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Propulsion and symmetry within the stroke cycle: a comparison between tethered and free swimming

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ABSTRACT

BACKGROUND: Asymmetry of propulsion is a key factor when the movements of two limbs occur in sequence. Considering the difficulties in quantifying thrust forces during free-swimming, tethered-swimming is proposed as an alternative tool. The purpose of this study was to investigate the thrust forces during tethered and free-swimming, including the effect of hand dominance.

METHODS: Eleven swimmers were analyzed during 10-s all-out front-crawl swimming test in both conditions using only arms. Two pressure sensors were attached to each swimmer’s hand (palmar and dorsal side) to estimate the propulsive forces as the horizontal component of the product of hand differential pressure and hand surface. Propelling forces in terms of average (F_{MEAN}), impulse (I), peak (F_{PEAK}), and as a pattern within the stroke cycle values were analyzed.

RESULTS: Larger hand propulsion was found in tethered than in free-swimming (~16%, 11%, and 21%, for F_{MEAN} , F_{PEAK} , and I, respectively). The SPM analysis highlighted larger values only at the beginning of the cycle (from 7% to 42%). Dominance analysis revealed a higher F_{PEAK} (~12 N) in the dominant limb than in the nondominant limb in both swimming conditions.

CONCLUSIONS: Larger hand force in tethered than free-swimming conditions is explained by differences from entry to catch phase.

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KEY WORDS: Swimming; Athletic performance; Athletes.

Swimming is characterized by propelling the body in water through the upper limbs as the main contributing factor.¹ According to the review of Santos *et al.*,² numerical and experimental investigations have been implemented to understand how propulsion could be improved, and both methods have advantages and drawbacks. Tethered-swimming setups, while enabling in-pool assessments with strong ecological validity, present several limitations. The use of cables, straps, and external devices may affect swimmers’ technique, and body alignment, thereby introducing artificial constraints. Moreover, the stationary nature of tethered swimming alters stroke mechanics, particularly by re-

stricting the upper arm’s forward movement and increasing the duration of the propulsive phase. It can also modify the temporal coordination between limbs, potentially leading to non-natural asymmetries in force production.^{3,4} However, with recent technological advances in the design of miniaturized and low-cost sensors, the analysis of swimmers’ propulsion has become more ecological, non-invasive, and economically efficient. Therefore, this approach does not require time-consuming analysis and does not have the field of view limitations of high-frequency cameras.^{5,6}

The propelling measurement during tethered-swimming was indeed proposed as an alternative tool since the di-

rect assessment during free-swimming remains difficult to quantify due to the forward movement of the swimmer. In the past, free and tethered conditions have been considered similar in terms of swimming technique, and tethered tests were often recommended as a viable alternative to free test conditions.⁷ However, more detailed investigations highlighted that due to the stationary nature of the tethered test, the swimmer's upper arm forward movement in water is inhibited, resulting in an increased duration of the propulsive phase compared to free-swimming.⁴ Furthermore, the propulsion overlapping between arms when the swimmer is fully tethered differs from the free-swimming;⁴ the use of tethering devices can potentially alter the swimmer's natural stroke consequently affecting several hand kinematic parameters, such as the angle of attack, velocity, and acceleration. In addition, asymmetry is a key factor in investigating propulsion when the movements of the two limbs occur in sequence.⁸ Specifically, greater symmetry in swimmers' body posture can enhance stability and minimize wasteful movements that increase drag.⁹⁻¹² The recent scoping review of Knihš *et al.* highlighted that asymmetry in tethered¹³⁻¹⁶ and free swimming^{17, 18} conditions seldom affect swimming performance. However, the relationship between the symmetry in the two swimming conditions was not investigated. Given that tethered-swimming is one of the most commonly used training methods and that the results regarding asymmetries are inconclusive,^{9, 15, 19} it is important to study the propulsive forces exerted by swimmers using novel and ecological instruments such as wireless pressure sensors.^{3, 5, 20} Thus, the current study aimed to investigate the comparisons of the propulsive forces exerted by the swimmer's hand during arms-only front crawl, with wearable pressure sensors. Specifically, the comparisons were made between 1) tethered- (TET) and free- (FREE) swimming; 2) dominant and non-dominant hands. We hypothesized that: 1) the propulsive forces exerted by the swimmer would be higher in tethered compared to the free-swimming, as suggested by the kinematic analysis of Samson *et al.*,⁷ and 2) there would be no differences occur between the dominant hand and the non-dominant coherently with the majority of previous studies investigating swimming conditions (or TET or FREE condition).¹⁹

Materials and methods

Participants

The experiment involved 11 regional-level swimmers (7 females and 4 males; age: 15.4 ± 0.5 years; height: 168.4 ± 0.5 cm; mass: 58.0 ± 7.1 kg), with FINA scores in the 50 m front

crawl (long course) of 492 ± 87 points. The sample size was based on a priori power analysis and aligned with previous studies in the field, which used similar cohorts (dos Santos *et al.*,¹³ N.=10; Samson *et al.*,⁴ N.=8; Psycharakis *et al.*,¹⁵ N.=15). Power analysis for a repeated-measures ANOVA, the primary model used, assumed a large effect size (Cohen's $d=1.0$), consistent with previous findings. Under these conditions, a minimum of 10 participants would provide 80% power at $\alpha = 0.05$. The final sample of 11 swimmers, therefore, met this threshold and reflects current standards in experimental swimming biomechanics.

All participants practiced swimming for at least 5 days a week, covering a distance of 4 ± 1 km per day, for a minimum of 6 years. None of the participants reported any prior upper limb injuries. Participants' dominant hand was determined through the Edinburgh Handedness Inventory questionnaire – short version:²¹ nine participants were right-handed, and two were left-handed.

Prior to the experiment, all participants signed an informed consent form. The Bioethics Review Board of the [Anonymized] approved the study (Prot. N. [Anonymized]) in accordance with the Declaration of Helsinki.

Experimental protocol

All participants completed a 20-minute self-selected warm-up session and familiarized themselves with the TET test and the use of the pull buoy. Each participant performed one TET and one FREE all-out 12 front-crawl stroke swimming test cycle (~15 seconds) using only arms (with a pull buoy between the lower limbs) in a counterbalanced order (15 minutes rest between). In both conditions, the central ten stroke cycles were analyzed, excluding the first and last cycles of the trial. No breathing was allowed during the tests to eliminate possible effects on symmetry and swimming technique.¹² The tests were conducted in a 25-meter swimming pool with a water temperature of 27 °C.

In the tethered condition, participants were docked to the pool wall through a non-elastic cable surrounded by a nylon belt. Leg sinking was prevented through support on a suspended rope. Before the start signal, swimmers assumed the horizontal position with the cable fully extended. In the FREE condition, the swimmer started with a stationary position, and the underwater phase was not performed.

Propulsion and symmetry assessment

The pressure was measured using one commercial armband wearable device placed on each hand between the second and fifth metacarpal joints (Seal, Platysens – Hong

Kong, sampling frequency 50Hz, dimensions 52 x 32 x 7 mm, mass 25 g, and measurement area 1 cm²). According to Gourgoulis and Nikodelis,²² this position is considered a reliable approximation for the point where the propulsive force vector is applied to the hand. Each device was composed of two sensors, one placed on the dorsal and one on the palmar side.

Hand force estimation was performed following these steps:

- the force exerted by the hand was calculated as the product of the differential hand pressure (palmar minus dorsal side [p_{diff}]) and the hand surface [A_{hand}] measured using computerized planimetry, ImageJ v. 1.43, Bethesda, USA,⁹ following Takagi's procedure using a single-pair of sensors $F = p_{diff} * A_{hand}$.²³
- considering the maximum instrumental error of the sensor,⁴ a threshold of 4 N was applied to identify the entry and exit of the hand through the water surface and the resultant force exerted by the hand (F_{rHAND}) was estimated;
- since the pressure sensor measured only the force acting in the normal direction to the hand surface, the horizontal component of the force exerted was estimated as the product of the force exerted (F_l) by the hand and $\sin(\alpha)$, where α was the underwater angle between the horizontal line (water surface) and upper arm; this procedure assumed a circle-shaped hand kinematic with a constant velocity of the hand and the rigidity of the upper limb segment (composed by the arm, forearm, and hand).²⁴

The following quantities were used for the successive analysis averaged over the ten strokes underwater cycles for the resultant and thrust force: mean force (F_{rMEAN} and F_{lMEAN} , respectively), peak force (F_{rPEAK} and F_{lPEAK} , respectively), impulse (I_r and I_l , respectively), and percentage of time within the stroke cycle at which force peak occurs (t_{rPEAK} and t_{lPEAK} , respectively). Furthermore, the symmetry index (SI) of F_{rMEAN} , F_{lMEAN} , F_{rPEAK} , F_{lPEAK} , I_r , I_l , t_{rPEAK} and t_{lPEAK} was computed and analyzed.^{14, 25} When the quantities are not distinguished in the resultant or thrust force, the finding is valid for both (F_{MEAN} , F_{PEAK} , I , t_{PEAK}). The F_{rMEAN} and F_{lMEAN} intra-class correlation (ICC) analysis between the cycles was performed separately for each hand and each test. The F_{rMEAN} and F_{lMEAN} ICC values for the dominant / non-dominant hand were: 0.94 ± 0.02 ; 0.93 ± 0.03 / 0.89 ± 0.05 ; 0.87 ± 0.05 ; for FREE, respectively, and 0.95 ± 0.02 ; 0.93 ± 0.03 / 0.89 ± 0.05 ; 0.86 ± 0.06 for the TET, respectively.

Two fixed underwater Go-Pro Hero 7 (GoPro Inc., USA; 60Hz) cameras recorded the propulsive (pull + push phases) and non-propulsive duration (entry to catch phase)²⁶

in central stroke cycles (*i.e.*, the 4th, 5th, and 6th) of each participant using Kinovea® (v. 0.9.5, Kinovea, Bordeaux, France). Each sagittal camera was positioned at 5m from the swimmer, on both sides.

Statistical analysis

t_{rPEAK} , t_{lPEAK} and SI variables (*i.e.*, F_{rMEAN} , F_{lMEAN} , I_r , t_{rPEAK} , and t_{lPEAK}) were normally distributed. The other variables, instead, were rank-transformed to normalize data. Normal distribution and homogeneity of variance were verified on transformed data and residuals through the Shapiro test and Levene's Test ($P > 0.05$). Repeated measurement (rm) ANOVAs for each dependent variable were performed. The independent variables were the "test" condition (TET *vs.* FREE) and the "hand dominance" (dominant *vs.* non-dominant) for F_{rMEAN} , F_{lMEAN} , F_{rPEAK} , F_{lPEAK} , I_r , I_l , t_{rPEAK} , and t_{lPEAK} . While "test" condition was the independent variable for SI of F_{rMEAN} and F_{lMEAN} , SI of F_{rPEAK} and F_{lPEAK} , SI of I_r and I_l dependent variables. Supplementary rmANOVAs were used to analyze differences in swimming cycle duration. In this case, the independent variables were: "test" condition, "hand dominance", and "phase" (propulsive *vs.* non-propulsive phases). Whenever necessary, Tukey *post-hoc* analyses were performed. Data analysis was conducted using JASP software (v. 0.18.3, <https://jasp-stats.org>).

In addition, two-way repeated measures ANOVAs using the Statistical Parametric Mapping (SPM, open-source spm1d code on Matlab, v.M0.1) technique was used to compare the 10-stroke cycles' patterns of F_r and F_l . F_r and F_l were normalized to stroke underwater duration identified through the entry and the exit of the hand from the water surface. The dependent variable was F_r -time series and F_l -time series, while the independent variables were "test" and "hand dominance" conditions. Supplementary Repeated Measurement ANOVAs were used to analyze stroke cycle duration. In this case, the independent variables were: "test" condition, "hand dominance," and "phase" (propulsive *vs.* non-propulsive phases).

Results

Repeated measurement ANOVA analysis on F_{MEAN} showed that only the single factor "test" was significant ($F_{1,10}=35.05$, $P < 0.001$, $\eta_p^2=0.78$; $F_{1,10}=26.34$, $P < 0.0001$, $\eta_p^2=0.72$, for F_{rMEAN} and F_{lMEAN} , respectively) where F_{MEAN} was higher in the TET when compared with the FREE (see Figure 1A and B).

Larger F_{PEAK} in the TET compared with the FREE was found ($F_{1,10}=12.66$, $P=0.0005$, $\eta_p^2=0.56$, Figure 1C;

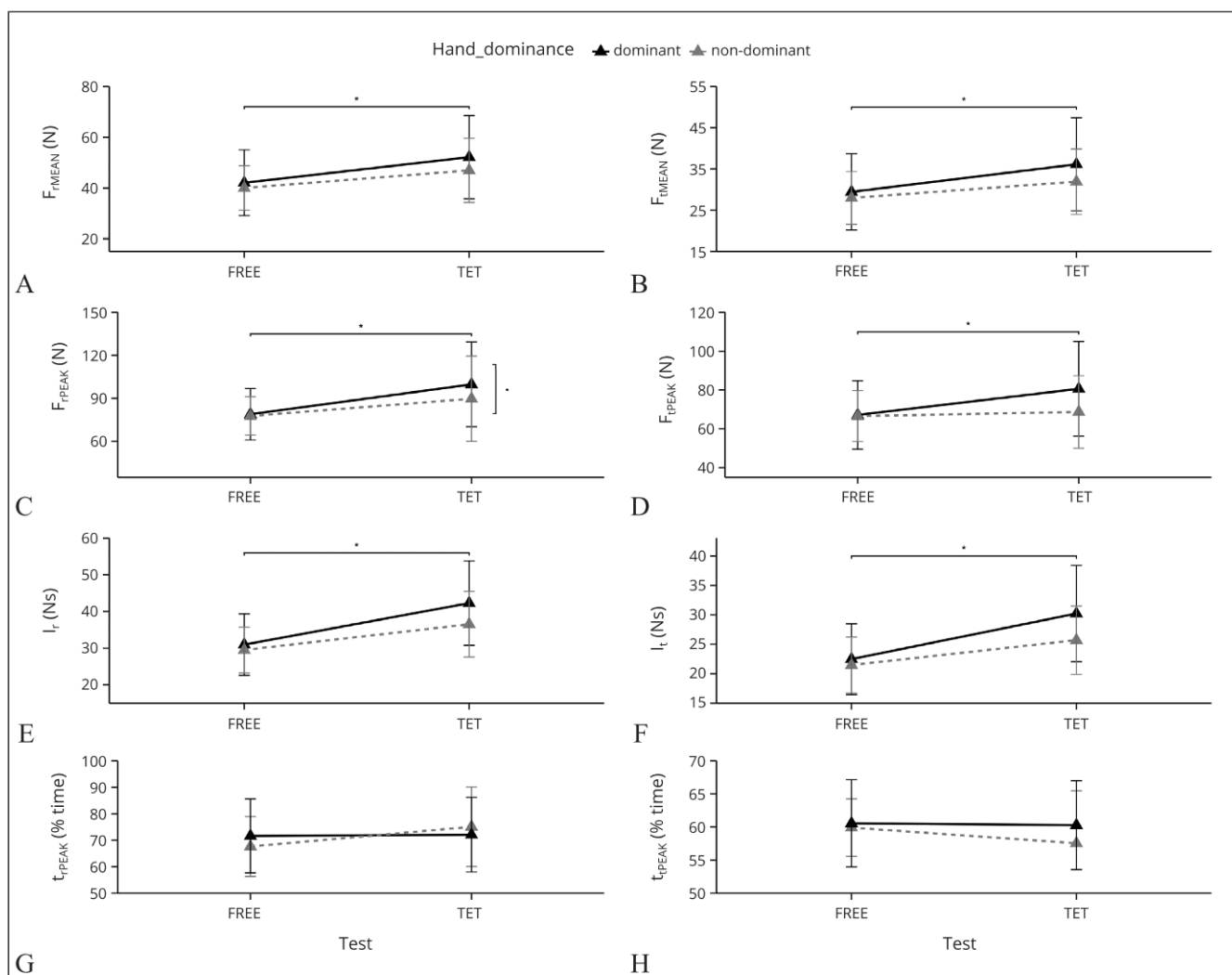


Figure 1.—Mean and SD for test condition (FREE and TET) and dominance factors (dominant, black, and non-dominant, grey) for F_{tMEAN} (A), F_{tPEAK} (B), I_r (E), t_{tPEAK} (G), F_{tMEAN} (B), F_{tPEAK} (D), I_t (F), and t_{tPEAK} (H). The crossed lines suggest an interaction effect between test condition and dominance factors. * $P < 0.05$.

$F_{1,10}=5.37$, $P=0.043$, $\eta_p^2=0.35$, Figure 1D, for F_{tPEAK} and F_{tPEAK} , respectively) and the interaction “test” x “hand dominance” was significant ($F_{1,10}=6.88$, $P=0.025$, $\eta_p^2=0.41$; $F_{1,10}=6.88$, $P=0.025$, $\eta_p^2=0.41$, respectively). Post-hoc comparisons in the dominant hand highlighted a larger F_{tPEAK} in the TET compared to the FREE ($t_{10}=4.41$, $P=0.002$, $d=0.96$; $t_{10}=3.22$, $P=0.021$, $d=0.79$). Furthermore, the dominant F_{tPEAK} hand was larger than the F_{tPEAK} in non-dominant in the TET condition ($t_{10}=2.79$, $P=0.05$, $d=0.76$). No differences in F_{tPEAK} between dominant and non-dominant hands were found ($t_{10}=2.78$, $P>0.05$, $d=0.59$).

Analysis on I highlighted that the single factor “test” was significant ($F_{1,10}=48.85$, $P<0.001$, $\eta_p^2=0.83$;

$F_{1,10}=59.73$, $P<0.001$, $\eta_p^2=0.61$, for I_r and I_t respectively). The single “hand dominance” was significant for I_t but not for I_r ($F_{1,10}=10.73$, $P=0.008$, $\eta_p^2=0.26$; $F_{1,10}=3.86$, $P>0.05$, $\eta_p^2=0.28$, respectively, Figure 1E and F). I_t was larger in the TET when compared with the FREE, and in the dominant hand when compared with the non-dominant hand.

The comparison between TET and FREE on SI variables highlighted that F_{tPEAK} ($F_{1,10}=8.40$, $P=.016$, $\eta_p^2=0.46$) and I_t ($F_{1,10}=5.97$, $P=0.02$, $\eta_p^2=0.30$) were found to be significant (Table I). Both variables showed a larger asymmetry of about 10% in the TET for the dominant hand.

TABLE I.—Symmetry Index (mean±standard deviation) for each dependent variable distinguishing the two test conditions.

Parameter	Test condition	
	Free [%]	Tethered [%]
SI of F_{rMEAN}	1.83±9.24	10.12±15.24
SI of F_{rPEAK}	-1.40±9.89	11.28±19.39
SI of I_r	0.84±9.46	12.60±14.02
SI of t_{rPEAK}	0.77±12.11	4.87±13.05
SI of F_{tMEAN}	2.80±11.18	11.65±15.56
SI of F_{tPEAK}	-2.27±10.34*	15.52±17.29
SI of I_t	1.19±10.76*	14.02±13.70
SI of t_{tPEAK}	5.13±27.78	-3.55±30.81

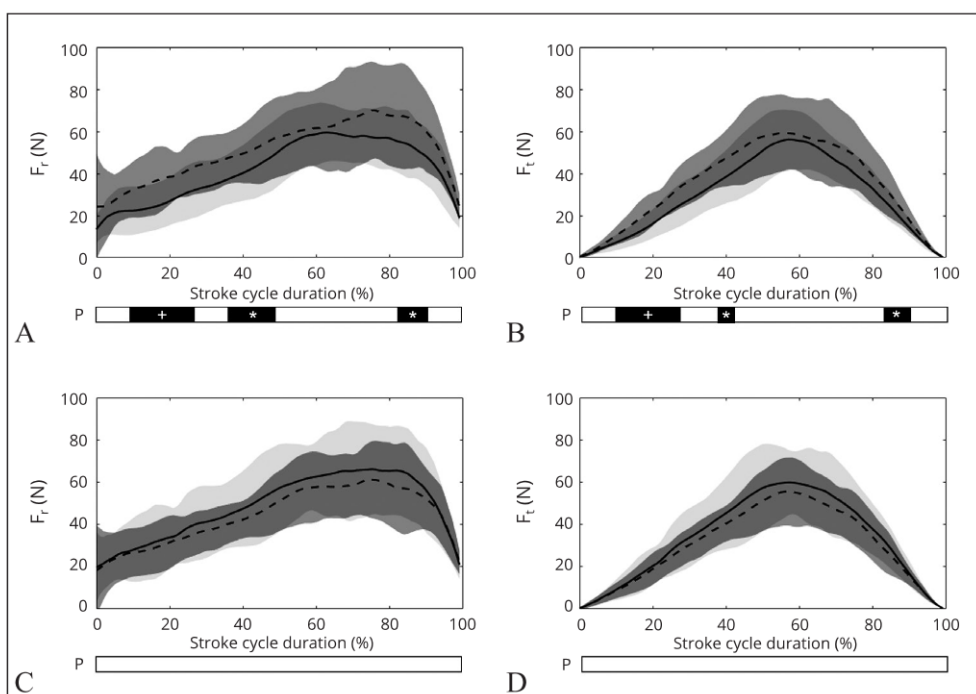
*Significant at $P \leq 0.05$ with the tethered condition.

TABLE II.—Phase duration of propulsive and non-propulsive phases.

Phase	Hand dominance	Test	Time (s)
Non-propulsive	Dominant	Free	0.66±0.11
		Tethered	0.56±0.09
	Non-dominant	Free	0.65±0.11
		Tethered	0.55±0.09
Propulsive	Dominant	Free	0.49±0.07
		Tethered	0.60±0.06
	Non-dominant	Free	0.50±0.05
		Tethered	0.59±0.06

*Significant at $P \leq 0.05$ between free and tethered conditions within propulsive phase.

Figure 2.—Mean and standard deviation of the F_r (A and C) and F_t (B and D) patterns throughout the stroke cycle together with the P value of the difference estimated with SPM analysis for: A, B) the two test conditions, tethered (dashed line and dark grey shade) and free-swimming (solid line and light grey shade); C, D) the dominance comparison, non-dominant (dashed line and dark grey shade) and dominant hand (solid line and light grey shade). * $P < 0.05$; + $P < 0.001$.



The interaction “test” x “phase” for stroke phases analysis was significant “ ($F_{1,10}=30.34$, $P < 0.001$, $\eta_p^2=0.34$). Post-hoc analysis revealed that the non-propulsive phase lasted more in the FREE compared with the TET ($t_{10}=4.14$, $P=0.0002$, $d=1.28$; Table II).

The comparison between the patterns of the force (F_r and F_t) in the SPM analysis revealed that the main factor “test” was significant ($F_{1,10}=15.86$, $P < 0.0001$; $F_{1,10}=18.57$, $P < 0.0001$, respectively). In particular, the analysis revealed significant differences between the two tests at three segments, as shown in Figure 2A and C. The ranges of the stroke cycles were similar for F_r and F_t : 7-28%, 35-48%, 84-90% and 7-27%, 38-42%, and 84-90%, respectively.

Discussion

The purpose of this study was to investigate the forces exerted during tethered and free-swimming tests and the effect of hand dominance. The results showed that resultant and thrust force parameters were significantly larger in the tethered- compared to the free-swimming, while no significant imbalance between the two hand forces was found. The analysis was performed with wearable pressure sensors that allowed an ecological evaluation with minimum encumbrance for the swimmer.

In the comparison between the two test conditions, data not only revealed the single three parameters (F_{MEAN} , F_{PEAK} ,

and I) were larger in tethered- than in free-swimming conditions (about 16%, 11%, and 21%, respectively) but also allowed to identify stroke phases that caused these differences. The SPM analysis highlighted larger values mainly only at the beginning of the stroke cycle (from 7 to 42% of the duration), corresponding to the interval from entry to catch events. Furthermore, the absence of difference in the timing of F_{PEAK} (occurring at ~60 and 70% of the duration of the stroke cycles, for F_{IPEAK} and F_{OPEAK} respectively) underscored the key role of the first stroke phases in the identification of the differences between FREE and TET. Indeed, due to the fixed body position of the tethered test, the swimmer's ability to move the upper arm forward in the water is restricted in the initial part of the stroke, leading to a potentially larger propulsive time for the upper arm.²⁷ In the present analysis, this latter consideration is substantiated by the larger duration of the non-propulsive phase in FREE compared to TET ($P < 0.001$), corroborating previous results in resisted swimming.²⁸

The values obtained in the present study (F_{MEAN} ranged between 40-49 N; F_{IPEAK} ranged between 29-34 N; F_{OPEAK} ranged between 78-97 N; F_{IPEAK} ranged between 67-75 N) are consistent with previous findings that reported approximately 27-55 N for F_{MEAN} and approximately 64-124 N for F_{PEAK} under both free and tethered conditions.² In addition, the pattern of the hand propulsive force is consistent with literature showing single or double peaks during the whole stroke.^{17, 23} However, no previous study reported a direct comparison of hand-propulsive forces between FREE and TET using pressure sensors. One experimental study attempted a comparison, but hand forces were estimated indirectly through kinematic analysis and inverse dynamics rather than measured directly,⁴ and a recent work has also investigated propulsive force generation during arms-only front crawl using 3D video-based reconstruction of arm and forearm segments, offering a complementary kinematic approach to propulsion analysis.²⁹

This latter comparison, investigating the orientation, the linear velocity, and acceleration of the hand, confirmed that the differences occur mainly in the entry to catch phases, as in the following phases, similar propulsive forces were generated. The statistical differences showed in our analysis should be interpreted together with the threshold accuracy of ~3 N of the measuring system assessed previously;^{5, 30} F_r (mean and peak) differed between FREE and TET far above the instrumental error (~5 N). Overall, as a main application perspective of the present analysis, the results supported the attention to technical differences in the first stroke phases that

coaches should have during fully-tethered training of the swimmers. Our results demonstrate that the coach can use fully resisted swimming to improve propulsion of the second part of their swimmer's stroke, while any adaptations in the initial phase may not have a direct transfer of propulsion to free swimming due to the differences in force here observed between these two swimming conditions. However, these differences between conditions are relevant only for the hand and not for the overall force comparison because hand propulsion is only a fraction of the overall body force exerted by the swimmer. In future studies, wireless pressure sensors could test the pressure and propulsion contribution of other body parts (e.g., forearm and arm).

In addition, we did not differentiate the sample into female and male swimmers, as the primary aim of the study was not to assess sex-based differences but to examine general propulsive force characteristics in adolescent athletes. Nonetheless, it is recognized that sex may influence swimming biomechanics due to differences in anthropometry, body composition, and neuromuscular coordination. Prior studies have reported mixed findings regarding the effect of sex on swimming performance and coordination patterns, particularly in front-crawl technique.³¹⁻³⁵ Therefore, future research with larger, stratified samples is warranted to systematically investigate how sex may affect both the magnitude and symmetry of propulsive forces, particularly when using instrumented approaches such as pressure sensors or motion capture.

Regarding the dominance analysis, controversial results were found. No differences were observed in the main effect for all quantities, with the exception of I_r . However, distinguishing FREE and TET conditions, a larger value of F_{PEAK} was also observed in the dominant with respect to the non-dominant (~12 N). These findings are consistent with the SI results. Specifically, an asymmetry of about 10% in the TET for the dominant hand was found for both variables I and F_{PEAK} . However, the lower effect size of these differences raises questions and suggests a need for further investigation. It is worth noting that the literature itself has shown some controversy on this matter: some authors reported differences,^{9, 13, 14} while others described no strong evidence on force exertion for the dominant side compared to the nondominant side.¹⁵ Finally, other studies showed differences only when investigating the interaction between consecutive arm-pulls and dominance.¹⁷ It is important to highlight that, differently from the present analysis, most of the mentioned studies investigated whole-stroke swimming (arms + legs); therefore, the dif-

ference between the dominant and non-dominant side of our analysis could be mitigated by the reduced rolling movement of the body typically performed when using only the arms as suggested by Bartolomeu and colleagues.⁹ In addition, even if Psycharakis *et al.*¹⁵ did not find differences between breathing and non-breathing during front-crawl in medium-level athletes, the lack of breathing could help reduce asymmetries in less experienced athletes, as in the case of our study.

Among the different approaches in the swimmer thrust estimation, one advantage of the differential pressure technique is considering the forces caused by unsteady factors (*e.g.*, turbulence and vortices). In the present study, however, the device used features a single couple of pressure sensors placed on the third metacarpophalangeal joint of the hand palmar and dorsal side, assuming that the pressure is equal on the whole hand surface. In accordance with Gourgoulis *et al.*,³⁶ this position is considered a reliable approximation for the point where the propulsive force vector is applied to the hand. Although a higher number of sensors will allow a more accurate and detailed estimation of the hand pressure distribution, it could significantly impact the natural action of the swimmer. In addition, previous studies that exploited a single-hand location^{3, 17, 37} did not distinguish between the horizontal and vertical components of the force but only the resultant one (normal to the hand surface, F_t) without a true investigation of the thrust force (F_t). In our F_t approach, the forces decomposition was tackled with the assumptions on the circular underwater path and on the constant underwater angular velocity of the hand, although the angle of attack and the relevant consequence on the different area of the hand were not taken into account. The only way to overcome these limitations is to incorporate video analysis of the hand kinematics, but it does come at the cost of reducing measurement space and consequently to the ecological validity approach of measurements. Furthermore, our approach offers greater user-friendliness compared to previous studies, as it eliminates the need for cables and elastic bands to secure the system and the connection to storage devices outside the pool. Therefore, wearable pressure sensors can be considered a valuable tool for trainers and coaches to precisely measure the force exerted during training sessions and seamlessly extrapolate data for future training plans. This technology can enhance the accuracy of performance analysis and support data-driven decision-making in athletic training, paving the way for optimized training protocols and improved athletic performance.

Conclusions

Our findings highlighted that larger hand force in tethered than free-swimming conditions are explained by differences in the first phases of the underwater stroke. These results can be important for coaches and athletes in the development of training sessions. However, our study does not provide a comprehensive explanation for the role of asymmetries in swimming. In general, the results of the present analysis highlighted the potentiality of an ecological approach using wireless wearable pressure sensors in swimmer performance monitoring.

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Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions

Silvia Fantozzi and Matteo Cortesi contributed equally and share senior authorship. Conceptualization: Matteo Cortesi, Silvia Fantozzi. Methodology: Gabriele Russo, Matteo Cortesi, Silvia Fantozzi. Software: Gabriele Russo, Vittorio Coloretti, Silvia Fantozzi. Validation: Vittorio Coloretti. Formal analysis: Gabriele Russo and Vittorio Coloretti. Investigation: Matteo Cortesi, Sandro Bartolomei, Ivan Malagoli Lanzoni. Data curation: Gabriele Russo, Vittorio Coloretti, Matteo Cortesi. Writing—original draft preparation: Gabriele Russo. Writing—review and editing: Gabriele Russo, Silvia Fantozzi, Matteo Cortesi, Sandro Bartolomei, Ivan Malagoli Lanzoni. Supervision: Matteo Cortesi, Silvia Fantozzi, Sandro Bartolomei, Ivan Malagoli Lanzoni. All authors read and approved the final version of the manuscript.

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