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Using Wearables to Monitor Swimmers' Propulsive Force to Get Real-Time Feedback and Understand Its Relationship to Swimming Velocity

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Abstract: Evidence on the role of propulsion compared to drag in swimming, based on experimental settings, is still lacking. However, higher levels of propulsion seem to lead to faster swimming velocities. The aim of this study was to understand the variation in a set of kinematic and kinetic variables between two swimming sections and their relationship to swimming velocity. The sample consisted of 15 young adult recreational swimmers (8 males: 20.84 ± 2.03 years; 7 females: 20.13 ± 1.90 years). Maximum swimming velocity and a set of kinematic and kinetic variables were measured during two consecutive sections of the swimming pool. Differences between sections were measured and the determinants of swimming velocity were analyzed. Swimming velocity, propulsive force, and the other kinematic and kinetic variables did not change significantly ($p < 0.05$) between sections (only the intra-cyclic fluctuation of swimming velocity decreased significantly, $p = 0.005$). The modeling identified the propulsive force, stroke length, and active drag coefficient as the determinants of swimming velocity. Swimming velocity was determined by the interaction of kinematic and kinetic variables, specifically propulsive force and active drag coefficient.

Keywords: performance; swimming analysis; propulsive force; kinematics; user-friendly data; training; sensors; swimming velocity determinants

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1. Introduction

Sports performance is a multifactorial phenomenon that depends on the interaction between different scientific fields. That is, it is known that physiology [1], biomechanics [2], nutrition [3], and psychology [4] (among others) play a fundamental role in improving performance. Of these, biomechanics receives much attention because researchers, coaches, and practitioners focus on motion analysis. Motion analysis in sports is considered to be the recording of sports movements and the subsequent computation of meaningful parameters describing the movement from raw kinematic data [5]. Therefore, the information provided to athletes is considered of great importance for the improvement of their performance.

In the past, motion analysis in sports was often based on video analysis [6,7]. However, due to the time-consuming process of data acquisition and handling [8], researchers are choosing a different method. Nowadays, the use of wearables (i.e., any technological device that can be worn or used as an accessory) is becoming a major approach. Wearables detect sport-specific movements and quantify sports demands that other monitoring technologies may not detect [9,10]. In the case of swimming, the limitations of video analysis are even more challenging because the cameras are mounted in an aquatic environment. Thus, using wearables consumes less time, provides immediate feedback, and allows data recording without the restriction of distance [11]. Additionally, wearables allow the delivery of more comprehensive data to coaches and, consequently, immediate feedback to swimmers.

Swimming velocity depends on the interaction between propulsive and resistive forces (i.e., drag) [12]. The literature reports substantial information on the drag of swimmers, indicating that swimmers who have a better hydrodynamic profile are more likely to perform better [13–15]. However, less information can be found on the swimmers' propulsion despite the theoretical idea that greater propulsion leads to faster swimming velocities. Nonetheless, based on experimental setups, it has been reported that faster stroke frequencies lead to greater propulsive force [16], and greater propulsive force leads to faster swimming velocity [17]. It must be highlighted that these experimental findings were only possible based on wearables that allow the swimmers to perform "freely", i.e., without any mechanical restriction. Moreover, it has been argued that increasing propulsion by itself or reducing drag alone may not provide better performance [18]. That is, swimmers must generate a great propulsive force while maintaining the "best" possible hydrodynamic position to take advantage of the achieved propulsion and reduce drag as much as possible. It was recently reported that the active drag coefficient (C_{Da}) is the variable that best represents the hydrodynamics of swimmers [19]. Additionally, the authors mentioned that the C_{Da} can be estimated based on drag or propulsive measurements (which in the past was estimated only through drag measurements) [19]. Therefore, in addition to the advantages of using wearables in general, and for propulsive force in particular, researchers and coaches can also obtain access to the C_{Da}.

The literature on swimming, specifically on maximum trial measurements, usually reports data based on the average of that same maximum trial [14,20]. However, it was argued that the average of a set of variables may not provide accurate insights about a given performance [21,22]. In elite-level swimmers competing in European Championships (long-course, i.e., 50 m length, swimming pool), it was observed that sprinting swimmers tend to decrease their swimming velocity along a short-distance event [23]. It was also observed that the stroke frequency and the stroke length tended to increase over the race [23]. Similar findings were observed in high-level swimmers during 25 m maximum trials [17,21]. Thus, it seems that, despite the length of the swimming pool (i.e., 50 or 25 m), there is a tendency for swimming velocity to decrease in maximal trials or sprinting events. However, little is known about the propulsive force of swimmers and its implication in improving swimming velocity. Moreover, and as previously mentioned, drag is one of the most important topics in swimming. Once again, drag-related variables (i.e., active drag or C_{Da}) are also typically measured as an average across a trial rather than across sections or strokes [24,25]. Consequently, little is known about the changes that may occur in the swimmers' hydrodynamics and their effect on their performance.

The aim of this study was to understand the variation of a set of kinematic and kinetic variables between two swimming sections and their relationship to swimming velocity. It was hypothesized that the propulsive force and the C_{Da} would have a meaningful effect on the velocity of swimmers.

2. Materials and Methods

The sample consisted of 15 young adult recreational swimmers (8 males: 20.84 ± 2.03 years, 73.87 ± 7.95 kg of body mass, 176.00 ± 7.21 cm of height, 174.81 ± 7.84 cm of arm span; 7 females: 20.13 ± 1.90 years, 69.14 ± 7.38 kg of body mass, 170.00 ± 7.34 cm of height, 171.21 ± 7.01 cm of arm span; all pooled together: 20.51 ± 1.93 years, 71.66 ± 7.80 kg of body mass, 173.20 ± 7.66 cm of height, 173.13 ± 7.43 cm of arm span). The participants were selected from a swimming lessons program. For three months prior to data collection, swimmers were in a twice-weekly (three hours) swimming lesson program. They had a previous background in swimming (4.07 ± 2.15 years of practice). All procedures were in accordance with the Declaration of Helsinki regarding human research, and the University Ethics Board approved the research design (N° 72/2022).

2.1. Anthropometrics

Body mass (BM, in kg) was measured on an electronic scale (Tanita, MC 780-P, Tokyo, Japan) with minimal clothing. Height (H, in cm) was collected using an electronic stadiometer (Seca, 242, Hamburg, Germany). Arm span (AS, in cm), hand surface area (HSA, in cm^2), and frontal surface area (FSA, in cm^2) were measured by digital photogrammetry. For the AS measurement, swimmers were placed near a 2D calibration object in an ortho-static position with both arms in lateral abduction at a 90° angle to the trunk. Both arms and fingers were fully extended. The distance between the tips of the third fingers was measured with a dedicated software program (Udruler, AVPSoft, United States) [26]. For HSA measurement, the swimmers' palms were photographed with a digital camera (Sony a6000, Tokyo, Japan). Each HSA was calculated using a dedicated software program (Udruler, AVPSoft, United States) [26].

For FSA measurement, the swimmers were photographed with a digital camera (Sony a6000, Tokyo, Japan) in the transverse plane next to a 2D calibration object to calibrate the image. While swimming, swimmers change their FSA. It is assumed that such a change has a direct effect on the hydrodynamics of the swimmers [27]. For this purpose, the swimmers were instructed to lie down on a bench wearing their swimsuits, cap, and goggles. Their lower trunk was supported on the bench so that swimmers could lean on the upper part of their trunk. Swimmers were photographed in the following positions: (i) right hand catch; (ii) right hand insweep; (iii) right hand exit and left hand catch; (iv) left hand insweep; and (v) left hand exit and right hand catch [27]. This was done to represent the duration of an entire stroke cycle. In this case, the beginning and end of each stroke cycle was considered the consecutive entry of the right hand into the water. Then, each FSA position was measured by digital photogrammetry as previously mentioned [26]. Values at each position were interpolated using a cubic spline from which the FSA values were calculated at each percentage point (each 5%) of the stroke (Figure 1). This was used to calculate the C_{Da} (see Section 2.4.2).

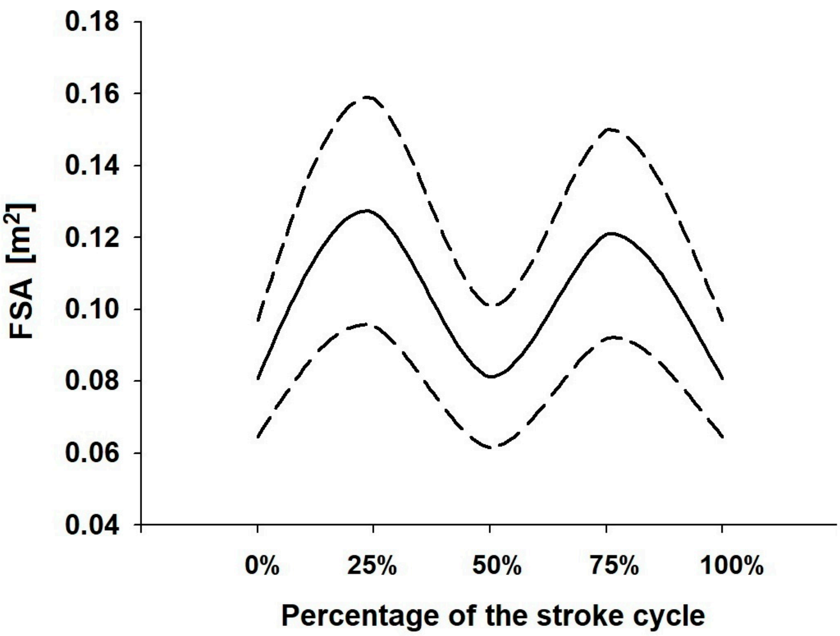

Figure 1. Frontal surface variation (FSA) during an entire stroke cycle. Solid line represents the average, and dashed lines represent the 95% confidence intervals.

2.2. Research Design of In-Water Data

After a standardized warm-up, swimmers were instructed to perform an all-out 25 m trial in front-crawl with a push-off start. They were advised not to breathe while performing between the 10th and the 20th meter marks to avoid changes in their stroke coordination or technique [28]. Between the 10th and the 20th meter marks, two sections were analyzed: (i) S10–15 m: distance between the 10th and 15th meter marks; and (ii) S15–20 m: distance between the 15th and 20th meter marks. In each section of the race, the average of a set of variables was measured.

2.3. Kinematics

To measure swimming velocity, the string of a speedometer (SpeedRT, ApLab, Rome, Italy) was attached to the swimmers' hip [22]. The speedometer calculated the displacement and velocity of the swimmers at a rate of 100 Hz. Afterwards, data were imported into a signal-processing software program (AcqKnowledge v. 3.9.0, Biopac Systems, Santa Barbara, CA, USA). The signal was handled with a Butterworth 4th-order low-pass filter (cut-off: 5 Hz) upon residual analysis. A GoPro Hero 7 video camera (at a sampling rate of 60 Hz) was synchronized to the speedometer to film the swimmers' performance in the sagittal plane to identify the passing moment of each section. The swimming velocity (in m/s) was obtained from the software in each section of the race (i.e., S10–15 m and S15–20 m). The intra-cyclic fluctuation of swimming velocity (dv, in %) was calculated as the coefficient of variation (CV:CV = (one standard deviation)/mean) × 100) [29]. The stroke frequency (SF, in Hz) was measured by calculating the number of cycles per unit of time from the time required to complete one full cycle (f = 1/t), and afterward converted to Hz. A complete stroke cycle was considered to end at the moment of consecutive entry of the right hand into the water. The stroke length (SL, in m) was computed as SL = v/SF, in which v is the swimming velocity (in m/s), and SF is the stroke frequency (in Hz) [30]. The stroke index (SI, in m^2/s) was used as a swimming efficiency indicator [31]. It was calculated as SI = v · SL, in which SI is the stroke index (in m^2/s), v is the swimming velocity (in m/s), and SL is the stroke length (in m). Figure 2A represents the speedometer setup.

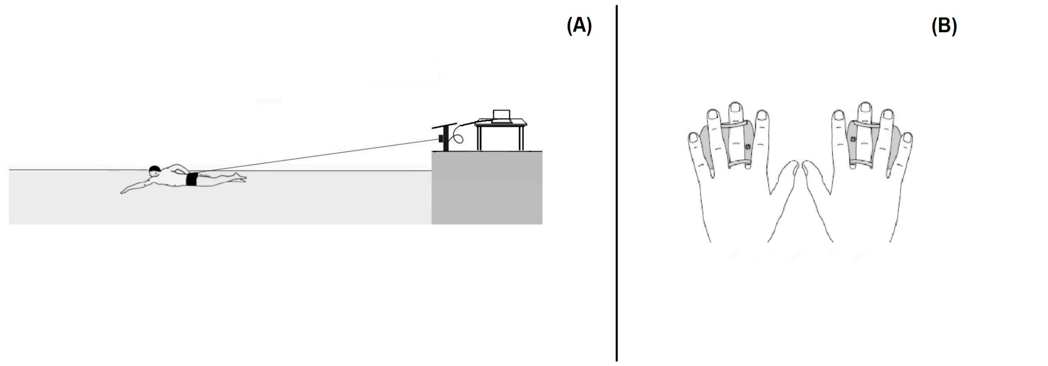

Figure 2. Panel (**A**)—speedometer setup for the swimming velocity measurement. Panel (**B**)—placement of the sensors for propulsive force measurement.

2.4. Kinetics

2.4.1. Propulsive Force

The propulsive force was measured with SmartPaddles® (Trainesense, Tampere, Finland). These are wearable sensors that measure a set of kinetic and kinematic variables during a swimming stroke [32]. It consists of three parts: the SmartPaddles®, the PoolShark Session Manager mobile application for recording, and the Analysis Center (https://sharksensors.com/) for analysis and data storage. The SmartPaddles® sensor unit is attached to the swimmer's hand with silicon straps (Figure 2B). It records the applied force using two pressure sensors and movement with 9-axis IMU. The device uses a sampling frequency of 100 Hz. The PoolShark Session Manager acts as a user interface between a mobile device and the SmartPaddles®. It is used to manage the recording and upload the data to the Analysis Center. The Analysis Center automatically analyzes the recordings and visualizes the performance. The main focus of the Analysis Center is to provide instantaneous information to train athletes in the training environment. Furthermore, it also allows downloading the data for further processing. As far as it is known, the SmartPaddles® calculation algorithm has not been published yet. The SmartPaddles® generates the processed data through the closed Matlab GUI (Graphical User Interface) (Tampere, Finland) developed by the Trainesense Oy (Tampere, Finland). This means that there is no access to SmartPaddles® raw data and the algorithm calculation constants cannot be adjusted.

As mentioned before, swimming velocity was obtained during three consecutive stroke cycles in each section (i.e., S10–15 m and S15–20 m). Consequently, the three corresponding arm-pulls of each upper limb were used. Figure 3 (panel B1—left upper limb; panel B2—right upper limb) shows an example of a swimmer's arm-pulls during the entire trial. Each arm-pull was defined as the time spent between the entry and exit of the hand. For the right (F_{mean_right}, in N) and left (F_{mean_left}, in N) arm-pulls, the mean propulsion was measured. Afterward, the mean propulsive force generated during an entire stroke ($F_{mean\_stroke\ cycle}$, in N) cycle was calculated as (F_{mean_right} + F_{mean_left})/2 (in N). The sum of the two arm-pulls (F_{total}, in N) was calculated to retrieve the total propulsive force generated during a full stroke cycle (F_{mean_right} + F_{mean_left}). The impulse related to each arm-pull was calculated as: $Imp = F \cdot \triangle t$, in which Imp is the impulse (in N·s), F is the propulsive force (in N), and $\triangle t$ is the amount of time the propulsive force was generated (in s).

(**A**)
(**B**)
(**C**)

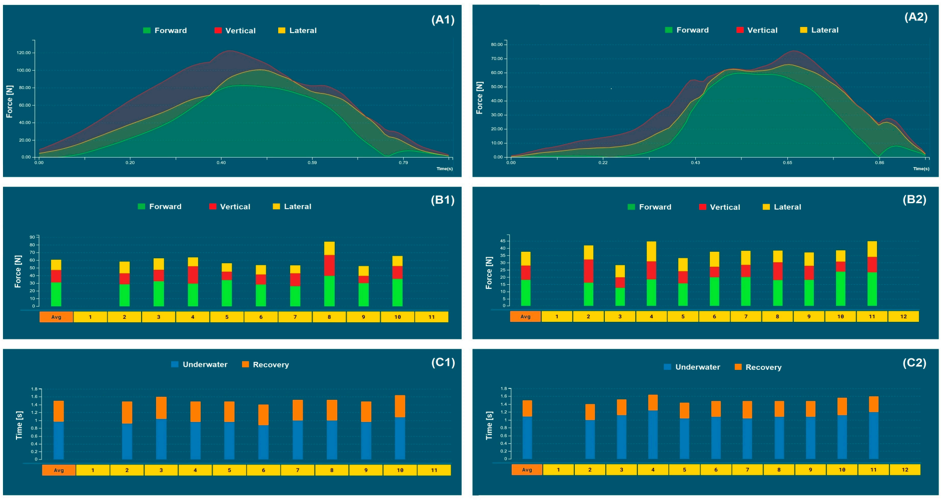

Figure 3. Example of data that can be analyzed in the Analysis Center. Suffixes 1 and 2 correspond to the left and right hand, respectively. Panels (**A**)—amount and force direction of the average arm-pull. Panels (**B**)—amount of force by arm-pull. Panels (**C**)—time spent in each arm-pull (underwater phase) and in recovery (aerial phase).

2.4.2. Active Drag Coefficient (C_{Da})

The C_{Da} was calculated based on inverse dynamics, taking the total propulsive force generated during an entire stroke cycle [19]. Therefore, the C_{Da} was calculated as C_{Da} = propulsive force/($0.5 \cdot v^2 \cdot \rho \cdot$ FSA), in which C_{Da} is the active drag coefficient (dimensionless), the propulsive force is the amount of propulsive force generated in an entire stroke cycle (sum of both upper limbs, in N), v is the swimming velocity (in m/s), ρ is the water density (assumed to be 997 kg/m^3), and FSA is the frontal surface area (assumed to be the variation verified during one entire stroke cycle, in m^2).

2.5. Statistical Analysis

The Shapiro–Wilk test and Levene's test were used to assess the normality and homoscedasticity, respectively. Mean plus one standard deviation was computed as descriptive statistics.

For the v, dv, SF, SL, SI, $F_{mean\_stroke\ cycle}$, $Imp_{mean\_stroke\ cycle}$, F_{total}, and C_{Da}, a paired sample *t*-test ($p < 0.05$) was used to verify the difference between the two sections. For the F_{mean_right}, Imp_{right}, F_{mean_left}, and Imp_{left}, a two-way repeated measures ANOVA ($p < 0.05$) was used: (i) arm-pull time effect (difference between S10–15 m and S15–20 m); and (ii) side effect (difference between the right and left upper limbs). In both analyses, a gender effect was tested ($p < 0.05$), revealing a non-significant effect in both analyses. Therefore, data are presented with the two genders grouped together. Cohen's d was used to estimate the pairwise standardized effect sizes and was deemed as: (i) trivial if $0 \leq d < 0.20$; (ii) small if $0.20 \leq d < 0.60$; (iii) moderate if $0.60 \leq d < 1.20$; (iv) large if $1.20 \leq d < 2.00$; (v) very large if $2.00 \leq d < 4.00$; and (vi) nearly perfect if $d \geq 4.00$ [33].

Hierarchical linear modeling (HLM) was used to identify the determinants of swimming velocity. Two models were tested. In the first model, the differences between genders and the changes over time were tested. In the second and final model, the determinants of swimming velocity were tested (i.e., kinematics and kinetics). The final model considered only the significant determinants. Maximum likelihood estimation was calculated on HLM7 software [34].

3. Results

3.1. SmartPaddles and Analysis Center

Figures 3 and 4 represent an example of data from a swimmer, which can be observed in the Analysis Center. Figure 3 reports the propulsive force data (i.e., average orientation, arm-pull by arm-pull propulsive force, and underwater and recovery times). Figure 4 represents an example of the trajectory of a swimmer's hands in the top, side, and back views. The trajectory data corresponds to the average of the total arm-pulls performed by each hand.

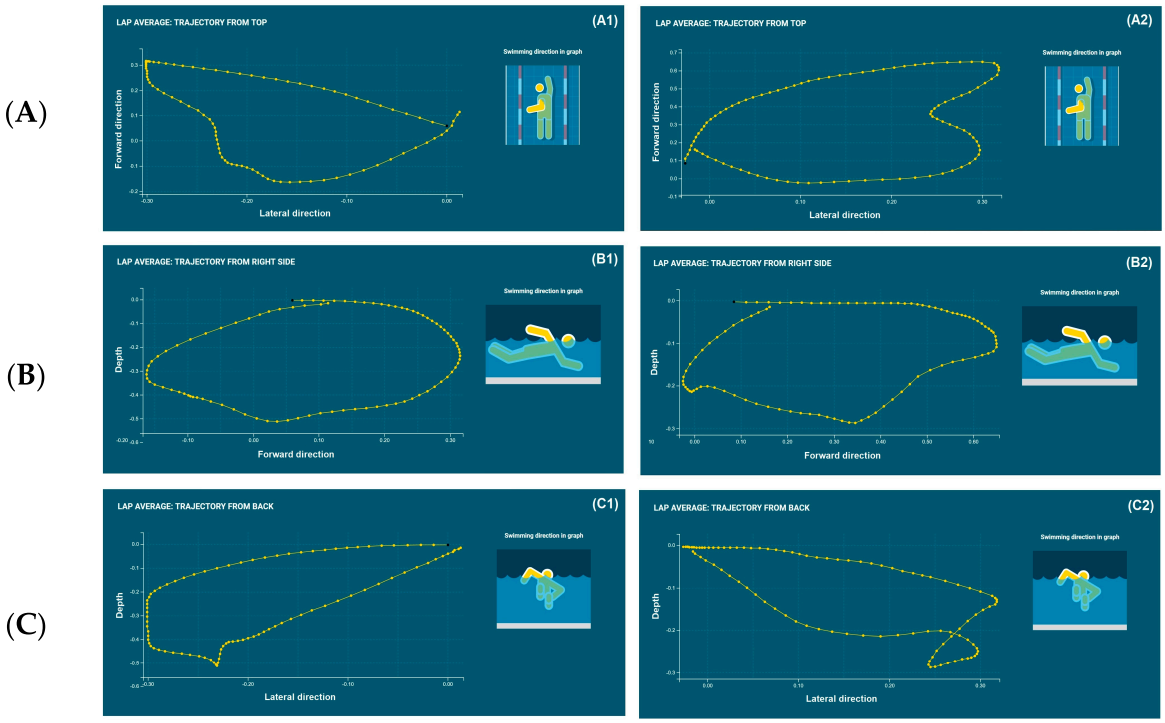

Figure 4. Example of a swimmer's hand trajectory that can be analyzed in the Analysis Center. Suffixes 1 and 2 correspond to the left and right hand, respectively. Panels (**A**)—top view of the arm-pulls. Panels (**B**)—side view of the arm-pulls. Panels (**C**)—back view of the arm-pulls.

3.2. Experimental Results

Table 1 presents the descriptive data (mean ± one standard deviation—1SD) of the propulsive force and impulse generated by each hand in each section. Inferential analysis revealed a non-significant time and side effect, as well as a non-significant time X side interaction for both variables. This shows that the propulsive force and impulse did not change significantly between sections, and non-significant differences were observed between hands. Notwithstanding, both variables showed higher values at S15–20 m than at S10–15 m (but with a trivial effect size).

Table 2 presents the descriptive data (mean ± one standard deviation—1SD) of the kinematic and kinetic variables by section. It also presents the comparison between sections.

Swimmers slightly increased their swimming velocity between sections (non-significantly with a trivial effect size). The same was observed for the other kinematic and kinetic variables. The C_{Da} slightly decreased between sections (trivial effect size). The dv was the only variable that presented a significant change (decrease, i.e., suggesting better performance but with a small effect size).

Table 1. Descriptive data (mean ± one standard deviation—1SD) of the propulsive force generated by hand in each section. It also presents the time effect (arm-pull difference between sections), side effect (difference between the propulsive force generated by both hands), and the respective interaction.

	Mean ± 1 SD		**Time**	**Side**	**Interaction Time X Side**	
	S10–15 m	**S15–20 m**	**F-Ratio (*p*)**	**F-Ratio (*p*)**	**F-Ratio (*p*)**	**d [Descriptor]**
F_{mean_right} [N]	23.87 ± 4.87	24.17 ± 5.13	0.472 (0.498)	1.794 (0.191)	0.002 (0.961)	0.06 [trivial]
F_{mean_left} [N]	27.03 ± 7.27	27.29 ± 8.15				0.03 [trivial]
Imp_{right} [N·s]	19.82 ± 5.00	20.02 ± 5.49	0.520 (0.477)	1.249 (0.273)	0.044 (0.835)	0.04 [trivial]
Imp_{left} [N·s]	22.45 ± 6.61	22.62 ± 7.58				0.02 [trivial]

F_{mean_right}—mean propulsive force generated by the right hand; F_{mean_left}—mean propulsive force generated by the left hand; Imp_{right}—impulse generated by the right hand; Imp_{left}—impulse generated by the left hand; *p*—significance value.

Table 2. Descriptive data (mean ± one standard deviation—1SD) of all variables measured and the *t*-test comparison between sections.

	Mean ± 1 SD					
	S10–15 m	**S15–20 m**	***t*-Test (*p*)**	**Mean Difference**	**95CI**	**d [Descriptor]**
v [m/s]	1.21 ± 0.16	1.22 ± 0.17	−1.391 (0.186)	−0.012	−0.031 to 0.007	0.06 [trivial]
dv [%]	33.82 ± 15.22	25.59 ± 13.15	3.280 (0.005)	8.241	2.853 to 13.629	0.58 [small]
SF [Hz]	0.83 ± 0.11	0.83 ± 0.13	−0.255 (0.803)	−0.003	−0.025 to 0.020	0.00 [trivial]
SL [m]	1.48 ± 0.20	1.49 ± 0.24	−0.737 (0.473)	−0.015	−0.059 to 0.029	0.05 [trivial]
SI [m^2/s]	1.80 ± 0.38	1.83 ± 0.43	−1.031 (0.320)	−0.037	−0.115 to 0.040	0.07 [trivial]
$F_{mean\_stroke\ cycle}$ [N]	25.45 ± 4.11	25.73 ± 5.34	−0.585 (0.568)	−0.274	−1.279 to 0.731	0.06 [trivial]
$Imp_{mean\_stroke\text{-}cycle}$ [N·s]	21.03 ± 4.68	21.32 ± 5.76	−0.570 (0.578)	−0.288	−1.370 to 0.794	0.06 [trivial]
F_{total} [N]	50.91 ± 8.24	51.46 ± 10.68	−0.583 (0.569)	−0.547	−2.558 to 1.464	0.06 [trivial]
C_{Da} [dimensionless]	0.76 ± 0.24	0.75 ± 0.27	0.112 (0.912)	0.002	−0.035 to 0.039	0.04 [trivial]

v—swimming velocity; dv—intra-cyclic variation of swimming velocity; SF—stroke frequency; SL—stroke length; SI—stroke index; $F_{mean\_stroke\ cycle}$—mean propulsive force (average of both hands) of the stroke cycle; $Imp_{mean\_stroke\ cycle}$—mean impulse (average of both hands) of the stroke cycle; F_{total}—total propulsive force (sum of both hands) of the stroke cycle; C_{Da}—active drag coefficient.

Table 3 presents the fixed effects of the final computed model, keeping only the significant determinants. The C_{Da} was the variable with the highest contribution to the swimming velocity. A one-unit increase in the C_{Da} imposed an increase of 0.593 m/s (95CI: −0.636 to −0.550; $p < 0.001$) in the swimming velocity. That is, an increase of the C_{Da} promoted a negative and significant effect on the swimming velocity. The other determinants had a positive (and significant) effect on the swimming velocity. That is, a larger SL and greater F_{mean} (right and left) led to a faster swimming velocity.

Table 3. Fixed effects of the final model including standard errors and (SE) and 95% confidence intervals (95CI).

Parameter Fixed Effect	**Estimate (SE)**	**95CI**	***p*-Value**
SL [m]	0.067 (0.025)	0.018 to 0.116	0.014
C_{Da} [dimensionless]	−0.593 (0.022)	−0.636 to −0.550	<0.001
F_{mean_right} [N]	0.007 (0.001)	0.005 to 0.009	<0.001
F_{mean_left} [N]	0.008 (0.001)	0.006 to 0.010	<0.001

SL—stroke length; C_{Da}—active drag coefficient; F_{mean_right}—mean propulsive force of the right hand; F_{mean_left}—mean propulsive force of the left hand.

4. Discussion

The aim of this study was to understand the variance of a set of kinematic and kinetic variables between two swimming sections and their relationship to swimming velocity. Swimming velocity did not significantly change between sections. The same was observed in the propulsive force with a non-significant side effect as well (i.e., difference between right and left arm-pulls). Likewise, the other kinematic and kinetic variables did not change significantly between sections, except for the dv (which significantly decreased between sections). Moreover, hierarchical modeling revealed that the SL, C_{Da}, and the propulsive force of both hands were the main determinants of the swimming velocity, with the C_{Da} being the greatest contributor.

4.1. SmartPaddles and Analysis Center

Several studies mention the advantages of using wearables in swimming and other sports, regardless of the type of variables measured and monitored [10,35]. However, regardless of whether it is based on IMU's or other sensors, data handling (after data collecting) may not be user-friendly for coaches and swimmers. That is, data often need to be filtered and manipulated to be presented to coaches and swimmers. Indeed, studies using wearables indicate that data often have noise that needs to be filtered out [9,36]. This process might be time-consuming and not user-friendly for non-experts with data handling such as coaches and swimmers. Therefore, having wearables that can be paired with operating systems that allow the presentation of filtered data to coaches and swimmers is an important step in the training process. As previously mentioned, the set of sensors used in this study is based on a system that includes the sensor units, an application for recording, and an analysis and data storage application for visualization [32]. Consequently, coaches and swimmers can visualize the propulsive force time-series (Figure 3A1,A2), the average of all arm-pulls performed (Figure 3B1,B2), and the time spent in the underwater and recovery phases (Figure 3C1,C2). Moreover, as the sensor units are based on IMU's, the hand's path can also be visualized from several perspectives (Figure 4). This visualization allows both coaches and swimmers to better understand the potential difficulties in their stroke mechanics. Indeed, information about the path of the swimmers' hand is of great importance for improving performance [37].

Propulsive force in swimming can be experimentally and directly measured based on pressure sensors or IMU's [17,32,38]. It can also be indirectly measured by tethered swimming [39]. Despite all the methods, there is still no gold-standard method to measure propulsive force in swimming. Notwithstanding, it should be mentioned that the sensor units used in the present study had a high agreement with a commonly used pressure sensor system [32].

4.2. Experimental Results

Most studies that analyze propulsive force in swimmers (as it relates to swimming velocity) tend to use the average of a given trial for further analysis [38,40]; however, in sports, an intravariability occurs [41]. That is, athletes may not always reproduce a given motion in the exact same way. In swimming, this phenomenon may be even greater due to the unstable conditions of the aquatic environment [42]. Therefore, to have a deeper insight, researchers and coaches can measure a given variable in different swimming pool sections as it is done in a race analysis context [23] or in a stroke-by-stroke analysis during a given trial [21,43]. In the present study, the researchers chose to analyze the variables between sections for convenience and because the sample consisted of recreational swimmers rather than high-level swimmers. The data revealed that the propulsive force of the swimmers in front-crawl did not differ between the sections and did not present a significant side effect (i.e., differences between right and left hand). The literature lacks information on the propulsive force variation during trials. Notwithstanding, Morais et al. [17] observed that, at least in high-level swimmers, propulsive force at maximum swimming velocity tended to decrease in a stroke-by-stroke analysis. However, the authors [17] observed a significant side effect (with a small effect size—based on the cut-off values of this study), which was not found in the present study. Therefore, based on sample demographics or other characteristics (such as dry-land strength or motor control), swimmers may or may not have a significant difference in the mean propulsive force between sides. This is a phenomenon that needs to be further studied, as well as its implications for swimming performance.

The activity observed in swimming velocity (and remaining kinematic variables) was the same as in the propulsive force, i.e., it did not significantly change between sections. In maximal trials or official sprinting events, swimming velocity tends to decrease significantly throughout the trial or front-crawl race in trained swimmers [17,23]. As this sample was composed of recreational swimmers, it seems that they presented an opposite profile when performing a maximal trial. As mentioned previously, swimming velocity and propulsive force did not change significantly between sections. The only variable that presented a significant difference between sections was the dv, in which a decrease was observed. The dv is considered an efficiency proxy, in which smaller values are usually related to better performances [14,20]. However, such an assumption is based on the average values of the entire trial. New approaches in swimming research are arguing that smaller values observed in the dv, at least in front-crawl, may not always be related to better performances and vice-versa [21]. Although swimming with greater gross efficiency may lead to lower energy expenditure [44], it is argued that swimmers can use different patterns of stroke mechanics (related to swimming efficiency) to maximize swimming velocity, at least in maximal trials or events [21]. Indeed, it can be argued that, in maximal trials or sprint events, swimmers are not concerned about saving energy. Therefore, swimmers can adopt a strategy based on generating greater propulsive forces and less efficient technique [21]. The C_{Da} also decreased slightly (but not significantly) between sections. As far as it is known, this is the first study that indicates the measurement of C_{Da} within the same trial. It was previously reported that, during swimming, FSA changes [27,45] and, consequently, active drag changes [27]. Therefore, it can be suggested that the C_{Da} can also change during swimming. The data of this study corroborates this assumption. Based on inverse dynamics, taking the propulsive force generated by the swimmers, their swimming velocity, and their FSA variation, it was possible to calculate the C_{Da} in each section. Overall, it can be stated that the increase in swimming velocity between sections (although not significant) may be related to the increase in propulsive force concurrently with the decrease observed in the dv and C_{Da}.

Hierarchical linear modeling was used to identify the determinants of swimming velocity. As male and female swimmers were tested together and repeated measurements were performed, the effects of gender and time were tested, respectively. Gender and time revealed a non-significant effect. This indicates that men and women can be grouped together to identify the determinants of swimming velocity. Moreover, a significant time effect for the swimming velocity test was not identified. This indicates that swimming velocity did not change significantly between sections (as previously tested). Thus, it can be stated that recreational swimmers do not have a profile similar to high-level swimmers, where a significant decrease in swimming velocity is observed between sections in a maximal trial or sprinting event [23]. The final model revealed SL, F_{mean_right}, F_{mean_left}, and C_{Da} as significant determinants of swimming velocity. Regarding SL, current data indicate that swimmers who were able to cover a greater distance per stroke are more likely to achieve faster swimming velocities, which is a well-known fact in swimming [14,20]. Regarding propulsive force, theoretical models based on numerical studies indicated that greater levels of propulsive force led to faster swimming velocities [46,47]. More recently, experimental studies have demonstrated this phenomenon, finding that higher values of propulsive force led to faster swimming velocities [16,17]. Here, it could even be argued that a greater propulsive force might also allow for a larger SL and, hence, a faster swimming velocity. Indeed, it has been argued that propulsive force may play a key role in the SF–SL interaction to increase swimming velocity [18]. The C_{Da} was also kept as a significant determinant of swimming velocity. The literature is committed to showing that hydrodynamics plays a fundamental role in the swimmers' performance, where swimmers who present smaller values are more likely to present better performances [13,48].

In the past, due to equipment constraints, it was more difficult to measure propulsive force directly and, hence, test it as a determinant of swimming velocity. The data of the current study indicates that swimming velocity was determined by the interaction of kinematics (SL) and kinetics (propulsive force and C_{Da}, i.e., hydrodynamics). This is in line with the literature, which highlights swimming as a holistic phenomenon. Notwithstanding, it should be mentioned that swimmers can achieve faster swimming velocities by generating propulsive forces while reducing resistive forces [12]. These findings reveal that both propulsion and C_{Da} are significant determinants of swimming velocity. Recently, it has been reported that swimmers can experience misalignments when producing propulsive force, which will lead them to have a larger FSA area and, therefore, a greater resistive force [27]. Consequently, they can be under a higher resistive force immediately after they generate propulsive force, promoting a decrease in their swimming velocity. Therefore, it can be suggested that there is no point in generating greater levels of propulsive force if immediately afterward one does not adopt a position that is as hydrodynamic as possible, i.e., decreases the water resistance.

As the main limitations of the present study, it can be considered that: (i) these data are suitable only for sprint trials or events, i.e., maximal swimming velocity; (ii) an indicator of the swimmers' motor control was not measured, for example, the index of coordination. This may bring a deeper insight on the relationship between the swimmers' velocity and the propulsive force and C_{Da}; and (iii) FSA variation was measured based on land positions simulating the key-moments of the swimming stroke. It should be stated that, whenever possible, researchers are advised to measure FSA based on an in-water approach [27,45]. Future studies should focus on understanding the relationship between propulsive force and swimming velocity at different paces or intensities. Moreover, whenever suitable, a stroke-by-stroke analysis should be performed to understand the variance of these variables and their relationship to swimming velocity.

5. Conclusions

This study concludes that recreational swimmers did not significantly change their swimming velocity between the two sections. The same activity was observed in the propulsive force and in the other kinematic and kinetic variables measured, except for the dv. Hierarchical modeling revealed that swimming velocity was determined by the interaction of kinematic (SL) and kinetic variables (F_{mean_right} and F_{mean_left}—propulsive force; C_{Da}—resistive force). Coaches and swimmers should be aware of the importance of balance in both generating propulsive forces and decreasing resistive forces.

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References

1. Kenney, W.L.; Wilmore, J.H.; Costill, D.L. *Physiology of Sport and Exercise*; Human Kinetics: Champaign, IL, USA, 2021; ISBN 1-71820-172-9.
2. Glazier, P.S.; Mehdizadeh, S. Challenging Conventional Paradigms in Applied Sports Biomechanics Research. *Sports Med.* **2019**, *49*, 171–176. [CrossRef]
3. Holway, F.E.; Spriet, L.L. Sport-Specific Nutrition: Practical Strategies for Team Sports. *J. Sports Sci.* **2011**, *29*, S115–S125. [CrossRef] [PubMed]
4. Brown, D.J.; Fletcher, D. Effects of Psychological and Psychosocial Interventions on Sport Performance: A Meta-Analysis. *Sports Med.* **2017**, *47*, 77–99. [CrossRef] [PubMed]
5. Ferdinands, R.E.D. Advanced applications of motion analysis in sports biomechanics. In Proceedings of the XXVIII International Symposium of Biomechanics in Sports, Marquette, MI, USA, 19–23 July 2010.
6. Shih, H.-C. A Survey of Content-Aware Video Analysis for Sports. *IEEE Trans. Circuits Syst. Video Technol.* **2017**, *28*, 1212–1231. [CrossRef]
7. Barris, S.; Button, C. A Review of Vision-Based Motion Analysis in Sport. *Sports Med.* **2008**, *38*, 1025–1043. [CrossRef]
8. Mooney, R.; Corley, G.; Godfrey, A.; Osborough, C.; Quinlan, L.; ÓLaighin, G. Application of Video-Based Methods for Competitive Swimming Analysis: A Systematic Review. *Sports Exerc. Med.* **2015**, *1*, 133–150. [CrossRef]
9. Chambers, R.; Gabbett, T.J.; Cole, M.H.; Beard, A. The Use of Wearable Microsensors to Quantify Sport-Specific Movements. *Sports Med.* **2015**, *45*, 1065–1081. [CrossRef]
10. Marković, S.; Dopsaj, M.; Tomažič, S.; Kos, A.; Nedeljković, A.; Umek, A. Can IMU Provide an Accurate Vertical Jump Height Estimate? *Appl. Sci.* **2021**, *11*, 12025. [CrossRef]
11. Morais, J.E.; Oliveira, J.P.; Sampaio, T.; Barbosa, T.M. Wearables in Swimming for Real-Time Feedback: A Systematic Review. *Sensors* **2022**, *22*, 3677. [CrossRef] [PubMed]
12. Toussaint, H.M.; Beek, P.J. Biomechanics of Competitive Front Crawl Swimming. *Sports Med.* **1992**, *13*, 8–24. [CrossRef]
13. Morais, J.E.; Forte, P.; Silva, A.J.; Barbosa, T.M.; Marinho, D.A. Data Modeling for Inter- and Intra-Individual Stability of Young Swimmers' Performance: A Longitudinal Cluster Analysis. *Res. Q. Exerc. Sport* **2021**, *92*, 21–33. [CrossRef] [PubMed]
14. Barbosa, T.M.; Bartolomeu, R.; Morais, J.E.; Costa, M.J. Skillful Swimming in Age-Groups Is Determined by Anthropometrics, Biomechanics and Energetics. *Front. Physiol.* **2019**, *10*, 73. [CrossRef] [PubMed]
15. Narita, K.; Nakashima, M.; Takagi, H. Developing a Methodology for Estimating the Drag in Front-Crawl Swimming at Various Velocities. *J. Biomech.* **2017**, *54*, 123–128. [CrossRef] [PubMed]
16. Koga, D.; Gonjo, T.; Kawai, E.; Tsunokawa, T.; Sakai, S.; Sengoku, Y.; Homma, M.; Takagi, H. Effects of Exceeding Stroke Frequency of Maximal Effort on Hand Kinematics and Hand Propulsive Force in Front Crawl. *Sports Biomech.* **2020**, 1–13. [CrossRef]
17. Morais, J.E.; Forte, P.; Nevill, A.M.; Barbosa, T.M.; Marinho, D.A. Upper-Limb Kinematics and Kinetics Imbalances in the Determinants of Front-Crawl Swimming at Maximal Speed in Young International Level Swimmers. *Sci. Rep.* **2020**, *10*, 11683. [CrossRef]
18. Morais, J.E.; Barbosa, T.M.; Nevill, A.M.; Cobley, S.; Marinho, D.A. Understanding the Role of Propulsion in the Prediction of Front-Crawl Swimming Velocity and in the Relationship Between Stroke Frequency and Stroke Length. *Front. Physiol.* **2022**, *13*, 876838. [CrossRef]
19. Morais, J.E.; Barbosa, T.M.; Garrido, N.D.; Cirilo-Sousa, M.S.; Silva, A.J.; Marinho, D.A. Agreement between Different Methods to Measure the Active Drag Coefficient in Front-Crawl Swimming. *J. Hum. Kinet.* **2023**, *86*, 41–49. [CrossRef]
20. Figueiredo, P.; Silva, A.; Sampaio, A.; Vilas-Boas, J.P.; Fernandes, R.J. Front Crawl Sprint Performance: A Cluster Analysis of Biomechanics, Energetics, Coordinative, and Anthropometric Determinants in Young Swimmers. *Mot. Control* **2016**, *20*, 209–221. [CrossRef]
21. Fernandes, A.; Mezêncio, B.; Soares, S.; Duarte Carvalho, D.; Silva, A.; Vilas-Boas, J.P.; Fernandes, R.J. Intra-and Inter-Cycle Velocity Variations in Sprint Front Crawl Swimming. *Sports Biomech.* **2022**, 1–14. [CrossRef]
22. Morais, J.E.; Marinho, D.A.; Oliveira, J.P.; Sampaio, T.; Lopes, T.; Barbosa, T.M. Using Statistical Parametric Mapping to Compare the Propulsion of Age-Group Swimmers in Front Crawl Acquired with the Aquanex System. *Sensors* **2022**, *22*, 8549. [CrossRef]
23. Morais, J.E.; Barbosa, T.M.; Silva, A.J.; Veiga, S.; Marinho, D.A. Profiling of Elite Male Junior 50 m Freestyle Sprinters: Understanding the Speed-Time Relationship. *Scand. J. Med. Sci. Sports* **2022**, *32*, 60–68. [CrossRef]
24. Morais, J.E.; Saavedra, J.M.; Costa, M.J.; Silva, A.J.; Marinho, D.A.; Barbosa, T.M. Tracking Young Talented Swimmers: Follow-up of Performance and Its Biomechanical Determinant Factors. *Acta Bioeng. Biomech.* **2013**, *15*, 129–138. [CrossRef] [PubMed]
25. Moreira, M.F.; Morais, J.E.; Marinho, D.A.; Silva, A.J.; Barbosa, T.M.; Costa, M.J. Growth Influences Biomechanical Profile of Talented Swimmers during the Summer Break. *Sports Biomech.* **2014**, *13*, 62–74. [CrossRef]
26. Morais, J.E.; Marques, M.C.; Rodríguez-Rosell, D.; Barbosa, T.M.; Marinho, D.A. Relationship between Thrust, Anthropometrics, and Dry-Land Strength in a National Junior Swimming Team. *Physician Sportsmed.* **2020**, *48*, 304–311. [CrossRef]
27. Morais, J.E.; Sanders, R.H.; Papic, C.; Barbosa, T.M.; Marinho, D.A. The Influence of the Frontal Surface Area and Swim Velocity Variation in Front Crawl Active Drag. *Med. Sci. Sports Exerc.* **2020**, *52*, 2357–2364. [CrossRef]
28. McCabe, C.B.; Sanders, R.H.; Psycharakis, S.G. Upper Limb Kinematic Differences between Breathing and Non-Breathing Conditions in Front Crawl Sprint Swimming. *J. Biomech.* **2015**, *48*, 3995–4001.

29. Barbosa, T.M.; Keskinen, K.L.; Fernandes, R.; Colašo, P.; Carmo, C.; Vilas-Boas, J.P. Relationships between Energetic, Stroke Determinants, and Velocity in Butterfly. *Int. J. Sports Med.* **2005**, *26*, 841–846. [CrossRef] [PubMed]
30. Craig, A.B.; Pendergast, D.R. Relationships of Stroke Rate, Distance per Stroke, and Velocity in Competitive Swimming. *Med. Sci. Sport* **1979**, *11*, 278–283. [CrossRef]
31. Costill, D.L.; Kovaleski, J.; Porter, D.; Kirwan, J.; Fielding, R.; King, D. Energy Expenditure during Front Crawl Swimming: Predicting Success in Middle-Distance Events. *Int. J. Sports Med.* **1985**, *6*, 266–270. [CrossRef]
32. Marinho, D.A.; Barbosa, T.M.; Auvinen, A.; Lopes, T.; Silva, A.J.; Morais, J.E. Smartpaddle as a New Tool for Monitoring Swimmers' Kinematic and Kinetic Variables in Real Time. *Open Sports Sci. J.* **2022**, *15*, e1875399X2210310. [CrossRef]
33. Hopkins, W. A Scale of Magnitudes for Effect Statistics. A New View of Statistics. 2002. Available online: http://sportsci.org/resource/stats/effectmag.html (accessed on 10 January 2023).
34. Raudenbush, S.W.; Bryk, A.S.; Cheong, Y.F.; Congdon, R.; Du Toit, M. *Hierarchical Linear and Nonlinear Modeling (HLM7)*; Scientific Software International: Lincolnwood, IL, USA, 2011; p. 1112.
35. Dadashi, F.; Crettenand, F.; Millet, G.P.; Aminian, K. Front-Crawl Instantaneous Velocity Estimation Using a Wearable Inertial Measurement Unit. *Sensors* **2012**, *12*, 12927–12939. [CrossRef]
36. Fusca, M.; Negrini, F.; Perego, P.; Magoni, L.; Molteni, F.; Andreoni, G. Validation of a Wearable IMU System for Gait Analysis: Protocol and Application to a New System. *Appl. Sci.* **2018**, *8*, 1167.
37. Sanders, R.; Takagi, H.; Vilas-Boas, J. How Technique Modifications in Elite 100m Swimmers Might Improve Front Crawl Performances to Podium Levels: Swimming 'Chariots of Fire'. *Sports Biomech.* **2021**, 1–20. [CrossRef]
38. Koga, D.; Tsunokawa, T.; Sengoku, Y.; Homoto, K.; Nakazono, Y.; Takagi, H. Relationship Between Hand Kinematics, Hand Hydrodynamic Pressure Distribution and Hand Propulsive Force in Sprint Front Crawl Swimming. *Front. Sports Act. Living* **2022**, *4*, 786459. [CrossRef]
39. Samson, M.; Monnet, T.; Bernard, A.; Lacouture, P.; David, L. Comparative Study between Fully Tethered and Free Swimming at Different Paces of Swimming in Front Crawl. *Sports Biomech.* **2019**, *18*, 571–586. [CrossRef] [PubMed]
40. Kadi, T.; Wada, T.; Narita, K.; Tsunokawa, T.; Mankyu, H.; Tamaki, H.; Ogita, F. Novel Method for Estimating Propulsive Force Generated by Swimmers' Hands Using Inertial Measurement Units and Pressure Sensors. *Sensors* **2022**, *22*, 6695. [CrossRef]
41. Preatoni, E.; Hamill, J.; Harrison, A.J.; Hayes, K.; Van Emmerik, R.E.; Wilson, C.; Rodano, R. Movement Variability and Skills Monitoring in Sports. *Sports Biomech.* **2013**, *12*, 69–92. [CrossRef] [PubMed]
42. Bideault, G.; Herault, R.; Seifert, L. Data Modelling Reveals Inter-Individual Variability of Front Crawl Swimming. *J. Sci. Med. Sport* **2013**, *16*, 281–285. [CrossRef] [PubMed]
43. Morais, J.; Barbosa, T.M.; Lopes, V.P.; Marques, M.C.; Marinho, D.A. Propulsive Force of Upper Limbs and Its Relationship to Swim Velocity in the Butterfly Stroke. *Int. J. Sports Med.* **2021**, *42*, 1105–1112. [CrossRef]
44. Ganzevles, S.P.; Beek, P.J.; Daanen, H.A.; Coolen, B.M.; Truijens, M.J. Differences in Swimming Smoothness between Elite and Non-Elite Swimmers. *Sports Biomech.* **2019**, 1–14. [CrossRef] [PubMed]
45. González-Ravé, J.M.; Moya-Fernández, F.; Hermosilla-Perona, F.; Castillo-García, F.J. Vision-Based System for Automated Estimation of the Frontal Area of Swimmers: Towards the Determination of the Instant Active Drag: A Pilot Study. *Sensors* **2022**, *22*, 955. [CrossRef] [PubMed]
46. Cappaert, J.M.; Pease, D.L.; Troup, J.P. Three-Dimensional Analysis of the Men's 100-m Freestyle during the 1992 Olympic Games. *J. Appl. Biomech.* **1995**, *11*, 103–112. [CrossRef]
47. Loebbecke, A.; Mittal, R. Comparative Analysis of Thrust Production for Distinct Arm-Pull Styles in Competitive Swimming. *J. Biomech. Eng.* **2012**, *134*, 074501. [CrossRef] [PubMed]
48. Marinho, D.A.; Barbosa, T.M.; Costa, M.J.; Figueiredo, C.; Reis, V.M.; Silva, A.J.; Marques, M.C. Can 8-Weeks of Training Affect Active Drag in Young Swimmers? *J. Sports Sci. Med.* **2010**, *9*, 71. [PubMed]