroke frequency, stroke length, motion analysis

Introduction

Front crawl and backstroke have similar kinematic characteristics, such as the alternating limb motions and the body roll around the longitudinal axis

(Psycharakis and Sanders, 2010; Seifert and Chollet, 2009). However, swimmers usually achieve faster swimming speeds in front crawl than in backstroke (Chollet et al., 2008, 2000; Craig et al., 1985). Swimming performance is determined by stroke frequency (*SF*) and stroke length (*SL*) (Pendergast et al., 1978). Therefore, the difference in the achievable swimming speed between the two techniques is attributed to higher *SF* and/or longer *SL* in front crawl than backstroke.

In races, swimmers have similar *SL* in front crawl and backstroke, but the former has a higher *SF* than the latter technique (Hellard et al., 2008; Kennedy et al., 1990), but the reason for this is still unclear. For example, the similarities and differences could be either due to the factors in swimming or indirect effects of distinct start and turn techniques. Furthermore, as both *SF* and *SL* are affected by the anthropometry of swimmers (Grimston and Hay, 1986), a within-participant comparison is necessary to investigate mechanical dissimilarities between the alternating techniques.

Since *SF* is the inverse of the upper-limb cycle time, the cycle duration should be investigated. The duration of the recovery phase in relation to one upper-limb cycle time at maximum speed is 26.3 and 29.3%, with *SF* being 51.8 and 44.3 cycles·min^{-1} in front crawl and backstroke, respectively (Chollet et al., 2008, 2000), suggesting that the absolute recovery and underwater phase duration of the respective techniques being 0.30 and 0.40 s (recovery phase), and 0.85 and 0.95 s (underwater phase). However, it is unclear whether these differences between front crawl and backstroke were due to differences in hand speed or the distance the hand travels (relative to the body in both cases).

Swimmers should not be able to move their hands relative to the body faster in water than in the air due to the hydrodynamic drag, and also must maintain effective bilateral coordination in both techniques (Chollet et al., 2008, 2000). This means that the hand speed and/or the distance the hand travels above the water is probably restricted by the contralateral in-water hand speed. Therefore, it is reasonable to assume that factors affecting *SF* are primarily underwater hand kinematics.

Bilateral coordination also affects *SF* in both front crawl and backstroke (Lerda and Cardelli, 2003; Potdevin et al., 2006), and the index of coordination (*IdC*) has been used to describe it (Chollet et al., 2008; Seifert and Chollet, 2008). *IdC* categorises the coordination into three patterns (catch-up, opposition, and superposition) using the lag time between the left and right upper-limb propulsive phases (Chollet et al., 2000). It has been reported that *SF* and *IdC* are related, i.e., the smaller the lag time is, the higher *SF* presented (Lerda and Cardelli, 2003; Potdevin et al., 2006). However, it is difficult to compare *IdC* between front crawl and backstroke directly, since the definition of underwater phases differs among the techniques (Chollet et al., 2008, 2000).

Given that *IdC* is a description of the timing between left and right upper-limb propulsive actions (Seifert and Chollet, 2008), rather than the duration of propulsion being actually produced, the difference in the inter-limb coordination between the techniques could be described differently. Theoretically, if the recovery phase duration becomes short while maintaining the underwater phase duration of the other upper-limb, that would make the hand entry timing early in relation to the timeline of the other upper-limb underwater phase and increase *SF* (Figure 1). Therefore, the ratio of the recovery and underwater phase duration and the timing of the hand entry can be indicators of the bilateral coordination and its influence on *SF*.

Figure 1 around here

Body roll is an angular motion of the body around the longitudinal axis, comprising shoulder and hip roll (*SR* and *HR*) (Psycharakis and Sanders, 2010). Theoretically, swimmers should reduce the amplitude of body roll and/or increase the body roll angular velocity to achieve high body roll frequency and, as a consequence, high *SF*. It has been reported that male swimmers decrease their *SR* and *HR* amplitude when increasing *SF* in front crawl (Yanai, 2003), while they do not change their *SR* and *HR* amplitude depending on the speed in backstroke (Gonjo et al., 2016). Therefore, it is possible that swimmers produce higher *SF* in front crawl by achieving smaller body roll amplitude than in backstroke. However, there are no studies in the extant literature in which *SR* and *HR* have been compared between front crawl and backstroke.

It is probable that front crawl is faster than backstroke due to its higher *SF*. However, it is unclear which kinematic factors produce this *SF* advantage in front crawl. Discovering the technical advantages of front crawl compared to backstroke would be useful to gain insights into performance improvement in backstroke swimming. The purpose of the present study was to investigate the three-dimensional (3D) kinematics of front crawl and backstroke to assess why front crawl is faster than backstroke.

Methods

Participants

Ten male well-trained swimmers —front crawl (n = 4), backstroke (n = 3), and medley (n = 3) specialists participated in this study (Table 1). They were informed about testing procedure, benefits, and potential risks, which were approved by the ethics committees of the University of Edinburgh as well as the University of Porto, and written informed consent was obtained from each participant.

Table 1 around here

Testing protocol

Before testing, participants were marked on 19 anatomical landmarks (the vertex of the head, the right and left: tip of the distal phalanx of the middle finger, wrist axis, elbow axis, shoulder axis, hip axis, knee axis, ankle axis, fifth metatarsophalangeal joint, and the distal phalanx of the middle toe) using black oil and wax-based cream (Grimas Créme Make-Up). To obtain personalised body segment parameter data (*p-BSP*), swimmers stand in the anatomical position in a calibrated space and were captured by two digital cameras (Lumix DMC-FZ40, Panasonic, Osaka, Japan) from front and side views simultaneously. The images were manually digitised to apply the elliptical zone method (Jensen, 1978), which is an approach to estimate *p-BSP* non-invasively by modelling each body segment as ellipses with known depth and diameters. From the digitised data and segmental density data reported in Dempster (1955), the mass, centre of mass (*COM*) location relative to the endpoints, and moments of inertia of each segment were obtained. The digitising and modelling process was conducted using the 'E-Zone' software (Deffeyes and Sanders, 2005; Sanders et al., 2015).

The testing was conducted in a centre lane of a 25 m indoor pool that was calibrated using a calibration frame of 6 m length aligned with the swimming direction (X), 2.5 m height (Y), and 2 m width (Z) (De Jesus et al., 2015) with 32 underwater and 32 above water control points as input to a 3D direct linear transformation (*DLT*) reconstruction. The reconstruction error was less than 0.1, 0.3, and 0.4% of the calibrated volume (30 m^3) for the X-, Y-, and Z-direction, respectively. Testing comprised two 50 m bouts at maximum effort, one for front crawl and the other for backstroke. Each testing session follows individual warm-ups on land and in water. The order of the trials was randomised, and swimmers were instructed to avoid underwater kicking after the push-off to prevent the technique affecting the motion in mid-pool. Since some swimmers spent longer time underwater after the first push-off than the second push-off, the latter half of 50 m was selected for the analysis to minimise potential effects of the transition from underwater to swimming phase.

Data collection

The calibrated space was captured by four underwater and two above-water cameras (HDR-CX160E, Sony, Tokyo, Japan) at a sampling frequency of 50 Hz. They were synchronised using a light-emitting diode system, which was visible from all cameras. To maximise the accuracy of the *DLT* calculations, all cameras were fixed at different heights and angles to the line of motion of the swimmer to avoid their axes being in the same plane. Swimmers were instructed to avoid breathing in the calibrated area in front crawl since it affects their upper-limb kinematics (McCabe et al., 2015).

Data processing and analysis

One upper-limb cycle (the duration between the left or right wrist entry to the subsequent entry of the same wrist) in the calibrated space was chosen for the analysis. Ariel Performance Analysis System software (Ariel

Dynamics, Inc, CA) was used for video digitising and 3D coordinates reconstruction using 2D coordinates digitised from four (underwater) and two (above-water) camera views. The digitising process was conducted separately for underwater and above-water views. Both data were synchronised and sharing the same global coordinates, therefore, the two sets of data were merged based on the vertical coordinates of each landmark. Since an appropriate sampling frequency in maximum effort swimming is between 22.0-27.5 Hz (Gonjo et al., 2018), every second video field from each camera was digitised to yield a sampling frequency of 25 Hz. To minimise errors at the end of the data sets associated with filtering and derivation of velocity data, five extra frames before and after the upper-limb cycle were digitised, with data being extrapolated by reflection to an additional 20 points beyond the start and finish of the cycle (Sanders et al., 2016). Then, a 4th order Butterworth filter with a 4 Hz cut-off frequency was applied.

Whole-body *COM* location was determined by summing the moments of the segment *COM* mass about the X-, Y-, and Z-reference axes using *p-BSP*. The velocity of *COM* (v_{com}) was obtained by differentiating the X-displacement of *COM* over the whole upper-limb cycle by the time taken for the cycle. *SF* was obtained as the inverse of the analysed upper-limb cycle duration. *SL* was obtained from the X-displacement of *COM* during the upper-limb cycle (McCabe et al., 2011). The analysed cycle was divided into the entry, pull, push, release, and recovery phases. As the phase definition in front crawl and backstroke varies in the literature, the five phases were established by mixing extant definitions (Chollet et al., 2000; Gourgoulis et al., 2006; Lerda and Cardelli, 2003; McCabe et al., 2015) so that they could be compared based on the same equivalent temporal events.

The entry phase commenced at the instant the wrist water entry and concluded at the instant of its first backward movement relative to the external reference frame. The pull phase was the interval between the end of the entry phase and the instant that the X-coordinate of the wrist is closest to that of the ipsilateral shoulder. The push phase was from the end of the pull phase to the wrist having a positive velocity in X-direction relative to the external reference frame. The release phase was defined as the interval between the end of the push phase and the wrist exit.

The timing of the hand entry was obtained as an indicator of the bilateral coordination of the upper-limbs, which was quantified as the time of the hand entry in relation to the underwater phase percentile timeline of the other hand (%). *SR* and *HR* angles were determined as the angles between the unit vector of the line joining the shoulders and hips projected onto the YZ-plane and the Y-axis. The wrist joint was assumed to represent the hand motion to avoid errors due to the difficulty of digitising the fingertip when occluded by turbulence. Relative wrist speed (RS_{wrist}) was defined as the mean of the instantaneous 3D wrist speeds relative to the shoulder. The distance the wrist moved (MD_{wrist}) in each phase was quantified by multiplying RS_{wrist} and the phase duration. The velocity of the wrist in X-direction ($v_{x\text{-}wrist}$) and YZ-direction ($v_{yz\text{-}wrist}$) was calculated by dividing the displacement change in the respective direction (X) and the plane (Y-Z) by the time. Since the displacement and velocity of the wrist are affected by the elbow joint kinematics, the elbow joint angles were quantified as the arc-cosine of the dot product of the upper and lower arm unit vectors (Figure 2), and the mean angle (θ_M) and the difference between the maximum and minimum angles (the range of elbow joint angle: θ_{ROA}) were calculated for each phase. All variables related to left and right upper limbs were assessed for both sides, and the mean values were assumed to represent the variable of each phase.

Figure 2 around here

Statistical analysis

To assess the differences in kinematic variables between the swimming techniques, a paired t-test was used with a statistical significance level of $p < 0.05$. Cohen's d was calculated to estimate the effect size with $d = 0.20$, 0.50, and 0.80 being deemed to represent small, medium, and large effects (Cohen, 1988). Before the t-test, the normality of all data in front crawl and backstroke was checked and confirmed using the Shapiro-Wilk test. The tests were conducted using IBM SPSS Statistics 19 (IBM Corporation, Somers, NY, USA).

Results

Table 2 displays the analysed kinematic variables. There was no difference in *SL* between front crawl and backstroke, while swimmers had around 10% faster v_{com} and 13% higher *SF* in front crawl than in backstroke. The recovery phase relative duration in front crawl was about 16% shorter than backstroke, and the timing of entry relative to the other hand's underwater phase timeline was 7% earlier in front crawl than backstroke. Maximum *SR* amplitude in front crawl was larger by 6% than backstroke, whereas maximum *HR* amplitude was smaller by 18% in front crawl than in backstroke. Swimmers had larger maximum *SR* and *HR* angular velocity in front crawl than backstroke (about 46 and 26% differences, respectively).

Table 2 around here

The differences in pull and push phase absolute duration between the two techniques were not significant, while swimmers had 59% longer entry phase and almost four times shorter release phase duration in front crawl than backstroke (Table 3). Swimmers also had a larger MD_{wrist} during the entry and push phases in front crawl than backstroke (about 29 and 13% difference, respectively). MD_{wrist} during the pull and release phases were smaller in front crawl than backstroke (8 and 149% difference, respectively). There were no differences in RS_{wrist} in both recovery and whole underwater phases, even though front crawl had faster RS_{wrist} in the push and release phases and slower RS_{wrist} in the entry and pull phases than backstroke. θ_M was larger in backstroke than front crawl in both whole underwater and recovery phases (3 and 23% differences, respectively). Among the underwater phases, the difference in the release phase was especially notable (about 19% larger in backstroke than in front crawl). θ_{ROA} was three times higher in front crawl than backstroke in the recovery phase. Even though there was no difference in the whole underwater θ_{ROA}, it was more than two times larger in backstroke than in front crawl in the release phase.

During the whole underwater phase, $vx_{\text{-}wrist}$ in front crawl was three times larger than in backstroke, whereas $vyz_{\text{-}wrist}$ during the whole underwater phase was not different between the techniques. Among the underwater phases, swimmers showed larger $vx_{\text{-}wrist}$ at every phase in front crawl than in backstroke except the pull phase where no difference was observed between the techniques. $vyz_{\text{-}wrist}$ was larger in backstroke than in front crawl in the entry and pull phases whereas that in push and release phases was smaller in backstroke than in front crawl. An example of the wrist displacement in X-, Y-, and Z-direction of the best participant is also provided in Appendix 1.

Table 3 around here

Discussion

Swimmers had faster v_{com} with higher SF in front crawl than backstroke, while SL was similar, indicating that front crawl is faster than backstroke because of its higher SF. However, there was no difference in RS_{wrist} in both whole underwater and recovery phases, demonstrating that the difference in SF was due to the smaller MD_{wrist} in front crawl than backstroke. Given that backstroke had a longer duration and larger MD_{wrist} than front crawl in the release phase, the difference in SF was primarily attributed to this phase. Even though differences in MD_{wrist} during the other phases were observed, the largest effect size (3.60) in MD_{wrist} during the release phase among all phases indicated that the primary source of the difference in SF was the release phase. Similarly, the differences in θ_M and θ_{ROA} (larger in backstroke than front crawl) during the release phase implied that the difference in MD_{wrist} was attributed to the elbow angle differences between the techniques.

In backstroke, the timing of the events defining the release phase varied among swimmers (Figure 3). However, all swimmers tended to conduct the entire last wrist underwater upward motion (clearing motion) in this phase, meaning that the clearing motion is a primary motion during the phase (Figure 3). Chollet et al. (2008) and Lerda and Cardelli (2003) emphasised the importance of minimising the time spent on this motion to keep continuous propulsion. Our results supported this suggestion, since minimising the clearing motion would reduce the release phase duration, which would lead swimmers to achieve high *SF*.

Figure 3 around here

To reduce the clearing motion duration, it would be essential to minimise the second down-sweep motion. However, swimmers probably should not sacrifice the force produced during this motion. Figure 4 displays examples of *SR* angular velocity and vertical wrist displacement in front crawl and backstroke of a participant who had the fastest best records in both techniques. In front crawl, this swimmer achieved the maximum angular velocity at the end of the push phase, while it occurred when the swimmer completed his second down-sweep in backstroke. This difference possibly indicates the role of *SR* differing between the techniques. For example, swimmers roll their shoulder to assist their up-sweep motion in front crawl, while the second down-sweep motion assists the shoulder to roll in backstroke. In other words, it is probably necessary for swimmers to produce a certain amount of downward force during the second down-sweep in backstroke to facilitate *SR*, which might contribute to an inline entry of the contralateral hand and placing it in a deep position to make a strong catch (Alves et al., 2004).

Figure 4 around here

As suggested in the introduction, an early wrist entry timing in relation to the timeline of the whole underwater phase of the other upper limb would theoretically contribute to high *SF*. In the current study, swimmers achieved a shorter relative recovery phase duration by entering the hand earlier in relation to the underwater phase timeline of the other hand in front crawl than backstroke. In other words, the swimmers had a more effective coordinative pattern in front crawl than backstroke, from the perspective of achieving high *SF*.

There was no difference in RS_{wrist} during the recovery phase while MD_{wrist} was longer in backstroke than in front crawl. These results suggest that the difference in the recovery phase duration (and consequently, the entry timing) was due to the difference in MD_{wrist} between the techniques. The longer MD_{wrist} in backstroke than front crawl was probably linked to the larger θ_M and smaller θ_{ROA} in backstroke than in front crawl (i.e. bended-elbow and straight-arm recovery). The cause-effect relationship between MD_{wrist} and the elbow kinematics is difficult to establish. However, if *SR* is strongly linked to the second down-sweep in backstroke as suggested above, the swimmers probably had the larger θ_M and smaller θ_{ROA} in backstroke than in front crawl because they had to achieve longer MD_{wrist} to maintain certain bilateral coordination (i.e., coincide the second down-sweep with the entry and first down-sweep of the other upper-limb).

In the introduction, differences in *SR* and *HR* between front crawl and backstroke were identified as possible factors contributing to the difference in *SF* between the techniques. However, contrary to the expectation, swimmers had approximately 6% larger maximum *SR* amplitude in front crawl than in backstroke. On the other hand, maximum *HR* angle in front crawl was 18% smaller than in backstroke. The differences in maximum *SR* and *HR* angular velocities were more obvious than the roll amplitudes with the differences of 46 and 26% (larger in front crawl than in backstroke) in the maximum *SR* and *HR* angular velocity, respectively. It is unclear whether the large roll angular velocity increased *SF*, or conversely, *SF* affected the roll angular velocity. Nevertheless, the roll angular velocity remains as a potential explanation of the *SF* difference between the techniques.

There was no difference in the underwater RS_{wrist} between the two techniques, despite the difference in *SF*. On the contrary, swimmers had smaller $v_{x\text{-}wrist}$ in backstroke than in front crawl during the whole underwater phase due to the smaller $v_{x\text{-}wrist}$ during the entry, push, and release phases, while there was no difference in $v_{yz\text{-}wrist}$ during the whole underwater phase. The difference in $v_{x\text{-}wrist}$ was due to the different v_{com} between the techniques. Even though swimmers moved their wrist with an identical speed relative to the body in both techniques, the wrist moved backwards faster relative to the water in backstroke than in front crawl due to the slower forward swimming speed.

Given that the forces in water are related to the hand speed (Kudo et al., 2012), the similar underwater $v_{yz\text{-}wrist}$ between the techniques might suggest that swimmers produced an equivalent amount of lift force by the hands in both techniques. On the other hand, the result of $v_{x\text{-}wrist}$ during the push phase implied a possibility that swimmers might have applied smaller propulsive drag force by the hands in front crawl than in backstroke because a negative $v_{x\text{-}wrist}$ indicates the wrist moving backwards relative to the swimming direction. If this is the case, it implies that either backstroke had a larger active drag than front crawl or the contribution of the other body parts (such as lower limbs, upper arm, and forearm) to the propulsion is much larger in front crawl than backstroke. Nevertheless, a limitation of the present study is the lack of kinetic factors such as propulsive and resistive forces as well as the hand orientation data, which should be further investigated using kinetic analysis such as pressure distribution analysis combined with a detailed 3D motion analysis (Kudo et al., 2017; Tsunokawa et al., 2017).

In conclusion, front crawl is faster than backstroke because of its higher *SF*, which was due to the shorter absolute release phase and relative recovery phase durations. Since the information in the present study is limited to kinematics, kinetic differences between the techniques should be examined in the future.

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Table 1. Age, height, weight, and 100 m performance information of the participants.

				100 m best record		100 m FINA point	
	Age (years)	Height (cm)	Weight (kg)	Front crawl [s (%WR)]	Backstroke [s (%WR)]	Front crawl	Backstroke
Mean	17.47	179.14	69.94	54.50 (82.49)	60.56 (80.85)	562.07	529.16
SD	1.00	5.43	6.54	1.23 (1.91)	1.29 (1.72)	40.08	33.85

Table 2. Centre of mass velocity, stroke frequency and length, the timing of entry, maximum shoulder and hip roll amplitude, and maximum shoulder and hip roll angular velocity in front crawl and backstroke.

	Front crawl	Backstroke	% difference	P-value	Cohen's d
Centre of mass velocity (m·s^{-1})	1.70 ± 0.04	1.54 ± 0.06	9.52	<0.01	3.14
Stroke frequency (cycles·min^{-1})	51.67 ± 6.38	44.81 ± 4.68	13.28	<0.01	1.23
Stroke length (m·cycle^{-1})	2.00 ± 0.25	2.07 ± 0.17	3.77	0.16	0.33
Relative recovery phase duration (% stroke cycle)	28.69 ± 2.50	33.21 ± 1.43	15.74	<0.01	2.22
Entry timing (% underwater phase)	69.90 ± 2.60	74.75 ± 1.76	6.94	<0.01	2.18
Max shoulder roll amplitude (°)	52.88 ± 4.89	49.73 ± 5.73	5.95	<0.05	0.59
Max hip roll amplitude (°)	33.79 ± 6.07	39.83 ± 7.25	17.90	<0.05	0.90
Max shoulder roll angular velocity (°·s^{-1})	442.37 ± 69.82	238.08 ± 70.83	46.18	<0.01	2.90
Max hip roll angular velocity (°·s^{-1})	254.33 ± 32.97	187.90 ± 42.97	26.12	<0.01	1.73

Table 3. Duration, the distance the wrist travelled, relative wrist speed, wrist velocity in X- and YZ-direction, mean and the range of the elbow joint angle of the entry, pull, push, release, recovery, and whole underwater phases in front crawl and backstroke. * and ** show significant differences from front crawl with p<0.05 and p<0.01, respectively.

		Entry	Pull	Push	Release	Whole underwater	Recovery
Duration (s)	Front crawl	0.35±0.09	0.21±0.01	0.22±0.01	0.07±0.03	0.84±0.11	0.34±0.04
	Backstroke	0.22±0.08**	0.20±0.01	0.22±0.04	0.26±0.07**	0.90±0.08**	0.45±0.05**
	Cohen's d	1.56	0.25	0.01	3.79	0.62	2.60
Distance the wrist moved (m)	Front crawl	0.57±0.07	0.62±0.04	0.77±0.05	0.25±0.07	2.20±0.12	1.52±0.17
	Backstroke	0.40±0.09**	0.67±0.02*	0.67±0.08*	0.63±0.13**	2.37±0.12**	1.98±0.11**
	Cohen's d	2.03	1.49	1.58	3.60	1.42	3.22
Relative wrist speed ($\mathrm{m \cdot s^{-1}}$)	Front crawl	1.71±0.46	2.99±0.13	3.55±0.17	4.02±0.55	2.66±0.33	4.55±0.52
	Backstroke	1.95±0.40**	3.32±0.28*	3.22±0.42*	2.35±0.38**	2.64±0.18	4.45±0.44
	Cohen's d	0.57	1.46	1.03	3.53	0.09	0.21
Wrist velocity in X-direction ($\mathrm{m \cdot s^{-1}}$)	Front crawl	1.58±0.12	-0.79±0.10	-0.97±0.15	1.49±0.46	0.32±0.20	5.06±0.37
	Backstroke	1.30±0.26**	-0.83±0.46	-1.14±0.24*	0.91±0.37**	0.10±0.13**	4.33±0.37**
	Cohen's d	1.41	0.13	0.85	1.40	1.29	1.97
Wrist velocity in YZ-direction ($\mathrm{m \cdot s^{-1}}$)	Front crawl	1.52±0.39	1.19±0.11	1.88±0.19	3.08±0.48	1.64±0.23	2.29±0.40
	Backstroke	1.71±0.31*	1.43±0.19**	1.21±0.18**	2.09±0.36**	1.60±0.13	2.76±0.25**
	Cohen's d	0.52	1.56	3.68	2.31	0.22	1.40
Mean elbow joint angle (°)	Front crawl	169.84±2.21	136.74±7.29	117.55±3.79	140.49±10.07	145.34±2.24	136.54±19.41
	Backstroke	166.74±3.01*	135.99±11.08	125.41±11.45	166.82±2.29**	150.52±5.41*	168.16±2.22**
	Cohen's d	1.17	0.08	0.92	3.60	1.25	2.29
The range of elbow joint angle (°)	Front crawl	18.63±6.28	49.60±8.08	36.90±11.19	10.25±5.50	72.66±8.13	56.76±25.66
	Backstroke	20.99±12.86	44.71±11.85	43.43±12.12	24.93±12.22**	68.34±10.86	18.87±3.21**
	Cohen's d	0.23	0.48	0.56	1.55	0.45	2.07

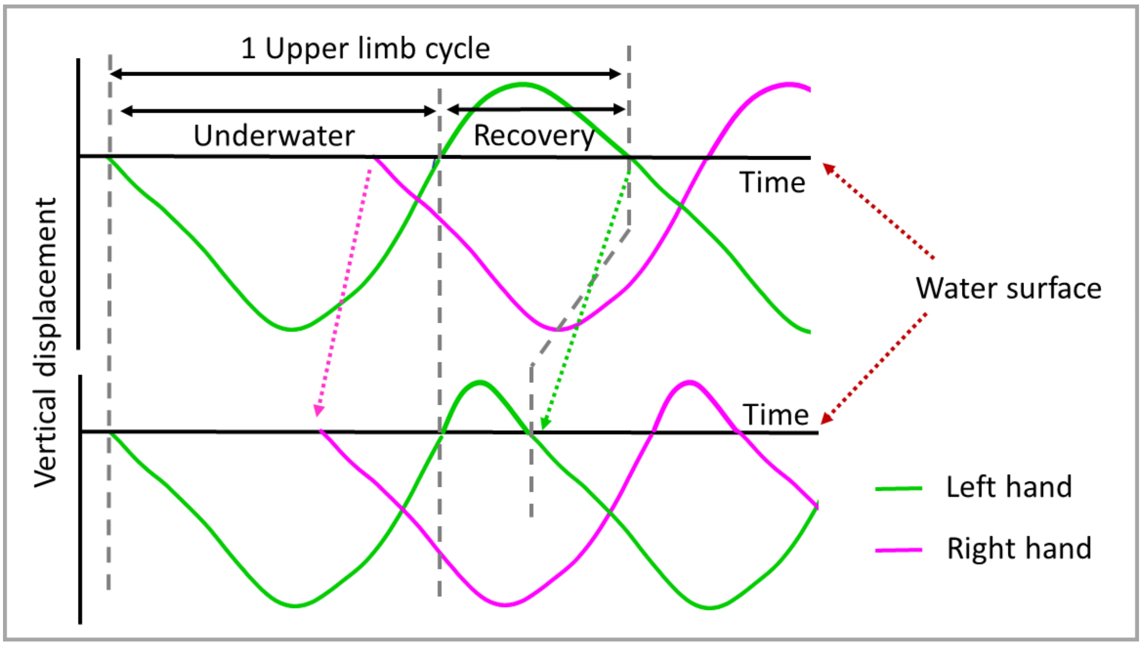


Figure 1. A model explaining the theoretical relationship between the recovery phase duration, the timing of hand entry, and upper limb cycle time (i.e., stroke frequency).

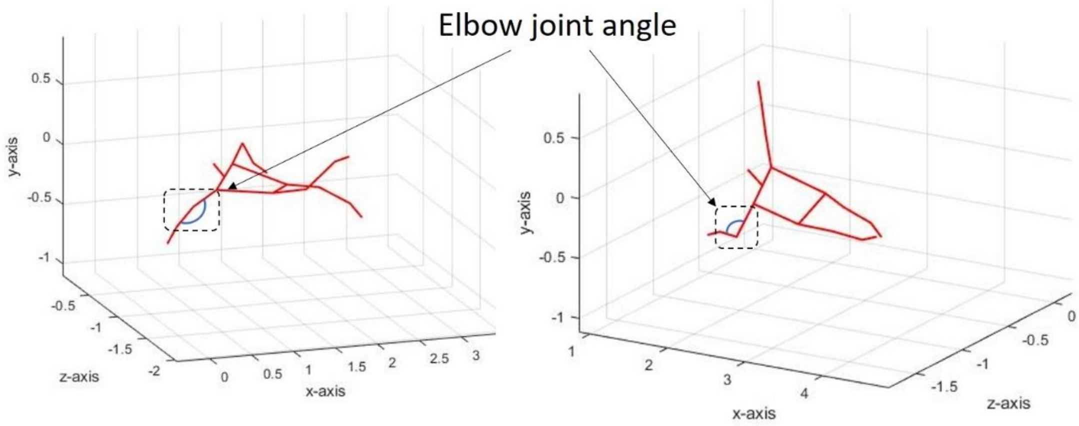


Figure 2. Elbow joint angle in front crawl and backstroke.

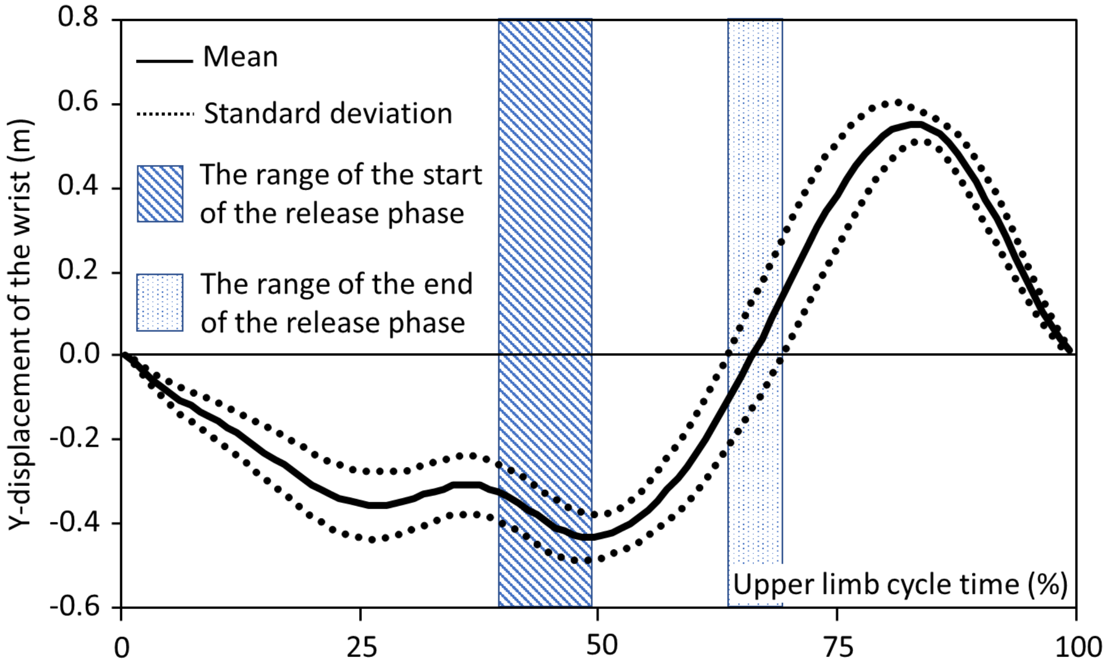


Figure 3. The mean Y-displacement (vertical direction) of the wrist among the ten participants over the upper limb cycle with a range of the start and the end of the release phase.

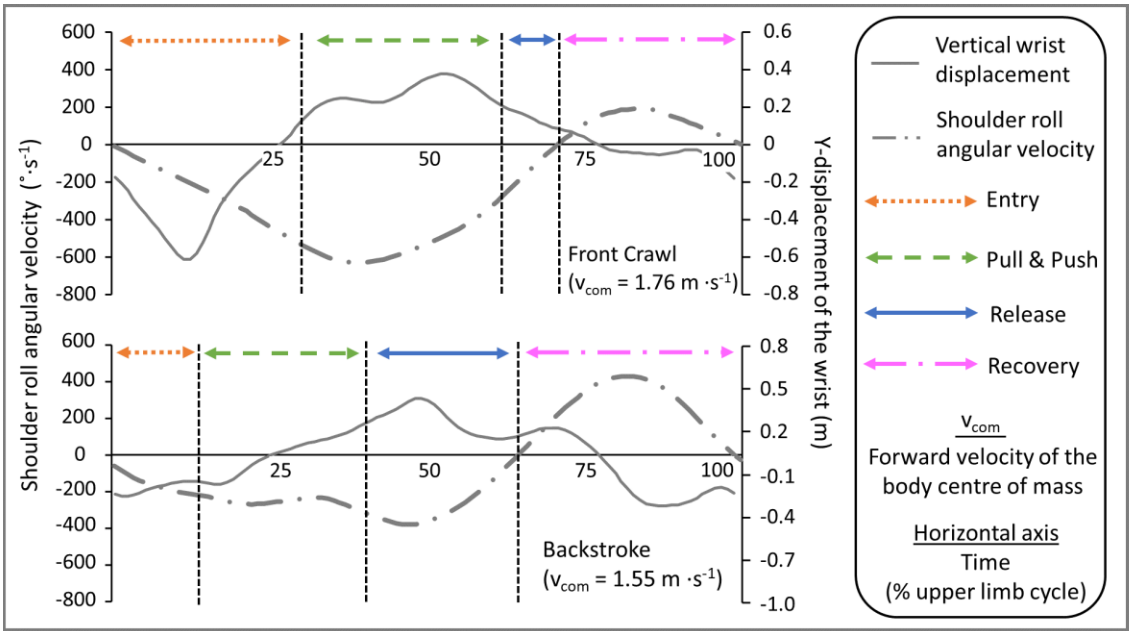
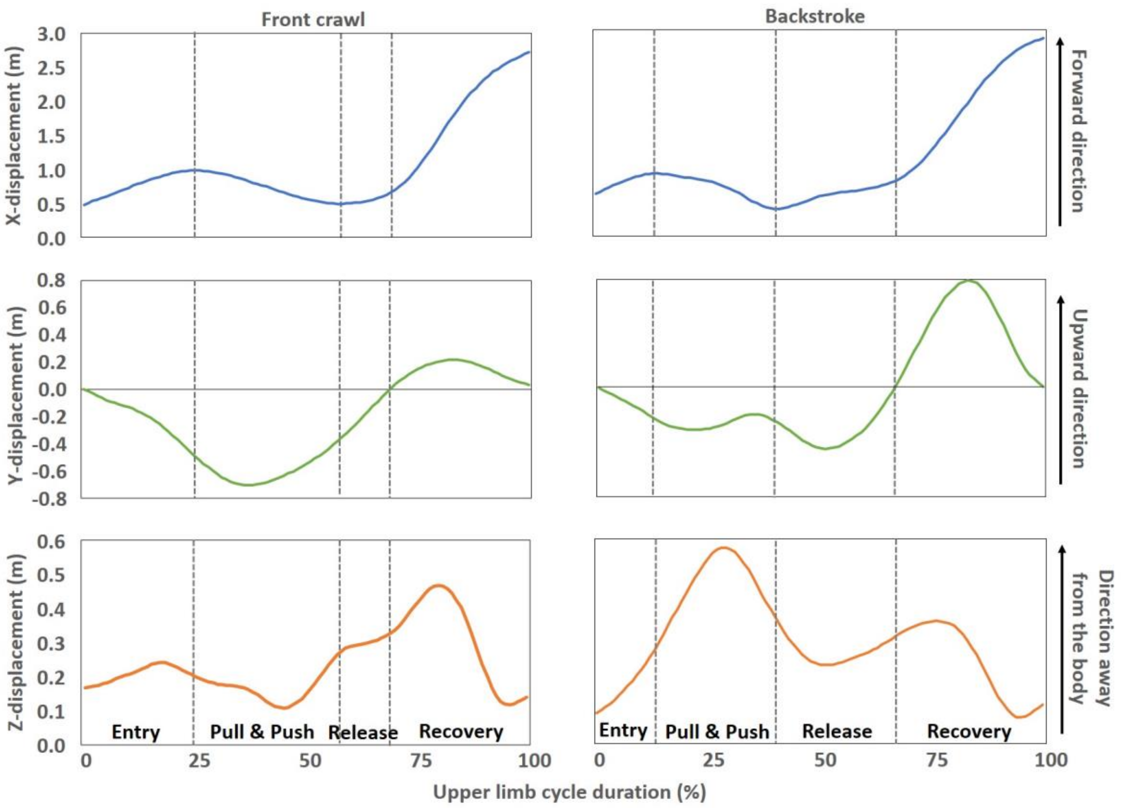


Figure 4. Examples of the Y-displacement (vertical direction) of the wrist and shoulder angular velocity in front crawl and backstroke.



Appendix 1. An example of the wrist displacement in X-, Y-, and Z-direction of the best participant.