International Journal of
EXERCISE SCIENCE

Original Research

Smartpaddle® as a New Monitoring Feature: A Comparison Between Inertial Measurement Unit- and Strain Gauge-Based Devices on Tethered Swimming Forces

JOÃO OCTAVIO R. P. DE CAMPOS†[1], FELIPE A. RIBEIRO†[2], GABRIEL LUCHES-PEREIRA†[1], and MARCELO PAPOTI‡[1,2]

[1]School of Physical Education and Sport of Ribeirao Preto, University of Sao Paulo, Ribeirao Preto, SP, BRAZIL; [2]Ribeirao Preto Medical School, University of Sao Paulo, Ribeirao Preto, SP, BRAZIL

†Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 17(6): 670-681, 2024. Smartpaddle® is a novel wearable device based on inertial measurement units (IMU) for in-field arm-stroke kinetics and kinematics analysis in swimming. However, the lack of data regarding its agreement and reliability, coupled with restricted access to raw data, emphasizes the need to evaluate it against a well-established strain gauge (SG) reference method for assessing swimming forces. Thus, this study aimed to investigate the agreement and reliability between the Smartpaddle® and strain gauge in a 30-s all-out arms-only tethered swimming test. Twelve trained young adult swimmers performed a test-retest 30-s all-out arms-only tethered swimming trial. Peak and mean forces were obtained from IMU (PF_{IMU} and MF_{IMU}) and SG (PF_{SG} and MF_{SG}) simultaneously. Statistical differences and correlations were found in both peak (PF_{SG} = 158.46 ± 48.85 N, PF_{IMU} = 75.47 ± 12.05 N, $p < 0.001$, $r = 0.88$) and mean (MF_{SG} = 69.62 ± 16.36 N, MF_{IMU} = 30.06 ± 5.42 N, $p < 0.001$, $r = 0.84$) forces between devices, presenting elevated systematic errors for both variables. No differences were found in IMU data between test-retest conditions in both peak (PF_{IMU} = 75.47 ± 12.05 N, PF_{IMU} = 75.45 ± 11.54 N, $p = 0.99$, ICC = 0.96) and mean (MF_{IMU} = 30.06 ± 5.42 N, MF_{IMU} = 30.21 ± 5.83 N, $p = 0.80$, ICC = 0.95) forces, with negligible systematic errors. In conclusion, although the Smartpaddle® device is not directly comparable to the strain gauge reference method, it has demonstrated high reliability levels in test-retest trials.

KEY WORDS: Kinematics, inertial sensor, pressure sensor

INTRODUCTION

The ability to apply force efficiently in water is a key factor for performance in competitive swimming events (19). Consequently, several methods and devices have been developed aiming to measure forces in swimming, and despite being a complex task due to the aquatic environment, it is considered essential by sports scientists, coaches, and practitioners to achieve peak sports performance (36).

Since the mid-20th century, there has been significant concern regarding investigations of the in-water forces applied by swimmers (1, 6, 16). Among the main methods developed for this, which involve force transducers (10, 28), pressure sensors (35, 38), 3-D motion analysis (13, 30), and computational fluid dynamics (32, 37), the complex setups, difficult data handling, and time-consuming feedback have been common drawbacks among these devices, limiting their use to those who are technically experts.

In an attempt to address these issues, commercial portable and wearable devices based on inertial measurement units (IMU), such as the Smartpaddle®, have been proposed as an alternative tool for in-field sports performance analysis, promising to provide coaches and swimmers with accurate outcomes, user-friendly data, and real-time feedback on arm-stroke kinetics and kinematics variables (17). Although there is no gold standard method for measuring in-water forces, the lack of data concerning the agreement and reliability of the Smartpaddle® data, coupled with the restriction of accessing raw data, emerges as the primary need to investigate its agreement and reliability against an extensively investigated reference-method in swimming.

The 30-s tethered swim test is a method based on strain gauges (SG) extensively used for direct force measurement in swimming. Due to its reliability (2, 3), it is highly employed in biomechanical and physiological research (9), including investigations on the training effects (29) and ergogenic aids (25), limb-asymmetry (20) and body-segment (21) assessments, and relationships with short-distance performances (22) and different swimming strokes (19). The comparison between the forces measured by the Smartpaddle® and strain gauges has not yet been investigated in swimming. The only study that compared these two devices conducted its research in kayaking (15), where the authors found no differences but statistical correlations in the force variables recorded by the Smartpaddle® and a strain gauge shift-paddle.

Despite suggesting that the devices can be compared to each other, the aforementioned results should not be extrapolated to swimming, and the lack of reliability analyses also increases the scientific gap regarding the use of Smartpaddle® in swimming. Therefore, to provide support to coaches and swimmers who currently use or intend to use the Smartpaddle® to assess their forces in daily training and time trial contexts, this study aimed to investigate the agreement and reliability between the Smartpaddle® and strain gauge device in a 30-s all-out arms-only tethered swimming test. We hypothesize that the Smartpaddle® is reliable but cannot be compared with the strain gauge device in a 30-s all-out arms-only tethered swimming test.

METHODS

Participants

Twelve trained young adult swimmers (18) voluntarily participated in this study. Participants' characteristics are shown in Table 1. The inclusion criterion was swimmers with an active training program of at least three months with five or more training sessions per week. The study was approved by the Ethics Committee of the University of Sao Paulo (protocol no: 55101221.1.0000.5659). All experimental procedures, performed only after obtaining the signed consent of the participants, were conducted in accordance with the Declaration of Helsinki (40) and the ethical standards of the International Journal of Exercise Science (24).

Table 1. Mean ± standard deviation of participants' characteristics.

Characteristics	Total (*n* = 12)	Men (*n* = 10)	Women (*n* = 2)
Age (years)	23.70 ± 2.22	23.37 ± 1.91	20.85 ± 1.06
Body mass (kg)	73.15 ± 7.95	75.19 ± 6.17	62.95 ± 4.45
Lean mass (kg)	54.90 ± 6.45	57.09 ± 4.19	44.48 ± 5.81
Body fat (%)	21.65 ± 5.60	20.65 ± 5.42	26.75 ± 4.45
Height (cm)	177.40 ± 7.26	179.41 ± 6.17	167.60 ± 2.26
Arm span (cm)	183.80 ± 8.89	186.40 ± 7.24	171.00 ± 1.41
50-m freestyle WAPS (a.u)	469.83 ± 106.98	493.50 ± 100.65	351.50 ± 33.23

WAPS: World Aquatic Point Scoring.

Protocol

Anthropometrical characteristics were determined using the densitometry method with dual-energy X-ray absorptiometry (Lunar iDXA, GE Healthcare) to assess the body mass, lean mass, and body fat percentual. Height and arm span were measured using a 1mm graded stadiometer (Micheletti, SP, BR) and a measuring tape, respectively. Additionally, individual World Aquatic Point Scores were calculated using the performance time of the last 50-m freestyle event in a 25-m short-course pool, as proposed (8).

To assess tethered swimming forces via IMU- and SG-based devices (*i.e.*, Smartpaddle® and strain gauge, respectively), and to determine their agreement and reliability, a test and retest 30-s all-out arms-only tethered swimming trial was performed at a 24 hr interval. The test protocol was adapted from a previously proposed method (28), to isolate the upper limb segment. Unlike the strain gauge, the Smartpaddle® cannot determine the resultant forces from leg kicks. Therefore, to simultaneously measure the forces exerted by swimmers in a single effort, we focused solely on the forces of the upper limbs. Experimental procedures were conducted after a familiarization protocol, the assessments were performed in a short-course indoor pool (25-m long × 12-m wide) at a temperature of 27 ± 1 °C, and all participants were advised not to ingest caffeine, alcohol, and energy drinks for at least 12 hr before each assessment.

First, the swimmers performed a 1000-m warm-up (composed of 400-m low-paced freestyle, 4 × 50-m technique drills, 8 × 25-m [12.5 to 12.5 m] fast to low regressive-paced front crawl, and 200-m low-paced best-technique front crawl), and then proceeded to the lane in which the test would be performed. After securing the Smartpaddles® in their hands and fastening the ankle strap of the tethered swimming test apparatus around their ankles, the swimmers were instructed to swim at a low pace until the cable was fully extended. At this point, they were to wait for an audible signal to start the 30-s all-out effort in stationary mode (Figure 1). Additionally, to inhibit any force coming from the swimmer's kick, an EVA pull buoy (24 × 15 × 7 cm) was placed between their ankles to improve buoyancy and prevent kicking throughout the efforts. In all

assessments, the stroke frequency and breathing pattern were chosen arbitrarily by the participants, and all swimmers were instructed and verbally encouraged to give maximum effort during the efforts.
IMU peak (PF_{IMU}, in N) and mean (MF_{IMU}, in N) forces were recorded from each hand by the Smartpaddle® (Trainesense Oy, FI), and the outcomes were presented as the average of the two hands. The device is attached to the swimmer's hand through silicon straps that allow for the measurement of force, velocity, and orientation of each arm stroke. The data is recorded at 100 Hz through pressure and inertial sensors with 9-axis IMU, downloaded via Bluetooth to Trainesense Session Manager between the device and a smartphone, and then uploaded to the web Analysis Center to provide instantaneous and real-time outcomes of kinematic and kinetic parameters. Furthermore, it is important to mention that the data processing algorithm (via closed MATLAB GUI [graphical user interface]) of the Smartpaddle® has not been published, making access to raw data impossible.

SG peak (PF_{SG}, in N) and mean (MF_{SG}, in N) forces were recorded by a strain gauge (CSA-100kg, MK Control and Instrumentations, SP, BR). The strain gauge was fixed to the starting block and attached to the swimmers' ankle through a 7-m inextensible steel cable. The force data were acquired at 1000 Hz, amplified by an analog signal amplifier (MKTC05, MK Control and Instrumentations, SP, BR), recorded by a data acquisition board (USB-6009, National Instruments, Inc), and analyzed by an algorithm specifically developed in MATLAB software (R2018a, The MathWorks, Inc). To convert the signals collected in volts into newtons, a linear gain factor was calculated before each assessment using a calibration protocol with six progressively known weights (ranging from 0.1 to 10.2 kg).

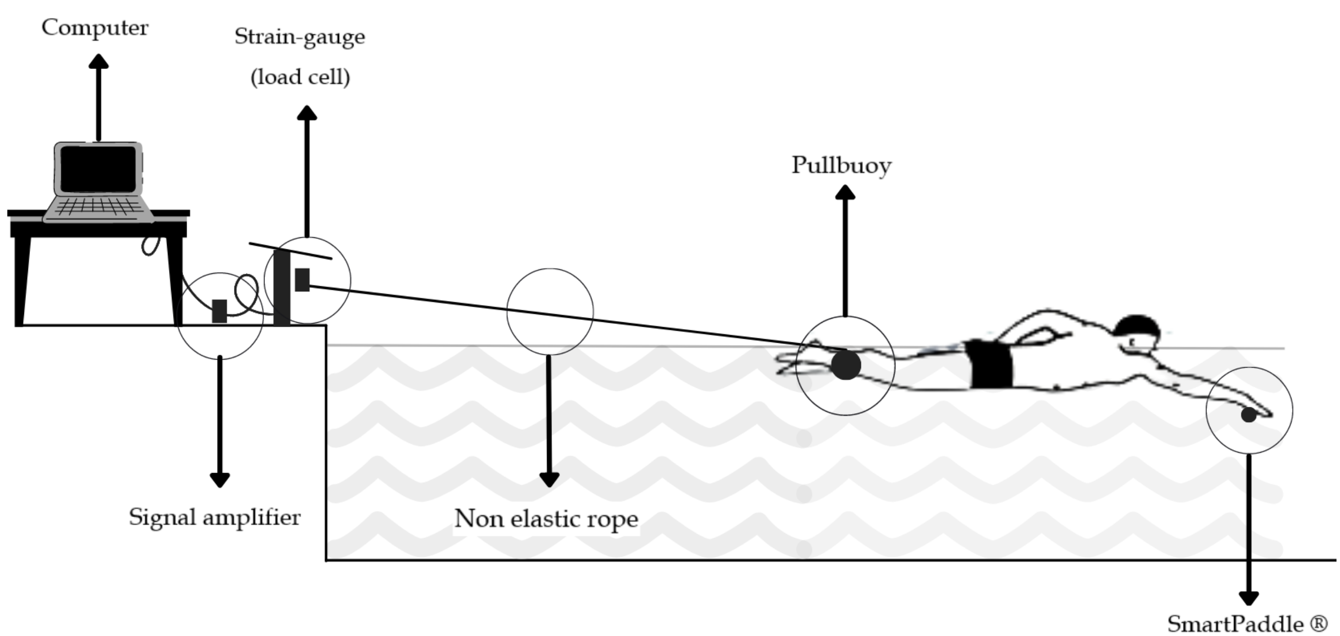

Figure 1. Schematic design of the method and apparatus used in the 30-s all-out arms-only tethered swimming test.

Statistical Analysis
Using the Statistical Package for Social Science software (version 20.0, SPSS Inc, Chicago, IL) the normal data distribution was confirmed by the Shapiro-Wilk test and then the results were reported as mean ± 95% confidence intervals (CI).

The concurrent agreement between the SG and IMU data was determined as previously proposed (7). Firstly, differences between data were analyzed by the paired *t*-test. Effect sizes were reported as Cohen's *d* (0 to 0.2 = small, 0.2 to 0.5 = medium, 0.5 to 0.8 = large) (5). Linear regression determinant (R^2) and Pearson's correlation (*r*) coefficients with their respective 95% CI were used to test the strength of the association between the peak and mean forces. The *r* cut-offs of 0.1, 0.3, 0.5, 0.7, and 0.9 were considered small, moderate, large, very large, and nearly perfect, respectively (11). In addition, the standard error of the estimate (SEE, in N) was calculated using the standard deviation of the residuals and interpreted as a measure of variation around the regression line. The agreement between both devices was additionally tested by the Bland-Altman graphical analysis, with the systematic bias accompanied by 95% limits of agreement (LoA = bias ± 1.96 SD) (4). In all cases, the significance level was set at $p < 0.05$

The reliability of IMU and SG data applied to the same individuals on repeated trials (*i.e.*, test-retest) was verified as previously proposed (12). Therefore, the differences between trials were verified by the paired *t*-test, ES, and interpreted as in the concurrent agreement analysis above. The intraclass correlation coefficient (ICC, in %) and the 95% CI were calculated as a measure of relative reliability based on a two-way mixed-effects model, single measures, and absolute agreement (model 2,1) (12, 39). Also, the typical error (TE, in N) was calculated to access the within-subject variation (absolute reliability) by the standard deviation of the individual's repeated measurements (12, 39). The TE was also expressed in relative terms as the coefficient of variation (CV, in %), as follows: CV = TE/mean · 100. Complementary, the smallest detectable difference (SDD, in N) was calculated as 1.96 · √2 · SEM (standard error of measurements), where SEM = SD · √(1–ICC) (39).

RESULTS

The agreement analysis between SG- and IMU-based devices is described in Table 2, and complementary Bland & Altman and linear regression graphical analysis are shown in Figure 2. Statistical differences and elevated systematic errors with individual residual values distributed within their LoAs were found between devices in both PF_{SG} (mean difference = 82.99 [58.45 - 107.53] N, $p < 0.001$) and MF_{SG} (mean difference = 39.56 [31.84 - 47.28] N, $p < 0.001$) in relation to PF_{IMU} and MF_{IMU}, respectively. However, very large significant correlations were found between PF_{SG} and PF_{IMU} ($r = 0.88$, $p < 0.001$), and MF_{SG} and MF_{IMU} ($r = 0.84$, $p < 0.001$).

Table 2. Mean ± 95% confidence intervals of tethered swim force data and agreement analysis between strain gauge and inertial measurement unit devices.

	SG	IMU	*p*	*d*	*r*	SEE
PF (N)	158.46 (127.42 - 189.49)	75.47 (67.81 - 83.12)	< 0.001	2.15	0.88 (0.63 - 0.97)	24.06
MF (N)	69.62 (59.22 - 80.01)	30.06 (26.62 - 33.50)	< 0.001	3.25	0.84 (0.52 - 0.95)	9.24

PF: peak force; MF: mean force; SG: strain gauge; IMU: inertial measurement unit; *p*: paired *t*-test *p*-value; *d*: Cohen's *d* effect size; *r*: Pearson's correlation coefficient; SEE: standard error of estimation.

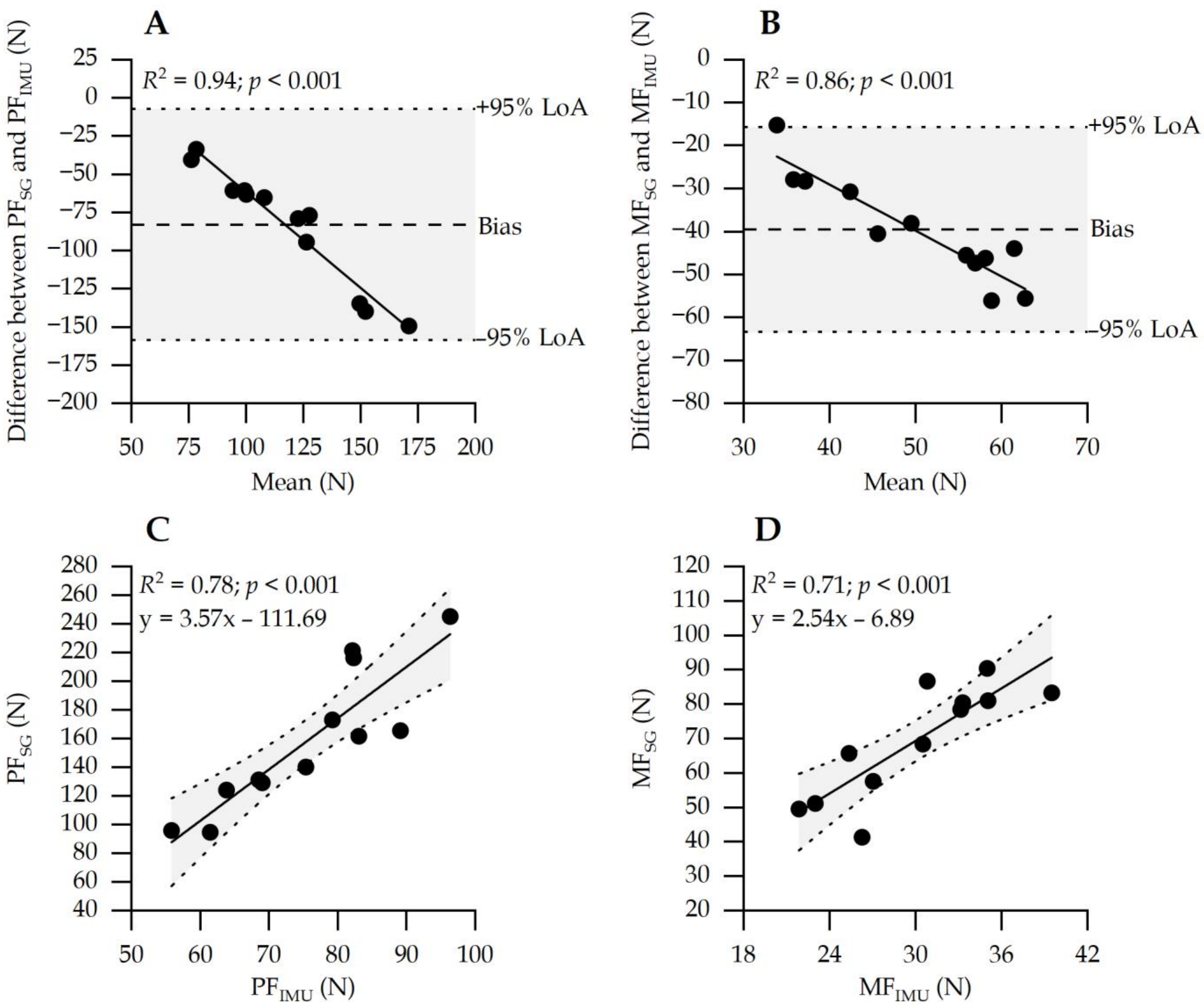

Figure 2. Panels **A** and **B** depict the agreement analysis between strain gauge and inertial measurement unit devices for peak and mean force variables through Bland-Altman graphical analysis. Panels **C** and **D** depict the linear regression analysis between strain gauge and inertial measurement unit devices for peak and mean force variables. The trend, dashed, and dotted lines denote the coefficient of determination, mean difference, and 95% confidence interval, respectively.

The reliability analyses of IMU- and SG-based devices are described in Table 3. No statistical differences in peak and mean force variables were found between test and retest conditions in both IMU and SG data ($p \geq 0.15$). Despite both devices exhibiting excellent reliability levels, higher ICC (PF_{IMU} = 0.96 [0.86 - 0.99], MF_{IMU} = 0.95 [0.83 - 0.98]) and lower TE (PF_{IMU} = 2.52 N, MF_{IMU} = 1.35 N), CV (PF_{IMU} = 3.33 %, MF_{IMU} = 4.48 %), and SDD (PF_{IMU} = 6.51 N, MF_{IMU} = 3.52 N) values were observed in IMU compared to SG data.

Table 3. Mean ± 95% confidence intervals of tethered swim force data and the respective reliability analysis between test and retest trials to inertial measurement unit device and strain gauge.

	Test	Retest	*p*	*d*	ICC	CV	TE	SDD
PF_{IMU} (N)	75.47 (67.81 - 83.12)	75.45 (68.12 - 82.78)	0.99	0.00	0.96 (0.86 - 0.99)	3.33	2.52	6.51
MF_{IMU} (N)	30.06 (26.62 - 33.50)	30.21 (26.51 - 33.92)	0.80	−0.03	0.95 (0.83 - 0.98)	4.48	1.35	3.52
PF_{SG} (N)	158.46 (127.42 - 189.49)	172.13 (141.99 - 202.27)	0.15	−0.28	0.78 (0.42 - 0.93)	13.09	21.64	61.89
MF_{SG} (N)	69.62 (59.22 - 80.01)	69.32 (57.75 - 80.89)	0.86	0.02	0.95 (0.82 - 0.98)	6.03	4.19	20.35

PF_{IMU}: peak force acquired by inertial measurement unit; MF_{IMU}: mean force acquired by inertial measurement unit; PF_{SG}: peak force acquired by strain gauge; MF_{SG}: mean force acquired by strain gauge; *p*: paired t-test *p*-value; *d*: Cohen's *d* effect size; ICC: intra-class correlation coefficients; CV: coefficient of variation; TE: typical error; SDD: smallest detectable difference.

DISCUSSION

This study aimed to investigate the agreement and reliability of Smartpaddle® and strain gauge devices during a test-retest 30-s all-out arms-only tethered swimming trial. The agreement analyses indicated a significant correlation between SG and IMU data; however, statistical differences with elevated systematic errors were observed in PF_{IMU} and MF_{IMU} compared to PF_{SG} and MF_{SG} values. This evidence suggests that the IMU data cannot be considered comparable to the SG data. Conversely, the reliability analyses revealed no statistical differences in both IMU and SG data between test-retest conditions, negligible systematic errors, excellent ICC, and small CV values for all variables, indicating high reliability of the Smartpaddle® wearable device.

To the best of your knowledge, this is the first study that proposed to investigate the agreement between Smartpaddle® with the strain gauge force variables in swimming. Although commercial IMU wearable devices (such as the Smartpaddle®) allow the assessment of kinematics and kinetics in free-swimming conditions, conducting a 30-s all-out arms-only tethered swimming test in a stationary mode was necessary to simultaneously compare the same phenomenon using IMU and SG-based devices and obtain thrust forces as an average value of both hands from both devices in a single effort. Peak and mean forces showed significant correlations ($r \geq 0.84$, $p \leq 0.001$) between IMU and SG devices; nonetheless, the IMU data could not be compared to the SG data, as statistical differences ($p \leq 0.001$) in PF_{SG} and MF_{SG} indicated 52.37% and 56.86% higher values compared to PF_{IMU} and MF_{IMU}, respectively.

Likewise, this study also represents the first investigation into the reliability of the Smartpaddle® in swimming. The data found suggest that force values obtained via IMU using the Smartpaddle® are highly reliable. There were no statistical differences observed in either PF_{IMU}

or MF_{IMU} ($p \geq 0.80$) between test and retest conditions. Concordance analyses revealed excellent ICC values (PF_{IMU} = 0.96, MF_{IMU} = 0.95), small CV (PF_{IMU} = 3.33%, MF_{IMU} = 4.48%), and individual residual values distributed within the LoA's. Thus, the Smartpaddle® appears to be a highly suitable monitoring tool for obtaining and analyzing the swimming forces of swimmers in both daily training and time-trials contexts.

To date, only one study has investigated the agreement between Smartpaddle® against strain gauge (15); however, this investigation was not conducted in swimming, but rather in open-water kayaking. In this study, a strain-gauge paddle shaft served as the reference method for comparing the Smartpaddle®, and similar to our findings, strong significant correlations were found between SG and IMU data in both peak and mean forces ($r \geq 0.84$) in kayaking. Nevertheless, no statistical differences ($p = 0.083$) were noted, with negligible systematic errors, and individual residual values distributed between LoAs, evidencing the agreement of the Smartpaddle® when compared to the strain-gauge paddle shaft in open-water kayaking (15).

In swimming, propulsive forces obtained by Smartpaddle® were compared with Aquanex® differential-pressure sensor in a 25-m all-out front crawl trial (17). The authors reported no statistical differences ($p = 0.065$), a significant relationship ($R^2 = 0.81$), and negligible systematic error in mean force values obtained between the wearable devices. Using a methodological approach similar to our study, the agreement between differential pressure systems and strain gauge-based devices was also investigated (34). Although agreement between devices has not been performed simultaneously in a single effort, both peak and mean forces obtained by differential pressure system in two 25-m all-out efforts could not be compared with those recorded by the strain gauge in a 30-s tethered swimming test. As with our study, although statistical differences ($p \leq 0.001$) and large biases (mean difference ≤ –43.79 N) were found, significant moderate to high relationships ($R^2 \geq 0.25$, $p \leq 0.05$) between devices also were observed.

The tethered swimming protocol is not only widely used due to its high reliability (2, 23), but also because it correlates with performance in short- and middle-distance race-pace events (19, 22, 29, 31), and produces similar metabolic and physiological responses (23, 26, 27). Interestingly, our 30.06 N of MF_{IMU} obtained from the average of both hands using the Smartpaddle® during the 30-s all-out arms-only tethered swimming test was similar to those of a 25-m all-out front crawl "free swimming" effort that measured the forces of both hands separately also by a Smartpaddle® (MF_{right} = 34.50 ± 5.28 N, MF_{left} = 33.83 ± 4.65 N) (17). Additionally, similar mean force values were observed during the 10 to 15-m (MF_{right} = 23.87 ± 4.87 N, MF_{left} = 27.03 ± 7.27 N) and 15 to 20-m (MF_{right} = 24.17 ± 5.13 N, MF_{left} = 27.29 ± 8.15 N) sections of a 25-m all-out effort (14). Thus, based on the available data, the IMU data recorded by the Smartpaddle®, although not equivalent to the SG data, can be considered an excellent IMU-based tool for measuring arm stroke propulsive forces, along with others kinetics and kinematics variables in swimming training sessions and time trials. Finally, since the absolute tethered swimming force values between methods cannot be directly compared, the correction equation provided in Figure 2 can be employed if necessary.

The discrepancy between monitoring features and experimental protocols, coupled with the absence of a gold-standard method to assess in-water forces, renders this topic a subject of heated debate within the sports science community. The central query surrounding swimming forces revolves around the comparison of "free *vs*. stationary swimming" evaluation methods, and the inconclusive findings thus far stem from the inherent complexity of this question. Our results, particularly elucidated through Bland & Altman's graphical analysis, indicate that the IMU data cannot be compared with the SG data due to the distinct nature of the force phenomenon each measure. While the SG device records the aggregated of all force-time curves during the tethered swimming effort, the IMU device measures the force exerted by individual body limbs separately. Given this perspective, isolating the arm strokes during the 30-s all-out effort was an attempt to mitigate this issue by preventing any type of force not originating from the hands to be exerted. In addition, the absence of drag forces and the water flow at zero velocity during stationary swimming may disrupt the ability to apply force in water, potentially resulting in an overestimation of these values compared to free swimming (33), thereby exacerbating the disparity in force data obtained between SG and IMU data.

Some limitations of the present study must be highlighted. Firstly, access to the raw data is unavailable to users in both smartphone Trainesense Session Manager and web Analysis Center. Furthermore, the MATLAB GUI data processing algorithm has not been published by the developers, rendering it impossible to process any type of raw data acquired via IMU by the Smartpaddle®. It is important to emphasize that our results were derived from the average between both hands; we did not include an analysis between dominant and non-dominant limbs, and we consider this to be a significant limitation for future studies. In addition, our results were obtained from trained swimmers (18), and thus cannot be extrapolated to elite and world-class competitive-level swimmers. Finally, we suggest that the high reliability of the Smartpaddle® be thoroughly tested against other devices (including other pressure sensors), in a free-swimming context, particularly regarding the device's reliability and sensibility in cross-sectional and longitudinal experimental designs (e.g., between different age-group and competitive-level swimmers, and effects of in-water or dry-land training periods).

In conclusion, although we have demonstrated that the Smartpaddle® cannot be interchangeably used with the strain gauge reference method in a 30-s all-out arms-only tethered swimming test, this device has demonstrated high reliability in the test-retest trial and provides a practical tool for daily use by coaches and swimmers

ACKNOWLEDGEMENTS

The authors are grateful to the FMRP swim team that voluntarily participated in this study.

REFERENCES

1. Alley LE. An analysis of water resistance and propulsion in swimming the crawl stroke. Res Q Am Assoc Health Phys Educ Recreation 23(3): 253-270, 1952.

2. Amaro N, Marinho DA, Batalha N, Marques MC, Morouço P. Reliability of tethered swimming evaluation in age group swimmers. J Hum Kinet 41(1): 155-162, 2014.

3. Amaro N, Marinho DA, Batalha N, Marques MC, Morouço P. Reliability of tethered swimming evaluation in age group swimmers. J Hum Kinet 41: 155-162, 2014.

4. Bland JM, Altman D. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 327(8476): 307-310, 1986.

5. Cohen J. Statistical power analysis for the behavioral sciences. New York, NY: Academic Press; 2013.

6. Counsilman JE. Forces in swimming two types of crawl stroke. Res Q Am Assoc Health Phys Educ Recreation 26(2): 127-139, 1955.

7. Currell K, Jeukendrup AE. Validity, reliability, and sensitivity of measures of sporting performance. Sports Med 38: 297-316, 2008.

8. Fédération Internationale de Natation (FINA). World aquatics point scoring. Retrieved from: https://www.worldaquatics.com/swimming/points; 2024.

9. Franken M, de Jesus K, de Jesus K, de Souza Castro FA. Variables and protocols of the tethered swimming method: A systematic review. Sport Sci Health https://doi.org/10.1007/s11332-023-01140-1; 2023.

10. Hollander AP, De Groot G, van Ingen Schenau GJ, Toussaint HM, De Best H, Peeters W, Meulemans A, Schreurs AW. Measurement of active drag during crawl arm stroke swimming. J Sports Sci 4(1): 21-30, 1986.

11. Hopkins W, Marshall S, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 41(1): 3-13, 2009.

12. Hopkins WG. Measures of reliability in sports medicine and science. Sports Med 30(1): 1-15, 2000.

13. 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 4: 786459, 2022.

14. Lopes TJ, Sampaio T, Oliveira JP, Pinto MP, Marinho DA, Morais JE. Using wearables to monitor swimmers' propulsive force to get real-time feedback and understand its relationship to swimming velocity. Appl Sci 13(6): 4027, 2023.

15. Löppönen A, Vänttinen T, Haverinen M, Linnamo V. The effect of paddle stroke variables measured by trainesense Smartpaddle & reg; on the velocity of the kayak. Sensors (Basel) 22(3): 938, 2022.

16. Magel JR. Propelling force measured during tethered swimming in the four competitive swimming styles. Res Q Am Assoc Health Phys Educ Recreation 41(1): 68-74, 1970.

17. Marinho DA, Barbosa TM, Auvinen A, Lopes T, Silva AJ, Morais JE. Smartpaddle as a new tool for monitoring swimmers' kinematic and kinetic variables in real time. Open Sports Sci J 15: e1875399X2210310, 2022.

18. McKay AKA, Stellingwerff T, Smith ES, Martin DT, Mujika I, Goosey-Tolfrey VL, Sheppard J, Burke LM. Defining training and performance caliber: A participant classification framework. Int J Sports Physiol Perform 17(2): 317-331, 2022.

19. Morouço P, Keskinen KL, Vilas-Boas JP, Fernandes RJ. Relationship between tethered forces and the four swimming techniques performance. J Appl Biomech 27(2): 161-169, 2011.

20. Morouço PG, Marinho DA, Fernandes RJ, Marques MC. Quantification of upper limb kinetic asymmetries in front crawl swimming. Hum Mov Sci 40: 185-192, 2015.

21. Morouço PG, Marinho DA, Izquierdo M, Neiva H, Marques MC. Relative contribution of arms and legs in 30 s fully tethered front crawl swimming. BioMed Research International 2015: 563206, 2015.

22. Morouço PG, Marinho DA, Keskinen KL, Badillo JJ, Marques MC. Tethered swimming can be used to evaluate force contribution for short-distance swimming performance. J Strength Cond Res 28(11): 3093-3099, 2014.

23. Nagle Zera J, Nagle EF, Nagai T, Lovalekar M, Abt JP, Lephart SM. Tethered swimming test: reliability and the association with swimming performance and land-based anaerobic performance. J Strength Cond Res 35(1): 212-220, 2021.

24. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1-8, 2019.

25. Norberto MS, Barbieri RA, Bertucci DR, Gobbi RB, Campos EZ, Zagatto AM, De Freitas EC, Papoti M. Beta alanine supplementation effects on metabolic contribution and swimming performance. J Int Soc Sports Nutr 17(1): 40, 2020.

26. Papoti M, Da Silva ASR, Araujo GG, Santiago V, Martins LEB, Cunha SA, Gobatto CA. Aerobic and anaerobic performances in tethered swimming. Int J Sports Med 34(08): 712-719, 2013.

27. Papoti M, da Silva ASR, Kalva-Filho CA, Araujo GG, Santiago V, Martins LB, Cunha SA, Gobatto CA. Tethered swimming for the evaluation and prescription of resistance training in young swimmers. Int J Sports Med 38(02): 125-133, 2017.

28. Papoti M, Martins L, Cunha S, Zagatto A, Gobatto C. Standardization of a specific protocol to determine the anaerobic conditioning in swimmers during a 30sec effort using load cells. Port J Sports Sci 3(3): 36-42, 2003.

29. Papoti M, Martins LEB, Cunha SA, Zagatto AM, Gobatto CA. Effects of taper on swimming force and swimmer performance after an experimental ten-week training program. J Strength Cond Res 21(2): 538-542, 2007.

30. Payton CJ, Bartlett RM. Estimating propulsive forces in swimming from three-dimensional kinematic data. J Sports Sci 13(6): 447-454, 1995.

31. Ruiz-Navarro JJ, Morouço PG, Arellano R. Relationship between tethered swimming in a flume and swimming performance. Int J Sports Physiol Perform 15(8): 1087-1094, 2020.

32. Samson M, Bernard A, Monnet T, Lacouture P, David L. Unsteady computational fluid dynamics in front crawl swimming. Comput Methods Biomech Biomed Engin 20(7): 783-793, 2017.

33. 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 18(6): 571-586, 2019.

34. Santos CC, Costa MJ, Forte P, Marinho DA. A comparison of load cell and pressure sensors to measure in-water force in young competitive swimmers. J Biomech 160: 111815, 2023.

35. Santos CC, Marinho DA, Costa MJ. The mechanical and efficiency constraints when swimming front crawl with the aquanex system. J Hum Kinet 84(1): 166-173, 2022.

36. Santos CC, Marinho DA, Neiva HP, Costa MJ. Propulsive forces in human competitive swimming: A systematic review on direct assessment methods. Sports Biomech https://doi.org/10.1080/14763141.2021.1953574, 2021.

37. Sato Y, Hino T. A computational fluid dynamics analysis of hydrodynamic force acting on a swimmer's hand in a swimming competition. J Sports Sci Med 12(4): 679-689, 2013.

38. Takagi H, Shimizu Y, Kodan N. A hydrodynamic study of active drag in swimming. JSME Int J Series B Fluids Therm Eng 42(2): 171-177, 1999.

39. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the sem. J Strength Cond Res 19(1): 231-240, 2005.

40. World Medical Association. World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. JAMA 310(20): 2191-2194, 2013.