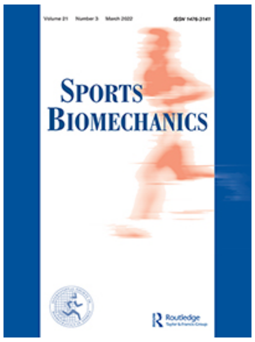


Routledge
Taylor & Francis Group

Sports Biomechanics

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rspb20

How do swimmers control their front crawl swimming velocity? Current knowledge and gaps from hydrodynamic perspectives

Hideki Takagi, Motomu Nakashima, Yasuo Sengoku, Takaaki Tsunokawa, Daiki Koga, Kenzo Narita, Shigetada Kudo, Ross Sanders & Tomohiro Gonjo

To cite this article: Hideki Takagi, Motomu Nakashima, Yasuo Sengoku, Takaaki Tsunokawa, Daiki Koga, Kenzo Narita, Shigetada Kudo, Ross Sanders & Tomohiro Gonjo (2021): How do swimmers control their front crawl swimming velocity? Current knowledge and gaps from hydrodynamic perspectives, Sports Biomechanics, DOI: 10.1080/14763141.2021.1959946

To link to this article: https://doi.org/10.1080/14763141.2021.1959946

SPORTS BIOMECHANICS
https://doi.org/10.1080/14763141.2021.1959946

How do swimmers control their front crawl swimming velocity? Current knowledge and gaps from hydrodynamic perspectives

Hideki Takagi[a], Motomu Nakashima[b], Yasuo Sengoku[a], Takaaki Tsunokawa[a], Daiki Koga[a], Kenzo Narita[c], Shigetada Kudo[d], Ross Sanders[e] and Tomohiro Gonjo[f]

[a]Faculty of Health and Sport Sciences, University of Tsukuba, Tsukuba, Ibaraki, Japan; [b]Department of Systems and Control Engineering, Tokyo Institute of Technology, Tokyo, Japan; [c]Coaching of Sports and Budo, National Institute of Fitness and Sports in Kanoya, Kanoya, Japan; [d]School Of Sports, Health & Leisure, Republic Polytechnic, Singapore, Singapore; [e]Faculty of Medicine and Health, The University of Sydney, Sydney, Australia; [f]Department of Physical Performance, Norwegian School of Sport Sciences, Oslo, Norway

ABSTRACT
The aim of this study was to review the literature on front crawl swimming biomechanics, focusing on propulsive and resistive forces at different swimming velocities. Recent studies show that the resistive force increases in proportion to the cube of the velocity, which implies that a proficient technique to miminise the resistive (and maximise the propulsive) force is particularly important in sprinters. To increase the velocity in races, swimmers increase their stroke frequency. However, experimental and simulation studies have revealed that there is a maximum frequency beyond which swimmers cannot further increase swimming velocity due to a change in the angle of attack of the hand that reduces its propulsive force. While the results of experimental and simulation studies are consistent regarding the effect of the arm actions on propulsion, the findings of investigations into the effect of the kicking motion are conflicting. Some studies have indicated a positive effect of kicking on propulsion at high swimming velocities while the others have yielded the opposite result. Therefore, this review contributes to knowledge of how the upper-limb propulsion can be optimised and indicates a need for further investigation to understand how the kicking action can be optimised in front crawl swimming.

Abbreviations: C: Energy cost [kJ/m]; $\dot{E}$: Metabolic power [W, kJ/s]; F_{hand}: Fluid resultant force exerted by the hand [N]; F_{total}: Total resultant force [N] (See Appendix A); F_{normal}: The sum of the fluid forces acting on body segments toward directions perpendicular to the segmental long axis, which is proportional to the square of the segmental velocity. [N] (See Appendix A); $F_{tangent}$: The sum of the fluid forces acting on body segments along the direction parallel to the segmental long axis, which is proportional to the square of the segmental velocity. [N] (See Appendix A); $F_{addmass}$: The sum of the inertial force acting on the body segments due to the acceleration

ARTICLE HISTORY
Received 20 January 2021
Accepted 20 July 2021

KEYWORDS
Optimum stroke frequency; propelling efficiency; computer simulation; fluid force; stroke technique

---

CONTACT Hideki Takagi takagi.hideki.ga@u.tsukuba.ac.jp

of a mass of water [N] (See Appendix A); $F_{buoyant}$: The sum of the buoyant forces acting on the body segments [N] (See Appendix A); *D*: Fluid resistive force acting on a swimmer's body (active drag) [N]; *T*: Thrust (propulsive) force acting in the swimming direction in reaction to the swimmer's actions [N]; T_{hand}: Thrust force produced in reaction to the actions of the hand [N]; T_{upper_limb}: Thrust force produced in reaction to the actions of the upper limbs [N]; T_{lower_limb}: Thrust force produced in reaction to the actions of the lower limbs [N]; M_{body}: Whole-body mass of the swimmer [kg]; *SF*: Stroke frequency (stroke number per second) [Hz]; *SL*: Stroke length (distance travelled per stroke) [m]; *v*: Instantaneous centre of mass velocity of the swimmer [m/s]; $\bar{V}$: Mean of the instantaneous centre of mass velocities in the swimming direction over the period of the stroke cycle [m/s]; *a*: Centre of mass acceleration of the swimmer [m/s2]; $\bar{V}_{hand}$: Mean of the instantaneous magnitudes of hand velocity over a period of time [m/s]; $\dot{W}_{tot}$: Total mechanical power [W]; $\dot{W}_{ext}$: External mechanical power [W]; $\dot{W}_{d}$: Drag power (mechanical power needed to overcome drag) [W, Nm/s]; *α*: Angle of attack of the palm plane with respect to the velocity vector of the hand [deg]; η_o: Overall efficiency [%]; η_p: Propelling efficiency [%]; MAD-system: Measuring Active Drag system; MRT method: Measuring Residual Thrust method.

Introduction

The recent development of technologies and methodologies in swimming biomechanics and physiology has enabled researchers to quantify complex human swimming mechanisms. In particular, knowledge of swimming energetics and fluid mechanics has improved our understanding of factors that determine swimming performance (swimming record or $\bar{v}$). A combination of energetics and biomechanics in swimming research is more informative for swimmers and coaches than findings from a single research area. Studies that employ both biomechanical and physiological methods have been summarised in review articles such as those by Barbosa et al. (2010), Zamparo et al. (2020), and Barbosa et al. (2010) summarised, in a simple diagram, the complex relationship between swimming performance, energetics (C and $\dot{E}$) and biomechanics ($\bar{v}$, a, $\bar{V}_{hand}$, *SF*, *SL* and the index of coordination). Zamparo et al. (2020) summarised findings of many studies of swimming energetics in a diagram showing the relationship between various metabolic power (e.g., C, $\dot{E}$, $\dot{W}_{total}$, $\dot{W}_{external}$ and $\dot{W}_{drag}$) and efficiency (e.g., η_o and η_p) indices. Furthermore, Zamparo et al. (2020) discussed those factors in combination with biomechanical indices such as *SF* and *SL* to illustrate how all those factors are associated with swimming performance.

In addition, *D* and *T* acting on swimmers have been popular topics. Due to the complexity of unsteady flow mechanics in human swimming, it is currently impossible to measure *D* and *T* directly. Thus, researchers have established indirect methods to estimate these forces, such as the 'energetics' approach (Pendergast et al., 2005; di Prampero et al., 1974; Zamparo et al., 2009), the MAD-system (Toussaint, 1990; Toussaint & Beek, 1992; Toussaint, Beelen et al., 1988; Toussaint & Hollander, 1994; Toussaint et al., 1991), velocity perturbation method (Kolmogorov & Duplishcheva,

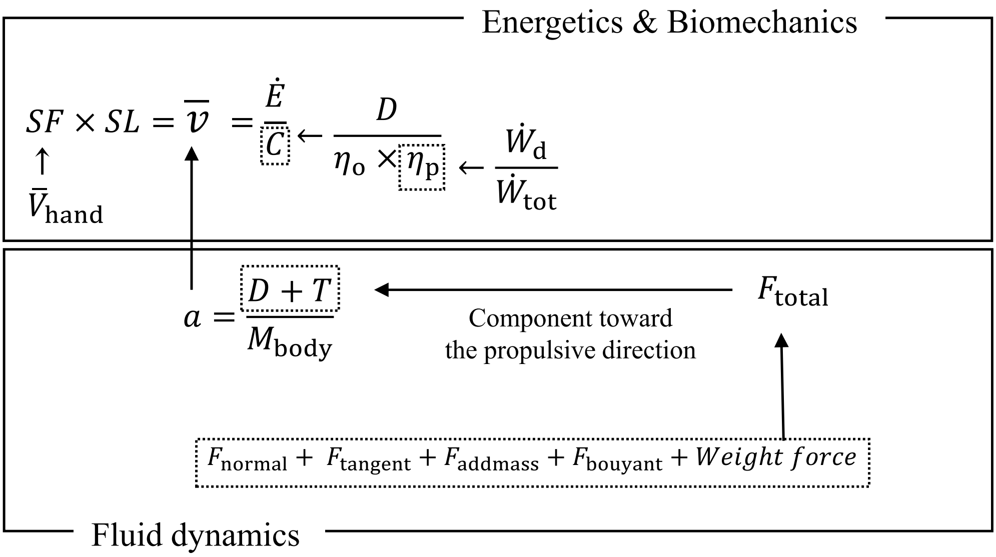


Figure 1. The relationships between energetic, biomechanical and fluid dynamics indices in competitive swimming. For the meaning of abbreviations, see the Abbreviations section in the main text. The upper panel shows the calculation method and relationship between the biomechanical and energetic indices. For detailed definitions and calculation procedures of each index, see Zamparo et al. (2020). The lower panel shows the equation describing the motion of the swimmer (Newton's second equation) and the five forces acting on the swimmer. These five forces correspond to the forces calculated by the Swimming Human Simulation Model (SWUM); see Appendix A for an overview as well as Nakashima (2007) and Nakashima et al. (2007) for details.

1992), assisted towing method (Formosa et al., 2012), MRT method (Gonjo et al., 2020; Narita et al., 2017, 2018). These methods enable researchers to estimate D (and consequently T, when the swimmer maintains a constant velocity) acting on the whole body but do not provide information on the sources of the total forces. Therefore, pressure sensors have been used to estimate T_{hand} in recent years (Koga et al., 2020, 2021; Kudo et al., 2012; Tsunokawa et al., 2019).

The interrelationships between the biomechanical and physiological factors presented above can be summarised as shown in Figure 1 (upper panel). These previous studies have established factors that determine $\bar{v}$. However, many phenomena require further investigation.

For example, it is not yet clear how hydrodynamic factors such as D and T change with control in $\bar{v}$. The lack of evidence might be due to many methods being only applicable in limited conditions. For example, the MAD-system consists of fixed-pads that are connected to a load cell, and the swimmer is required to propel forward by pushing off each pad. Under the assumptions of (i) $\bar{v}$ being constant during the trial and (ii) the pushing-off force is the only source of the propulsion, the measured force can be considered as T, and D can be assumed to be the same amount of force acting in the opposite direction. However, due to this specific setting and assumptions, the only type of locomotion that suits the system is arm-only front crawl.

The fully tethered swimming method is a useful approach to assess T exerted by the swimmer in all four swimming strokes (Morouço et al., 2011). With this method, swimmers are connected to a load cell with a wire, and they are required to swim at a fixed position. As the load cell would not be able to measure the tether force when the wire is loose, it is essential to ensure that the wire is taut throughout the trial. However, this is not always the case as all four swimming strokes have a period of time between left and right upper-limb motion or upper- and lower-limb motion during which the swimmer is likely to be accelerated backwards due to the reaction force from the wire. The duration of that time period has a negative correlation with the swimming velocity, meaning that the duration increases with decreasing swimming intensity (Chollet et al., 2000, 2006, 2008; Seifert & Chollet, 2005). Thus, it is likely that applying the fully tethered swimming method for testing swimmers with their sub-maximal effort (in which there is a long time gap between propulsive phases) causes larger systematic errors than testing with the maximal effort.

Methods to estimate D during a whole-body swimming condition include the velocity perturbation method (Kolmogorov & Duplishcheva, 1992) and the assisted towing method (Formosa et al., 2012). Both methods require two testing conditions; one with free-swimming and the other with passive or active towing with a known force. Under the assumption that the swimmer produces the same $\dot{W}_{\mathrm{d}}$ in the two conditions, D can be mathematically computed. Unlike the MAD-system, which can only be applicable to arm-only front crawl, these methods can be utilised for all four strokes without limiting their locomotion mode to arm-only swimming. However, since controlling $\dot{W}_{\mathrm{d}}$ is an unrealistic task for swimmers, the two methods have only been employed when assessing D at the maximal effort under the assumption that $\dot{W}_{\mathrm{d}}$ is unchanged when swimming with the maximal effort regardless of the addition of external resistance. Nevertheless, even in the maximal effort condition, the 'same power output' assumption has sometimes been criticised because standardising the subjective effort (by assigning maximum effort tasks) does not necessarily guarantee equal $\dot{W}_{\mathrm{d}}$ between the conditions (Toussaint et al., 2004).

A paucity of information on the relationships among hydrodynamic factors at a wide range of $\bar{v}$ caused a lack of evidence on simple swimming phenomena such as *SF*, *SL*, and $\bar{v}$. In swimming, $\bar{v}$is expressed as the product of *SF* and *SL*, and swimmers usually increase their $\bar{v}$ by increasing *SF* in a short term because it is essential to increase the speed of the limbs in the water to produce larger propulsive forces (Schleihauf, 1979). However, beyond a certain *SF*, $\bar{v}$ decreases (Barbosa et al., 2008; Craig & Pendergast, 1979; Termin & Pendergast, 2000); this phenomenon is illustrated in Figure 2 using datasets obtained by Koga et al. (2020); (2021)). Swimmers increase *SF* to gain a large T so that they can offset D that increases in a $2 - 3$ power exponential relationship with the increase in $\bar{v}$ (Hollander et al., 1986; Narita et al., 2018). However, the relationship between *SF* and $\bar{v}$ presented in the literature (Barbosa et al., 2008; Craig & Pendergast, 1979; Termin & Pendergast, 2000) and Figure 2 indicate that, after a certain *SF*, swimmers cannot increase their T by further increasing their *SF*.

Furthermore, knowledge of the contribution of kicking to propulsion is also lacking. A previous study (Gatta et al., 2012) showed that kicking could produce propulsion up to 2 m/s speed but the kicking propulsion reduced from 42 to 9 N when increasing the speed from 1.27 to 2 m/s. This result suggests that the effect of kicking on swimming performance is different between high and low $\bar{v}$ conditions.

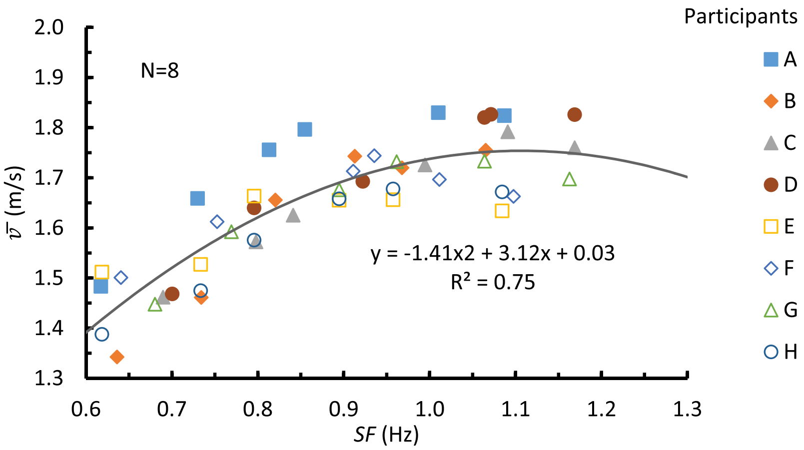


Figure 2. Relationship between SF and $\bar{v}$in front crawl. New drawing with data presented in Koga et al. 2020, 2021, in which eight male university swimmers (A—H) participated.

Most of the swimming races are performed under the maximal $\bar{v}$ except for a very short event (e.g., 50 yards or 50 m), because the goal of the race is not to achieve the fastest $\bar{v}$ possible at one point of the race, but to control the energy output to maximise the mean $\bar{v}$ during the race. Therefore, it is of great importance for researchers to investigate fluid dynamics in swimming performed at a wide range of $\bar{v}$. The purpose of the current article is to summarise the literature on D and T at different $\bar{v}$, with a specific focus on front crawl swimming. An initial search of the articles was conducted using three electronic databases (SPORTDiscus, Web of Science, and PubMed) using Front crawl OR freestyle; drag OR thrust OR propulsive force OR resistive force; velocity change OR velocity increase OR velocity decrease; and stroke frequency OR stroke rate as key words. Since only 11 articles remained after a screening process following the study focus, materials based on the reference list of the 11 articles and manual search were also included. This study consists of different sections that focus on D (acting on the whole-body) and T (exerted by the upper- and lower-limbs) and different methods to quantify these factors. In Section 2, simulation and experimental methods that enable researchers to assess D acting on the whole-body at a wide range of $\bar{v}$ are introduced and discussed.

Relationships between swimming velocity and the mean thrust and resistive force

The magnitude of D and T are equal at constant $\bar{v}$, meaning that investigating the mean D during swimming can be rephrased to the mean T assessment as long as the net acceleration of the analysed period is zero. A pioneer of assessing D is a group led by di Prampero. They established a method of estimating D using a linear relationship between the energy expenditure and external loads (di Prampero et al., 1974). As the method is based on physiological measures, it is beneficial to assess not only D but also propelling efficiency (Zamparo et al., 2005). On the other hand, the limitation of this energetics approach is that it relies on the accuracy of the energy expenditure measurement. Even though this approach has been used to assess D at large using both oxygen uptake and conversion of the blood lactate value to oxygen equivalent using fixed values (e.g., 3 mlO_2/mM/kg), the accuracy of which at high exercise intensities has still been debated (Zamparo et al., 2011) due, for example, to a large inter-individual variability of the oxygen-lactate relationship (Thevelein et al., 1984).

Toussaint et al. (1988) investigated the relationship between $\bar{v}$ and D during front crawl without lower-limb movements using the MAD-system and reported that D increased in proportion to the square of $\bar{v}$. The MAD-system overcame the limitation of the energetics approach as it does not require the energy expenditure assessment, i.e., the accuracy of the method does not depend on the exercise intensity. Nevertheless, the system can only be applied to arm-only front crawl, which is its own limitation.

Narita et al. (2017) established the MRT method, which is similar to the energetics approach. Instead of the energy expenditure, this method utilises the residual thrust produced by the flow velocity change (while maintaining a given swimming motion) to compute D, which enables the approach to be applied to any types of surface swimming with a wide range of $\bar{v}$. In their study, it was reported that D had a cubic relationship with $\bar{v}$ in whole-body front crawl (Narita et al., 2017, 2018). In another study (Narita et al., 2018), it was shown that the degree of a polynomial in the modelled relationship between D and $\bar{v}$ is larger in the MRT method (degree of a polynomial = 2.5) than that obtained with the MAD-system (degree of a polynomial = 1.9) in arm-only front crawl.

The cause of the difference between the methods is currently unknown. However, it might be due to a difference in the propulsive mechanism between the methods. With the MAD-system, the $\bar{V}_{\text{hand}}$ relative to the water is always zero as the swimmer propels through the water by pushing a fixed pad, which potentially means that the production of turbulence and vortices by the hand is also minimal because the kinetic energy transferred from the hand to the water is zero. In the MRT method, the hand sweeps the water freely, as is the case in free-swimming. During free-swimming, the ratio of $\bar{v}$ to $\bar{V}_{\text{hand}}$ reduces as $\bar{v}$ increases (Gonjo et al., 2020), meaning that $\bar{V}_{\text{hand}}$ increases more than $\bar{v}$ when incrementing the swimming intensity. This suggests that the amount of kinetic energy transferred from the hand to the water has a positive relationship with $\bar{v}$, which could mean greater turbulence and vortices produced by the hand when swimming fast than slow. In other words, the MAD-system might underestimate D due to a lack of unsteady fluid factors. Furthermore, it should be borne in mind that the swimming technique with the MAD system may not replicate the postures adopted in free-swimming due to a lack of lower-limb motions, the stroke length is constrained by the spacing of the pads, and the effects of reaction torques from the pad that are likely to generate torques different from the torques obtained from the water in free-swimming. Nevertheless, it should be noted that the MRT method also has a limitation that swimmers are assumed to be able to reproduce the same motion regardless of the environmental (flow velocity) change.

The polynomial association between D and $\bar{v}$ and the positive relationship of SF with $\bar{v}$ suggest that SF also has a positive relationship with D. Indeed, a study by Narita et al. (2018) showed strong positive correlations between D and SF in both MAD-system ($r = 0.97$) and MRT methods ($r = 0.81$). However, the interpretation of the relationships of D with SF is complex as SF and $\bar{v}$ are strongly related to each other. Since the increase or decrease in SF changes $\bar{v}$, it would be difficult to discuss the relationship between SF

and D independent of the effect of changes in $\bar{v}$. In experimental conditions, it would not be practical for swimmers to control only SF without changing $\bar{v}$; therefore, simulation studies would be useful to assess the single effect of SF on D.

Even though assessing the mean D and T using the methods summarised in this section are useful to know the overall effect of these forces on the velocity, it is currently difficult to investigate sources of T and D in detail as drag coefficient changes with the velocity. For example, Zamparo et al. (2009) reported a decrease in the drag coefficient with the increase in the velocity due to the change in the trunk incline and the frontal surface area. A similar result was reported by Gonjo et al. (2020) who showed that the underwater body volume in front crawl decreases with an increase in $\bar{v}$. It is unclear how much that change affects D. It is currently challenging to explore such detailed relationships between swimmers' kinematics and D experimentally. Computer simulation is a useful method to overcome the difficulty, and several simulation models for swimming research have been established in the last several decades. In the next section, computer simulation studies of D and T in different swimming $\bar{v}$ conditions are summarised.

Swimming motion simulation at various swimming velocities

Among several computer simulation methods, the application of computational fluid dynamics (CFD) in swimming research has been growing in recent years [e.g., Cohen et al. (2015)]; the history of the research and its main results are summarised in a paper by Takagi et al. (2016). The CFD is a powerful tool to visually assess the fluid flow around swimmers to understand the propulsive mechanisms. However, despite the advantages of CFD, it might not be convenient for the determination of hydrodynamic phenomena over a wide range of $\bar{v}$ (in other words, a large number of simulations), due to long computational time required. For example, CFD simulation on front crawl swimming has been conducted by Cohen et al. (2014, 2015, 2018, 2020), but they have reported that the simulation took around 44 – 141 h with 12 core Intel Xeon processors (Cohen et al., 2020) that greatly outperform common processors (such as Intel Core i5 series with four or six cores).

Therefore, an alternative computer simulation method that requires less computation time than CFD has been developed by Nakashima and his group (Nakashima, 2007; Nakashima et al., 2007), which is called the SWUM model. An advantage of the SWUM model is a simplified calculation. This model considers fluid forces (F_{normal} and F_{tangent}), F_{bouoyant}, F_{addmass} and weight force acting on each body segment, while it does not expand the calculation to the complex flow field (see Appendix A). Therefore, the computation time of SWUM is much shorter than the CFD and thereby it enables researchers to conduct multiple simulations, such as swimming motion at different $\bar{v}$. Omitting the flow field calculation could potentially cause errors when there are interactions between flows generated by body parts or between the flow and an object, such as the in-sweep in butterfly upper-limb stroke motion, the last phase of the breaststroke kicking, or when swimming near the wall. However, in front crawl, the primary source of the propulsion is the upper-limbs (Deschodt et al., 1999) that move alternatively; therefore, it is unlikely that there are major flow interactions that affect the simulation result. Thus, the SWUM model is especially useful when simulating front crawl at a wide range of $\bar{v}$. The SWUM model was validated by comparing the experimental and simulated velocities and forces (Nakashima, 2009; Nakashima & Ejiri, 2012; Nakashima et al., 2018; Nakashima & Takahashi, 2012; Nakashima et al., 2020, 2019). The results showed errors of 1–7.5% in velocity and 10% in force for various strokes, including the front crawl (see Appendix B). Among the studies with the SWUM model, papers that are particularly relevant to swimming velocity control (i.e., changes in *SF*) are summarised in the next sub-sections together with other relevant simulation and experimental studies.

Relationships between SF and each parameter (SL, $\bar{v}$, T_{upper_limb}, T_{lower_limb}, $\dot{W}_{tot}$ and η_p)

Figure 3 shows the relationship between each index (*SL*, $\bar{v}$, $T_{\mathrm{upper\_limb}}$, $T_{\mathrm{lower\_limb}}$, $\dot{W}_{\mathrm{tot}}$ and η_{p}) and *SF* (8 levels) when the SWUM model was used to optimise front crawl swimming motion with 6-beat kicking (Nakashima et al., 2012). Relationships among *SF*, *SL* and $\bar{v}$ derived from the simulation (Figure 3(a)) are similar to those from experimental studies (Figure 2). The similarity in *SF*-$\bar{v}$ curve between Figures 2 and 3(a) was particularly notable, which peaked at around *SF* = 1.1 Hz and then decreased.

T produced by human swimmers can be divided into $T_{\mathrm{upper\_limb}}$ and $T_{\mathrm{lower\_limb}}$. As shown in Figure 3(b), in the simulation, $T_{\mathrm{upper\_limb}}$ increased with increasing *SF* but peaked at *SF* = 1.1 Hz. On the other hand, $T_{\mathrm{lower\_limb}}$ was negative in most of *SF*s (0.6–1.1 Hz) and then became positive above the *SF* range, meaning that it acted as *D* in most of the cases except for very high $\bar{v}$ condition. However, it should be taken into account that the SWUM model uses a 6-beat kicking even at low velocity, which is different from that of an actual human swimmer. On the other hand, another simulation study with a CFD model (Cohen et al., 2018) showed the opposite result. They reported that the ratio of $T_{\mathrm{upper\_limb}}$ to $T_{\mathrm{lower\_limb}}$ was 1.1 and 2.5 when *SF* was 0.71 and 1.00, respectively, meaning that nearly 50% of propulsion was produced by the lower limbs at the low *SF* condition, which reduced to around 19% as *SF* increased to 1.1 Hz.

Experimental studies have also shown inconsistent evidence. For example, Gatta et al. (2012) used a towing device to measure the drag of elite swimmers who performed maximal kicking motion while maintaining a streamlined posture. They reported that $T_{\mathrm{lower\_limb}}$ became lower as the velocity increased, implying that the kicking motion has a more positive effect at low $\bar{v}$ than at high $\bar{v}$, which is opposite of what was reported in Nakashima et al. (2012). On the other hand, Narita et al. (2018) compared *D* between whole-body and arm-only front crawl swimming and reported that *D* during the whole-body swimming was almost the same as arm-only when $\bar{v}$ was 1.1 m/s while it was higher than arm-only swimming when $\bar{v}$ was increased to 1.3 m/s. This result suggested that the kicking had a negative effect at 1.3 m/s.

As it is currently difficult to directly measure $T_{\mathrm{upper\_limb}}$ and $T_{\mathrm{lower\_limb}}$ separately during a free-swimming condition, it is inconclusive whether front crawl kicking has a positive or negative effect on *T* at a wide range of $\bar{v}$. Therefore, further studies are necessary to establish the effect of kicking on *T*. As the first step, conducting a study with a flow visualisation technique, such as Particle Image Velocimetry, would be useful to quantify the flow field around the feet during front crawl swimming, as has been done for undulatory swimming (Shimojo et al., 2019)

As presented in Figure 3(c), $\dot{W}_{\mathrm{tot}}$ increased linearly with *SF* and reached 897.6 W at *SF* of 1.1 Hz, where the modelled swimmer also achieved its maximum $\bar{v}$. This result agreed well

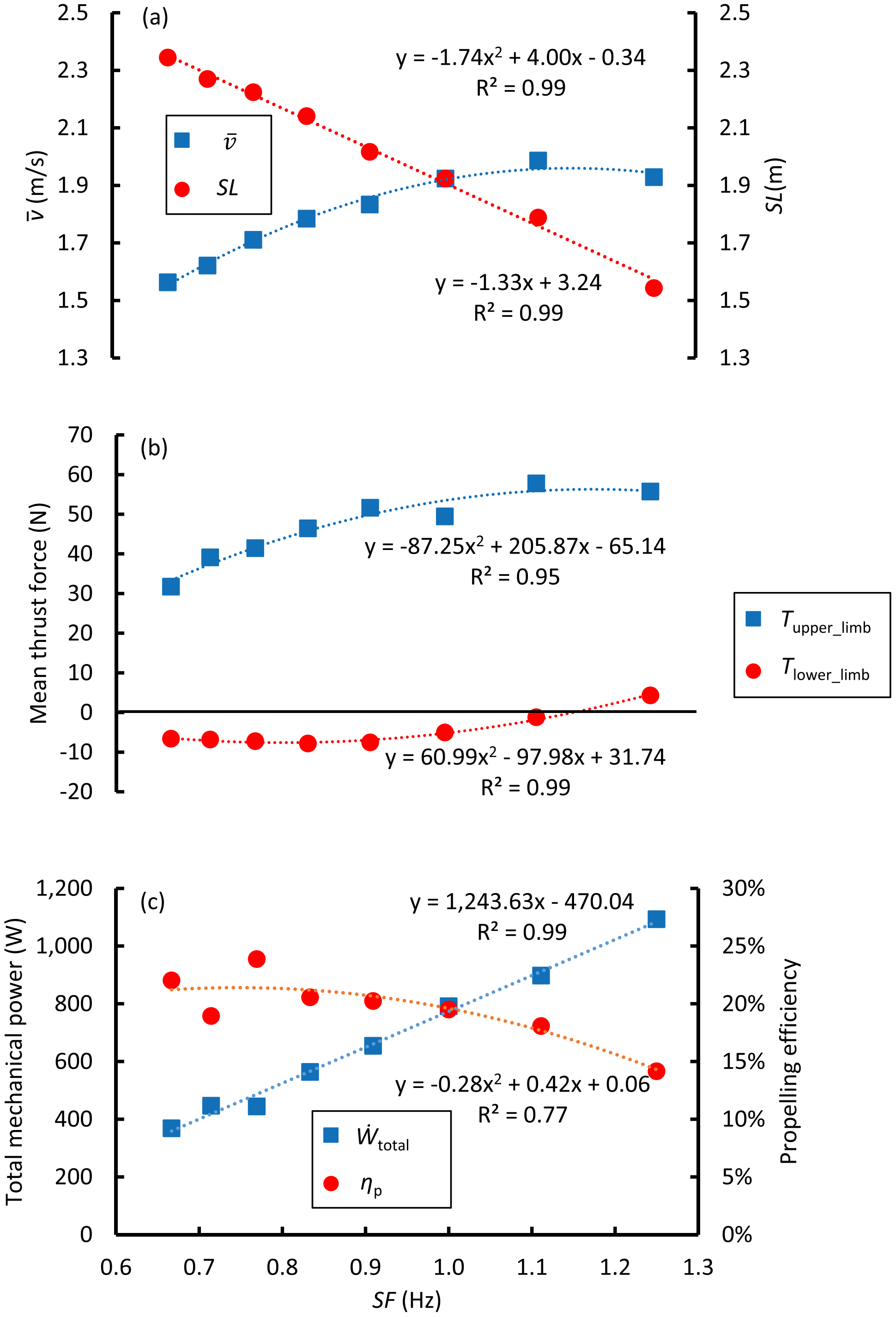


Figure 3. The relationship between *SF* and other parameters (*SL*, $\bar{v}$, $T_{\text{upper\_limb}}$, $T_{\text{lower\_limb}}$, $\dot{W}_{\text{total}}$ and η_p) when the swimming motion is optimised to maximise $\bar{v}$at each *SF* (Results of swimming simulations using SWUM) .

with the findings of an experimental study by Gatta et al. (2018) who reported $\dot{W}_{\mathrm{tot}}$ of 940 ± 92 W from an on-land front crawl motion test with a full-body ergometer. On the other hand, results of η_{p} are conflicting between simulation and experimental studies. Figure 3(c) displays a negative relationship trend between *SF* and η_{p} derived from the SWUM model, with the maximum and minimum η_{p} of 23.9% (at $SF = 0.77$ Hz) and 14.2% (at $SF = 1.25$ Hz), respectively. However, in an experimental study (Zamparo et al., 2005), the estimated efficiency during the front crawl was reported to be around 25–40% depending on competitive levels, sex, and age (Zamparo, 2006; Zamparo et al., 2011, 2008). There is currently no method that enables researchers to obtain a 'true' η_{p}, and it is unclear which results (the simulation or experimental testing) are more accurate than the other. Nevertheless, it can be stated that η_{p} during front crawl swimming falls somewhere between 15% and 40% and that most of the work done by the swimmer does not contribute to *T*.

As shown in Figure 3(b), the primary source of *T* is the action of the upper-limbs (Nakashima et al., 2012). The question then arises as to which part of the upper-limb contributes the most to *T*.

Which parts of the upper-limb contribute to propulsive force?

Table 1 summarises the mean thrust exerted by each upper-limb part and its contribution to *T* produced by the whole upper-limb at various *SF*, using simulation results by Nakashima et al. (2012). Most of the thrust was produced by the hand (94%), followed by the contribution of the forearm and upper arm. This means that the hand has a major influence on $\bar{v}$. Interestingly, the actions of the upper arm did not contribute much to *T*; rather, they contributed to *D* at all *SF* conditions (the contribution ranged from −8.44% to −4.51%). Another notable simulation result is that the contribution of the hand dropped to less than 90% when $SF \geq 1.1$ Hz. This was probably due to a change in the hand kinematics in the push phase as Nakashima et al. (2012) reported that 'it can be seen that the hand did not push the water at this moment by turning the palm to the side when $T = 0.9$ s, while the hand pushed the water firmly when $T = 1.3$ s' (Here, 'at the moment' refers to the end of the underwater stroke motion, and unlike the current study where '*T*' is defined as the thrust, Nakashima et al. (2012) defined it as a stroke cycle duration). Even though this result from the simulation was rather descriptive, researchers confirmed the same phenomenon in experimental studies, which are summarised in Section 4.

Table 1. The mean thrust exerted by each upper limb segment and its contribution to the total thrust exerted by the whole upper limb at various *SF*.

SF	v	Hand		Forearm		Upper arm		Upper limb
(Hz)	(m/s)	(N)	(%)	(N)	(%)	(N)	(%)	(N)
0.67	1.56	31.07	97.92	3.24	10.20	−2.58	−8.12	31.73
0.71	1.62	35.87	91.73	4.99	12.77	−1.76	−4.51	39.10
0.77	1.71	39.28	94.79	4.68	11.29	−2.52	−6.08	41.44
0.83	1.78	44.01	94.79	4.75	10.24	−2.33	−5.03	46.43
0.91	1.83	51.68	100.12	3.71	7.19	−3.77	−7.31	51.62
1.00	1.92	50.73	102.60	2.89	5.84	−4.17	−8.44	49.44
1.11	1.99	49.21	85.18	12.50	21.64	−3.94	−6.82	57.77
1.25	1.93	49.12	88.12	10.17	18.24	−3.55	−6.36	55.74
Average		43.87	94.41	5.87	12.17	−3.08	−6.58	46.66

Measurement of biomechanical and fluid mechanic parameters using actual swimmers

In the previous section, the simulation results showed that most of the contribution to T from the upper-limbs is due to the hand. In the current section, we review the results of experimental studies that measured the fluid force produced by actual swimmers' hands. Since a quasi-static study by Schleihauf (1979) and Schleihauf et al. (1988) was published, the estimation of the hand thrust was mainly conducted using the same or similar method based on underwater film or video analysis [e.g., Berger et al. (1995); Cappaert et al. (1995)]. However, Pai and Hay (1988) reported that a quasi-static approach severely underestimates fluid forces when assessing motions with high frequency and acceleration, including swimming. In the last two decades, studies using pressure distribution measurement methods have been utilised [e.g., Kudo et al. (2008), Schnitzler et al. (2011), Takagi and Wilson (1999), Tsunokawa et al. (2019), and Tsunokawa et al. (2012), and Tsunokawa et al. (2018)]. The advantage of the pressure distribution measurement method is that, unlike the quasi-steady method, it estimates the fluid force acting on the hand by constantly measuring pressure changes on the surface of the hand caused by unsteady factors (e.g., turbulence and vortices). The pressure sensors provide kinetic information as a scalar quantity. However, in combination with 3D underwater motion analysis, the direction of the fluid force acting on the hand can also be obtained. Here we present the results of experiments (Koga et al., 2020, 2021) that measured the kinematic parameters of swimming motion and fluid mechanical parameters acting on the hand for a range of *SF*. In the following sub-sections, the impact of changing *SF* on other variables is discussed. Section 4.1 focuses on kinematic variables, and Section 4.2 discussed kinetic parameters, respectively.

Changes in kinematic parameters (SL, $\bar{v}$, $\bar{V}_{\text{hand}}$ and α) when increasing SF

Figure 4(a), which was created by the authors using the experimental data presented in Koga et al. (2020, 2021)), shows *SL* and $\bar{v}$ at 70%, 80%, 90%, 100%, 110% and 120% of the *SF* in the pre-measured maximal front crawl condition. The figure shows that $\bar{v}$peaked at *SF* = 100% and then plateaued or slightly decreased as the *SF* increased to 110% and 120%. On the other hand, *SL* decreased linearly with the increase in *SF*. These results are in good agreement with the SWUM simulation results (Figure 3(a)) and other experimental studies (Barbosa et al., 2008; Craig & Pendergast, 1979; Termin & Pendergast, 2000). $\bar{V}_{\text{hand}}$ during three stroke segments generally increased with increasing *SF* as shown in Figure 4(b). During the push phase, however, did not change much at 70%-80% *SF* but increased linearly above 90% *SF*. Changes in $\bar{V}_{\text{hand}}$ over one stroke cycle and *SF* were also examined in 10 various $\bar{v}$ conditions in another study (Tsunokawa et al., 2019), where a linear increase in $\bar{V}_{\text{hand}}$ was also observed from low to high $\bar{v}$. Changes in the mean α in each phase are also shown in Figure 4(c). The mean α in all phases did not show a clear increase or decrease trend up to 100% *SF*, which was in accordance with (Samson et al., 2015, 2019). On the other hand, the mean α during the push phase tended to decrease when *SF* exceeded 100% *SF*.

In summary, $\bar{v}$ increased with increasing *SF*, but plateaued or decreased when *SF* exceeded a certain *SF*, and a change in α due to an excessive increase of *SF* was also

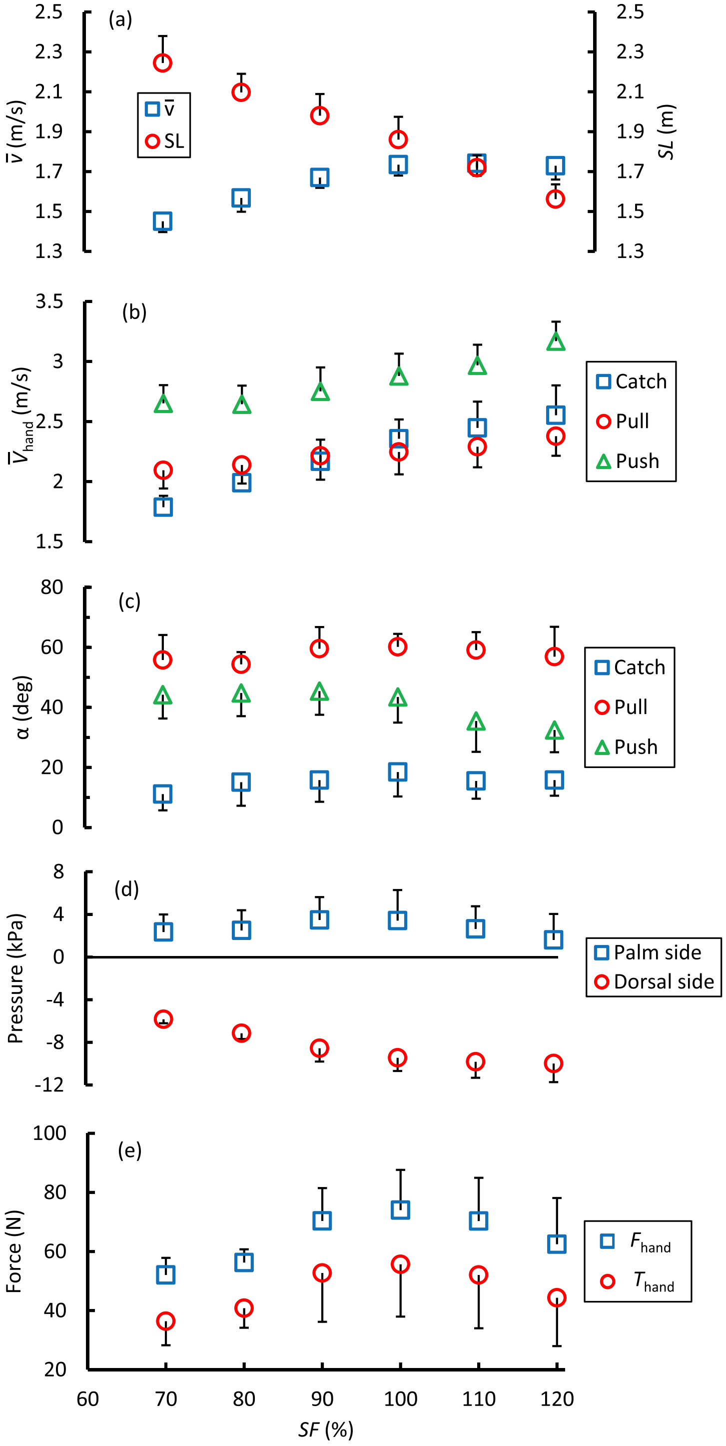


Figure 4. Changes in kinematic indices (*SF*, *SL*, $\bar{v}$, $\bar{V}_{hand}$, *α*), pressure values, F_{hand} and T_{hand} at 70%, 80%, 90%, 100%, 110% and 120% of the *SF* at a pre-measured maximal front crawl.

observed, suggesting that SF may be a key factor in controlling $\bar{v}$ but excessive SF may not have a positive effect on performance because it negatively affects other kinematic variables.

Changes in fluid mechanic parameters (pressure values, F_{hand} and T_{hand}) in each stroke phase at varied SF

In section 4.1, we summarised that $\bar{v}$ increases in proportion to SF only up to a certain SF. In this section, we discuss how pressure around the hand, F_{hand} and T_{hand} change as SF increases. Figure 4(d), which was again created using experimental data presented in Koga et al. (2020, 2021)), shows changes in average pressure on the palm side and dorsal side (average value of three pressure sensors put on each side) of a hand at six selected SF. As the pressure describes the fluid force acting on a unit area (m^2), F_{hand} can be estimated by multiplying the area of the hand by the difference in the pressure between the palm- and dorsal-side of the hand (Takagi & Wilson, 1999). Due to commonly used words such as ‘pull’ or ‘push’ to describe swimming stroke motion, one might think that increasing the pressure acting on the palm side of the hand would result in a large F_{hand}. As shown in Figure 4(d), the pressure on the palm indeed shows a slight increase from 70% to 100% SF (and decreased from 100% to 120% SF, assumingly due to a decrease in α, as discussed in the previous section). However, a decrease (with an increase in SF) in the dorsal side’s pressure is more notable than the palm side. For detailed information on why the pressure on the dorsal hand changes more than the palm side, refer to other studies (Takagi et al., 2013; Takagi, Nakashima et al., 2014; Takagi, Shimada et al., 2014). Briefly, strong vortices on the dorsal surface of the hand affected an increase in the negative pressure.

Figure 4(e) shows that both F_{hand} and its propelling directional component T_{hand} increased from 70% to 90% SF, peaked at 100% SF, and then decreased from 110% to 120% SF. The increase in the mean T_{hand} was indirectly supported by Schnitzler et al. (2011) who showed the propulsive impulse during one stroke cycle was unchanged among five velocity conditions (ranging from 60% to 100% of maximum velocity) with a similar method as Koga et al. (2020, 2021). Given that the stroke duration becomes shorter when increasing SF ($34.8 - 51.8$ Hz in the study by Schnitzler et al.), the mean T_{hand} should also have been increased in their study. Combining these data and the kinematic changes described in the previous section, a likely explanation of the mechanism of the plateau in $\bar{v}$ would be: Swimmers need to increase SF to achieve a large $\bar{v}$, but beyond a certain SF, swimmers cannot maintain a proper α, which causes a decrease in the palm side pressure, and as a consequence, the pressure difference and F_{hand} also decrease.

Practical implication and recommendations

As discussed in the previous sections, characteristics of D and T exerted on swimmers differ between low and high $\bar{v}$ in front crawl swimming. Therefore, the required swimming technique is likely to be different between long-, middle- and short-distance swimmers. Because D has a $2 - 3$ power exponential relationship with $\bar{v}$ (Narita et al., 2017, 2018), obtaining a swimming technique to increase η_{p} is essential for sprint swimmers so that they can overcome a large D by maximising T. Swimmers make much effort to improve their η_p, and one of the effective methods is the use of equipment. In swimming training, various tools are used to improve η_p, among which hand paddles are common training equipment (Toussaint et al., 1991). A recent paper (Tsunokawa et al., 2018) showed that the use of hand paddles did not increase F_{hand} but make T_{hand} higher compared with swimming without paddles. Furthermore, it has also been suggested that the use of paddles does not increase $\dot{W}_d$ at the same $\bar{v}$ (Tsunokawa et al., 2019); however, as moving a large mass of water with a small velocity is more efficient than moving a small mass of water with a high velocity (Alexander, 1983), the use of paddles is more efficient than a free-swimming condition due to a larger surface area of the paddle than the hand (Gourgoulis et al., 2008; Toussaint et al., 1991; Tsunokawa et al., 2019). In other words, paddle training is probably not as effective to improve swimming-specific strength as often believed (Mujika & Crowley, 2019), but it may help to minimise the waste of kinetic energy and maximise the force produced by the upper limbs in the swimming direction.

Given that the increase in the negative pressure acting on the dorsal side of the hand is crucial for increasing propulsion (Koga et al., 2020, 2021), swimmers are not simply ‘pushing’ or ‘pulling’ the water to increase $\bar{v}$. Therefore, techniques to increase propulsive force during the down-sweep and the in-sweep movement in the glide phase (which is often considered to be non-propulsive) should not be underestimated and have to be further investigated. The evidence on the complex propulsive mechanism also suggests that there is a limitation to increase simply by increasing $\bar{V}_{hand}$, and appropriate position and alignment of the upper-limb, such as α, should be considered to maximise the performance of swimmers.

Acknowledgements

The authors thank all members of the Swimming Laboratory at the University of Tsukuba for their contributions to the experiments and data analysis discussed in this article.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the University of Tsukuba.

ORCID

Hideki Takagi http://orcid.org/0000-0001-8797-7014
Motomu Nakashima http://orcid.org/0000-0002-1349-8763
Yasuo Sengoku http://orcid.org/0000-0002-8175-6859
Takaaki Tsunokawa http://orcid.org/0000-0001-9862-3123
Daiki Koga http://orcid.org/0000-0001-9429-3331
Kenzo Narita http://orcid.org/0000-0002-0429-1859
Shigetada Kudo http://orcid.org/0000-0002-5344-6167
Ross Sanders http://orcid.org/0000-0003-0489-3048

Tomohiro Gonjo http://orcid.org/0000-0001-9118-5167

References

Alexander, R. M. (1983). *Motion in fluids.Animal mechanics* (pp. 183–233). Blackwell Science.

Barbosa, T., Bragada, J., Reis, V., Marinho, D., Carvalho, C., & Silva, A. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, *13*(2), 262–269. https://doi.org/10.1016/j.jsams.2009.01.003

Barbosa, T., Fernandes, R., Keskinen, K., & Vilas-Boas, J. (2008). The influence of stroke mechanics into energy cost of elite swimmers. *European Journal of Applied Physiology*, *103*(2), 139–149. https://doi.org/10.1007/s00421-008-0676-z

Berger, M. A., de-Groot, M. G., & Hollander, A. P. (1995). Hydrodynamic drag and lift forces on human hand/arm models. *Journal of Biomechanics*, *28*(2), 125–133. https://doi.org/10.1016/0021-9290(94)00053-7

Cappaert, J. M., Pease, D. L., & Troup, J. P. (1995). Three-dimensional analysis of the men's 100-m freestyle during the 1992 olympic games. *Journal of Applied Biomechanics*, *11*(1), 103–112. https://doi.org/10.1123/jab.11.1.103

Chollet, D., Chalies, S., & Chatard, J. (2000). A new index of coordination for the crawl: Description and usefulness. *International Journal of Sports Medicine*, *21*(1), 54–59. https://doi.org/10.1055/s-2000-8855

Chollet, D., Seifert, L., Boulesteix, L., & Carter, M. (2006). Arm to leg coordination in elite butterfly swimmers. *International Journal of Sports Medicine*, *27*(4), 322–329. https://doi.org/10.1055/s-2005-865658

Chollet, D., Seifert, L. M., & Carter, M. (2008). Arm coordination in elite backstroke swimmers. *Journal of Sports Sciences*, *26*(7), 675–682. https://doi.org/10.1080/02640410701787791

Cohen, R., Cleary, P., Harrison, S., Mason, B., & Pease, D. (2014). Pitching effects of buoyancy during four competitive swimming strokes. *Journal of Applied Biomechanics*, *30*(5), 609–618. https://doi.org/10.1123/jab.2013-0260

Cohen, R., Cleary, P., Mason, B., & Pease, D. (2015). The role of the hand during freestyle swimming. *Journal of Biomechanical Engineering*, *137*(11), 111007. https://doi.org/10.1115/1.4031586

Cohen, R., Cleary, P., Mason, B., & Pease, D. (2018). Forces during front crawl swimming at different stroke rates. *Sports Engineering*, *21*(1), 63–73. https://doi.org/10.1007/s12283-017-0246-x

Cohen, R., Cleary, P., Mason, B., & Pease, D. (2020). Studying the effects of asymmetry on freestyle swimming using smoothed particle hydrodynamics. *Computer Methods in Biomechanics and Biomedical Engineering*, *23*(7), 271–284. https://doi.org/10.1080/10255842.2020.1718663

Craig, A. B., & Pendergast, D. R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine and Science in Sports and Exercise*, *11*(3), 278–283. https://doi.org/10.1249/00005768-197901130-00011

Deschodt, V., Arsac, L., & Rouard, A. (1999). Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. *European Journal of Applied Physiology and Occupational Physiology*, *80*(3), 192–199. https://doi.org/10.1007/s004210050581

di Prampero, P. E., Pendergast, D. R., Wilson, D. W., & Rennie, D. W. (1974). Energetics of swimming in man. *Journal of Applied Physiology*, *37*(1), 1–5. https://doi.org/10.1152/jappl.1974.37.1.1

Formosa, D., Toussaint, H., Mason, B., & Burkett, B. (2012). Comparative analysis of active drag using the MAD system and an assisted towing method in front crawl swimming. *Journal of Applied Biomechanics*, *28*(6), 746–750. https://doi.org/10.1123/jab.28.6.746

Gatta, G., Cortesi, M., & Di Michele, R. (2012). Power production of the lower limbs in flutter-kick swimming. *Sports Biomechanics*, *11*(4), 480–491. https://doi.org/10.1080/14763141.2012.670663

Gatta, G., Cortesi, M., Swaine, I., & Zamparo, P. (2018). Mechanical power, thrust power and propelling efficiency: Relationships with elite sprint swimming performance. *Journal of Sports Sciences*, *36*(5), 506–512. https://doi.org/10.1080/02640414.2017.1322214

Gonjo, T., Narita, K., McCabe, C., Fernandes, R. J., Vilas-Boas, J. P., Takagi, H., & Sanders, R. (2020). Front crawl is more efficient and has smaller active drag than backstroke swimming: Kinematic and kinetic comparison between the two techniques at the same swimming speeds. *Frontiers in Bioengineering and Biotechnology*, *8*(1134), 570657. https://doi.org/10.3389/fbioe.2020.570657

Gourgoulis, V., Aggeloussis, N., Vezos, N., Kasimatis, P., Antoniou, P., & Mavromatis, G. (2008). Estimation of hand forces and propelling efficiency during front crawl swimming with hand paddles. *Journal of Biomechanics*, *41*(1), 208–215. https://doi.org/10.1016/j.jbiomech.2007.06.032

Hollander, A. P., Groot, G. D., van Ingen Schenau, G. J., Toussaint, H. M., Best, H. D., Peeters, W., Meulemans, A., & Schreurs, A. W. (1986). Measurement of active drag during crawl arm stroke swimming. *Journal of Sports Science*, *4*(1), 21–30. https://doi.org/10.1080/02640418608732094

Koga, D., Gonjo, T., Kawai, E., Tsunokawa, T., Sakai, S., Sengoku, Y., Homma, M., & Takagi, H. (2020). Effects of exceeding stroke frequency of maximal effort on hand kinematics and hand propulsive force in front crawl. *Sports Biomechanics*, 1–13. https://doi.org/10.1080/14763141.2020.1814852

Koga, D., Tsunokawa, T., Sengoku, Y., Homma, M., & Takagi, H. (2021). Relationship between stroke frequency and hand propulsive force in front crawl. *Taiikugaku Kenkyu (Japan Journal of Physical Education, Health and Sport .Sciences)*, *66*, 207–218. https://doi.org/10.5432/jjpehss.20123

Kolmogorov, S. V., & Duplishcheva, O. A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of Biomechanics*, *25*(3), 311–318. https://doi.org/10.1016/0021-9290(92)90028-Y

Kudo, S., Sujae, I. H., & Jabbar, K. (2012). Application of pressure measures to predict propulsive forces exerted by the hand during swimming. In *The ISBS-conference proceedings archive* (pp. 192–195). https://ojs.ub.uni-konstanz.de/cpa/article/download/5262/4836

Kudo, S., Yanai, T., Wilson, B., Takagi, H., & Vennell, R. (2008). Prediction of fluid forces acting on a hand model in unsteady flow conditions. *Journal of Biomechanics*, *41*(5), 1131–1136. https://doi.org/10.1016/j.jbiomech.2007.12.007

Morouço, P., Keskinen, K. L., Vilas-Boas, J. P., & Fernandes, R. J. (2011). Relationship between tethered forces and the four swimming techniques performance. *Journal of Applied Biomechanics*, *27*(2), 161–169. https://doi.org/10.1123/jab.27.2.161

Mujika, I., & Crowley, E. (2019). Strength training for swimmers. In *Concurrent Aerobic and strength training* (pp. 369–386). Springer. https://doi.org/10.1007/978-3-319-75547-2_25

Nakashima, M. (2007). Mechanical study of standard six beat front crawl swimming by using swimming human simulation model. *Journal of Fluid Science and Technology*, *2*(1), 290–301. https://doi.org/10.1299/jfst.2.290

Nakashima, M. (2009). Simulation analysis of the effect of trunk undulation on swimming performance in underwater dolphin kick of human. *Journal of Biomechanical Science and Engineering*, *4*(1), 94–104. https://doi.org/10.1299/jbse.4.94

Nakashima, M., & Ejiri, Y. (2012). Measurement and modeling of unsteady fluid force acting on the trunk of a swimmer using a swimmer mannequin robot. *Journal of Fluid Science and Technology*, *7*(1), 11–24. https://doi.org/10.1299/jfst.7.11

Nakashima, M., Maeda, S., Miwa, T., & Ichikawa, H. (2012). Optimizing simulation of the arm stroke in crawl swimming considering muscle strength characteristics of athlete swimmers. *Journal of Biomechanical Science and Engineering*, *7*(2), 102–117. https://doi.org/10.1299/jbse.7.102

Nakashima, M., Nemoto, C., Kishimoto, T., Terada, M., & Ikuta, Y. (2018). Optimizing simulation of arm stroke in freestyle for swimmers with hemiplegia. *Mechanical Engineering Journal*, *5*(1), 17–00377. https://doi.org/10.1299/mej.17-00377

Nakashima, M., Satou, K., & Miura, Y. (2007). Development of swimming human simulation model considering rigid body dynamics and unsteady fluid force for whole body. *Journal of Fluid Science and Technology*, *2*(1), 56–67. https://doi.org/10.1299/jfst.2.56

Nakashima, M., & Takahashi, A. (2012). Clarification of unsteady fluid forces acting on limbs in swimming using an underwater robot arm. *Journal of Fluid Science and Technology*, *7*(1), 100–113. https://doi.org/10.1299/jfst.7.100

Nakashima, M., Takahashi, R., & Kishimoto, T. (2020). Optimizing simulation of deficient limb's strokes in freestyle for swimmers with unilateral transradial deficiency. *Journal of Biomechanical Science and Engineering*, *15*(1), 19–00467. https://doi.org/10.1299/jbse.19-00467

Nakashima, M., Yoneda, T., & Tanigawa, T. (2019). Simulation analysis of fin swimming with bi-fins. *Mechanical Engineering Journal*, *6*(4), 19-00011-00019-0001. https://doi.org/10.1299/mej.19-00011

Narita, K., Nakashima, M., & Takagi, H. (2017). Developing a methodology for estimating the drag in front-crawl swimming at various velocities. *Journal of Biomechanics*, *54*, 123–128. https://doi.org/10.1016/j.jbiomech.2017.01.037

Narita, K., Nakashima, M., & Takagi, H. (2018). Effect of leg kick on active drag in front-crawl swimming: Comparison of whole stroke and arms-only stroke during front-crawl and the streamlined position. *Journal of Biomechanics*, *76*, 197–203. https://doi.org/10.1016/j.jbiomech.2018.05.027

Pai, Y. C., & Hay, J. G. (1988). A hydrodynamic study of the oscillation motion in swimming. *Journal of Applied Biomechanics*, *4*(1), 21–37.

Pendergast, D., Mollendorf, J., Zamparo, P., Termin, A., Bushnell, D., & Paschke, D. (2005). The influence of drag on human locomotion in water. *Undersea & Hyperbaric Medicine: Journal of the Undersea and Hyperbaric Medical Society, Inc*, *32*(1), 45–57.

Samson, M., Monnet, T., Bernard, A., Lacouture, P., & David, L. (2015). Kinematic hand parameters in front crawl at different paces of swimming. *Journal of Biomechanics*, *48*(14), 3743–3750. https://doi.org/10.1016/j.jbiomech.2015.07.034

Samson, M., Monnet, T., Bernard, A., Lacouture, P., & David, L. (2019). Comparative study between fully tethered and free swimming at different paces of swimming in front crawl. *Sports Biomechanics*, *18*(6), 571–586. https://doi.org/10.1080/14763141.2018.1443492

Schleihauf, R. E. (1979). A hydrodynamic analysis of swimming propulsion. In J. Terauds & E. W. Bedingfield (Eds.), *Swimming III* (pp. 173–184). University Park Press.

Schleihauf, R. E., Higgins, J. R., Hinrichs, R., Luedtke, D., Maglischo, C., Maglischo, E. W., & Thayer, A. (1988). Propulsive techniques: Front crawl stroke, butterfly, backstroke, and breaststroke. In B. E. Ungerechts, K. Reischle, & K. Wilke (Eds.), *Swimming science V* (pp. 53–59). Human Kinetics.

Schnitzler, C., Brazier, T., Button, C., Seifert, L., & Chollet, D. (2011). Effect of velocity and added resistance on selected coordination and force parameters in front crawl. *The Journal of Strength & Conditioning Research*, *25*(10), 2681–2690. https://doi.org/10.1519/JSC.0b013e318207ef5e

Seifert, L., & Chollet, D. (2005). A new index of flat breaststroke propulsion: A comparison of elite men and women. *Journal of Sports Sciences*, *23*(3), 309–320. https://doi.org/10.1080/02640410410001729964

Shimojo, H., Gonjo, T., Sakakibara, J., Sengoku, Y., Sanders, R., & Takagi, H. (2019). A quasi three-dimensional visualization of unsteady wake flow in human undulatory swimming. *Journal of Biomechanics*, *93*, 60–69. https://doi.org/10.1016/j.jbiomech.2019.06.013

Takagi, H., & Wilson, B. (1999). Calculating hydrodynamic force by using pressure differences in swimming. In K. L. Keskinen, P. V. Komi, & A. P. Hollander (Eds.), *Biomechanics and medicine in swimming VIII* (pp. 101–106). Gummerus Printing.

Takagi, H., Nakashima, M., Ozaki, T., & Matsuuchi, K. (2013). Unsteady hydrodynamic forces acting on a robotic hand and its flow field. *Journal of Biomechanics*, *46*(11), 1825–1832. https://doi.org/10.1016/j.jbiomech.2014.01.046

Takagi, H., Nakashima, M., Ozaki, T., & Matsuuchi, K. (2014). Unsteady hydrodynamic forces acting on a robotic arm and its flow field: Application to the crawl stroke. *Journal of Biomechanics*, *47*(6), 1401–1408. https://doi.org/doi:10.1016/j.jbiomech.2014.01.046

Takagi, H., Nakashima, M., Sato, Y., Matsuuchi, K., & Sanders, R. H. (2016). Numerical and experimental investigations of human swimming motions. *Journal of Sports Sciences*, *34*(16), 1564–1580. https://doi.org/10.1080/02640414.2015.1123284

Takagi, H., Shimada, S., Miwa, T., Kudo, S., Sanders, R., & Matsuuchi, K. (2014). Unsteady hydrodynamic forces acting on a hand and its flow field during sculling motion. *Human Movement Science*, *38*, 133–142. https://doi.org/10.1016/j.humov.2014.09.003

Termin, B., & Pendergast, D. R. (2000). Training using the stroke frequency-velocity relationship to combine biomechanical and metabolic paradigms. *Journal of Swimming Research*, *14*, 9–17.

Thevelein, X., Daly, D., & Persyn, U. (1984). Measurement of total energy use in the evaluation of competitive swimmers. In Bachl, N., Prokop, L., & Suckert, R. (Eds.), *Current topics in sports medicine* (pp. 668–676). Urban & Schwarzenberg.

Toussaint, H. M. (1990). Differences in propelling efficiency between competitive and triathlon swimmers. *Medicine and Science in Sports and Exercise*, *22*(3), 409–415. https://doi.org/10.1249/00005768-199006000-00020

Toussaint, H. M., & Hollander, A. P. (1994). Mechanics and energetics of front crawl swimming. In M. Miyashita, Y. Mutoh, & A. B. Richardson (Eds.), *Medicine and science in aquatic sports* (Vol. 39, pp. 107–116). Karger.

Toussaint, H. M., & Beek, P. J. (1992). Biomechanics of competitive front crawl swimming. *Sports Medicine*, *13*(1), 8–24. https://doi.org/10.2165/00007256-199213010-00002

Toussaint, H. M., Beelen, A., Rodenburg, A., Sargeant, A. J., de Groot, G., Hollander, A. P., & van Ingen Shenau, G. J. (1988). Propelling efficiency of front-crawl swimming. *Journal of Applied Physiology*, *65*(6), 2506–2512. https://doi.org/10.1152/jappl.1988.65.6.2506

Toussaint, H. M., de Groot, G., Savelberg, H. H. C. M., Vervoorn, K., Hollander, A. P., & van Ingen Shenau, G. J. (1988). Active drag related to velocity in male and female swimmers. *Journal of Biomechanics*, *21*(5), 433–438. https://doi.org/10.1016/0021-9290(88)90149-2

Toussaint, H. M., Janssen, T., & Kluft, M. (1991). Effect of propelling surface size on the mechanics and energetics of front crawl swimming. *Journal of Biomechanics*, *24*(3/4), 205–211. https://doi.org/10.1016/0021-9290(91)90178-P

Toussaint, H. M., Roos, P. E., & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of Biomechanics*, *37*(11), 1655–1663. https://doi.org/10.1016/j.jbiomech.2004.02.020

Tsunokawa, T., Mankyu, H., Takagi, H., & Ogita, F. (2019). The effect of using paddles on hand propulsive forces and Froude efficiency in arm-stroke-only front-crawl swimming at various velocities. *Human Movement Science*, *64*, 378–388. https://doi.org/10.1016/j.humov.2019.03.007

Tsunokawa, T., Takagi, H., Sengoku, Y., & Tsubakimoto, S. (2012). Relationship between swimming performance and fluid force determined by pressure distribution analysis of breaststroke kicking motion. *Japan Journal of Physical Education, Health and Sport Sciences*, *57*(2), 515–525. https://doi.org/10.5432/jjpehss.12003

Tsunokawa, T., Tsuno, T., Mankyu, H., Takagi, H., & Ogita, F. (2018). The effect of paddles on pressure and force generation at the hand during front crawl. *Human Movement Science*, *57*, 409–416. https://doi.org/10.1016/j.humov.2019.03.007

Zamparo, P. (2006). Effects of age and gender on the propelling efficiency of the arm stroke. *European Journal of Applied Physiology*, *97*(1), 52. https://doi.org/10.1007/s00421-006-0133-9

Zamparo, P., Capelli, C., & Pendergast, D. (2011). Energetics of swimming: A historical perspective. *European Journal of Applied Physiology*, *111*(3), 367–378. https://doi.org/10.1007/s00421-010-1433-7

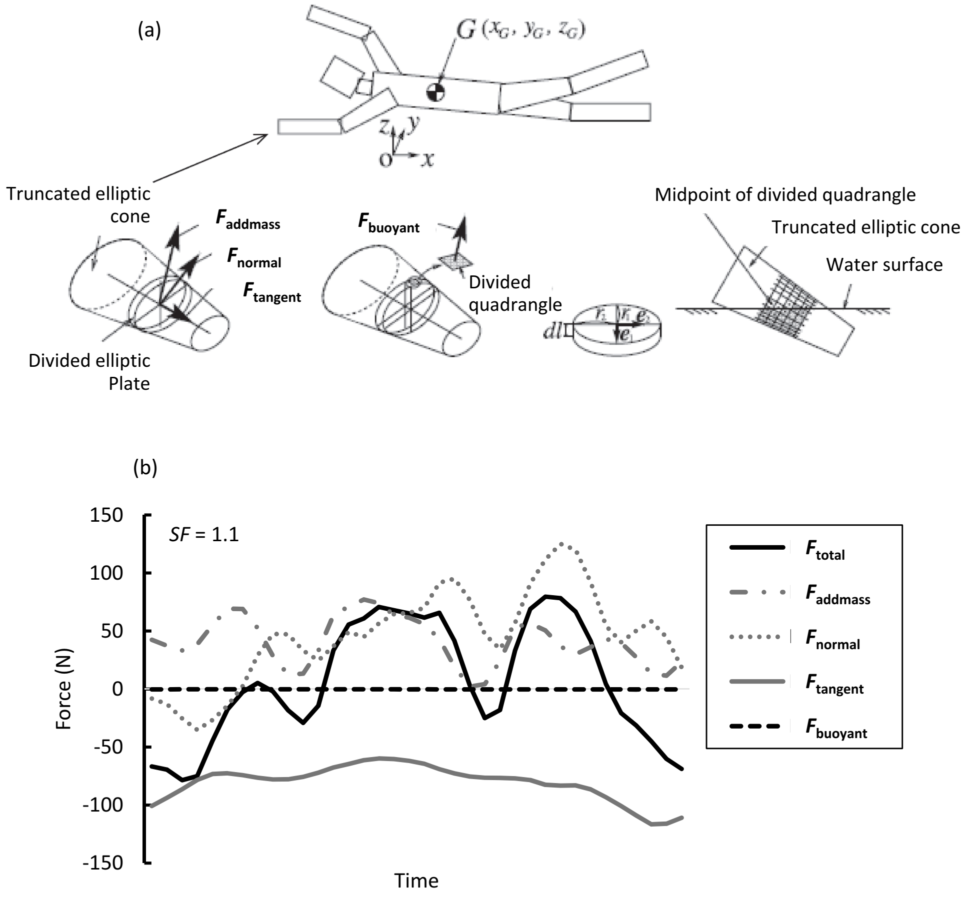
Zamparo, P., Cortesi, M., & Gatta, G. (2020). The energy cost of swimming and its determinants. *European Journal of Applied Physiology*, *120*(1), 41–66. https://doi.org/10.1007/s00421-019-04270-y

Zamparo, P., Gatta, G., Pendergast, D., & Capelli, C. (2009). Active and passive drag: The role of trunk incline. *European Journal of Applied Physiology*, *106*(2), 195–205. https://doi.org/10.1007/s00421-009-1007-8

Zamparo, P., Lazzer, S., Antoniazzi, C., Cedolin, S., Avon, R., & Lesa, C. (2008). The interplay between propelling efficiency, hydrodynamic position and energy cost of front crawl in 8 to 19-year-old swimmers. *European Journal of Applied Physiology*, *104*(4), 689. https://doi.org/10.1007/s00421-008-0822-7

Zamparo, P., Pendergast, D. R., Mollendorf, J., Termin, A., & Minetti, A. E. (2005). An energy balance of front crawl. *European Journal of Applied Physiology*, *94*(1–2), 134–144. https://doi.org/10.1007/s00421-004-1281-4

Appendix A. Conceptual diagram of the forces ($F_{addmass}$, F_{nomal}, $F_{tangent}$, $F_{buoyant}$) calculated by the optimal simulation using the SWUM model (a) and the change of each force acting on a whole body during one cycle at *SF* = 1.1 Hz when the maximum swimming speed was reached (b). For detailed definitions of variables and calculation process, please refer to Nakashima (2007) and Nakashima et al. (2007)



Appendix B. List of errors between the swimming speed and fluid force value (average or maximum) calculated by the simulation using the SWUM model and the benchmarked values

Reference	Analysis object	Evaluation index	Benchmark error (%)	Evaluated variable (average or maximum value)
Nakashima (2007)	Front crawl	Swimming speed	7.5	Average
Nakashima et al. (2007)	Front crawl	Time course of fluid force acting on a physical limb model	10	Average
Nakashima (2009)	Dolphin kick	Swimming speed	0.6	Average
Nakashima and Takahashi (2012)	4 strokes	Time course of fluid force acting on a robot arm	10	Average
Nakashima and Ejiri (2012)	Breast and Butterfly	Time course of fluid force acting on a mannequin robot	10	Average
Nakashima et al. (2018)	Front crawl by a swimmer with hemiplegia	Swimming speed	3	Average
Nakashima et al. (2019)	Front crawl with bi-fins	Swimming speed	6	Maximum
Nakashima et al. (2020)	Front crawl by a swimmer with unilateral transracial deficiency	Swimming speed	1	Average