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Experimental and Numerical Investigation on the Effect of Finger Spread on Swimmer Performance

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Abstract

This study presents an experimental and numerical investigation on the effect of finger spread on the flow field around the swimmer's hand. Three hand models having different finger positions were analysed. The models were created by taking resin moulds of the hand of elite-level swimmer László Cseh. The models were digitised by high-resolution 3D scanning. Wind tunnel experiments were performed to measure the drag and lift forces acting on the hand. The measured data were also used to evaluate the performance of the CFD models in ANSYS Fluent. It was found that the magnitude of the drag force varied only slightly (by 1.65%) regarding the investigated cases; however, the maximum achievable lift increased significantly in the fully closed finger position. The difference in the measured maximum lift forces was ~67% between the fully open and fully closed finger positions. The numerical models underestimated the drag force but showed trends similar to the experimental results. The study highlights that while the finger spread influences the hydrodynamic forces acting on the swimmer's hand, the determination of an optimal finger spread requires further investigations considering the complete stroke trajectory. The presented methodology provides a solid foundation for future studies aimed to optimise swimmer performance and training.

Keywords

CFD, wind tunnel testing, swimmer, sports aerodynamics, finger position

1 Introduction

In addition to the human hand's congenital shape, the hand position during the swimmer's propulsive stroke also influences performance. Investigating and understanding the effects of these parameters can help personalise and improve training effectiveness, leading to better results. It is generally accepted that the hand acts as an airfoil, and the combined effect of lift and drag forces generated by the submerged hand in water ultimately produces the propelling force. The swimmer's hand cannot be simplified to a blunt body by using only its drag for the propelling force [1]. Results from experiments on model hands conducted in open water tank facilities suggest that finger spread and thumb abduction significantly affect lift-producing motions, and an increased lift-to-drag ratio can be achieved with closed fingers and a fully abducted thumb [2–4]. Measurements of the hydrodynamic forces acting on the forearm and the hand also highlighted challenges in conducting such laboratory experiments due to wave and ventilation drag generated by the hand when piercing the free water surface, resulting in inaccuracies in drag and lift measurements [5]. The Computational Fluid Dynamics (CFD) modelling, however, has proven to be a valid and cost-effective alternative to direct measurements [6]. The introduction of CFD in swimming propulsion has opened new perspectives for further analysis of the swimmer's hand. With CFD, it was possible to investigate multiple finger positions, revealing that, under certain circumstances, a small distance between fingers can generate higher drag coefficient (c_D) values than hands with fully closed or widely open fingers [7]. Increased drag resulted from overlapping laminar boundary layers developing between two neighbouring fingers with a small gap, which caused enough obstruction to the flow of water to increase the effective projected area of the hand [8]. This increase in drag depends significantly on the Reynolds number (Re), making the definition of realistic swimming conditions crucial for providing valuable information [9]. Conversely, a simplified 2D CFD study modelling the

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unsteady flow field around closely positioned cylinders, representing the swimmer's fingers while excluding the effect of the thumb, found that the highest drag force could be achieved with fully closed fingers [10]. Contrary to earlier findings [8], it was shown that the small increment in friction drag caused by the gaps between the cylinders did not compensate for the predicted drop in form drag resulting from the interaction of the gap flows.

2 Methodology

A representative model had to be created to establish an adequate baseline for further investigations on the swimmer's hand. The wind tunnel model was developed by taking a mould from László Cseh's elite-level swimmer's hand. László Cseh is a six-time Olympic medalist, a two-time World Champion, and a 33-time European Champion in breaststroke [11]. Three moulds were created with distinct finger spreads. The models were cast from resin and are presented in Fig. 1.

The image of Fig. 1 (b) shows the nominal finger position that László Cseh uses when swimming, while Fig. 1 (a) depicts a fully closed finger position and Fig. 1 (c) represents a more open finger position than the nominal one. The finger spread angles (Θ) were defined based on the preliminary established conventions [9, 12], as shown in Fig. 2. The hand with fully closed fingers in Fig. 1 (a) and Fig. 2 (a) is denoted by the zero average finger spread angle (Θ_{SP} = 0°). The average finger spread angle (Θ_{SP}) of a given hand model is calculated by the finger spread angles ($\Theta_{i=1,2,3,4}$, see in Fig. 2 (b)) of each fingers except the middle finger, which is used as reference. The three swimmer's hand models are differentiated based on the calculated average finger spread angle (Θ_{SP}).

The wind tunnel experiments were carried out in the low-speed, open-return NPL-type (Eiffel-type) wind tunnel of the Theodore von Kármán Wind Tunnel Laboratory of the Department of Fluid Mechanics at BME [13]. The test section's cross-sectional area is 0.5 m × 0.5 m. Drag and lift force components were measured by load cells connected to an aerodynamic balance system, which carried the hand model. The dynamic pressure was measured by a SETRA Model 239 pressure transducer with an accuracy of δp_{dyn} = ± 0.1 Pa. The initial angular position of the hand was defined when the hand's thumb faced the flow direction, as it is presented in Fig. 3. The hand position in the wind tunnel was set by an angle-gauge system with 0.1° accuracy.

The c_D and lift force coefficients (c_L) were defined by the following equations, see Eqs. (1) and (2), respectively:

(a)

(b)

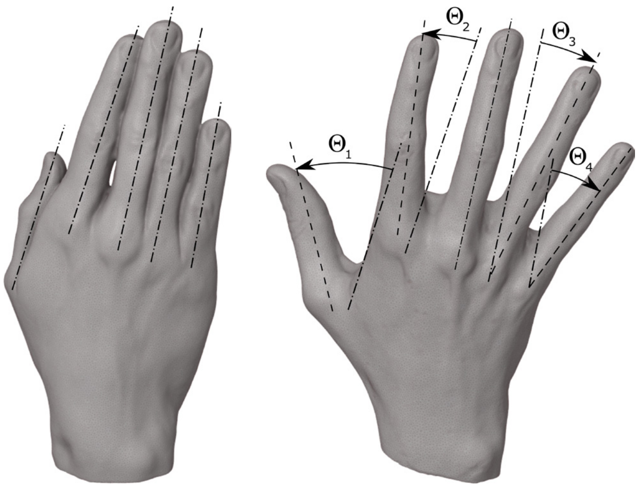
(c)

Fig. 1 Three hand models with different average finger spreads (Θ_{SP}); (a) Θ_{SP} = 0°; (b) Θ_{SP} = 10°; (c) Θ_{SP} = 23°

$$c_D = \frac{F_D}{0.5 \rho U^2 A_{proj}}, \quad (1)$$

$$c_L = \frac{F_L}{0.5 \rho U^2 A_{proj}}, \quad (2)$$

where F_D and F_L are the drag and lift forces acting on the hand, respectively; ρ is the air density; U represents the free-stream velocity of air; and A_{proj} is the maximum projected area of the swimmer's hand to a plane perpendicular to the flow direction for each finger spread setup.



(a) (b)

Fig. 2 The definition of finger spread angle (Θ): (a) the dash-dot lines show the reference finger positions ($\Theta_{i=1,2,3,4} = 0°$) on the hand of fully closed fingers ($\Theta_{SP} = 0°$); (b) the dashed lines show each finger's spread angle (Θ_1, Θ_2, Θ_3, Θ_4) measured to their reference finger positions

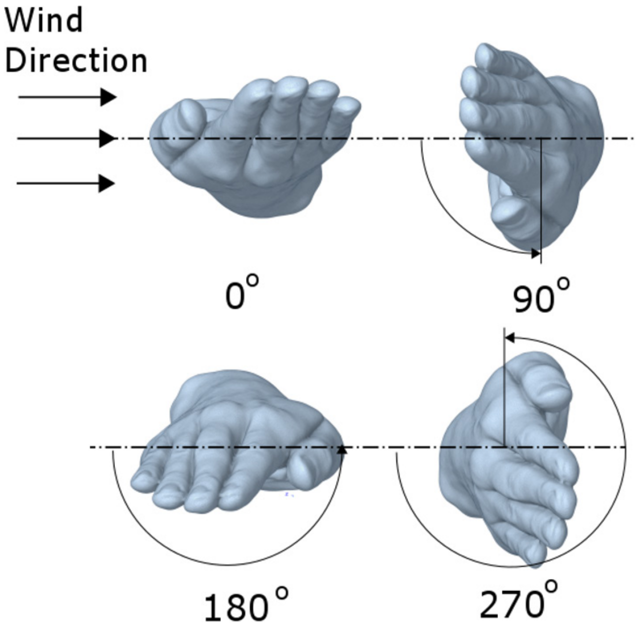


Fig. 3 The definition of the hand's angular positions

Since the working fluid of the wind tunnel is air rather than water, the conditions within the test section had to be set accordingly to represent realistic swimming conditions. This was accomplished by adjusting the wind tunnel Re to correspond with the Re that would be observed in water, a method which proved to provide accurate results [14]. The flow Re was defined as follows (Eq. (3)):

$$\mathrm{Re}\left(\Theta_{SP}\right) = \frac{v_{WT} \cdot l_{ref}\left(\Theta_{SP}\right)}{v_{air}} = \frac{v_R \cdot l_{ref}\left(\Theta_{SP}\right)}{v_{water}}, \quad (3)$$

where the reference length $l_{ref}(\Theta_{SP})$ is defined as the square root of the maximum projected area A_{proj}; v_{WT} is the wind tunnel flow velocity; v_R is the reference flow velocity, which would be achieved in water; and v_{air} and v_{water} are the kinematic viscosities of the air and water, respectively.

The ratio of the hands' projected cross-section (A_{proj}) to the wind tunnel cross-section (A_{WT}) is approximately ~15%, and therefore, the measured data had to be corrected for the blockage [15] by applying a solid blockage correction factor defined as follows in Eq. (4):

$$K_{corr} = \left(1 - \frac{A_{proj}\left(\Theta_{SP}\right) + A_{proj,elements}}{A_{WT}}\right)^2, \quad (4)$$

where $A_{proj,elements}$ is the total projected area of the internal elements inside the test section (excluding the area of the hand model). As a result, Eqs. (5) and (6) show the blockage-corrected drag and lift force coefficients, respectively.

$$c_D = c_{D,meas} \times K_{corr} \quad (5)$$

$$c_L = c_{L,meas} \times K_{corr} \quad (6)$$

The three semi-rigid urethane resin wind tunnel models of the hands were digitised with a high-resolution topographic 3D scanner and converted to stereolithography (STL) format. This facilitated the definition of the geometrical properties of the hand models and was used as the geometry input for the CFD model.

The CFD simulations were set up in the ANSYS Workbench (2024 R1) [16] environment using the Fluent solver [16]. The steady-state simulations were carried out with a pressure-based solver, using the coupled algorithm for pressure-velocity coupling. Initially, the k-ω shear stress transport (SST) turbulence MODEL [17] was used to model the effect of unresolved turbulent structures. The working fluid was set to water, assuming constant fluid properties; thus, the pressure-based solver was utilised.

The extension of the computational domain (H) is presented in Fig. 4. where the dimensions were given concerning the extrusion of the hand model into the H. The dimensions of the H are consistent with the guidelines for the CFD modelling of individually investigated blunt bodies [18]. The effect of the size of the domain was also investigated, with the dimensions increased in steps until the drag and lift forces became independent from the distance to the domain boundaries. The domain was discretised by a polyhedral mesh containing ~3.7 million cells.

Boundary conditions were applied on the domain boundaries: a uniform inlet flow velocity and 0.5% turbulent intensity on the inlet surface; pressure outlet (0 gauge pressure) on the outlet surface; symmetry on the side and upper walls; no-slip condition on the ground surface.

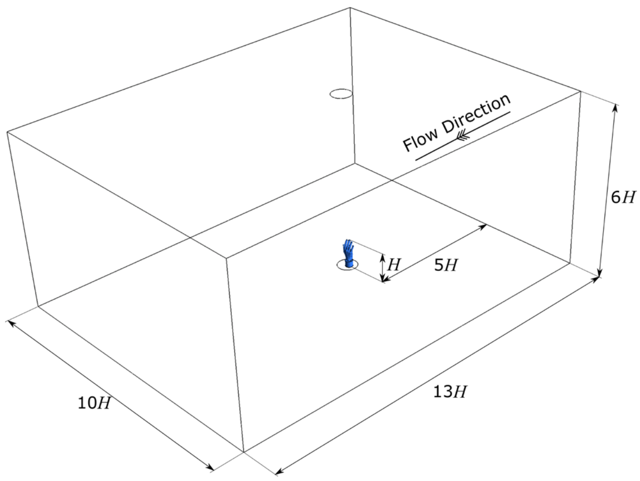


Fig. 4 The extension of the H

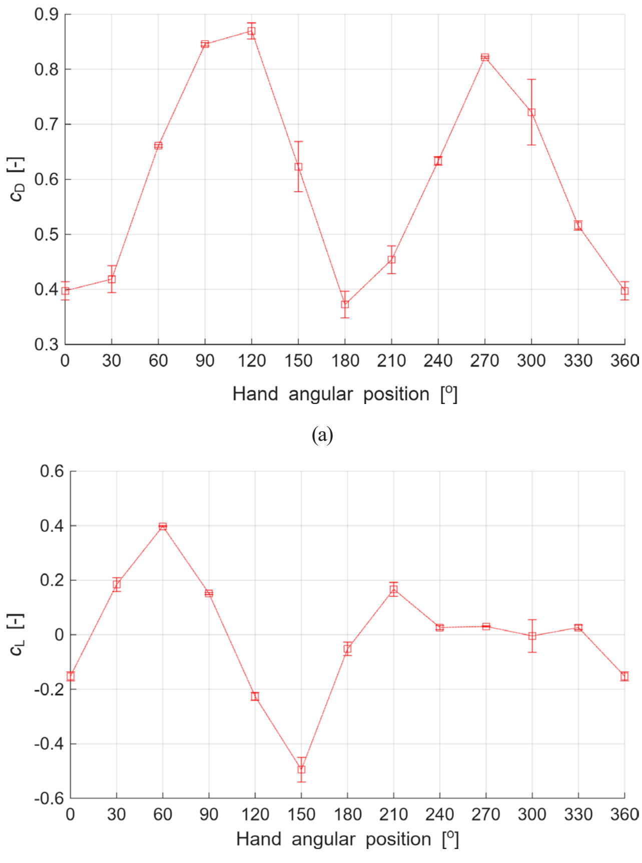


Fig. 5 The distribution of the expected discretisation error, i.e., numerical uncertainty [19] (Θ_{SP} = 10° case, SST model): (a) drag coefficient (c_D); (b) lift coefficient (c_L)

The boundary layer on the surface of the hand was resolved with an 18-layer boundary layer mesh where the dimensionless wall distance (y^+) was kept below 1 ($y^+ < 1$).

The discretisation uncertainty of the numerical results was estimated based on the Grid Convergency Index (GCI) method proposed by the ASME [19]. To access the discretisation error, the base mesh for the Θ_{SP} = 10° finger spread case (~3.7 million cells) was refined and coarsened by factor $r_{ref} > 1.31$, resulting in ~8.3 million cells for the refined and ~1.5 million cells for the coarsened mesh. Fig. 5 shows the resulting distribution of the discretisation error within the investigated hand angular position range.

3 Results

The measurements were carried out within the Reynolds number (Re) range of 87000 < Re < 150000 at three wind-tunnel velocities (v_{WT}). The maximum normalised root mean square deviation (NRMSD) was 2.5% for the measured c_L and 1.7% for the c_D at the different wind tunnel velocities over the 0°–360° hand angular position range. Therefore, the results are considered Re independent.

3.1 Experimental results

The results of the drag and lift force measurements are presented in Fig. 6 in terms of the c_L and c_D. In all cases, the maximum projected areas (A_{proj}) for defining the c_L and c_D were established based on the 3D scans by using the ANSYS SpaceClaim (2024 R1) [20].

Due to the lack of an explicit reference system for the definition of the hand angular position for comparing the different models, an arbitrary reference system was established where the minimum drag forces were aligned. As shown in Fig. 6, the distribution of forces concerning the hand angular position varies noticeably with the change in finger spread, especially for the lift.

The highest drag force was measured when the finger spread was the largest Θ_{SP} = 23°; however, the difference to the fully closed finger posture (Θ_{SP} = 0°) was found to be marginal, as shown in Fig. 7. The maximum difference in the measured achievable drag force is 1.65%.

The maximum lift force occurred in case when the fingers were fully closed (Θ_{SP} = 0°). As it can be seen in Fig. 7, the lift force decreases as the finger spread increases regarding the investigated cases, with a change in the achievable lift of 67%. In the case of breaststroke, the positive values indicate the generation of upward lift force for the swimmer.

Theoretically, the combined force (c_F) from lift and drag acting on the hand is the available force whose streamwise forward (swimming direction) component can be used to propel the swimmer [1]. The highest combined force was measured with fully opened fingers (Θ_{SP} = 23°), hence, the swimmer can exploit it throughout the whole stroke.

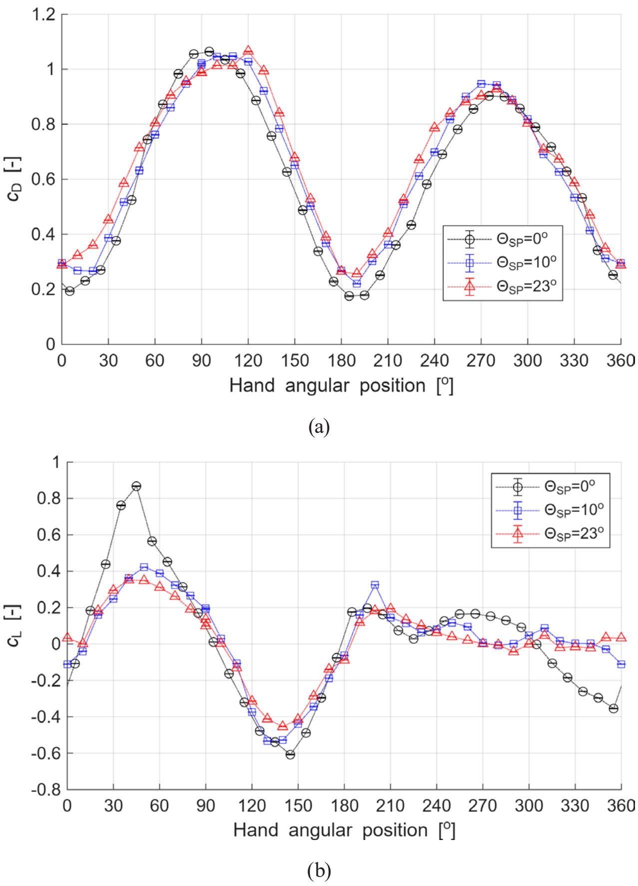


Fig. 6 The distribution of c_D and c_L measured on the three hand models with different finger postures: (a) drag coefficient (c_D); (b) lift coefficient (c_L)

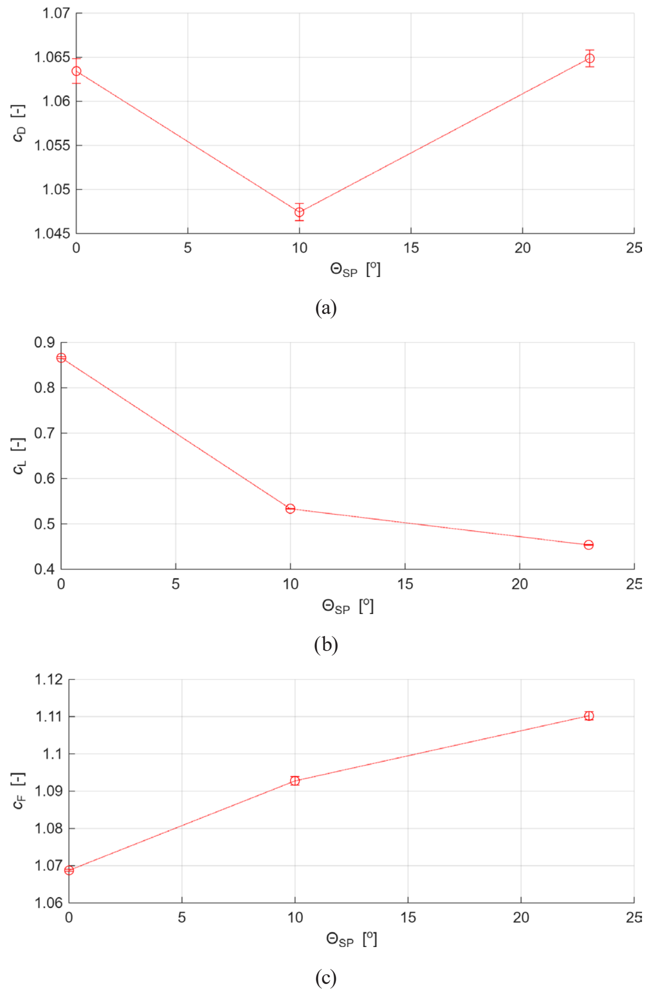


Fig. 7 Maximum measured forces at the finger spread angles (Θ_{SP}): (a) drag coefficient (c_D); (b) lift coefficient (c_L); (c) combined force coefficient (c_F)

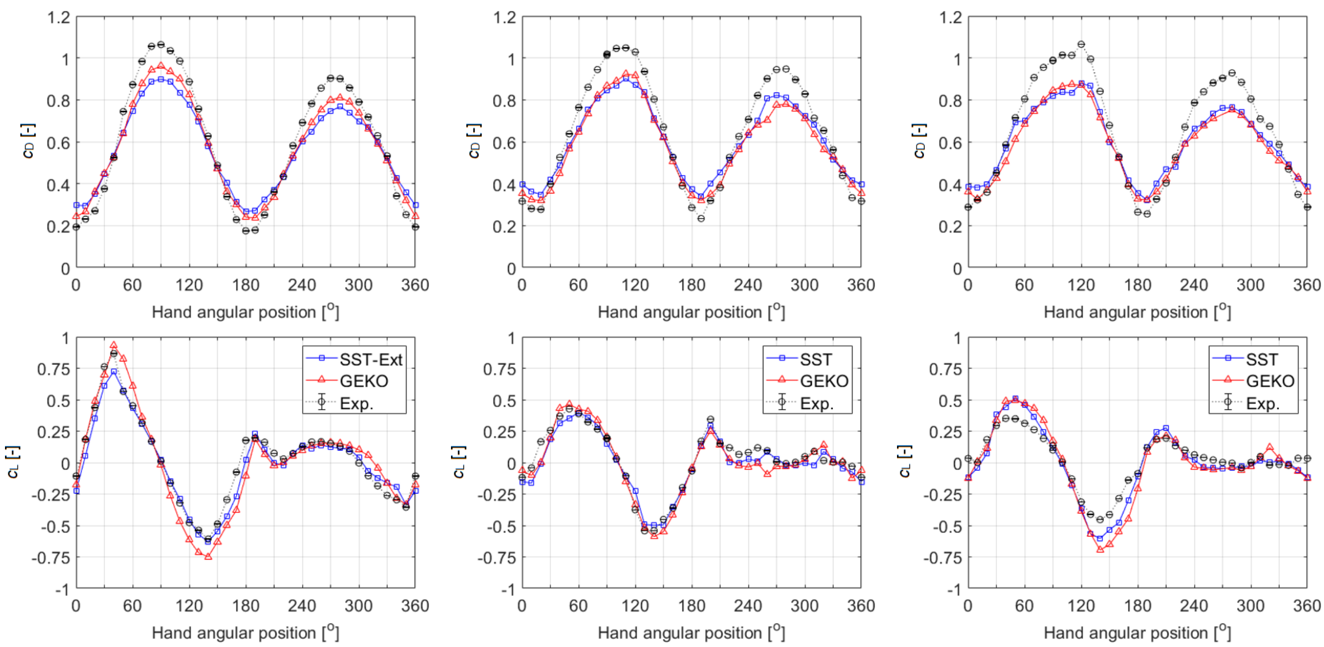
The lift increases proportionally with the finger spread angle regarding the investigated cases. The measured maximum difference in the achievable propelling force is 3.8%.

3.2 Numerical model results

As shown in Fig. 8, the qualitative predictions of the SST model are adequate. Notably, the measured sudden increase at 120° angular position for the fully opened fingers (Θ_{SP} = 23°) is also shown in the CFD results. However, the model underpredicts the maximum c_D and overpredicts the minimum c_D, while closely predicting the c_L across the entire hand angular position domain.

The relatively novel Generalized *k-ω* (GEKO) model [21] has also been tested as it has been showed improved results in recent studies where other standard two-equation models failed [22]. Following the published guidelines of ANSYS [21], various combinations of the adjustable free parameters (Separation parameter (CSEP), Near Wall parameter (CNW), Mixing parameter (CMIX), Jet parameter (CJET)) were investigated. Since significant discrepancies appeared in the highest drag predictions, e.g., at near 90° hand angular position, the effect of the free parameters was investigated when the palm is facing stood to the incoming flow. The set of free parameters examined, along with the differences between the predicted and measured drag and c_L, are listed in Table 1. below. As shown, the best results for the fully closed finger position (Θ_{SP} = 0°) were obtained in case of the default settings, as presented in the 1st row of Table 1. The best overall result, which provided better agreement across all investigated finger positions, is presented in the 12th row of Table 1 and is highlighted in bold.

Calculations using this latter set of free parameters were performed over the full 360° range of hand angular positions, and the results are shown in Fig. 8. Despite the improved results with the new model, the maximum drag remained under- and the minimum drag overpredicted. The GEKO-predicted c_L also aligned well with the measured data, although the results showed some deterioration compared to those from the SST model.



(a) (b) (c)

Fig. 8 The CFD ("SST", "GEKO") predicted c_D and c_L compared to the measurement data ("Exp."); (a) $\Theta_{SP} = 0°$; (b) $\Theta_{SP} = 10°$; (c) $\Theta_{SP} = 23°$

Table 1 The results of the GEKO parameter study

No.	Free GEKO Parameters				$\Theta_{SP} = 0°$		$\Theta_{SP} = 10°$		$\Theta_{SP} = 23°$	
	CSEP	CNW	CMIX	CJET	$\Delta c_{D\,90}$ [–]	$\Delta c_{L\,90}$ [–]	$\Delta c_{D\,90}$ [–]	$\Delta c_{L\,90}$ [–]	$\Delta c_{D\,90}$ [–]	$\Delta c_{L\,90}$ [–]
#1.	1.75	0.5	f(CSEP)*	0.9	9%	22%	26%	30%	22%	0%
#2.	1	0.5	f(CSEP)	0.9	18%	38%	26%	17%	23%	2%
#3.	2	0.5	f(CSEP)	0.9	17%	235%	26%	32%	22%	535%
#4.	1.75	−0.5	f(CSEP)	0.9	19%	3%	26%	36%	21%	11%
#5.	1.75	0.75	f(CSEP)	0.9	18%	3%	26%	33%	22%	7%
#6.	1.75	0.5	0	0.9	18%	1%	22%	34%	20%	25%
#7.	1.75	0.5	1	0.9	25%	154%	23%	25%	18%	0%
#8.	1.75	0.5	f(CSEP)	0.2	14%	1%	25%	31%	21%	3%
#9.	1	0	f(CSEP)	0.5	18%	18%	26%	25%	23%	5%
#10.	2	0.75	f(CSEP)	0.9	18%	214%	26%	23%	22%	4%
#11.	2	0.75	3	0.9	19%	18%	20%	11%	15%	13%
#12.	**1**	**0**	**3**	**0.5**	**11%**	**10%**	**20%**	**0%**	**15%**	**32%**
#13.	1.75	0.75	3	0.5	10%	299%	20%	15%	14%	15%
#14.	1.75	0.75	1	0.5	11%	1%	22%	16%	14%	4%

* f(CSEP): the value of CMIX is calculated as function of CSEP

The quality of the CFD predictions was also quantified using NRMSD between the model results and the measured data over the investigated angular position range. The NRMSD results are summarised in Table 2. The flow field around the hand model with fully closed fingers ($\Theta_{SP} = 0°$) was also simulated with the realizable low-Re k-ε model, but the results (see in Table 2) showed reduced prediction quality, therefore, this model was abandoned for future investigations.

Table 2 NRMSD of the applied CFD models

		NRMSD		
	Θ_{SP}	SST	GEKO	low-Re k-ε
c_D	0°	0.116	0.080	0.221
	10°	0.121	0.119	–
	23°	0.135	0.139	–
c_L	0°	0.052	0.081	0.147
	10°	0.066	0.075	–
	23°	0.113	0.154	–

However, selecting and tuning the most appropriate model requires more detailed information about the flow field around the object under investigation.

Neither the experimental nor the CFD models show a significant difference in drag force on the hand with varying finger positions. Although, both the predicted and measured lift forces vary significantly with changes in the finger spread angle Θ_{SP}. Defining an optimal finger position requires knowledge of the hand's trajectory during the stroke, as this strongly influences which components of the force acting on the hand contribute to propulsion, lift, and energy losses.

4 Conclusions

The presented study investigates the influence of the finger position on the hydrodynamic performance of the swimmer's hand using both physical modelling (wind tunnel measurements) and numerical modelling (CFD simulations). The investigated hand models were created by taking mould samples from László Cseh elite-level swimmer's hand and provided an accurate and usable foundation for both current and future studies.

The experimental results demonstrated that in the case of the studied models, finger spread had a limited effect on the achievable drag force, with the maximum increase of 1.65%. The lift force, however, was increased by 67% at the fully closed finger position compared to the fully open.

The numerical simulations complemented the wind tunnel experiments and showed similar trends to the measured data. The predictions of the lift forces proved to be accurate, however, the numerically predicted drag forces deviated more significantly from the experimental results. The more advanced GEKO turbulence models showed improved performance and tunability compared to the SST model, but more detailed flow field measurements are necessary to provide better guidelines for setting the model parameters.

Overall, the results indicate that the optimal finger spread for maximising propulsive effectiveness cannot be determined solely by static force measurements. The effectiveness of finger spreading likely depends on the trajectory of the swimmer's hand during the applied strokes. Further research is recommended to capture these effects, which involves dynamic testing and flow visualisation. The applied methodology offers a solid and adaptable framework for future investigations into swimmers' performance optimisation.

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