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A comparison of load cell and pressure sensors to measure in-water force in young competitive swimmers

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ABSTRACT

The purpose of this study was to compare the in-water force of young competitive swimmers using tethered swimming and differential pressure sensors. Thirty-one swimmers (16 girls and 15 boys) were randomly assigned to perform two in-water tests. Swimmers completed two maximum bouts of 25 m front crawl with a differential pressure system and a 30 s maximum bout with an attached load cell (tethered-swimming). The peak force (F_{PEAK}, in N) of dominant and non-dominant upper limbs was retrieved for further analysis. Comparison between methods revealed significant differences in all force variables ($p \leq 0.05$) and the biases (mean differences) were large in girls (F_{PEAK} dominant, 45.89 N; F_{PEAK} non-dominant, 43.79 N) and boys (F_{PEAK} dominant, 67.26 N; F_{PEAK} non-dominant, 61.78 N). Despite that, simple linear regression models between the two methods showed significant relationships with a moderate effect in all variables for girls, whereas in boys a high and moderate effect was verified for F_{PEAK} of dominant and non-dominant limbs (respectively). It seems that using pressure sensors and tethered swimming leads to different F_{PEAK} values in young competitive, where correction factors are needed to compare data between both methods.

1. Introduction

In competitive swimming the ability to effectively apply force in the water plays a crucial role in the swimmers' forward displacement. As it is a topic of great importance for the training process, there is a regular and systematic innovation of different methods to measure and control these forces (Santos et al., 2021). From these cutting-edge setups, experimental methods allow researchers to directly obtain individual force–time curves and consequently link them to performance (i.e., swimming velocity).

The use of tethered-swimming and differential pressure sensors has become the easiest available methods to measure in-water force as both are less time-consuming compared to other methods. However, some mixed-findings have been documented when using these methods, which may be due to the nature of the assessments (Santos et al., 2021). In tethered-swimming, the swimmer remains connected to a load cell/strain gauge by a non-elastic cable with no forward displacement (Yeater et al., 1981). This method appears to sustain the swimmer's strength potential rather than the ability to apply force effectively (Ruiz-Navarro et al., 2020), leading to overestimation of force (Samson et al., 2018). The use of tethered-swimming in a flume can help to overcome this aspect (i.e., absence of drag) due to the existence of a water flow that will influence the swimmer's speed (Ruiz-Navarro et al., 2022). However, advanced technology (e.g., swim flume, sensors) may not be available in all competitive squads due to cost/accessibility (Mooney et al., 2015). In contrast, with differential pressure sensors, the swimmer can move through the water and the forces of each limb (i.e., hand or foot) are estimated (Santos et al., 2021). This method allows for a more "free swimming" condition, but the two sensors only measure the resultant force of the hand rather than the effective propulsive force. Nevertheless, the two-hand sensors set-up (Aquanex System) has been increasingly used (e.g., Bartolomeu et al., 2021, ; Barbosa et al. 2020), as it allows an assessment in a more ecologically valid environment without constraints on stroke mechanics and efficiency (Santos et al.,

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Table 1
Characteristics of the swimmers.

Variables	Girls (n = 16)	Boys (n = 15)
Age (yo)	12.00 ± 0.50	12.87 ± 0.62
Body mass (kg)	47.46 ± 9.71	49.94 ± 8.11
Body height (cm)	154.84 ± 6.73	157.81 ± 7.64
HSA dominant (cm^2)	99.95 ± 8.87	107.13 ± 12.07
HSA non-dominant (cm^2)	100.71 ± 7.95	108.85 ± 13.34
World Aquatics Point Scoring (50 m freestyle)	226.88 ± 43.90	221.17 ± 37.32

HSA, hand surface area; yo, years old; kg, kilogram; cm^2, square centimetre.

2022a).

Although there is still no consensus on a gold standard method for measuring propulsive force, tethered-swimming (Amaro et al., 2014) and pressure sensors have been found to be reliable (Santos et al., 2022b). Most studies were performed using one of these methods individually (e.g., Morouço et al., 2014). To date, no research has been carried out to verify agreement or compare these two methods. However, comparisons between other methods/procedures have already been made in swimming (Barbosa et al., 2015; Barbosa et al., 2018), canoe polo (Löppönen et al., 2022), and cycling (Forte et al., 2020). In the specific case of swimming, Barbosa et al. (2015) found that using different procedures to measure passive drag can lead to data bias. The same authors suggested the application of a correction factor to adjust the estimates. Various swimming squads and laboratories still differ in the type of setup they have at their disposal for their daily assessments. Thus, it becomes extremely useful to provide comparable data between tethered swimming and pressure sensors. Researchers and practitioners are also interested in gaining deeper insight into data in ecological settings (Barbosa et al., 2021), such as "free-swimming". Thus, ensuring that the availability or costs of different tools (e.g., sensors) do not impair training monitoring can help coaches to use only the resources available in the squads (e.g., tethered-swimming). Therefore, the aim of this study was to compare the in-water force of young swimmers using tethered swimming and differential pressure sensors. It was hypothesized that, as argued by Santos et al. (2021), there would be no agreement between the methods and a correction factor should be used for accurate estimates between the methods.

2. Materials and methods

2.1. Participants

Thirty-one highly trained (Mckay et al., 2022) swimmers (16 girls and 15 boys) volunteered to participate in this study (Table 1). Swimmers were recruited from local swimming squads and assessed at the end of the third macrocycle (competitive peak form). The inclusion criteria for the participants were: (i) being previously familiar with the hand differential pressure system and tethered swimming; (ii) having a minimum of two years in competitive swimming in regional or national events; (iii) practicing more than four swim training sessions per week; and (iv) not having suffered any injuries in the past six months. Swimmers who did not meet these criteria from the beginning of the season until the data collection were not considered. The swimmers' parents or

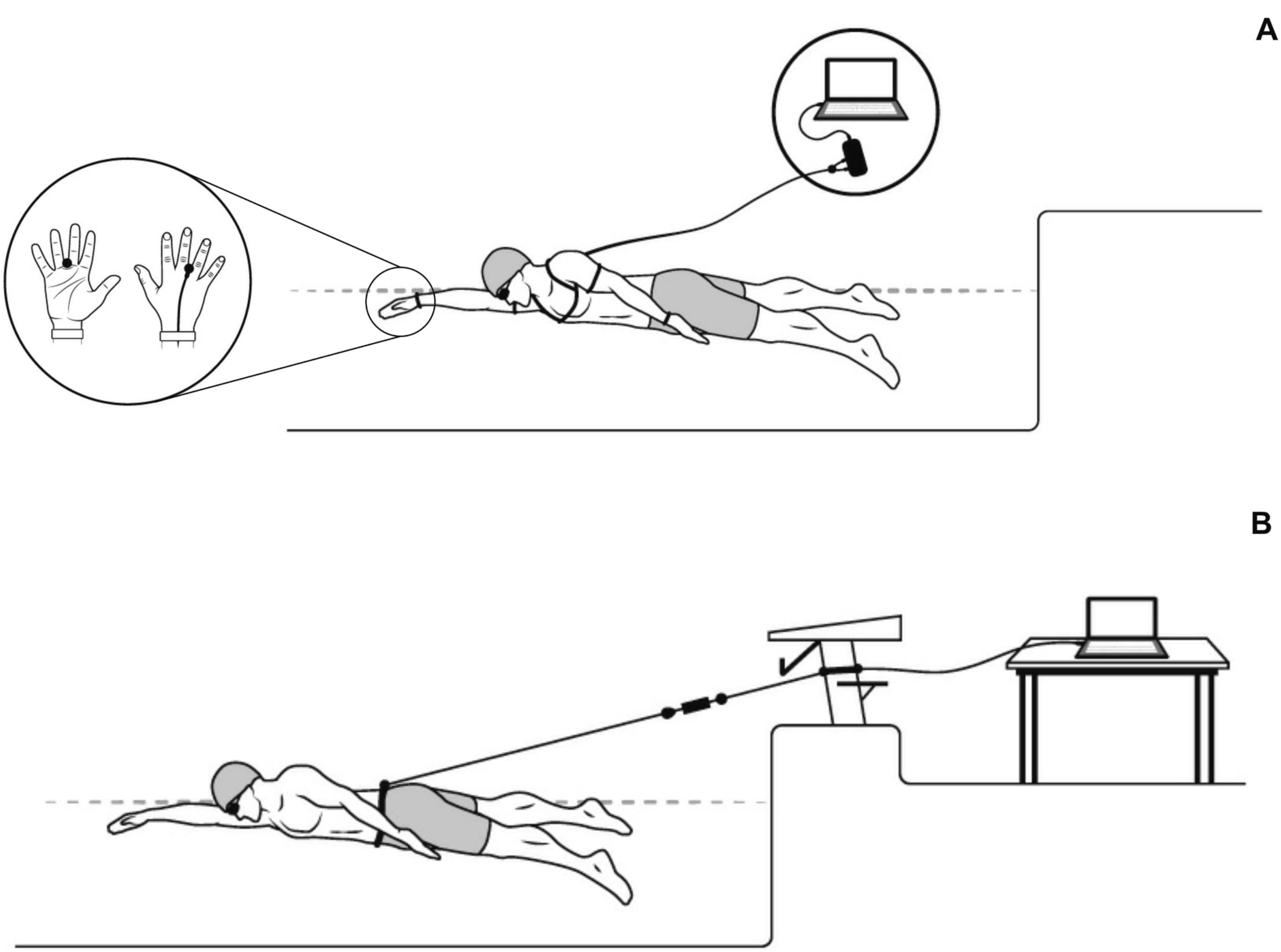

Fig. 1. The pressure sensors (Panel A) and tethered swimming (Panel B) tests.

guardians were informed about the benefits and experimental risks before signing a written informed consent form. All procedures were in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee (code: CE-UBI-Pj-2020–058).

2.2. Data collection

A cross-sectional research design was conducted to measure in-water forces using a differential pressure system (Fig. 1, Panel A) and tethered-swimming (Fig. 1, Panel B). Participants attended two test sessions on different days with a maximum interval of 48 h. At the beginning of the first session, the swimmers underwent anthropometric and body composition tests wearing only a textile swimsuit and a cap. Height (in cm) and body mass were measured with a digital stadiometer (SECA, 242, Hamburg, Germany) and a scale (TANITA, BC-730, Amsterdam, Netherlands), respectively. The hand surface area (HSA, in cm^2) for the dominant and non-dominant sides was measured by digital photogrammetry (Moreira et al., 2014). Swimmers placed each hand on a flat surface with a 2D calibration frame (3x3 cm) and from there all images were exported to an on-screen digitizer that allows accurate measurement of areas (Universal Desktop Ruler, v3.8, AVPSoft, USA). The swimmers' hand dominance was assessed by self-report.

The in-water experimental testing was carried out in a 25 m indoor swimming pool (water temperature: 27.5 °C; relative humidity: 60%) and force measurements were performed separately during the two test sessions (the first session used for the pressure sensors test and the second session for the tethered swimming test). A standardized warm-up (400 m swim, 100 m pull, 100 kick, 4x50 at increasing speed, 200 m easy swim) was performed individually by each swimmer before the two data collection (Morouço et al., 2018). Although all swimmers were familiar with the two force methods prior to testing, they underwent a familiarisation protocol with each procedure. In addition, all participants were asked to abstain from intense exercise the day before the tests to avoid data bias due to fatigue.

2.2.1. Pressure sensors test

Swimmers completed two maximum bouts of 25 m front crawl (full-body) with their normal breathing pattern for sprint events. The test began with an in-water push-off without gliding controlled by an auditory signal. A 30 min active rest was applied between each bout. Swimmers were randomly assigned for the first bout and followed the same order in the second. A differential pressure system composed of two hand sensors (Type A, Swimming Technology Research, Richmond, VA, USA) positioned between the third and fourth proximal phalanges and metacarpals was used to measure the pressure differences between the palmar and dorsal surfaces of both hands (Santos et al., 2022b). The resultant force of the hand (in N) was obtained by the system from the product of differential pressure of the hand surface area of each swimmer.

A two-channel A/D converter connected to a laptop with the Aquanex software (v.4.1, Model DU2, Swimming Technology Research, Richmond, VA, USA) was used to acquire data in real-time. Swimmers carried the system with elastic straps on their shoulders and arms (Fig. 1, Panel A). At the beginning of each bout, swimmers were reminded to keep their hands immersed for 10 s at the waistline level to calibrate the system. Data was acquired with a sampling frequency of 100 Hz for each maximum bout.

2.2.2. Tethered swimming test

A 30 s tethered swimming (full body) was performed at maximum intensity. The swimmers remained connected to a load cell (TS, C2, 300 kg, AEP Transducers, Modena, Italy) by means of a steel cable (length: 3.50 m) attached to a rigid surface and a belt around their waist (Fig. 1, Panel B). The load cell was aligned with the direction of the swim forming an angle of 6° with the water surface. To avoid the inertial effect, participants began the test by swimming for 5 s at low intensity before reaching the 30 s. A stopwatch (FINIS 3x300, Finis Inc., USA) was used to control the start and end of the test, and an auditory signal was provided for the swimmer. The normal breathing pattern for sprint events was encouraged as the action of breathing does not affect force production in tethered swimming (Psycharakis al., 2021). In addition, the swimmers followed the same order as in the previous session.

Data was acquired with a sampling frequency of 100 Hz using an A/D converter (2 mV/V, TAUSB, AEP Transducers, Modena, Italy) connected to a laptop. The calibration of load cell was verified before the test by using specific loads, as reported elsewhere (Amaro et al., 2014).

2.2.3. Force variables

The peak force (F_{PEAK}, in N) of the dominant and non-dominant upper limbs was assessed during the underwater paths for both methods. The F_{PEAK} was defined as the maximum value obtained from the individual force–time curve of three consecutive stroke cycles. The force–time curves retrieved from pressure sensors were analysed between the 11th and 24th meters (Santos et al., 2022b), while for tethered swimming they were considered after the 5 s of low intensity (±6 arm stroke cycles). As swimmers remain stationary in tethered swimming, the first two-stroke cycles were discarded due to the inertial effect. The distance covered by the swimmers with the pressure sensors was recorded using a video camera (Sony, HDR-CX 240, Japan) and a visual mark was applied in the defined interval. For TS, the swimmers were also recorded on video to define which side of the body to begin the test with.

Data from both methods were imported into a signal-processing software (AcqKnowledge v.3.7.3, Biopac Systems, Santa Barbara, CA, USA) and the signal was handled with a 5 Hz cut-off low-pass fourth order Butterworth filter. In addition, further analysis of tethered swimming comprised an angle correction by computing the horizontal component of force (Baratto de Azevedo et al., 2021).

2.3. Statistical analysis

The normality and homoscedasticity of the data were verified by the Shapiro-Wilk and Levene's tests, respectively. The mean and one standard deviation (M ± 1SD) were computed as descriptive statistics. As data presented a normal distribution, differences between swimmers' sex were analysed with an unpaired sample *t*-test. A paired sample *t*-test was used to compare the variables between both methods, and between measured and predicted values in the selected in-water force variables. Cohen's d was selected as an effect size (*d*) and interpreted as: trivial if $|d| < 0.2$, medium if $0.2 > |d| < 0.5$, and large if $|d| \geq 0.5$ (Cohen, 1988). Bland-Altman plots with 95% limits of agreement (LoA) were used to display within-subject variation and systematic differences between the two methods. The bias (mean difference), standard deviation (SD), and upper and lower LoA were calculated (Bland and Altman, 1986).

Simple linear regression models between both methods were computed for all variables. As there is still no consensus on the gold standard method for measuring in-water forces, dependent (y-axis) and independent (x-axis) variables were analysed using two approaches: (i) y-axis, tethered-swimming; x-axis, pressure sensors; and (ii) y-axis, pressure sensors; x-axis, tethered-swimming. Scattergrams were included with the main trendline, determination coefficient (R^2), adjusted determination coefficient (R^2_a), and standard error of estimate (SEE). As a rule of thumb, effect sizes were interpreted as: (i) very weak if $R^2 < 0.04$, weak if $0.04 \geq R^2 < 0.16$, moderate if $0.16 \geq R^2 < 0.49$, high if $0.49 \geq R^2 < 0.81$, and very high if $0.81 \geq R^2 < 1.0$ (Barbosa et al., 2015). The trendline equation obtained from the two approaches ($Y = a + bX$) was defined as the Correction Factor.

All statistical analyses were performed using the SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, USA) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, USA). The statistical significance was set at $p \leq 0.05$.

Table 2
Descriptive statistics for the selected in-water force variables according to the girls (n = 16) and boys (n = 15).

Group	Variable	PS (M ± 1SD)	TS (M ± 1SD)	Mean difference (95CI)	*t*-test (*p*)	*d*
Girls	F_{PEAK} dominant (N)	57.28 ± 11.26	103.17 ± 19.79	−45.89 (-55.08 to −36.70)	−10.64 (<0.001)	2.92
	F_{PEAK} non-dominant (N)	55.67 ± 14.35	99.46 ± 20.56	−43.79 (-52.25 to −35.32)	−11.02 (<0.001)	2.53
Boys	F_{PEAK} dominant (N)	60.78 ± 15.31	128.04 ± 35.28	−67.26 (-81.58 to −52.95)	−10.08 (<0.001)	2.56
	F_{PEAK} non-dominant (N)	61.56 ± 19.95	123.34 ± 36.02	−61.78 (-76.99 to −46.56)	− 8.71 (<0.001)	2.20

95CI, 95% confidence interval; *d*, Cohen's *d*; F_{PEAK}, peak force; N, Newton; PS, pressure sensors; TS, tethered-swimming; (-), TS presents higher values than PS.

3. Results

Boys and girls were analysed separately as differences were found in mostly variables. The descriptive analysis of force variables is shown in Table 2. The comparison between methods revealed significant differences ($p \leq 0.05$) with a large effect in all variables.

The Bland-Altman plots are presented in Fig. 2. Biases (mean differences) were large for dominant and non-dominant limbs in girls (Panel A and Panel B) and boys (Panel C and Panel D). Visual inspection of the plots revealed that most data points were within the LoA for all variables.

Simple linear regression models (Fig. 3) showed significant relationships in girls (F_{PEAK} dominant, $p = 0.051$; F_{PEAK} non-dominant, $p = 0.008$) and boys (F_{PEAK} dominant, $p = 0.001$; F_{PEAK} non-dominant, $p = 0.008$). A moderate effect was found in all variables for girls, while in boys a high and moderate effect was verified for F_{PEAK} of dominant and non-dominant limbs (respectively). From the trendline equations, correction factors were obtained (Table 3). No differences were found between the measured values (Table 2) and the estimated values for girls and boys.

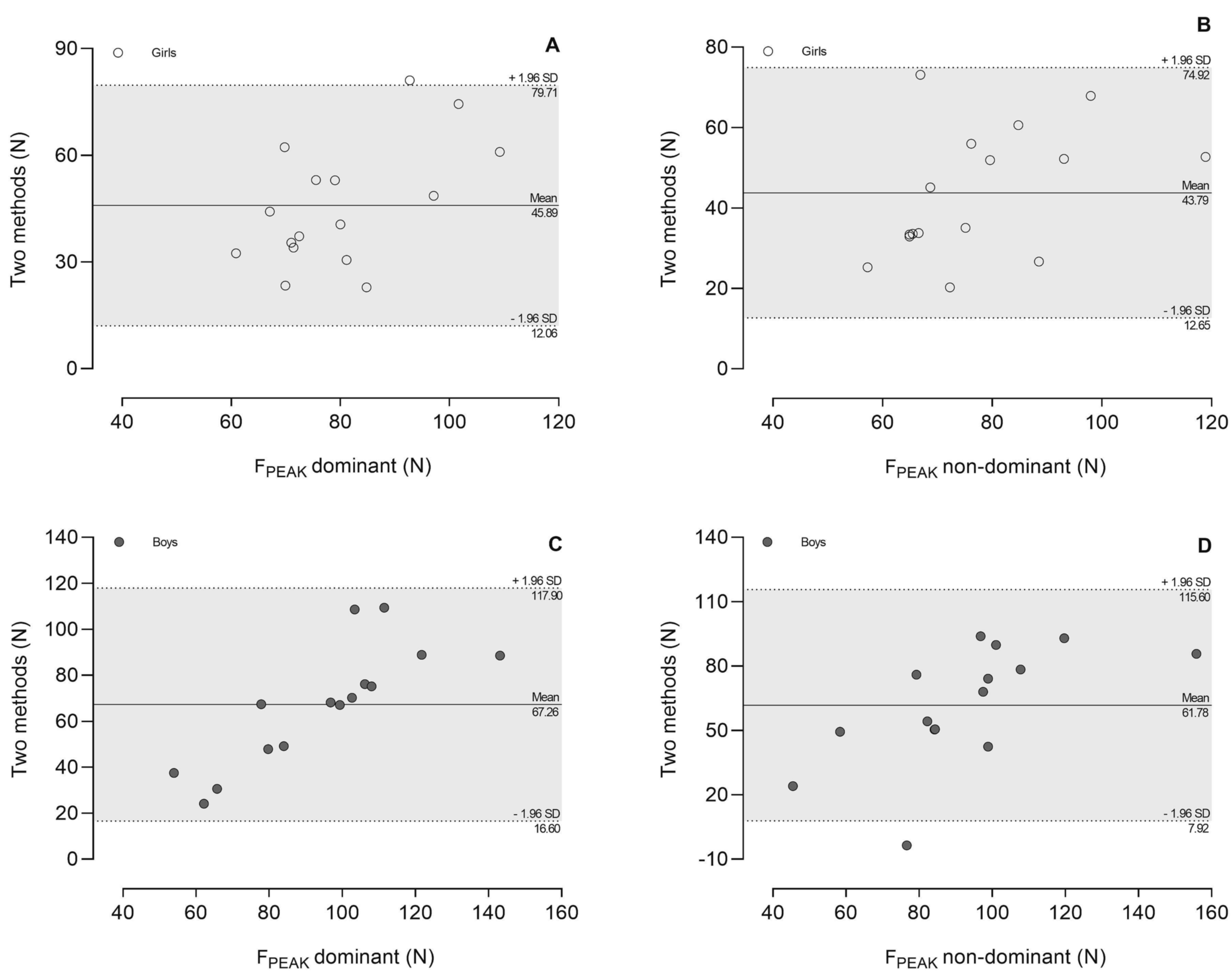

Fig. 2. Bland-Altman plots of the difference between PS and TS (y-axis) and mean of measurements (x-axis) for all variables. Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean differences between the two methods (bias). N, newton; F_{PEAK}, peak force.

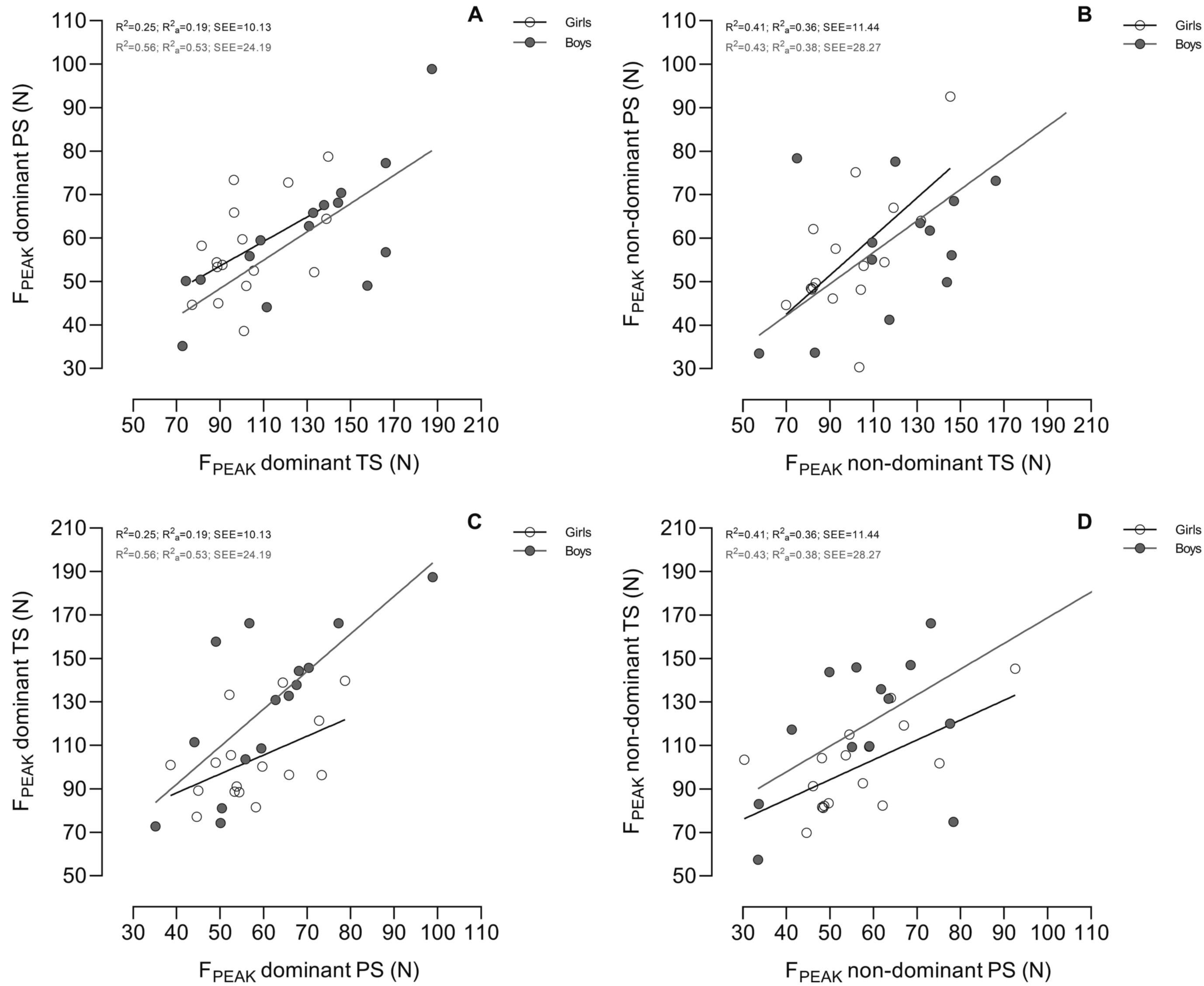

Fig. 3. Scattergrams with the main trendline, determination coefficient (R^2), adjusted determination coefficient (R^2_a), and standard error of estimate (SEE). Black trendlines or white dots represent girls, and light grey trendlines or filled dots represent boys. N, newton; F_{PEAK}, peak force; PS, pressure sensors; TS, tethered-swimming.

Table 3
Correction Factor for the selected in-water force variables.

Group	Predictor variable	Correction Factor
Girls	F_{PEAK} dominant PS (N)	= 0.2817 • F_{PEAK} dominant TS + 28.22
	F_{PEAK} non-dominant PS (N)	= 0.4451 • F_{PEAK} non-dominant TS + 11.40
	F_{PEAK} dominant TS (N)	= 0.8697 • F_{PEAK} dominant PS + 53.35
	F_{PEAK} non-dominant TS (N)	= 0.9133 • F_{PEAK} non-dominant PS + 48.61
Boys	F_{PEAK} dominant PS (N)	= 0.3257 • F_{PEAK} dominant TS + 19.07
	F_{PEAK} non-dominant PS (N)	= 0.3624 • F_{PEAK} non-dominant TS + 16.86
	F_{PEAK} dominant TS (N)	= 1.7300 • F_{PEAK} dominant PS + 22.92
	F_{PEAK} non-dominant TS (N)	= 1.1810 • F_{PEAK} non-dominant PS + 50.64

N, newton; F_{PEAK}, peak force; PS, pressure sensors; TS, tethered-swimming.

4. Discussion

The main finding of the present study was that the peak force measured by tethered swimming and pressure sensors differ significantly. These results confirm the established hypothesis, as large biases were found in all force variables for girls and boys. Thus, a correction factor was developed to make it comparable.

The upper limbs play an important role in swimming propulsion during front crawl (Deschodt et al., 1999), mainly due to the trajectory and orientation of the swimmer's hand. Due to the complexity of unsteady flow mechanics in human swimming, available methods to directly measure in-water force are scarce. Some advances in technology led to a regular and systematically use of tethered swimming and pressure sensors to control these forces (Santos et al., 2021). Still, there is a paucity of information on how the data from both methods can be comparable.

The results of the present study showed F_{PEAK} values similar to those previously reported (Santos et al., 2021). For instance, Santos et al. (2022b) reported values using pressure sensors of ≈50 N in young competitive swimmers (12.38 ± 0.48 yo), while an F_{PEAK} of 20.2 kgf (≈198 N) was found for young girls (12.50 ± 1.80 yo) in tethered swimming (Oliveira et al., 2021). It is noteworthy that most of the available studies included swimmers over 15 years of age (Santos et al., 2021), therefore, higher F_{PEAK} values were shown compared to those in this study.

The mean differences in this study were around ≈46 N and ≈67 N in girls and boys (respectively) when both methods were compared. As far as our understanding goes, only one study attempted a similar approach

(Löppönen et al., 2022). The authors aimed to compare a load cell with a commercial paddle (9-axis IMU plus 1 pressure sensor) to measure the in-water forces of paddle stroke in canoe polo. The same authors found that the paddles used overestimated the F_{PEAK} compared to the load cell (mean difference of 26.8 N), arguing that the differences might be due to data filtering. Despite this, the results of the present study showed a higher F_{PEAK} for tethered swimming (i.e., load cell) when compared to pressure sensors. Again, these differences seem to exist due to the "nature" of the assessments. Tethered swimming requires a fixed position, but it is essential to ensure that the cable remains taut. Even so, a gap in the period of time between propulsive phases of dominant and non-dominant upper or lower limbs can lead to backward acceleration due to the loss of cable tension (Takagi et al., 2021). Thus, the swimmer will need to re-tension the cable, which can lead to an overestimation of the F_{PEAK}. The absence of drag force acting on the swimmers can also impact the force data (Barbosa et al., 2020). The lack of fluid flow at a certain speed supports the idea that tethered swimming measures muscle strength potential rather than the force actually applied (Ruiz-Navarro et al., 2020). As testing in-water should resemble the "free swimming" actions (i.e., ecologically valid environment) as closely as possible, interest in the use of sensors is increasing (Santos et al., 2021). The absence of a gold standard method to measure these forces does not allow a deeper understanding of propulsion mechanics in water. Thus, the use of correction factors can help researchers and coaches to compare data between methods, at least if they use tethered swimming or pressure sensors (i.e., Aquanex System).

The methodology for comparing and providing correction factors for force estimation is not new to the sports sciences (e.g., Forte et al., 2020). Some of them were proposed to make the data comparable in competitive swimming (e.g., Barbosa et al., 2015). Again, this is the first study that provides a correction factor to compare methods that measure forces (i.e., acting on the direction of the displacement) in swimmers. Although there was a significant relationship between the methods, a bias existed, and a correction factor has been applied to all variables. The accuracy/error of the predictions in girls was around 11 N for both limbs, while in boys was from 24 N to 28 N. A previous study conducted with experimental and analytical procedures to measure passive drag in swimming also found a SEE near to 11 N (Barbosa et al., 2015). When analytical procedures were compared with the numerical simulations (CFD; Barbosa et al., 2018) values presented a lower error (SEE = 5.40 N). So, we may argue that our values are not so far from the ones reported in the same context.

It is also worth mentioning that SEE fitted better for girls than for boys. Despite the chronological age of the swimmers being the same, the variation between the swimmers may explain some bias in the data, as at this stage they are susceptible to the biological maturation process (dos Santos et al., 2021). Finally, some limitations of the study are worth mentioning: (i) only young swimmers were considered; it is expected that the performance variability in young swimmers will be greater than their adult counterparts; (ii) only one swimming stroke and condition (full stroke) were assessed; and (iii) the pressure sensors were placed in the hands only. However, it is important to highlight that the present study allows, for the first time, the estimate of F_{PEAK} with PS or TS, enabling the swimming community to easily obtain precise and accurate data through different methods.

5. Conclusion

The in-water force values in young competitive swimmers rely on different assessment methods. Based on the general findings, tethered swimming (i.e., load cell) presents higher values when compared to pressure sensors. To provide insightful benchmarks on swimmers' progression by monitoring training, correction factors can be used when different methods are considered.

CRediT authorship contribution statement

Catarina C. Santos: Methodology, Investigation, Data curation, Writing - original draft. **Mário J. Costa:** Supervision, Resources, Methodology, Investigation, Conceptualization, Writing - review & editing. **Pedro Forte:** Writing – review & editing, Visualization, Methodology, Formal analysis. **Daniel A. Marinho:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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