Efficacy of hand-mounted pressure sensors for in-water force analysis in high performance swimmers

Thesis submitted in accordance with the requirements of University of Stirling for the degree of Master of Philosophy

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August 2024

For my family,

because without them this degree

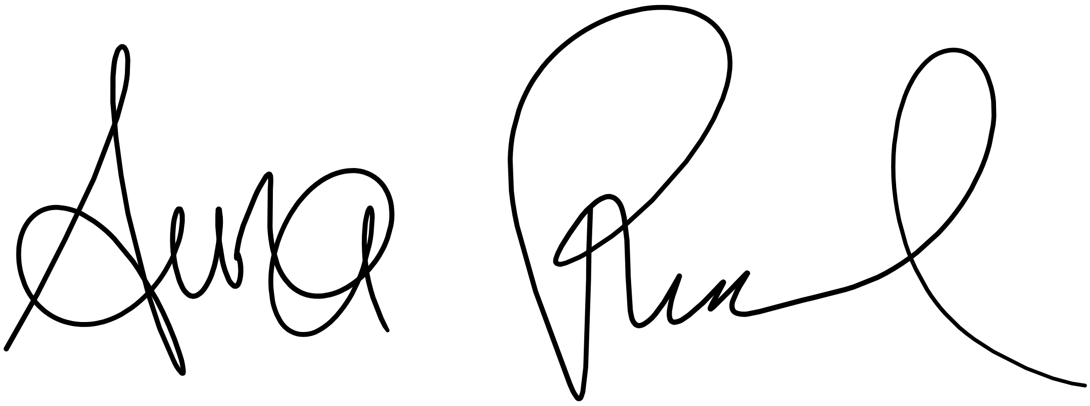
would not have been possible.

Contents

Declaration

I declare that the contents of this thesis are entirely my own work, and that the document was composed by myself under the supervision of Dr. Lewis Macgregor, Dr. James H. Dugdale, and Dr. Nidia Rodriguez-Sanchez**.** The experimental studies within this thesis were all approved by the University of Stirling cross-faculty ethics committees, and procedures were conducted as they were approved. Neither the thesis, nor the original work within have been submitted to this or any other institution towards a higher degree. This thesis does not infringe upon anyone’s copyright and any material from the work of others included in this thesis are fully acknowledged in accordance with common reference practices.

Signed:



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Abstract

Introduction: Kinetic analysis in swimming is the quantification of propulsive force output which has potential to improve swimming efficiency and overall swimming performance. While the kinetic analysis of the start, turn, and finish phases of swimming performance are recognised and established in the literature, kinetic analysis of the free swim phase has previously been limited due to technological constraints. **Aim:** This study aimed to investigate the efficacy of the Smart Paddle™ for in-water, free swim force analysis across strokes in high performance swimmers by: 1) determining intra-day absolute and relative reliability of the Smart Paddle™, 2) determining validity by objective comparison between Smart Paddle™ and manual stroke rate testing and 3) determining the sensitivity of the Smart Paddle™ to discriminate between varied intensities of swimming. **Results:** No significant difference in kinetic variables between T1 and T2 was determined between for any intensity or any stroke. ICC scores for all strokes were good-excellent for all intensities, CV% was <5%, and effect size was small between trials 1 and 2. No significant difference in stroke rate was observed between manual stroke count and the Smart Paddle™. Swim performance at 90% of maximum produced significantly higher results than at low work intensity (50%) for average force, impulse, and efficiency for all strokes between low and high intensities. **Conclusion:** The Smart Paddle™ appears to demonstrate sufficient reliability, validity, and sensitivity making it a potentially useful tool for the determination of kinetic variables in free swim performance. The Smart Paddle™ can be used in applied environments for kinetic analysis across multiple days, various strokes, and over a range of training intensities.

List of Tables

List of Figures

Abbreviations

T1	Trial 1
T2	Trial 2
M	Mean
SD	Standard deviation
ICC	Interclass correlation coefficient
CV	Coefficient of variation
SEM	Standard error of mean
d	Cohen’s d effect size
PS	Pressure sensors
N	Newtons
N•s	Newtons per second
Spm	Strokes per minute
m/s	Metres per second

SECTION 1

INTRODUCTION

1.1 An introduction to swimming

Swimming is a popular form of lifelong exercise because of its accessibility to all ages and abilities, and the valuable physiological and neurological benefits that it provides (Swim England, 2017). Swimming helps to prevent musculoskeletal injury such as sprains or tears (Tanaka and Seals, 1997) by enhancing muscular strength development (The Health and Wellbeing Benefits of Swimming report, 2017), and reduces conditions of poor health (cardiac, respiratory or obesity centred issues) by improving metabolic processes (Kawasaki et al., 2011), aerobic capacity (Rosimini, 2003; Wang and Hung, 2009), and advancing motor skills, balance, and hand-eye coordination (Kawasaki et al., 2011; Mazzeo and Tanaka, 2001; Wong et al., 2011). Swimming also elicits neurological benefits associated to cognitive function and memory (Abou-Dest et al., 2012; Petrescu et al., 2014) and is popular activity choice for enjoyment and stress mediation across all ages and abilities (Abou-Dest et al., 2012; Köroglu and Yigiter, 2016; Mische Lawson et al., 2019).

1.2 Competitive swimming

From a competitive perspective, the objective of swimming is to achieve the fastest performance time at a set distance and stroke. Performance development is measured using quantitative analysis of performance metrics such as stroke metrics, speed, and time improvement. Quantitative performance analysis is introduced in the early years of athlete training and its use progresses as athletes reach elite level (Santos et al., 2023; Zacca et al., 2020). The primary focus of age-group swimmers is technique refinement and aerobic capacity building (Lang and Light, 2010; Morais et al., 2017), compared to elite level swimming where the development of velocity, power, and force are prioritised. As the primary objective of a competitive swimming performance is to achieve the fastest race time, velocity is an important variable for performance analysis (Barbosa et al., 2011; Bartolomeu et al., 2018; Fernandes et al., 2022). Velocity and force exhibit causality for faster swimming performance, demonstrating that greater velocity cannot be achieved without greater force production (Barbosa et al., 2021; Santos et al., 2023; Seifert et al., 2010, 2004).

Accordingly, performance may be limited by the inability to produce effective and sustainable force.

Quantitative analysis of swimming can be categorised to temporal, kinetic, and kinematic analysis, all of which evaluate a specific swimming performance metric, and require specific methodologies (Mooney et al. 2015). Kinetic analysis in swimming is the quantification of force output which has potential to improve swimming efficiency and overall swimming performance due to its established relationships with kinematics in swimming (Santos et al, 2021). Kinetic analysis of swimming is broken down to components of race phases (start, free swim, turn, and finish; (Barbosa et al., 2021; Gonjo and Olstad, 2021)). While the kinetic analysis of start, turn, and finish phases of swimming performance are recognised and established in the literature, the free swim phase is limited in kinetic analysis due to the lack of technology available. However, recent emergence of pressure sensors (PS) in that last decade (2015) within aquatic environments has now made this type of analysis possible (Santos et al., 2021). The introduction of PS grants opportunities for in-water force analysis to be performed for the free swim phase. Yet, a lack of scientific research establishing the efficacy of PS means that the efficacy of new equipment must first be investigated.

SECTION 2

LITERATURE REVIEW

This literature review will first discuss the fundamentals of swimming as a competitive sport and outline basic knowledge of swimming from a competitor and coach's perspective (**Section 2.1**). It will then outline the in-water and in-land performance variables associated with swimming analysis (**Sections 2.2**). This literature review will then go on to discuss the kinetic and kinematic variables associated with swimming performance analysis (**Sections 2.2.1 and 2.2.2**), before discussing the historical analysis of kinetic and kinematic variables within swimming performance (**Section 2.3**). It is beyond the scope of this literature review to explain the swimming patterns of all strokes explicitly, as well as to discuss methodologies not concerning that of velocity or force analysis. It is also beyond the scope of this literature review to critically discuss the impact of anthropometrics on swimming performance. The purpose of this literature review is to outline the fundamentals of swimming from a coach and practitioner perspective, to discuss the relationships between force and swimming performance, and provide an overview of established methodologies for force analysis in swimming to date.

2.1 Overview of competitive swimming

2.1.1 Characteristics of competitive swimming

Swimming is a popular competitive sport that has existed in the Olympic Games since the first hosted event in 1896. Olympic indoor swimming has 37 different events in distances ranging from 50-1500m, conducting several rounds of heats and finals. Performance duration in competitive swimming can range between <20 seconds to >17 minutes depending on stroke and/or distance (IOC - Olympics, 2017). Swimming mechanics have evolved over time to be more efficient in generating high propulsive forces for greater velocities. For instance, the ‘S’ shaped pulling pattern in freestyle was considered the best as it used sculling to propel forward (Troup, 1999). However, in recent years the ‘straight arm’ pulling pattern has been adopted as this has demonstrated to produce higher propulsive force outputs due to the deep catch method (Wei et al., 2014).

Swimming is a unique sport due to being conducted within an aquatic environment. The physical properties of water elicit physiological adaptations in the body to meet the demands of the environment, such as cardiovascular and respiratory adjustments (Lahart and Metsios, 2018). Swimming is typically performed in a supine position resulting in altered gravitational effects on circulation, restricted breathing, and eliminates perfusion pressure. In turn this lowers cardiac output, inducing an increased venous filling, triggering renal diuresis and haemoconcentration (Holmer, 1992; Troup, 1999). Because of the physiological differences elicited in swimming compared to land-based sports, the environmental condition of swimming requires the knowledge of hydrodynamics to perform effective performance analysis.

Competitive swimming is comprised of four types of strokes: freestyle, backstroke, butterfly, and breaststroke. All strokes have their own technical and performance requirements (Troup, 1999). Swimming strokes freestyle, backstroke, and butterfly have similar stroke analysis phases (hand entry, catch, in-sweep, finish, and recovery), whereas breaststroke only has three stroke phases (out-sweep, in-sweep, and recovery) (Troup, 1999). Similar lower limb kicking patterns are observed in both freestyle and backstroke, whereas in butterfly, legs kick in unison, and breaststroke possesses a different pattern entirely with technical phases separated to recover, out-sweep and in-sweep. Competitive swimming training sessions are aerobic based or anaerobic based (Hellard et al., 2017), with focus on specific skills or performance plans where session training load is determined primarily using daily/weekly distance covered (Barry et al., 2022).

Regardless of stroke, swimming performance is broken down into 4 phases: start, turn, free swim, and finish (Barbosa et al., 2021; Gonjo and Olstad, 2021). Start performance consists of analysis from the starting block up until 15m of a race. During this phase, metrics such as force and power off the block, reaction time from the gun, and speed of swimmer to the 15m mark are influential factors for performance improvement (Dingley et al., 2015; Thng et al., 2020). Turn performance data were captured from 5m distance away from, and 10m after turning at the wall where force off the wall, speed of turn, and speed to 15m post-wall are determining factors for improving velocity (Born et al., 2021; Julian V Jones et al., 2018; Marinho et al., 2020; J. E. Morais et al., 2019). The finish phase refers to the final 5m of a race where the swimmer must time their stroke and touch to minimise their swim time. Finally, the free swim phase is defined as the distance between completing the start phase and prior to the finish phase, minus turn phases. Due to technological constraints, free swim performance is the most underrepresented phase within published reports (Gonjo and Olstad, 2021).

2.1.2 In-water performance characteristics

The fastest stroke in swimming is freestyle followed by butterfly, backstroke, and breaststroke, respectively. Most speed from a swimming performance, regardless of stroke, comes from the upper body where arm velocity contributes at least 80% of overall velocity. This ranges from contributing as much as 90% to total velocity in freestyle to contributing ~78% in breaststroke (Bartolomeu et al., 2018), whereas the lower body contributes approximately average 10% to total velocity across all strokes (Deschodt et al., 1999). Velocity is suggested to be one of the most important variables contributing to swimming performance, and is fundamental to analysis of race phase, stroke kinematics, and kinetic variables (Barbosa et al., 2011, 2021).

Stroke kinematics categorise the variables associated to stroke performance: stroke count (the number of strokes per swim), stroke rate (the number of strokes per minute; spm), distance per stroke (or stroke length - the distance covered in metres by each stroke), and stroke index (efficiency of a swimmer of combining speed and distance per stroke; (Barbosa et al., 2011). Stroke kinematics are influential to performance due to their relationship with velocity. A polynomial relationship exists between stroke rate and stroke length as, during a swimming performance, stroke rate will increase and stroke length will decrease corresponding to an increased velocity (Barbosa et al., 2011, 2008; Seifert et al., 2007). Velocity throughout a race will also decrease as distance increases, requiring stroke rate to remain high to maintain as great a velocity as possible (Toussaint et al., 2006). Velocity plateaus and decreases when stroke rate goes beyond 100% relative value, identifying that stroke kinematics can only influence velocity so far before other variables contribute (Takagi et al., 2023). High-performance swimmers can change kinematics mid-performance to maintain high swimming velocity and thus, achieve a more efficient swimming performance (Barbosa et al., 2011, 2008; Chollet et al., 1997; Didier et al., 1996; Fernandes et al., 2022; Lätt et al., 2010). Greater stroke rates are observed in short distance events (i.e., 50-100m; (Didier et al., 1996), lower stroke rates and greater stroke length values are observed in mid to long-distance events (i.e., 200m-1500m; (Barbosa et al., 2011)), where these polynomial relationships still apply regardless of distance.

High-performance swimmers will incorporate stroke kinematics to produce a greater velocity such as a greater stroke rate, longer stroke length, and unchanged intra-stroke velocity (Barbosa et al., 2021; Chollet et al., 1997; Fernandes et al., 2022; Gonjo et al., 2020; Seifert et al., 2010, 2004). Body roll is an outcome of stroke kinematics in freestyle and backstroke where the body rotates along the spine and is important in the production of greater propelling forces to pull and push hands through the water. However, this is suggested to be less important in butterfly and breaststroke which rely more upon body and hand position to minimise resistance forces (Barbosa et al., 2011; Troup, 1999). While freestyle and backstroke produce similar stroke rates and distance per stroke, freestyle produces greater velocity, potentially due to the greater arm reach and shoulder rotation available in freestyle (Formosa et al., 2012). Propulsion efficiency is paramount to a more economical performance from an energy expenditure perspective with freestyle being most economic and breaststroke the least due to propulsive forces primarily coming from the upper limbs using an 'arm pull' technique. However, this is not as evident in breaststroke technique which contains the less energy efficient 'leg push' technique (Barbosa et al., 2006; Zamparo et al., 2020). Across all strokes, maintaining a low 'energy cost' (achieving high velocity with low stroke rate and high stroke length) is a primary objective during swim performance (Zamparo et al., 2020).

2.2 Performance analysis in competitive swimming

Stroke rate can influence velocity only so much until velocity plateaus; therefore, generation of propulsive force is important for the increase of velocity. It is the understanding of force relationships in water and efficiency of force that will influence the increase in velocity (Troup, 1999). The effective generation of propulsive force of the hand is a skill learned in age-group swimming by training the technique 'sculling.' This is a movement where the hands in the water are in search of 'still water', to which when swimming the swimmer will use to push off of to propel forward thus generating large amounts of propulsive force and so achieving a greater velocity (Troup, 1999). Through refinement of this skill and practice of correct stroke technique will lead to better understanding of the flow and movement of body in water and so better efficiency of propulsive force development in performance (Takagi et al., 2023). Propulsive force efficiency is essential for high performance athletes to maintain throughout a performance for propulsive force is directly correlated with velocity. Therefore, analysis of technique, force, and velocity of the upper limbs are required for effective progression and development of performance in competitive swimming.

2.2.1 Biomechanics in swimming and kinetic analysis

Forces existing in the aquatic environment are more complex than other sports due to the differing gravitational, buoyancy and resistive forces in play, especially in free swimming. Newton's laws of motion are the foundation to the understanding the relationship between force and swimmer (Stager and Tanner, 2008). The resistive forces of drag force (force acting against the swimmer when moving forward) and buoyancy/lift force (force acting perpendicular to the swimmer), and their relationship to propulsive force (force acting with the swimmer to propel forward) are fundamental to greater velocity and improved performance (Barbosa et al., 2011, 2021; Seifert et al., 2010; Stager and Tanner, 2008) (**Figure 1**).

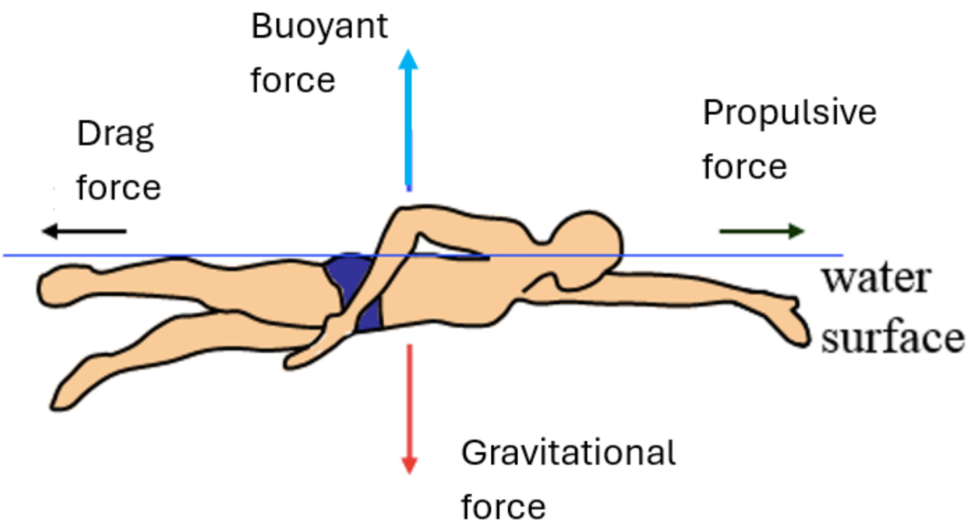

Figure 1. Forces acting in dynamic environment when swimmer moving forwards.

The foundation of quantitative analysis of kinetic variables (velocity and force) use video analysis, velocity analysis, and force platforms. Video analysis is considered the gold standard method for accurate and reliable biomechanical, temporal, kinetic and kinematic analysis of a swimming performance (Chainok et al., 2021; Magalhaes et al., 2015) and is used as a reference for kinematic performance and for reliability and validating analysis of other swimming performance analysis devices (Cortesi et al., 2021, 2019; Fantozzi et al., 2022; Morais et al., 2022; Tsunokawa et al., 2019). The use of video analysis with other performance analysis devices have proven to be valid for kinetic analysis (Ceseracciu et al., 2011a), where filming would capture the kinematics stroke metrics data and combined with velocity or force capturing data, could develop a true image of performance. Velocity based measurements display data on acceleration, peak velocity, average velocity, and time (Butterfield et al., 2020; Callaway, 2014, 2015; Clément et al., 2021; Cortesi et al., 2021, 2019; Fantozzi et al., 2022; Hamidi Rad et al., 2021; Mooney et al., 2016; Morais et al., 2022; Pla et al., 2021; Stamm et al., 2013). One assessment method of velocity in swimming is the use of tethered swimming, commonly referred to as 'speed reel' within coaching environment (Borges dos Santos et al., 2013; Craig and Pendeegast, 1979; Dadashi et al., 2012; Dominguez-Castells et al., 2013; Loturco et al., 2016; Morouço et al., 2011, 2014; Rakovic et al., 2020; Soncin et al., 2017). This device can also produce force profiles when the tethered device is attached to force capturing equipment, referred to as the tethered swimming method which will be discussed in more detail further in **section 2.3.2**. Force profiles identify performance characteristics such as average force, peak force, impulse, and efficiency which can be valuable for the analysis and understanding of kinetic variable relationships in swimming.

Force-based equipment can be implemented for on-land and in-water force output measurements using force platforms. Force platforms are considered the gold standard method for measuring on-land power in jump tests (Castagna et al., 2013; Hermosilla et al., 2021; Julian V. Jones et al., 2018; Peterson Silveira et al., 2017), proving to be a valid and reliable method for kinetic analysis of start (de Jesus et al., 2019; Mason et al., 2012; Mourão et al., 2015; Peterson Silveira et al., 2017; West et al., 2011) and turns (de Jesus et al., 2019; Julian V. Jones et al., 2018; Ling et al., 2004; Mason et al., 2012; Nicol et al., 2021; Peterson Silveira et al., 2017; Puel et al., 2012) of in-water swimming performances. A recently developed method of force-capturing technology that have the potential to provide force analysis of not only start and turns but in the free-swimming phase of performance are PS (Bartolomeu et al., 2021; Kauhanen, 2020; Löppönen et al., 2022; Santos et al., 2022a). PS have the capability to provide individual stroke kinetic measurements from the upper body, rather than methods for start and turn measuring kinetic output from only lower body.

Swimmers must work to overcome resistive forces of the water to elicit greater velocities and produce greater propulsive forces to propel themselves forward in the water at higher velocities (Stager and Tanner, 2008), which is generated from the upper limbs (Takagi et al., 2023). High-performance athletes have been observed to generate greater propulsive forces during the in-sweep phase to increase stroke efficiency and impulse per stroke (Seifert et al., 2004; Stager and Tanner, 2008). Achieving a greater velocity in swimming is dependent on the ability to produce a high propulsive force profile relative to their drag force (Borges dos Santos et al., 2013; Seifert et al., 2010, 2004), meaning that swimmers must train to produce and maintain large propulsive forces over repeated bouts. The development of velocity in swimming is limited without the production of high propulsive forces. Therefore, monitoring such levels of force production is important since force, as demonstrated, is fundamental to the development of velocity and power and overall, a more successful performance.

2.2.2 Evaluating velocity and force characteristics in start and turn performances

As previously mentioned, specific methodologies for force analysis have been employed to examine start and turn performance; however, not extensively within the free swim phase. Kinetic analysis of start and turn performances have proven essential for the development of velocity and power amongst high-performance swimmers. Kinetic variable equipment has developed to measure both land and water force output using force plates/platforms. Force platforms are considered the gold standard method for measuring land based power in jump tests, as mentioned in Section 2.2.1 (Castagna et al., 2013; Hermosilla et al., 2021; Julian V. Jones et al., 2018; Peterson Silveira et al., 2017) and have demonstrated high validity and reliability for measuring force metrics (peak force, average force, impulse, time, peak power) in start (de Jesus et al., 2019; Mason et al., 2012; Mourão et al., 2015; Peterson Silveira et al., 2017; West et al., 2011) and turn (de Jesus et al., 2019; Julian V. Jones et al., 2018; Ling et al., 2004; Mason et al., 2012; Nicol et al., 2021; Peterson Silveira et al., 2017; Puel et al., 2012) in-water performances. The extensive investigation of start and turn phases have identified many relationships between velocity and power, and performance. For example, large correlations between acceleration and force generation in start and turn push off's and overall velocity have been identified (Gonjo and Olstad, 2020). This has led to the understanding that the ability to produce substantial amounts of force is fundamental to achieve higher velocities in start and turn performances, and success in swimming.

Start and turn performances have large transferability to land velocity and power measurements and positive relationships between plyometric and maximum strength tests for force and power production and increased velocity in start and turn performances have been observed (Cossor et al., 2011; Cuenca-Fernández et al., 2022; Dingley et al., 2015; Hermosilla et al., 2021; Potdevin et al., 2011; Thng et al., 2020). Although these relationships are useful for the evaluation of swimming performance and identifying the use of force and power analysis in swimming, there is a lack of sufficient new discoveries in start and turn performance, highlighting that there is a sufficient volume of information surrounding starts and turn that we understand the performance relationships, unlike that for free-swim. Understanding kinetic relationships in start and turn phases have been fundamental to the improvement of swimming performance velocity, where performance metrics can be quantified to determine the kinetic criteria for a high performance swimmer (Barbosa et al., 2021; Borges dos Santos et al., 2013).

2.3 Methodologies investigating kinetic analysis in free-swimming phase

Analysis of force in free swimming phase has been investigated since as early as 1933 (Karpovich and Pestrecov, 1939). However, it is only in recent years, that relationships truly representable of a free-swimming performance have been established via the use of PS within performance analysis (Santos, 2021). The pressure distribution method estimates force acting on the hands by measuring pressure changes on hand surface caused by unsteady forces (Takagi et al., 2023). PS's convert pressure data of water against the hand to force on a 3-dimensonal scale (propulsive force, vertical force, and lateral force). Independent data from left to right can be analysed for performance, a factor for up until recently, could only be estimated from overall force. It is the advancement of this technology and the understanding of forces in swimming from previous methods that has allowed for more comprehensive analysis of in-water swimming performance.

2.3.1 Assessment methodologies and relationships with drag force

The first method to assess any form of swimming force performance was the identification of drag force. In accordance with Newton's laws of motion, motion will not occur unless a force acts onto the object. In swimming, if propulsive force is not applied by the swimmer, then motion will not occur. The interactions between forces directly impact swimming velocity. The resistograph towing method was developed in 1933 as a way to measure drag force by measuring the resistance of the swimmer while being pulled through the water (Karpovich and Pestrecov, 1939; Peter V. Karpovich M. D., 2013). This method identified that forces exerted against a swimmer (drag force) are equal to the forces exerted by the swimmer (propulsive force) at a constant velocity (Di Prampero et al., 1974), identifying that to overcome drag, the swimmer must generate propulsive forces greater than the opposing forces. The towing method demonstrates moderate-high inter- and intra-day reliability (Di Prampero et al., 1974; Hazrati et al., 2016; Karpovich and Pestrecov, 1939). However, the use of the resistograph method is limited as it can only measure drag force in a streamlined position, thus, the glide position within the start phase is the only performance phase that it is useful for. Although it is useful to understand the relationship between of forces at the glide portion of a start performance (Hermosilla et al., 2022), the start phase accounts for only 30% of a 50m long course performance (de Jesus et al., 2014), and is not a discriminating factor for overall start performance (Fischer and Kibele, 2016; Vantorre et al., 2014). Overall, the towing method is useful for the understanding of a swimmer's relationship with drag, but the data measured with relevance to force analysis is not transferable to an overall performance.

The hand model protocol (HMP) was developed in 1979 to further understand the relationship with drag force by measuring the effect of drag at different hand positions, a limitation of the towing method (Schleihauf, 1979). The HMP combined force analysis with video systems to analyse the movement pattern of water around the hand at different velocities and hand 'catch' positions using a prosthetic hand in an open water channel. Unlike the towing method where drag could only be measured in a prone or supine position, HMP can identify how drag forces change in response to different hand positions, which can be used to determine relative optimum pitch and angle of the hand to achieve optimum catch performance (Berger et al., 1995; Bixler and Riewald, 2002; Deschodt, 1996; Marinho et al., 2010; Schleihauf, 1983, 1979).

Despite this, the hand model is fixed and moves at a constant velocity, a protocol that is not representable of a free swim performance. The HMP was used to measure force on a 3-dimensional axis with a swimmer (Schleihauf, 1983) using video recordings of the swimmer and utilising the original HMP method. The conclusions drawn were not representable of forces in free swimming because the forces were not directly determined but estimated from a protocol that measured forces on a 2-dimensional scale (Schleihauf, 1983). The HMP model was developed to be used in a dynamic environment where a fixed hand model was towed to measure force interactions on the hand using a force transducer (Berger et al., 1995), demonstrating to be more representable of a swimming performance (Deschodt, 1996; Sanders, 1999). However, HMP remains to be a prosthetic model and can only determine kinetic relationships in a fixed environment. A swimmer's hand during swimming does not stay fixed but is fluid, dynamic, and moves and responds to the movement of the water (Barbosa et al., 2021). Even though the information provided is useful for the determination of the optimum hand angle of entry to reduce lift and drag forces (Bixler et al., 2007), it does not inform of force analysis in a free swim performance.

The measuring active drag (MAD) system was developed in 1986 for the analysis of drag on a swimming performance using swimmers (Hollander et al., 1986), confirming the findings identified in 1933, but now in a dynamic setting (Karpovich, 2013). The MAD system demonstrated to be reliable for kinetic analysis and useful for measuring force and power representative of sprint performance distances (Toussaint et al., 2006, 2004). Unfortunately, it is not truly representative of a swimming performance as the protocol involves push off grips that create an unnatural movement compared to a regular swimming performance and elicits technique changes such as extended reach, shoulder overwork, and shorter catch during the protocol (Formosa et al., 2012). The MAD system, despite being able to measure force in a dynamic swimming performance, does not provide a representation of natural free swimming force production as the swimmer has to change their performance to meet the requirements of the protocol.

Lastly, the computational fluid dynamics (CFD) model is a methodology developed based on the foundations of the hand model but with the addition of a computer simulation model to measure drag and lift forces for various hand angles and pitches to provide a 3-dimensional understanding of force relationships to performance (Bixler and Riewald, 2002). The CFD model is a simulation of a swimmer's hand and forearm in steady state flow conditions where hand angle and pitch can be changed along with velocity, allowing for estimation of drag and lift forces. Subsequently, the CFD protocol can determine relationships between forces, angles, and pitches and at varying velocities (Bixler and Riewald, 2002; Marinho et al., 2010). This provides interesting feedback for in-water performance. However, much like the relationships identified from the HMP, CFD is considered to be reliable but not valid for free-swimming force representation (Bixler et al., 2007).

2.3.2 Tethered swimming method for kinetic analysis

The tethered swimming method is the most widely used method for kinetic analysis in swimming as it establishes relationships between force and free-swimming performance in a representative manner (Morouço et al., 2011; Santos et al., 2021). The swimmer performs a free swim at a given length at any velocity and the force exerted by the swimmer is determined by the displacement of the cord and time (Mosterd and Jongbloed, 1964). The tethered swimming method was the first protocol developed that captured a true swim performance, making the method most appealing for performance analysis purposes. This method permitted the discovery of the positive linear relationship between propulsive force and swimming velocity that would the foundation of understanding of the betterment of performance (Amaro et al., 2017; Mosterd and Jongbloed, 1964). This method also provided high-performance swimmers with a quantitative metric to measure progress to aid with the planning on training to increase velocity. It identified the same relationship between propulsive force and drag force at constant velocity as previous towing methods and the MAD system; however, as the tethered swimming method can directly determine propulsive, it is with greater confidence that this relationship is indeed true (Magel, 2013). The tethered swimming method has been identified as a "good estimate" of kinetic analysis in free swimming performance (Dadashi et al., 2012; Magel, 2013) due to its high reliability (Amaro et al., 2014, 2017; Joaquim Baratto de Azevedo et al., 2021; Kjendlie and Thorsvald, 2005; Morouço et al., 2011, 2014; Nagle Zera et al., 2021; Psycharakis et al., 2011; Rakovic et al., 2020; Santos et al., 2021), and moderate-high validity to maximum force, minimum force, and rate of force development (Dopsaj et al., 2004; Nagle Zera et al., 2021; Rakovic et al., 2020). Comparing all force analysis methodologies, the tethered swimming method is the method that is most representative of free-swimming performance.

The tethered swimming method does, however, demonstrate several limitations such as contradicting findings and a risk of overestimation of kinetic results. Within sprinting events, mixed findings have been established whether there is a correlation between kinetic variables measured by the tethered swimming method and velocity of sprint performance (Joaquim Baratto de Azevedo et al., 2021; Loturco et al., 2016; Morouço et al., 2011, 2014; Yeater et al., 1981). The tethered swimming method is also unable to determine impulse which is a useful metric for performance analysis (Dopsaj et al., 2004; Loturco et al., 2016). Furthermore, the tethered swimming method has proven to overestimate kinetic variables (Gatta et al., 2016; Samson et al., 2019; Yeater et al., 1981) and cause performance impairment due to the use of external wires (Samson et al., 2019; Yeater et al., 1981). The tethered swimming method is useful when considering overall force production and propulsive force analysis in swimming, but not when investigating accurate force determination or limb specific force investigation. Despite the tethered swimming method providing a direct assessment of propulsive force in free-swimming, it is argued whether the kinetic variable values from this method are truly representative of a free-swimming performance.

2.3.3 Pressure sensors method for kinetic analysis

The method for force analysis that is gaining a reputation for being the most effective and representative form of analysis of a swimming performance are PS due to the real-time feedback provided during a free-swimming performance (Santos et al., 2021). PS detect how much pressure is being applied by the swimmer and by the water on the 3-dimensional axis, and translates this through as force via a transmitter unit to an associated database (Havriluk, 1987). PS can determine propulsive forces and other meaningful force data of independent upper body limbs, developing a more representable image of how a swimmer interacts with water (Bartolomeu et al., 2021; Kauhanen, 2020; Tsunokawa et al., 2018). PS have identified positive relationships between upper body speed and upper body propulsive force with overall swimming velocity, a relationship that was only assumed and not established prior to the emergence of this method of assessment (Koga et al., 2022; Tsunokawa et al., 2019).

PS can be used for kinetic analysis and measuring maximum force, minimum force, average force, peak force, and symmetry index in a swimming performance (Bartolomeu et al., 2021; Pereira et al., 2015; Santos et al., 2022a). PS are attached to the hands, wrists, or arms and measure kinetic variables independent of which limb is used. Collecting data in this way surpasses all other methods and their data collection for free-swimming kinetic variable measures because others measures force as a whole body sum (Kauhanen, 2020; Koga et al., 2022; Löppönen et al., 2022; Santos et al., 2022a; Tsunokawa et al., 2018, 2019), rather than the more informative way of limb specific measures.

In earlier models of PS, limitations included a lack of an accelerometer in the device meaning data collection was initiated manually using motion capture video (Bartolomeu et al., 2021; Koga et al., 2022; Pereira et al., 2015; Tsunokawa et al., 2019, 2018), subjecting opportunity for error. Furthermore, the PS design was not applicable for performance replication as the placement of the sensor wires and the required attachment of physical transmitter units on the swimmer (Bartolomeu et al., 2021; Koga et al., 2022; Pereira et al., 2015; Tsunokawa et al., 2019, 2018) posed disruptive to the swimmer's natural performance and risk of producing invalid force results. Such issues were resolved in 2020 when an accelerometer was included in the Smart Paddle™ apparatus and wireless connection was developed (Kauhanen, 2020). The use of wireless connection between sensors and a server allowed for an efficient and easy protocol, allowing the swimmer to swim with less restriction or distraction and ensuring that the force data was representable of a swimming performance. Smart Paddle™ has been proved to be reliable in the measurements of kinetic and kinematic variables compared to other PS (Marinho et al., 2022). One recurring drawback, however, is that the sensors require airtime to correctly determine stroke metrics and force measurements. Therefore, freestyle, backstroke, and butterfly are most suitable for measurement using this assessment method, as breaststroke may be more difficult to examine as the swimmer's hands do not exit the water during this stroke.

Previously, PS have presented accurate and reliable data for measuring force in swimming performances (Löppönen et al., 2022; Santos et al., 2022a), and have identified relationships of in-water kinetic variables in free swimming for upper limb independent analysis. However, given the recent emergence of the Smart Paddle™

technology, understanding of their efficacy to assess swimming performance across stroke, intensity, and across multiple timepoints remain unknown. Establishing this will provide coaches and practitioners with guidance on the suitability of this assessment method for utilisation within applied environments.

2.4 Aims and Objectives

The aim of this thesis is to investigate the efficacy of the Smart Paddle™ for in-water force analysis in high-performance swimmers in freestyle, backstroke and butterfly by measuring force output metrics. Breaststroke was excluded from investigation in this study due to the challenges of data collection by Smart Paddle™ already established in section 2.3.3. Specifically, the objectives of this thesis are to i) determine if intra-day absolute and relative reliability is evident of the Smart Paddle™; ii) to determine if objective validity is evident of the Smart Paddle™; and iii) to determine if the sensitivity of the Smart Paddle™ to identify changes in kinetic variables at different swimming intensities is evident. If this study successfully addresses these aims and objectives, this study will pose potential applications of how to apply the Smart Paddle™ to address performance related questions in a high-performance swimming environment.

SECTION 3

METHODS

3.1 Participants

In total, 31 participants (male: 19, female: 12) participated in the study. Participants were high-performance swimmers within the University of Stirling, **sport**scotland Institute of Sport high-performance swim programme. Participants performed 1 of 3 strokes: freestyle (*n*=17 (12 male, 5 female)), M ± SD: 21.4 ± 2.4 years-old, 78.0 ± 8.2kg, 180.8 ± 8.7cm, 814 ± 57 World Aquatics Points); backstroke (*n*=10 (5 male, 5 female)), M ± SD: 21.6 ± 2.5 years-old, 77.9 ± 8.5kg, 180.3 ± 8.7cm, 823 ± 61 World Aquatics Points); or butterfly (*n*=4 (2 male, 2 female)), M ± SD: 20.4 ± 1.4 years-old, 74.1 ± 7.8kg, 177.3 ± 7.7cm, 831 ± 24 World Aquatics Points). Participants were assessed at the end of the tapered season and free of injury. Participants were included if they were 18 years old or over, had competed at national level or above within the last 12 months, obtained over 700 World aquatics points (previously known as FINA), and had at least 5 years' experience training as part of a high-performance swimming programme. Participants were excluded from the study if they were injured or did not meet the inclusion criteria.

3.2 Procedures

3.2.1 Protocol

Ethical approval was obtained by the NHS, Invasive or Clinical Research panel at the University of Stirling (Ethical clearance reference number: 11032). The lead researcher met with the high-performance swimming coaches prior to commencing the project where the protocol, aims, and objectives were discussed and gatekeeper consent for participation in the study was provided. Consent was provided for the storage of anonymous performance data over an 18-month period. A signed and dated physical consent form acknowledged that the participant understood the purpose of data were collected and agreed to take part in the project and to the storage of their data. Data collection took place at the Scottish Swimming National Swimming Academy located at the University of Stirling. Data collection took place over a course of 3 weeks between April – May 2023. All data collection took place during participants' regular training schedule to minimise cumulative fatigue, avoid disrupting their training schedule, and maintain circadian rhythm.

3.2.2 Anthropometric measurements

Standing stature (cm) and body mass (kg) were measured using a stadiometer (Leicester Height Measure, Marsden Weighing Machine Group Ltd, Oxon, UK) and digital flat scales (849 Flat Scale, SECA, Hamburg, Germany), respectively, for each participant.

3.2.3 In-water testing

Participants were encouraged to not make any changes regarding their regular daily routine and to follow their regular sleeping pattern, nutrition regimen and hydration status for pre-test control measures.

A single group, repeated measures design was selected for this study to assess intra-day reliability, validity, and sensitivity of the Smart Paddle™ PS. Data were collected in the 50m indoor pool (~28°C) of the Scottish Swimming National Swimming Academy located at the University of Stirling. Swimmers were randomly assigned a date for intra-day reliability across a 3-week data collection period. Swimmers performed two bouts of 50m swimming at each of the following intensities: low (50% maximum speed), moderate (70% maximum speed), and high (90% maximum speed) based on their second 50m stroke rate of a 100m race achieved between 2-4 weeks prior to the testing date. For the purpose of this thesis, 'intensity' is a proxy for 'speed'.

Participants performed bouts from a push start off wall and performed underwater kick swimming up to 15m as according to their normal swimming performance. Prior to each bout, participants were cued with a verbal countdown by the researcher to push off. Participants performed one of the three swimming strokes (freestyle, backstroke, or butterfly) based on chosen specialised competitive stroke. Stroke rates were standardised using a stroke rate pacer device (Tempo Trainer, FINIS, California, United States of America), where individualised stroke rates for each intensity were inputted by the researcher prior to each bout. Stroke rate pacer devices were worn inside the swim cap at a position audible to the swimmer throughout swimming. Rest was standardised by performing bouts every 2 minutes. Swimmers wore a government body 'World Aquatics' approved race suit and cap during in-water testing. Participants performed a standardised warm-up of 1000m swimming followed by a 100m familiarisation period with force sensor devices where the participants swam 2 reps of 50m, first 50m was performed at individualised 50% rate and second 50m was performed at 70% rate. The research team requested feedback from all participants after this familiarisation period regarding maintenance of rates throughout swim and feedback from paddle devices. Participants were encouraged to swim normally for true representation of swimming performance.

3.2.4 Equipment

Pressure sensor devices (Smart Paddle™, Trainesense Ltd, Finnish Institute of Technology, Finland) were worn on both the right and left hand on the palmar face of the second and third phalanges (Kauhanen, 2020; Löppönen et al., 2022). The Smart Paddle™ is a system that consists of a wearable device, a Trainesense session manager mobile application for data recording and uploading, and an analysis centre for data analysis and storage. The Smart Paddle™ measures pressure differentials between palmar and dorsal faces across a $10x10cm^2$ surface area using two pressure sensors and movement on a 9-axis inertial measurement unit. Accelerometers and gyroscope sensor types were embedded into the device. Device sampling frequency of the Smart Paddle™ was 100Hz, with a memory capacity of 40 minutes and wirelessly charged battery of 33 hours. Discrete data is provided where data is collected every 10ms and raw data is able to be exported from the server once swim bout completed. The Smart Paddle™ is attached to the hand using silicon straps around the second and third phalanges on the palmar face of the hand. Data were collected by Smart Paddle™ was transferred to mobile device via Bluetooth (protocol range was 50m). The mobile device recorded and uploaded the data to the analysis centre from which the analysis centre would automatically and instantaneously analyse recorded data and display visual analysis graphs of performance metrics. Each sensor measured force output propulsive, lateral, and vertical force from each hand. The Smart Paddle™ determined average force, peak force, efficiency, impulse, and hand velocity for both left and right hands individually.

Standardisation of swimming intensities were determined using individualised stroke rates with pacer devices being used to cue each swimmer (Williams et al. 2023). Participants did not require a familiarisation period for the pacer devices as these were a routine device used regularly by participants within their training. Data from swimming bouts were uploaded to the Smart Paddle™ software following every participant's bout of testing and renamed with the individualised pseudonymised ID associated to each participant, an ID privy only to the research team. Underwater video filming (GoPro 7 Black, GoPro, San Mateo, California, United States of America) was performed to determine the manual stroke rate for each bout (Ceseracciu et al., 2011b; Magalhaes et al., 2015).

Figure 2. Smart Paddle™ placement on hand

3.3 Data Analysis

Data from each Smart Paddle™ were collected using the Trainesense session manager mobile application. Data were processed onto a single-signalling software 'the analysis centre' for analysis and data storage and stored offline onto the lead researcher's server. Output data on the PS software included: average force (N); peak force (N); efficiency (%); impulse (N•s); hand velocity (m/s); and stroke rate (spm) of the left and right hand separately. 50m was the total testing distance, 15m underwater swimming with no upper body activity and 35m of free-swimming was the data collected.

3.4 Statistical Analysis

Statistical analysis was performed on statistical software jamovi (version 2.0.0, Sydney, Australia) and Microsoft Excel (version Microsoft 365, Microsoft, New Mexico, USA). Figures were developed using GraphPad Prism software (version 9.0.0, Insight Partners, Graphpad Holdings, LLC). Prior to analysis, the assumption of normality and homoscedasticity of the data were verified using the Shapiro-Wilk and Levene tests, respectively. The mean, standard error of mean, and standard deviation (M, SEM, SD) were computed as descriptive statistics. A two-way random effects intra-class correlation coefficient (ICC) with absolute agreement and coefficient of variation (CV) was used to report relative test-retest reliability. Standardised effect size, reported as Cohen's *d*, using the pooled SD as the denominator, was calculated to evaluate the magnitude of the test-retest differences. A paired samples t-test was used to compare the outcome variables between T1 and T2 of 50%, 70%, and 90% intensities and for stroke rate validity test. Relative test-retest reliability of each variable was assessed using Pearson's *r* correlation coefficients (*r*), the intraclass correlation coefficient (ICC) with 95% confidence intervals, coefficient of variation (CV%) and standard error of measurement (SEM) from pooled SD for individual strokes (Atkinson and Nevill, 1998). Correlation coefficient was categorised as negligible (r=0.0-0.1), weak (r=0.1-0.39), moderate (r=0.4-0.69), strong (r=0.7-0.89) and very strong (r=0.9-1.0) (Schober et al., 2018). Based on the ICC estimate, values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9 and greater than 0.90 are indicative of poor, moderate, good, and excellent reliability, respectively (Koo and Li, 2016). The CV% values were interpreted as poor if CV% was > 10%, moderate if CV% was 5% ≥ 10%, and good if CV% was <5% (Scott et al., 2016). Effect size was interpreted as small (d<0.2), medium (0.3>d<0.7), and large (d>0.8) (Cohen 1977). The tests were deemed as reliable if a good-excellent ICC score was identified (>0.80), a good CV (<5%) and effect size was small-medium (d<0.7) (Atkinson and Nevill, 1998; Cohen, 1977; Hopkins, 2000; Koo and Li, 2016; Scott et al., 2016). Sensitivity was determined by significant difference through paired sample t-tests and effect size values between 50% and 90% swimming intensity bouts. No comparison for sensitivity was conducted for 70% speed as force metrics values were not varied enough to provide significant sensitivity determination. Pearson's r correlation coefficients were used to determine association between stroke rate and force variables, a positive strong correlation was determined if r>0.70 and a negative strong correlation when r<0.70 (Schober et al., 2018). Effect size large (d>0.8) were used to determine as sensitive results (Cohen, 1977). Bland–Altman plots with 95% limits of agreement (LoA) were used to display the within-subject variation and systematic differences between stroke rate data collection by Smart Paddle™ and manual collection for validity determination. The bias (mean difference), standard deviation (SD), and upper and lower LoA were calculated (Martin Bland and Altman, 1986). Data were collected with 80% power, confidence was maintained through effect sizes small-large (Cohen, 1977). Statistical significance was identified as p≤0.05.

SECTION 4

RESULTS

4.1 Descriptive analysis of swimming performance using the Smart Paddle™

Freestyle presented the highest kinetic variable values compared to backstroke and butterfly at all intensities for average force, peak force, efficiency, and impulse (**Tables 1-3**). Backstroke presented the lowest values compared to freestyle and butterfly at all intensities for average force, peak force, impulse, and hand velocity (**Tables 1-3**). Butterfly presented the highest values for hand velocity at lower intensities (**Table 3**) and highest values for efficiency at higher intensities (70% and 90%) compared to backstroke but not compared to freestyle.

4.2 Reliability of the Smart Paddle™

4.2.1 Reliability of the Smart Paddle™ during freestyle

Trial 1 and Trial 2 presented no significant differences (p>0.05) between performance bouts for average force, peak force, efficiency, impulse, and hand velocity for all swimming speeds for both left- and right-hand during freestyle (**Table 1**) and demonstrated a significant positive correlation for T1 and T2 kinetic variable values (r>0.70). Average force presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds (50%: r=0.97; 70%: r=0.93; 90% r=0.97). Peak force presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds (50%: r=0.96; 70%: r=0.97; 90% r=0.94). Efficiency presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds (50%: r=0.95; 70%: r=0.92; 90%: r=0.94). Impulse presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds (50%: r=0.98; 70%: r=0.92; 90%: r=0.92). 'Very strong' positive correlations were identified for hand velocity for combined left- and right-hand for all speeds (50%: r=0.89; 70%: r=0.97; 90%: r=0.98). Effect size was 'small' for all speeds for combined left- and right- hand for average force, peak force, and efficiency (d<0.2). Effect size was 'small' for 50% speed for impulse and hand velocity (d<0.2) and hand velocity 90% and was 'medium' for 70% and 90% for impulse (d=0.3-0.5) and 70% hand velocity (d=0.3). SEM was negligible for all force variables in freestyle with SEM ranging from 0.0-1.0N for all speeds (**Table 1**). Hand velocity presented the lowest

SEM across all speeds (~0.0m/s), whereas impulse presented the highest SEM across speeds (~0.4N•s).

ICC values were 'good-to-excellent' for all force variables (ICC = 0.75-0.99) except from left hand velocity at 50% intensity which was moderate (ICC = 0.72) (**Table 1**). Average and peak force had ICC values of 'excellent' (ICC>0.90) across all swimming speeds. Peak force presented 'good' ICC values for peak right-hand force at 90% (ICC = 0.75-0.89). Efficiency presented ICC values of 'excellent' for all speeds apart from 50% speed for left-hand, and 70% speed for right-hand where ICC values were 'good' (ICC = 0.75-0.89). Impulse had 'excellent' ICC values for all speeds apart from at 70% speed for the right-hand which was 'good' (ICC = 0.79). For hand velocity, all speeds produced 'excellent' ICC values except for the left-hand at 50% speed (ICC = 0.72). CV for all force variables at all speeds was scored 'good' (CV<5%), with peak force scoring the lowest average CV (1.3%) across all speeds, and impulse scoring the highest average CV (2.2%).

4.2.2 Reliability of the Smart Paddle™ during backstroke

Trial 1 and Trial 2 in backstroke presented no significant difference for all kinetic variables at any speed 50, 70, 90% for both left- and right-hand ($p>0.05$) (**Table 2**) and all kinetic variables have a significant positive correlation for T1 and T2 ($r>0.70$). Average force presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds (50%: $r=0.97$; 70%: $r=0.98$; 90%: $r=0.99$). Peak force presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds ($r=0.98$). Efficiency presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds (50%: $r=0.99$; 70%: $r=0.97$; 90%: $r=0.98$). Impulse presented significant 'very strong' positive correlations for combined left- and right-hand for all speeds (50%: $r=0.97$; 70%: $r=0.94$; 90%: $r=0.98$). 'Very strong' positive correlations were identified for hand velocity for combined left- and right-hand for 50% speed ($r=0.95$), and 'strong positive' correlations (70%: $r=0.84$; 90%: $r=0.78$).

Effect size was 'small' for all speeds for combined left- and right-hand for average force, peak force, and impulse ($d<0.2$). Effect size was 'medium' for efficiency at 90% speed ($d=0.5$) and 50% hand velocity ($d=0.3$), all other speeds for efficiency and hand velocity were 'small' effect sizes ($d<0.2$). SEM for backstroke was negligible

(0.0-0.5N), with average force and hand velocity presenting the lowest SEM (0.0N, 0.0m/s) and Peak Force and Impulse the highest at (0.2N, 0.2N•s).

ICC scores were ‘good-to-excellent’ (ICC = 0.75 - 0.99) for all force variables for left- and right-hand at all speeds except hand velocity right hand at 90% which was ‘moderate’ score (ICC = 0.65). Average force and peak force demonstrated the highest average ICC scores across all speeds (ICC = 0.98) followed by ‘excellent’ average scores of efficiency (ICC = 0.97), impulse (ICC = 0.96) and ‘good’ score for hand velocity (ICC = 0.86). Average force, peak force and efficiency had ‘excellent’ ICC scores across all speeds for both left- and right-hand (ICC>0.90). CV for all force and velocity Smart Paddle™ variables were scored ‘good’ (CV<5%), with hand velocity scoring the highest average CV (2.5 - 4.1%) across all speeds 90% demonstrating the most variation, and efficiency scoring the lowest average CV (0.8 - 1.2%) with the coefficient of variation increasing with speed, a trend not observed in any other force variables (**Table 2**).

4.2.3 Reliability of the Smart Paddle™ during butterfly

Trial 1 and Trial 2 presented no significant difference between performance bouts for average force, peak force, efficiency, impulse and hand velocity ($p>0.05$) for all swimming speeds for both left- and right-hand for butterfly (**Table 3**) and demonstrated to have a significant positive correlation for T1 and T2 kinetic variable values ($r>0.70$). Average force presented significant ‘very strong’ positive correlations for combined left- and right-hand for all speeds (50%: r=0.97; 70%: r=0.97; 90%: r=0.91). Peak force presented significant ‘very strong’ positive correlations for combined left- and right-hand for all speeds (50%: r=0.96; 70% r=0.97; 90%: r=0.92). Efficiency presented significant ‘very strong’ positive correlations for combined left- and right-hand for low intensity (50%: r=0.95), ‘poor’ insignificant positive correlations at moderate intensity (70%: r=0.32), and ‘strong’ positive significant correlations at high intensity (90%: r=0.87). Impulse presented significant ‘very strong’ positive correlations for combined left- and right-hand for all speeds (50%: r=0.99; 70%: r=0.99; 90%: r=0.94). ‘Very strong’ positive correlations were identified for hand velocity for combined left- and right-hand for all speeds (50%: r=0.99; 70%: r=0.98; 90%: r=0.98).

ICC presented ‘good-to-excellent’ scores for butterfly for all Smart Paddle™ kinetic variables (**Table 3**). Hand velocity presented the highest average score (ICC =

0.99), and efficiency presented the lowest ICC (ICC = 0.81). ICC score in butterfly decreased with increased speed with 50 and 70% speed presented ‘excellent’ score (ICC = 0.95) and 90% speed with ‘good’ score (ICC = 0.88). All Smart Paddle™ kinetic variables demonstrated a CV%<5. All kinetic variables demonstrated an average CV% of less than 2% (1.3 - 1.8%) except hand velocity 2.7%. Increased intensity increased the CV with 90% speed CV being 2.1% compared to that of 50 and 70% speeds where CV was 1.9% and 1.4% respectively (**Table 3**).

SEM for butterfly was negligible (0.0-0.8N) for all force variables, with peak force and efficiency presenting a highest SEM (0.3N, 0.3%) and hand velocity presenting the lowest SEM (0.0m/s). Effect size was ‘small’ for average force, peak force, efficiency and impulse at 50% speed, efficiency at 90% speed and hand velocity at 70% and 90% speed (d<0.2). ‘Medium’ effect size was determined at 70% for average force, peak force, and efficiency, and at 90% speed for average force, peak force and impulse (d<0.8). ‘Large’ effect size was found for impulse at 70% speed (d=1.1) and 50% speed at hand velocity (d=0.9) (**Table 3**).

Table 1. Force variable reliability results for left, right, and combined hand at three intensity speeds for freestyle

		50%			70%			90%		
		Left hand	Right hand	Combined	Left hand	Right hand	Combined	Left hand	Right hand	Combined
Average Force	T1 (M+SD) [N]	16.8±2.3	14.6±2.5	15.7±2.6	20.3±3.0	17.9±3.7	19.1±3.5	22.2±3.6	20.1±3.9	21.1±3.8
	T2 (M+SD) [N]	17.1±2.3	14.7±2.4	15.9±2.6	20.4±3.2	17.7±4.0	19.0±3.8	22.0±3.8	19.9±4.2	21.0±4.1
	ICC (95% CI)	0.98 (0.94-0.99)	0.95 (0.88-0.98)	0.97(0.94-0.99)	0.95 (0.86-0.98)	0.90 (0.74-0.96)	0.93 (0.86-0.96)	0.94 (0.85-0.98)	0.98 (0.94-0.99)	0.96 (0.93-0.98)
	CV [%]	1.4	1.9	2.1	1.6	3.3	2.5	1.8	1.6	1.7
	SEM [N]	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.0	0.1
	d	0.33	0.19	0.02	0.06	0.13	0.06	0.16	0.15	0.16
Peak Force	T1 (M+SD) [N]	90.4±10.7	88.3±14.2	89.3±12.5	90.3±13.0	85.3±13.7	87.7±13.4	86.1±15.0	82.1±13.4	84.1±14.2
	T2 (M+SD) [N]	90.2±11.7	88.3±13.2	89.3±12.3	90.9±14.1	83.4±14.8	87.2±14.7	85.9±15.5	82.0±14.9	83.9±15.1
	ICC (CI)	0.93 (0.780-0.97)	0.99 (0.96-0.99)	0.96 (0.92-0.98)	0.97 (0.91-0.99)	0.95 (0.86-0.98)	0.96 (0.92-0.98)	0.98 (0.94-0.99)	0.89 (0.73-0.96)	0.94 (0.89-0.97)
	CV [%]	1.5	1.0	1.2	1.1	1.8	1.4	1.1	1.2	1.8
	SEM [N]	0.4	0.1	0.2	0.2	0.3	0.3	0.1	0.3	0.4
	d	0.07	0.02	0.05	0.42	0.48	0.09	0.07	0.01	0.03
Efficiency	T1 (M+SD) [%]	48.6±4.7	44.2±6.0	46.4±5.8	52.1±4.8	49.5±5.9	50.7±5.5	54.0±5.4	52.8±5.9	53.4±5.6
	T2 (M+SD) [%]	48.2±4.2	44.2±5.9	46.2±5.4	52.0±5.3	50.4±5.3	51.2±5.3	54.0±5.5	53.0±5.9	53.5±5.7
	ICC (CI)	0.89 (0.72-0.96)	0.97 (0.92-0.99)	0.95 (0.90-0.98)	0.97 (0.91-0.99)	0.88 (0.71-0.96)	0.92 (0.84-0.96)	0.97 (0.91-0.99)	0.93 (0.82-0.97)	0.95 (0.89-0.97)
	CV [%]	1.6	1.0	1.3	1.0	1.8	1.4	1.1	1.6	1.3
	SEM [N]	0.3	0.1	0.3	0.1	0.3	0.4	0.1	0.2	0.2
	d	0.17	0.04	0.08	0.16	0.34	0.16	0.05	0.09	0.04
Impulse	T1 (M+SD) [N•s]	82.7±17.8	80.6±20.0	81.6±18.7	67.6±14.7	62.4±10.8	64.9±12.9	56.7±11.1	52.0±8.5	54.3±10.0
	T2 (M+SD) [N•s]	84.8±17.3	79.8±17.4	82.3±17.3	66.3±13.3	58.6±11.3	62.4±12.8	55.2±11.7	51.3±9.1	53.3±10.5
	ICC (CI)	0.97 (0.91-0.99)	0.98 (0.95-0.99)	0.98 (0.95-0.99)	0.98 (0.94-0.99)	0.79 (0.45-0.92)	0.91 (0.79-0.96)	0.90 (0.75-0.96)	0.93 (0.82-0.97)	0.91 (0.83-0.96)
	CV [%]	1.7	1.2	1.5	1.7	3.7	2.6	2.9	1.9	2.4
	SEM [N•s]	0.3	0.1	0.2	0.2	1.0	0.5	0.5	0.3	0.4
	d	0.20	0.22	0.01	0.38	0.59	0.48	0.29	0.21	0.25
Hand Velocity	T1 (M+SD) [m/s]	1.0±0.3	1.4±0.2	1.2±0.3	1.3±0.3	1.6±0.3	1.5±0.3	1.6±0.4	1.7±0.3	1.6±0.4
	T2 (M+SD) [m/s]	1.0±0.2	1.4±0.2	1.2±0.3	1.4±0.4	1.6±0.3	1.5±0.3	1.6±0.5	1.7±0.3	1.6±0.4
	ICC (CI)	0.72 (0.37-0.89)	0.95 (0.87-0.98)	0.88 (0.77-0.94)	0.98 (0.95-1.00)	0.95 (0.87-0.98)	0.97 (0.94-0.99)	0.98 (0.94-0.99)	0.98 (0.95-0.99)	0.98 (0.96-0.99)
	CV [%]	2.1	1.9	2.0	1.7	2.5	2.1	2.1	1.4	1.7
	SEM [m/s]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	d	0.25	0.32	0.24	0.48	0.22	0.31	0.28	0.18	0.09

Note: T1 = trial 1: mean ± SD, T2 = trial 2: mean ±SD, ICC = interclass correlation coefficient: 95% confidence intervals, CV = coefficient of variation, SEM = standard error of mean, d = Cohen's d.

Table 2. Force variable reliability results for left, right, and combined hand at three intensity speeds for backstroke

		50%			70%			90%		
		Left hand	Right hand	Combined	Left hand	Right hand	Combined	Left hand	Right hand	Combined
Average Force	T1 (M+SD) [N]	11.3±2.5	10.6±2.7	10.9±2.6	13.2±3.5	12.2±3.3	12.7±3.4	15.0±4.5	13.8±3.8	14.4±4.1
	T2 (M+SD) [N]	11.0±2.1	10.6±2.8	10.8±2.4	13.2±3.4	11.7±3.4	12.5±3.4	15.2±4.7	13.9±4.1	14.5±4.4
	ICC (95% CI)	0.96 (0.84-0.99)	0.99 (0.94-1.00)	0.97 (0.93-0.99)	0.99 (0.98-1.00)	0.97 (0.91-0.99)	0.98 (0.96-0.99)	0.98 (0.93-0.99)	0.99 (0.96-1.00)	0.99 (0.96-0.99)
	CV [%]	1.7	1.8	2.1	1.2	1.8	1.5	2.0	1.3	1.8
	SEM [N]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	d	0.39	0.04	0.24	0.04	0.36	0.24	0.21	0.17	0.19
Peak Force	T1 (M+SD) [N]	54.8±15.7	56.8±14.4	55.8±14.7	53.0±15.0	53.5±14.7	53.2±14.5	53.3±13.0	51.7±12.2	52.5±12.3
	T2 (M+SD) [N]	53.9±14.6	57.4±14.7	55.6±14.3	53.6±15.7	51.5±15.5	52.6±15.2	52.0±13.9	47.7±17.0	52.1±13.5
	ICC (CI)	0.99 (0.95-1.00)	0.98 (0.92-0.99)	0.98 (0.95-0.99)	0.99 (0.95-1.00)	0.98 (0.91-1.00)	0.98 (0.95-0.99)	0.98 (0.91-0.99)	0.98 (0.94-1.00)	0.98 (0.95-0.99)
	CV [%]	1.9	2.1	2.0	1.9	2.1	2.0	2.3	3.1	4.2
	SEM [N]	0.1	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.3
	d	0.39	0.19	0.06	0.22	0.16	0.02	0.46	0.16	0.16
Efficiency	T1 (M+SD) [%]	42.2±5.6	39.2±4.9	40.7±5.4	46.6±6.2	42.9±5.7	44.7±6.1	47.9±6.0	44.7±5.3	46.3±5.8
	T2 (M+SD) [%]	42.2±5.4	38.9±5.0	40.6±5.3	47.0±5.9	42.7±5.7	45.0±6.1	48.5±6.2	45.6±6.4	47.0±6.3
	ICC (CI)	1.00 (0.98-1.00)	0.98 (0.91-0.99)	0.99 (0.97-0.99)	0.98 (0.94-1.00)	0.95 (0.81-0.99)	0.97 (0.93-0.99)	0.98 (0.92-1.00)	0.95 (0.80-0.99)	0.97 (0.90-0.99)
	CV [%]	0.5	1.0	0.7	0.9	1.3	1.0	0.9	1.5	1.2
	SEM [N]	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.2	0.1
	d	0.08	0.26	0.14	0.44	0.08	0.12	0.64	0.48	0.52
Impulse	T1 (M+SD) [N•s]	66.8±10.1	66.6±11.7	66.7±10.6	51.3±10.9	51.3±8.7	51.3±9.6	46.1±10.1	45.0±8.4	45.6±9.1
	T2 (M+SD) [N•s]	65.5±8.71	67.3±11.7	66.4±10.1	51.1±10.8	50.0±37.8	50.6±10.6	45.8±10.8	44.7±8.3	45.2±9.4
	ICC (CI)	0.96 (0.83-0.99)	0.98 (0.91-0.99)	0.97 (0.92-0.99)	0.99 (0.98-1.00)	0.87 (0.51-0.97)	0.94 (0.85-0.96)	0.99 (0.96-1.00)	0.97 (0.90-0.99)	0.98 (0.96-0.99)
	CV [%]	1.4	1.5	1.4	0.9	2.8	1.8	1.5	2.0	1.7
	SEM [N•s]	0.2	0.2	0.2	0.0	0.5	0.2	0.1	0.1	0.1
	d	0.50	0.27	0.11	0.14	0.06	0.06	0.21	0.17	0.19
Hand Velocity	T1 (M+SD) [m/s]	0.9±0.3	0.9±0.3	0.9±0.2	1.0±0.3	1.1±0.2	1.1±0.2	1.2±0.3	1.2±0.3	1.2±0.3
	T2 (M+SD) [m/s]	0.9±0.2	0.9±0.2	0.9±0.2	1.1±0.2	1.1±0.3	1.1±0.2	1.2±0.2	1.2±0.2	1.2±0.2
	ICC (CI)	0.93 (0.74-0.98)	0.97 (0.86-0.99)	0.95 (0.87-0.98)	0.84 (0.50-0.96)	0.86 (0.50-0.97)	0.85 (0.65-0.94)	0.93 (0.74-0.98)	0.65 (0.06-0.90)	0.78 (0.52-0.91)
	CV [%]	4.1	2.8	3.5	2.5	2.5	2.5	3.3	4.8	4.3
	SEM [m/s]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	d	0.10	0.61	0.29	0.25	0.08	0.18	0.49	0.11	0.06

Note: T1 = trial 1: mean ± SD, T2 = trial 2: mean ±SD, ICC = interclass correlation coefficient: 95% confidence intervals, CV = coefficient of variation, SEM = standard error of mean, d = Cohen's d.

Table 3. Force variable reliability results for left, right, and combined hand at three intensity speeds for butterfly

		50%			70%			90%		
		Left hand	Right hand	Combined	Left hand	Right hand	Combined	Left hand	Right hand	Combined
Average Force	T1 (M+SD) [N]	16.8±2.3	13.8±2.7	15.3±2.8	18.9±1.4	17.0±2.4	18.0±2.0	20.0±1.9	17.1±5.8	19.8±2.1
	T2 (M+SD) [N]	16.7±2.2	13.8±2.8	15.2±2.8	19.2±1.7	17.3±2.3	18.3±2.1	19.8±2.2	19.0±3.1	19.4±2.5
	ICC (95% CI)	0.96 (0.53-1.00)	0.96 (0.54-1.00)	0.97 (0.87-0.99)	0.94 (0.50-1.00)	0.98 (0.78-1.00)	0.97 (0.83-0.99)	0.86 (-0.23-0.99)	0.93 (0.46-1.00)	0.89 (0.60-0.98)
	CV [%]	1.7	1.8	2.2	1.2	1.1	1.3	2.5	2.6	2.6
	SEM [N]	0.1	0.1	0.1	0.1	0.0	0.1	0.2	0.1	0.2
	d	0.05	0.05	0.06	0.51	0.64	0.61	0.14	0.66	0.34
Peak Force	T1 (M+SD) [N]	66.8±8.8	66.1±10.2	66.4±8.8	67.2±5.7	67.5±9.2	67.4±7.1	64.8±6.2	66.3±9.7	65.5±7.8
	T2 (M+SD) [N]	67.0±8.2	66.0±10.0	66.5±8.5	66.7±6.4	66.8±9.6	66.8±7.6	62.7±5.3	65.1±8.9	63.9±6.9
	ICC (CI)	0.94 (0.28-1.00)	0.99 (0.85-1.00)	0.96 (0.83-0.99)	0.95 (0.48-1.00)	0.98 (0.77-1.00)	0.97 (0.85-0.99)	0.75 (0.19-0.98)	0.98 (0.79-1.00)	0.91 (0.62-0.98)
	CV [%]	1.9	2.1	1.6	1.1	0.9	1.1	2.7	0.5	1.9
	SEM [N]	0.3	0.1	0.2	0.2	0.1	0.1	0.8	0.0	0.4
	d	0.05	0.03	0.02	0.24	0.33	0.31	0.50	0.70	0.55
Efficiency	T1 (M+SD) [%]	42.5±1.4	36.7±4.7	39.6±4.4	48.4±2.5	45.8±5.5	47.1±4.2	51.3±2.6	43.0±4.7	49.7±3.9
	T2 (M+SD) [%]	42.1±2.3	36.3±4.7	39.2±4.6	49.6±1.8	45.3±3.7	47.4±3.5	51.2±1.7	48.5±2.0	49.8±2.2
	ICC (CI)	0.77 (0.42-0.98)	0.95 (0.44-1.00)	0.77 (0.42-0.98)	0.83 (0.07-0.99)	0.87 (0.13-0.99)	0.87 (0.49-0.97)	0.72 (0.83-0.98)	0.72 (0.70-0.98)	0.77 (0.18-0.95)
	CV [%]	0.5	1.0	1.7	1.2	1.9	1.5	1.1	2.1	1.7
	SEM [N]	0.3	0.2	0.3	0.2	0.3	0.3	0.4	0.5	0.2
	d	0.26	0.22	0.23	1.36	0.19	0.61	0.07	0.16	0.08
Impulse	T1 (M+SD) [N•s]	73.3±8.4	69.6±7.8	71.4±7.7	57.7±11.1	55.1±11.1	56.4±10.3	47.4±7.9	48.4±11.7	47.9±9.2
	T2 (M+SD) [N•s]	73.2±6.9	69.5±6.6	71.4±7.1	56.1±10.9	54.5±11.3	55.3±10.3	46.5±8.0	45.4±7.8	45.9±7.3
	ICC (CI)	0.97 (0.63-1.00)	0.99 (0.80-1.00)	0.99 (0.93-1.00)	0.99 (0.36-1.00)	0.99 (0.95-1.00)	0.99 (0.87-1.00)	0.99 (0.82-1.00)	0.87 (0.19-0.99)	0.90 (0.59-0.98)
	CV [%]	1.4	1.5	0.8	1.4	0.8	1.1	1.1	3.3	2.2
	SEM [N•s]	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.6	0.3
	d	0.07	0.04	0.05	1.88	0.55	1.05	0.90	0.64	0.58
Hand Velocity	T1 (M+SD) [m/s]	1.16±0.5	1.39±0.6	1.3±0.5	1.32±0.4	1.44±0.6	1.4±0.4	1.55±0.6	1.46±0.6	1.5±0.5
	T2 (M+SD) [m/s]	1.23±0.5	1.44±0.6	1.3±0.5	1.35±0.5	1.42±0.5	1.4±0.5	1.54±0.6	1.46±0.6	1.5±0.5
	ICC (CI)	0.98 (0.71-1.00)	0.99 (0.86-1.00)	0.99 (0.87-1.00)	0.98 (0.56-1.00)	1.00 (0.98-1.00)	0.98 (0.91-1.00)	1.00 (0.93-1.00)	0.98 (0.74-1.00)	0.99 (0.93-1.00)
	CV [%]	4.1	2.8	2.9	3.4	0.7	2.0	1.6	3.5	2.5
	SEM [m/s]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	d	1.04	0.63	0.86	0.25	0.93	0.08	0.15	0.06	0.01

Note: T1 = trial 1: mean ± SD, T2 = trial 2: mean ±SD, ICC = interclass correlation coefficient: 95% confidence intervals, CV = coefficient of variation, SEM = standard error of mean, d = Cohen's d.

4.3 Validity of the Smart Paddle™

Establishing direct face validity of Smart Paddle™ was challenging due to the lack of comparable techniques for measuring in-water kinetic variables. Therefore, an objective validity analysis was performed for the comparison of stroke rate between Smart Paddle™ and manual stroke rate calculation. Manual stroke rate was determined by manually counting strokes over 35m segment of bouts. Smart Paddle™ and manual stroke rate ranges had non-significant differences between methods for freestyle, backstroke and butterfly for all intensities (p>0.05).

4.3.1 Validity of stroke rate using Smart Paddle™ for freestyle

Stroke rate for freestyle using the Smart Paddle™ ranged 25-28spm compared to 23-28spm manually observed for low intensity (50%). Similar range differences were observed at 70% intensity (Smart Paddle™: 32-40spm, manual: 30-40spm), and 90% intensity (Smart Paddle™: 40-52spm, manual: 37-50spm). There was no significant difference for stroke rate between Smart Paddle™ or manual for freestyle (p=0.09), however, this value was approaching significance. Biases (mean differences) was 0.3 between methods with a range of 6spm, and most data points were within the limits of agreement for freestyle (**Figure 3**).

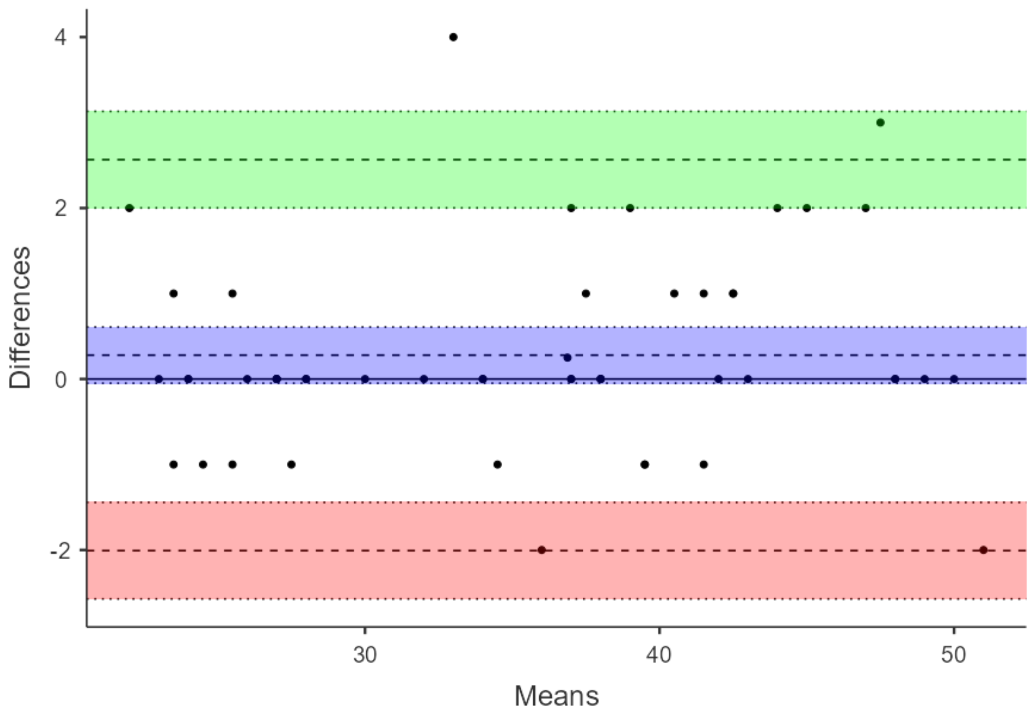

Figure 3. Bland-Altman plots of the difference between Smart Paddle™ and Manual (y-axis) and mean of measurements (x-axis) for stroke rate in freestyle. Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean differences between the two trials (bias). Shaded areas represent the 95% confidence intervals of upper and lower limits.

4.3.2 Validity of stroke rate using Smart Paddle™ for backstroke

Backstroke Smart Paddle™ ranged 20-26spm compared to manual 20-26spm for low intensity (50%), similar range differences were exhibited in 70% intensity (Smart Paddle™: 30-38spm, and manual: 30-37spm), and 90% intensity (Smart Paddle™: 35-44spm, and manual: 36-44spm). There was no significant difference between Smart Paddle™ determined stroke rate or manual determined stroke rate for backstroke (p=0.60). Biases (mean differences) was 0.1 between methods with a range of 6spm, and most data points were within the limits of agreement on both stroke rate data collection methodologies for backstroke (**Figure 4**).

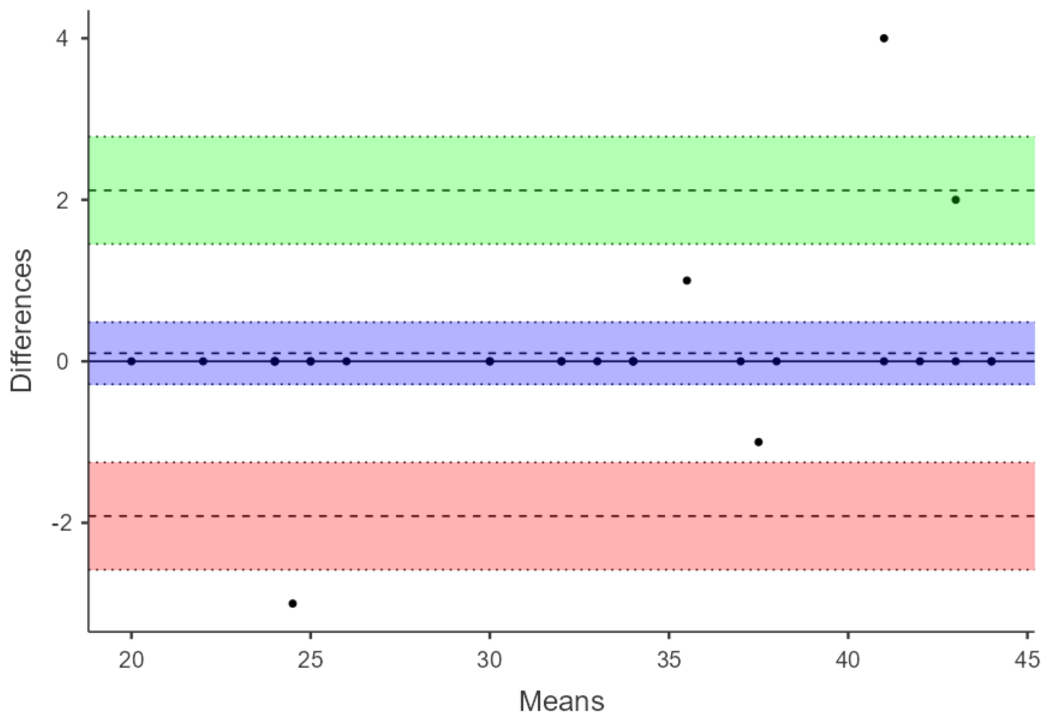

Figure 4. Bland-Altman plots of the difference between Smart Paddle™ and Manual (y-axis) and mean of measurements (x-axis) for stroke rate in backstroke. Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean

differences between the two trials (bias). Shaded areas represent the 95% confidence intervals of upper and lower limits.

4.3.3 Validity of stroke rate using Smart Paddle™ for butterfly

Butterfly Smart Paddle™ ranged 32-42spm compared to manual 30-36spm for low intensity (50%), similar range differences were exhibited in 70% intensity (Smart Paddle™: 37-47spm, and manual: 37-47spm), and 90% intensity (Smart Paddle™: 44-56spm, and manual: 48-56spm). There was no significant difference between Smart Paddle™ determined stroke rate or manual determined stroke rate for butterfly (*p*=1.00). Biases (mean differences) were zero between methods with a range of 4spm, and most data points were within the limits of agreement on both stroke rate data collection methodologies for butterfly (**Figure 5**).

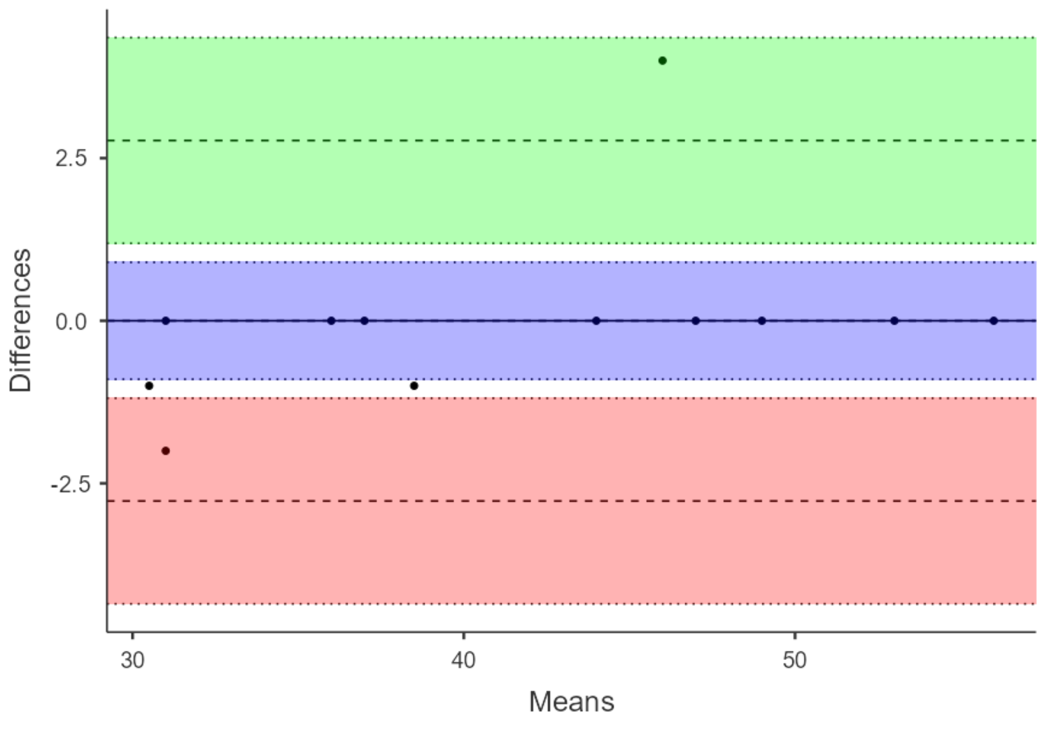

Figure 5. Bland-Altman plots of the difference between Smart Paddle™ and Manual (y-axis) and mean of measurements (x-axis) for stroke rate in butterfly. Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean differences between the two trials (bias). Shaded areas represent the 95% confidence intervals of upper and lower limits.

4.4 Sensitivity of the Smart Paddle™

4.4.1 Sensitivity of the Smart Paddle™ during freestyle

Average force for freestyle was significantly greater ($t = 9.1$, $p < 0.01$) at 90% (21.1±4.1N) than 50% (16.1±2.7N) with a 5±1.4N increase with relative speed (**Figure 6A**). Peak force for freestyle was significantly less ($t = 2.3$, $p = 0.03$) at 90% (83.9±15.1N) than 50% (89.3±12.3N) with a 5.4±2.8N decrease with relative speed (**Figure 7A**). Efficiency for freestyle was significantly greater ($t = 7.7$, $p<0.01$) at 90% (53.5±5.7%) than 50% (46.2±5.4%) with a 7.3±0.3% increase with relative speed (**Figure 8A**). Impulse for freestyle was significantly less ($t = 13.3$, $p<0.01$) at 90% (53.3±10.5N•s) than 50% (82.3±17.3N•s) with a 29±6.8N•s decrease with relative speed (**Figure 9A**). Hand Velocity for freestyle was significantly greater ($t = 8.0$, $p<0.01$) at 90% (1.6±0.4m/s) than 50% (1.2±0.3m/s) with a 0.4±0.1m/s increase with relative swim speed (**Figure 10A**).

4.4.2 Sensitivity of the Smart Paddle™ during backstroke

Average Force for backstroke was significantly greater ($t = 6.9$, $p<0.01$) at 90% (14.9±4.6N) than 50% (11.1±2.6N) with a 3.8±2.0N increase with relative speed (**Figure 6B**). Peak Force for backstroke was not significantly different ($t = 1.9$, $p=0.08$) at 90% (49.9±15.3N) than 50% (55.6±14.3N) with a decrease of 5.7±1.0N with relative speed (**Figure 7B**). Efficiency for backstroke was significantly greater ($t = 7.2$, $p<0.01$) at 90% (47.0±6.3%) than 50% (40.6±5.3%) with a 6.4±1.0% increase with relative speed (**Figure 8B**). Impulse for backstroke was significantly less ($t = 15.8$, $p<0.01$) at 90% (45.2±9.4N•s) than 50% (66.4±10.1N•s) with a 21.2±0.7N•s decrease with relative speed (**Figure 9B**). Hand Velocity for backstroke was significantly greater ($t = 5.0$, $p<0.01$) at 90% (1.7±0.2m/s) than 50% (0.9±0.2m/s) with a 0.6m/s increase with relative swim speed (**Figure 10B**).

4.4.3 Sensitivity of the Smart Paddle™ during butterfly

Average Force for butterfly was significantly greater ($t = 6.9$, $p<0.01$) at 90% (19.7±2.6N) than 50% (15.3±2.6N) with a 4.4N increase with relative speed (**Figure 6C**). Peak Force for butterfly was not significantly different ($t = 1.3$, $p=0.24$) at 90% (63.9±6.9N) than 50% (66.5±8.5N) with a decrease of 2.6±1.6N with relative speed (**Figure 7C**). Efficiency for butterfly was significantly greater ($t = 6.6$, $p=0.0003$) at

90% (49.8±2.2%) than 50% (39.2±4.6%) with a 10.6±2.4% increase with relative speed (**Figure 8C**). Impulse for butterfly was significantly less ($t = 16.2$, $p<0.01$) at 90% (45.9±7.3N•s) than 50% (71.3±6.6N•s) with a 25.4±0.7N•s decrease with relative speed (**Figure 9C**). Hand Velocity for butterfly was not significantly different ($t = 1.9$, $p=0.1$) at 90% (1.5±0.5m/s) than 50% (1.3±0.5m/s) with a 0.2m/s increase with relative swim speed (**Figure 10C**).

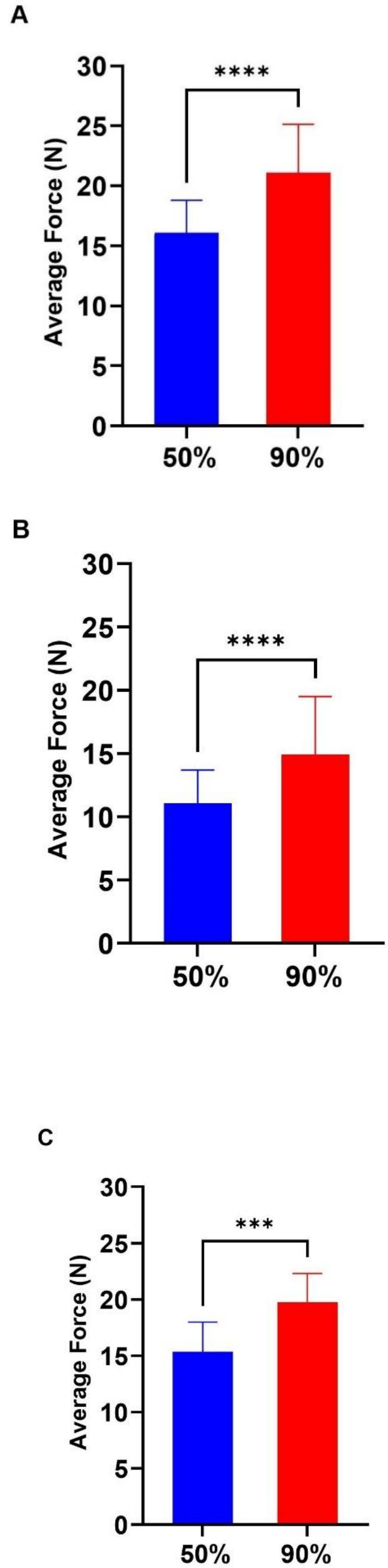

Figure 6. Average Force during 50% and 90% speeds for freestyle (A), backstroke (B), and butterfly (C).'Significance of $p<0.05$ represented by *, $p=0.001$ represented by *** and $p<0.001$ represented by ****.

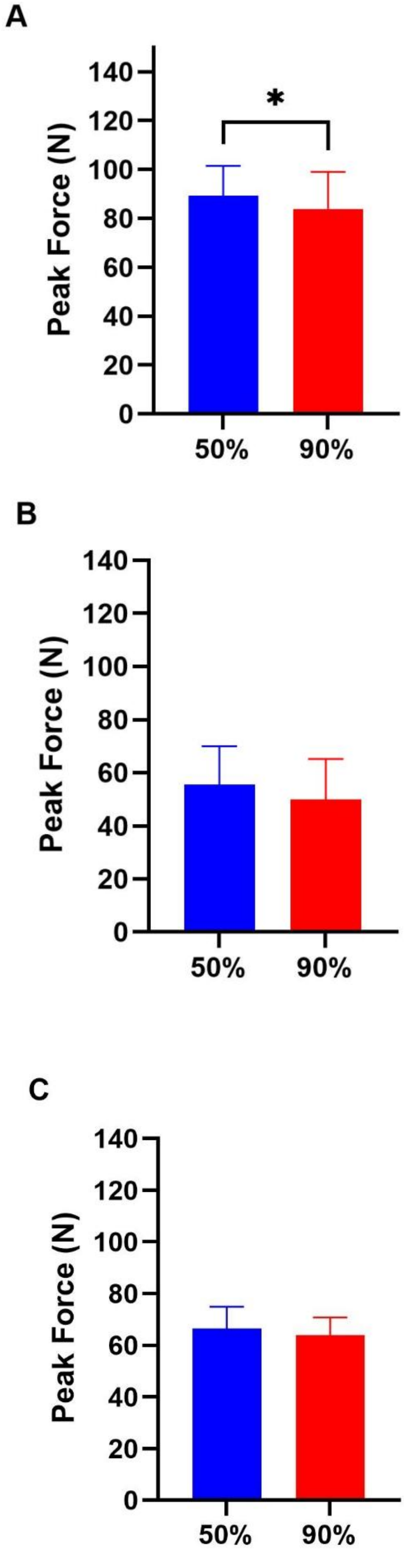

Figure 7. Peak Force during 50% and 90% speeds for freestyle (A), backstroke (B), and butterfly (C). Significance of p<0.05 represented by *.

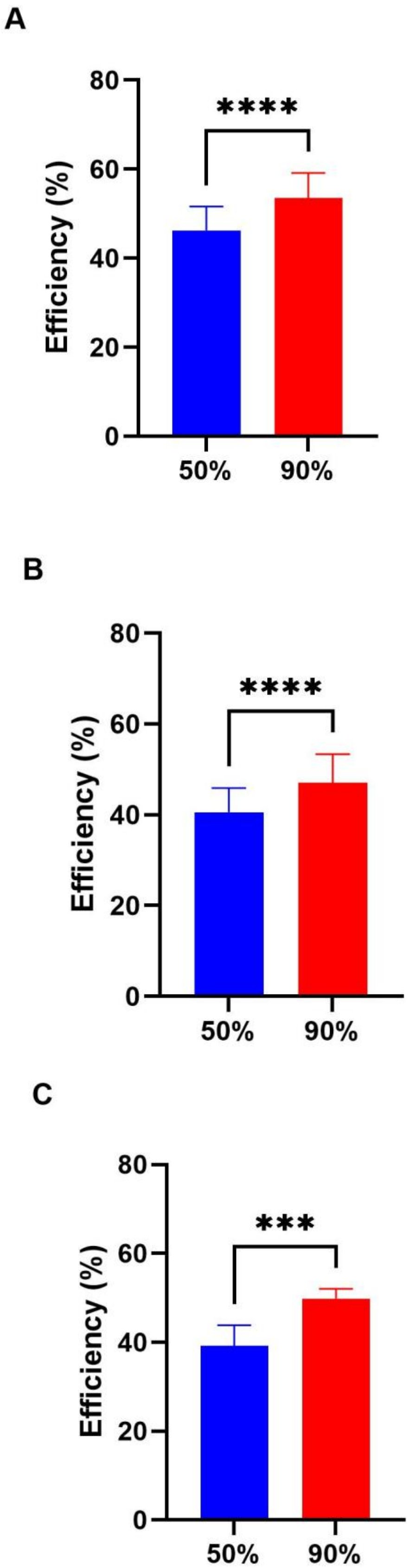

Figure 8. Efficiency during 50% and 90% speeds for freestyle (A), backstroke (B), and butterfly (C). 'Significance of p<0.05 represented by *, p=0.001 represented by *** and p<0.001 represented by ****.

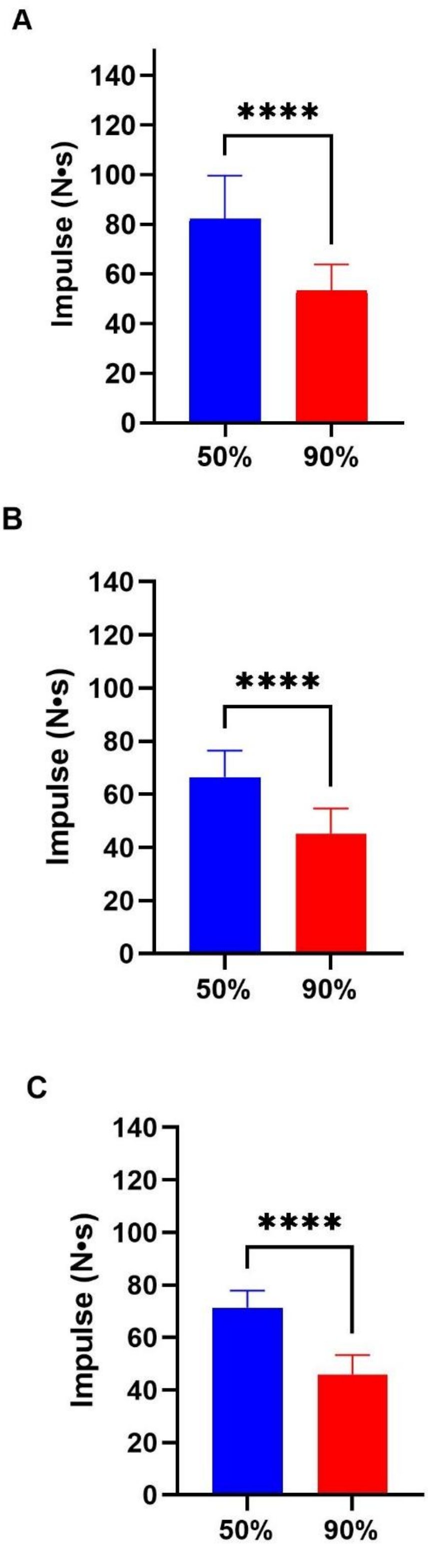

Figure 9. Impulse during 50% and 90% speeds for freestyle (A), backstroke (B), and butterfly (C).'Significance of $p<0.05$ represented by *, $p=0.001$ represented by *** and $p<0.001$ represented by ****.

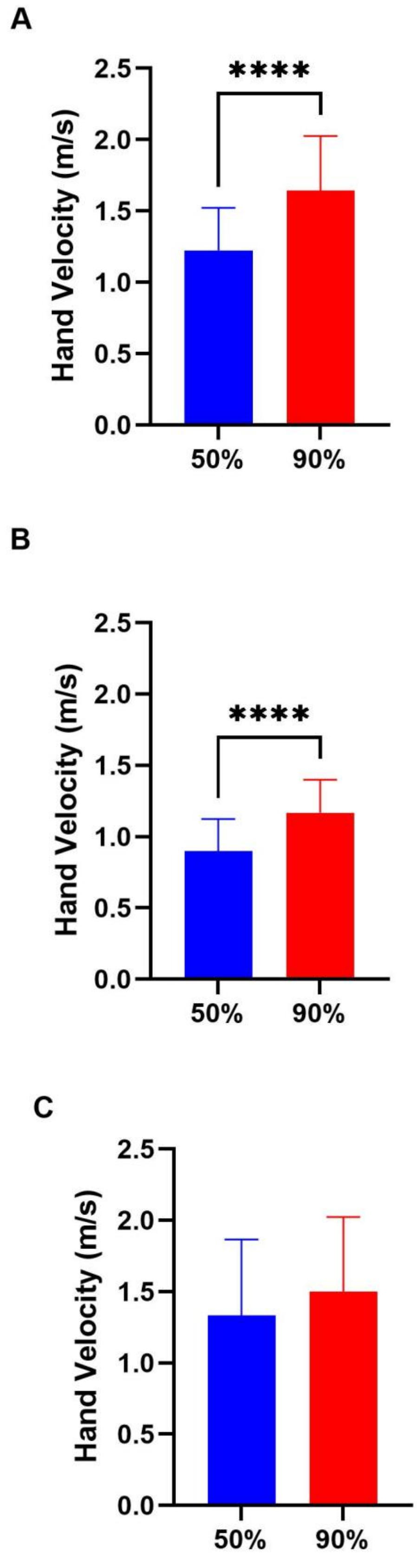

Figure 10. Hand velocity during 50% and 90% speeds for freestyle (A), backstroke (B), and butterfly (C). 'Significance of $p<0.05$ represented by *, $p=0.001$ represented by *** and $p<0.001$ represented by ****.

Table 4. Effect size (cohen's d), mean, confidence intervals (95%) and significance (p-value) of force variables for left and right hand comparing easy 50% to high 90% speed to determine whether small detectable force changes could be determined from different speeds of significantly different standards

		Freestyle		Backstroke		Butterfly	
		LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT
Average Force	50% (M, 95%CI) [N]	17.3 (16.1-18.4)	14.7 (13.6-15.9)	11.0 (9.7-12.3)	10.6 (8.9-12.3)	19.8 (17.7-21.9)	13.8 (11.0-16.5)
	90% (M, 95% CI) [N]	22.0 (20.2-23.8)	19.9 (18.0-21.9)	15.2 (12.3-18.2)	13.9 (11.3-16.4)	16.7 (14.6-18.9)	19.0 (15.9-22.0)
	P value	<0.001	<0.001	<0.05	<0.001	<0.05	<0.05
	d	1.41	1.76	1.35	1.67	4.33	2.37
Peak Force	50% (M, 95%CI) [N]	90.2 (84.6-95.7)	88.3 (82.1-94.6)	53.9 (44.9-62.9)	57.4 (48.3-66.5)	67.0 (58.9-75.0)	66.0 (56.2-75.8)
	90% (M, 95% CI) [N]	85.9 (78.5-93.3)	82.0 (74.9-89.1)	52.0 (43.4-60.7)	47.7 (37.1-58.2)	62.7 (57.6-67.9)	65.1 (56.4-73.8)
	P value	0.31	<0.05	0.37	0.13	0.20	0.80
	d	0.25	0.66	0.29	0.53	0.83	0.14
Efficiency	50% (M, 95%CI) [%]	48.2 (46.4-50.2)	44.2 (41.4-47.1)	42.2 (38.9-45.6)	38.9 (35.8-42.0)	42.1 (39.8-44.4)	36.3 (31.7-40.9)
	90% (M, 95% CI) [%]	54.0 (51.3-56.6)	53.0 (50.2-55.9)	48.5 (44.6-52.3)	45.6 (41.6-49.6)	51.2 (49.5-52.8)	48.5 (46.6-50.4)
	P value	<0.001	<0.001	<0.05	<0.001	<0.05	<0.05
	d	0.94	1.93	1.37	1.85	3.69	2.02
Impulse	50% (M, 95%CI) [N•s]	84.8 (76.6-93.0)	79.8 (71.5-88.0)	65.5 (60.1-70.9)	67.3 (60.1-74.6)	73.2 (66.4-79.9)	69.5 (63.0-76.0)
	90% (M, 95% CI) [N•s]	55.2 (49.7-60.8)	51.3 (47.0-55.6)	45.8 (39.1-52.5)	44.7 (39.5-49.8)	46.5 (38.7-54.3)	45.4 (37.8-53.0)
	P value	<0.001	<0.001	<0.001	<0.001	<0.05	<0.05
	d	2.62	1.99	4.12	3.28	5.49	5.71
Hand Velocity	50% (M, 95%CI) [m/s]	1.0 (0.9-1.1)	1.4 (1.3-1.5)	0.9 (0.8-1.1)	0.9 (0.7-1.0)	1.2 (0.7-1.7)	1.5 (0.8-2.0)
	90%(M, 95% CI) [m/s]	1.6 (1.4-1.8)	1.7 (1.5-1.8)	1.2 (1.0-1.3)	1.2 (1.0-1.3)	1.5 (1.0-2.1)	1.5 (0.9-2.0)
	P value	<0.001	<0.001	<0.05	<0.05	0.10	0.78
	d	1.88	1.21	0.92	1.30	1.16	0.17

Note: Significance determiend by p value ($p<0.05$). Trivial-small effect determined if $d<0.6$.

‘Large’ effect sizes were determined for left- and right-hand in average force, efficiency, impulse, and hand velocity for all strokes, and peak force had effect sizes of ‘small’ ($d<0.2$) (**Table 4**).

SECTION 5

DISCUSSION

This thesis aimed to evaluate the efficacy of the Smart Paddle™ to assess kinetic force during free swimming in high-performance swimmers. Intra-day absolute and relative reliability were investigated and the Smart Paddle™ was determined as a reliable tool for kinetic variable analysis for all strokes within this study. Validity of Smart Paddle™ was investigated by the objective comparison between stroke rate values from Smart Paddle™ compared to known stroke rate values by manual testing. Sensitivity of the Smart Paddle™ was also investigated and determined that average force, impulse, and efficiency were sensitive to changes in swimming intensity irrespective of stroke type. However, changes in peak force and hand velocity were stroke dependent.

5.1 Reliability of the Smart Paddle™

The Smart Paddle™ demonstrated ‘strong’ absolute reliability and small, non-significant differences in kinetic variables between trials. These findings are similar to previous investigations investigating the reliability of the Smart Paddle™ within water-based sports (Löppönen et al., 2022; Marinho et al., 2022). This thesis differed from Löppönen as their study investigated kayak as the sport and Marinho investigated only freestyle stroke with 4 high-performance participants, therefore findings from this thesis contribute to the literature by investigating multiple strokes with a larger sample size. This strong intra-day reliability of the Smart Paddle™ suggests that these devices may confidently be used for training analysis within an applied environment.

PS (**see Section 2.3.3**), are reported to be reliable measures of kinetic and kinematic variables in free swimming (Havriluk, 1987; Pereira et al., 2015; Santos et al., 2022a). This is comparable to findings from tethered swimming methods which, up until the development of water-based PS devices, were most widely used for kinetic analysis in free-swim performance for the assessment of average force, peak force (Dopsaj et al., 2004; Joaquim Baratto de Azevedo et al., 2021; Nagle Zera et al., 2021; Psycharakis et al., 2011), and impulse (Amaro et al., 2014; Joaquim Baratto de Azevedo et al., 2021).

Limitations illustrated by previous research examining the efficacy of the Smart Paddle™ include only measuring freestyle with small group samples (Marinho et al., 2022), or examining the device in different water-based sports (Löppönen et al., 2022). This study recruited a reasonable sample of high-performance swimmers due to their ability to maintain swimming pace because of their refined technical ability and training experience. Thus, this sample may have a greater understanding and feel of pace, reflected in the reliability results obtained. This study, unlike other reliability studies (Bartolomeu et al., 2018), explored multiple stroke types to identify whether the Smart Paddle™ was reliable for use in all strokes, given the varied kinetic and kinematic demands elicited by different strokes (Troup, 1999). Despite these differences, this thesis found that the Smart Paddle™ produced reliable data for freestyle, butterfly, and backstroke within testing sessions.

Intra-day reliability and inter-day reliability are both important to determine the practical utility of a device. Ensuring reliable results would allow for the integration of this assessment within training to assess and monitor performance. This thesis chose to investigate intra-day reliability as it is more representative of a swimmer's training schedule as they perform either large, volume driven aerobic sets or perform anaerobic sets with many repetitions of high intensity bouts (Hellard et al., 2017; Nugent et al., 2017). Nevertheless, both of these forms of training are structured to perform repeated bouts of swimming with the purpose of maintaining intensity (Hellard et al., 2017; Nugent et al., 2017). To emulate this structure, this thesis prescribed repeated bouts of similar intensities in an intra-day reliability testing procedure. While the intra-day reliability established within this thesis is useful to determine if results are reliable within a session, future research should seek to establish inter-day reliability of the Smart Paddle™ across varied strokes and intensities.

Previous reliability studies established intensity either by subjective maximum intensity (Bartolomeu et al., 2021; Koga et al., 2022; Santos et al., 2022a; Tsunokawa et al., 2018) or by an arbitrary increasing intensity controlled by the swimmer (Tsunokawa et al., 2019). Both situations are dependent on the condition of the swimmer's physical and mental state during that day as these internal factors could influence swimming intent which could reduce reliability credibility. This study chose to control intensity based off known stroke rate values so to control these variables and minimise effect of human behaviour influencing what maximum intensity could be.

Furthermore, this study investigated reliability at multiple intensities to investigate whether the Smart Paddle™ can be used exhaustively within training. The excellent reliability observed for the Smart Paddle™ across multiple intensities and multiple strokes means that these devices can confidentiality be used for training analysis purposes and has value to coaches and practitioners looking to establish objective kinetic and kinematic data within applied environments.

5.2 Validity of the Smart Paddle™

An acknowledgment for this study's validity investigation is that no face validity test was performed. As of the time of writing this thesis, there is no literature investigating the validity of PS or Smart Paddle™ using face validity, this should be a consideration for future use of Smart Paddle™ and considered when reading this study's findings. Establishing validity of Smart Paddle™ was challenging because there is limited comparable data to PS based on the limited data available and from the data, which is available to compare, the analysis is performed over shorter distances in smaller pools which can impact kinetic output results. Furthermore, the tethered swimming method is not an appropriate comparison to PS based on overestimation of kinetic variable values (Samson et al., 2019; Santos et al., 2023, 2021) due to the method calculating force as a whole-body sum whereas PS determine force limb specific (Barbosa et al., 2020; Santos et al., 2021). In addition, due to the nature of the sport environment, research is limited, and this creates challenges to perform direct face validity tests.

This study investigated objective comparison between Smart Paddle™ and manual stroke rate testing to assess the validity of the Smart Paddle™. In addition, construct validity was determined to observe whether similar kinetic relationships existed in this study compared to other literature. Force could not be compared directly, therefore this study used the linear positive relationship between propulsive force and velocity (Borges dos Santos et al., 2013; Seifert et al., 2010, 2004; Troup, 1999) to evaluate whether there were similar relationships of force production in Smart Paddle™ and stroke specific velocity results in the external literature. Criterion validity tests have been performed with tethered swimming (Nagle Zera et al., 2021) and Smart Paddle™ (Löppönen et al., 2022), with Smart Paddle™ eliciting promising results. This study attempts to create an overview of validity as in depth as possible under the constraints of limited comparable data, incomparable methodologies, and the challenging testing environment.

This study investigated the objective comparison for validity between Smart Paddle™ and manual stroke rate testing to assess validity of Smart Paddle™ and identified that there was no significant difference between the two methods. The validity of Smart Paddle™ ability to accurately determine stroke kinematics has been established by this study, thus contributing to the image of Smart Paddle™ accurate representation of kinetic variable results. An observation that was made for butterfly stroke was the poor correlation of stroke rate at moderate intensity (70%) which can be explained by the prone body position which means at certain speeds the swimmer's legs can sink, unlike freestyle and backstroke that have the body roll element to stay controlled in the water.

This study evaluated discriminative, construct validity by investigating whether there were similar relationships of force production in Smart Paddle™ and stroke specific velocity results in the external literature. Smart Paddle™ for freestyle generated the greatest propulsive force output, followed by butterfly and then backstroke. These are similar findings to that of previous research involving velocity (Bartolomeu et al., 2018; Craig and Pendeegast, 1979), suggesting that Smart Paddle™ could be valid for kinetic analysis based on the comparability of stroke specific kinetic variable findings established in previous literature. Construct validity of the Smart Paddle™ was further investigated by comparing findings of Smart Paddle™ to other pressure sensor brands and kinetic variables measuring methodologies. Smart Paddle™ was deemed as valid for the determination of kinetic variables during free swimming performance in high-performance swimmers, identifying that the devices will produce an accurate representation of force measurements in the free-swim phase of swimming performance. Studies identified as comparable for validity testing were studies that used PS to measure force in maximal intensity swimming (Barbosa et al., 2006; Bartolomeu et al., 2018; Takagi et al., 2023). All studies used wired devices whereas this study used wireless Smart Paddle™. Testing distance ranged from 16m to 25m unlike the 35m free-swimming tested distance in this study, and all studies identified swimming intensity being maximal on an arbitrary scale and a testing sample of national to regional level swimmers. This study's findings of average force production at high intensities (see table 1-3) is lower than the majority of results reported elsewhere for freestyle stroke: 34-35N (Bartolomeu et al., 2018), 31-44N (J. Morais et al., 2019), 35-55N. This study produced lower results compared to all other studies for backstroke: 29-31N (Bartolomeu et al., 2018) and butterfly: 33-35N (Bartolomeu et al., 2018), 33-35N (Pereira et al., 2015). For peak force, this study measured kinetic values that were lower (see table 1-3) compared to the majority of prior studies; freestyle: 102-105N (Bartolomeu et al., 2018), 55-74N (J. Morais et al., 2019). Backstroke 87-89N and butterfly 97-107N (Bartolomeu et al., 2018) displayed lower values in this study compared to prior studies. Hand velocity also reported lower values in this study (see table 1) compared to other PS studies 2.3m/s (Tsunokawa et al., 2018).

The overwhelming evidence of this study's findings being lower than prior studies could be because prior studies measured kinetic variables over a shorter distance (16-25m), and this would generate a higher force output because swimmers would have maintained a higher average force production due to reduced measured swimming time. Interestingly, Barbosa et al. (2020) produced similar average force (20-36N) and peak force (61-84N) results to this study when performing a maximum effort swim in a 25m pool. This raises questions such as whether the quality and competitive ability of swimmers are influential to kinetic force outputs. Further investigations of different sample populations using Smart Paddle™ would further validity discussions. The value of this study testing kinetic variables over a 50m length is that it is more representative of swimming performance as majority of swimming events are competed in 50m pool. Despite kinetic variable results being lower in this study compared to prior research, based on the distance selected for this protocol and the relationships already understood in the literature about force performance over increased distance, the results are justified. In addition, Smart Paddle™ exhibited common kinetic variable relationships to swimming performance such as positive correlations between swimming velocity and average force, efficiency and hand velocity, and negative correlations with peak force (Alcazar et al., 2019) and impulse (Schilling et al., 2008) further highlighting validity by comparison to other research.

This study has identified Smart Paddle™ is valid for kinetic variable analysis of multiple swimming strokes and has justified its validity compared to other findings in literature. It should be considered that this study measured performance over a 50m pool for better performance representation, however other studies measured over shorter distances, therefore consideration of foundational kinetic relationships should be incorporated into the validity results of this study.

5.3 Sensitivity of the Smart Paddle™

Sensitivity of the Smart Paddle™ was determined by examining differences in kinetic variable outcomes between two significantly different working intensities: high (90%) and low (50%). The Smart Paddle™ was found to be sensitive for measuring differences in average force, efficiency, and impulse for all strokes between high (90%) and low (50%) intensity bouts. However, peak force produced ambiguous results for backstroke and butterfly, and hand velocity produced ambiguous results for butterfly. The ability of the Smart Paddle™ to discriminate between different intensities allows for the confident use of these devices for a range of training and testing purposes.

The intensities selected within this thesis, 50% and 90% stroke rates of a second 50m stroke rate of a 100m peak swim performance, were chosen to represent low and high working intensities representative of a swimmer's typical training prescription. In collaboration with coaches of the participant group within this thesis, these intensities represent a form of training usually seen in high-performance swimming, where 50% intensity represents paces of swimming performed in aerobic work and 90% intensity representing the paces of swimming during intensive anaerobic sessions (Hellard et al., 2019; Nugent et al., 2017). Accordingly, the kinetic and kinematic outputs required to produce 50% and 90% intensity bouts should demonstrate observable differences via the Smart Paddle™ technology.

This study analysed kinetic variables over multiple strokes, which is important to determine sensitivity as strokes exhibit different in-water pathways and thus, exhibit different force productions (Troup, 1999). This would also produce differences in kinetic variable measurements that would be significantly different between strokes. For instance, freestyle produced the greatest output for all kinetic variables in this study and similar findings were found in other research where freestyle is identified as being the most energy efficient (Barbosa et al., 2006), with the fastest velocity (Bartolomeu et al., 2018) and greatest in propulsive force production (Takagi et al., 2023; Troup, 1999; Zamparo et al., 2020) of all the strokes. The findings of this study where peak force decreases as swimming intensity increases is as expected and aligns with past findings in accordance to the force-velocity curve (Alcazar et al., 2019). Impulse decreases with increasing velocity is also expected as past research states when velocity increases causing time in exercise to decrease, so shall impulse decrease with decreased performance time (Schilling et al., 2008).

The findings within this thesis suggest that the Smart Paddle™ can distinguish between small, significant differences between kinetic variables average force, efficiency, and impulse for freestyle, backstroke and butterfly between high (90%) and low (50%) intensity bouts. In addition, Smart Paddle™ failed to identify significant differences for peak force between high (90%) and low (50%) intensity bouts in backstroke and butterfly and hand velocity in butterfly. It is important for future practical applications using Smart Paddle™ for assessment of kinetic variables, to consider the unbalanced distribution of swimmers in stroke groups in this study as it could be influential to observing lower sensitivity results for backstroke and butterfly compared to that of freestyle. Overall, Smart Paddle™ can be considered sensitive for all kinetic variable measurements in freestyle, all kinetic variable measurements except peak force in backstroke, and some variable in butterfly.

5.4 Potential applications of the Smart Paddle™ for analysis of swimming performance

The strong intra-day absolute and relative reliability, validity, and sensitivity demonstrated within this thesis endorse the use of the Smart Paddle™ to be utilised within applied swimming settings to assess and monitor performance across various intensities in freestyle, butterfly, and backstroke. Smart Paddle™ can be used as a benchmarking tool for training volume, return to sport rehabilitation and performance development. The Smart Paddle™, as previously mentioned, could be used for training purposes during both technical and capacity focused training sessions at different intensities. The findings of this thesis suggest that Smart Paddle™ can be used to evaluate technical performance via the observation of kinetic outputs. In training, technical adjustments could be made and assessed using the Smart Paddle™ to refine performance. Furthermore, the real-time feedback of the Smart Paddle™ can provide immediate feedback and changes to performance to be performed within session, making it more efficient for both athlete and coach for training developments. For instance, the Smart Paddle™ could be used to evaluate the impact of breathing side or frequency on kinetic output to investigate whether there is any effect on kinetic output when changing breathing rhythm or side. In addition, another training focus utilising the Smart Paddle™ could be to identify optimal hand positions on water entry for propulsive force generation. Research thus far states that hand position and orientation upon water entry influences velocity and propulsive force generation (Schleihauf, 1983; Van Houwelingen et al., 2017). Repeated bouts could be performed with the Smart Paddle™ with slight hand position adjustments to determine which orientation elicits preferred kinetic outcomes. These opportunities afforded by the Smart Paddle™ demonstrate a creative freedom for both coaches and athletes due to the established confident efficacy of Smart Paddle™ in this thesis.

As previously mentioned, the Smart Paddle™ can be used for capacity focused sessions at intensities that target both aerobic and anaerobic energy systems. This highlights a potential use for measuring the impact of fatigue on kinetic variables using the Smart Paddle™. It has been established that there is a relationship between stroke kinematics and propulsive force generation during swimming performance (Mathews 2017). Therefore, the Smart Paddle™ could be used to measure the point whereby force output declines or plateaus during performance. This would be useful to identify from a high-performance perspective as efficiency and the maintenance of propulsive force throughout performance is important for maintaining velocity in a race. Lastly, the ability of the Smart Paddle™ to accurately and reliably differentiate between the upper limbs highlights a potential use for muscle and joint injury rehabilitation. This is particularly of interest as the upper limbs represent a primary area of injury concern amongst performance-level swimmers (Wanivenhaus et al., 2012).

5.5 Limitations and directions for future research

When designing this study, the challenges of establishing the face validity of the Smart Paddle™ were identified due to an inability to implement comparable methods simultaneously. Therefore, it would be useful for future research to establish the face validity of Smart Paddle™ if an appropriate study design can be configured, or construct validity if this study design could be replicated. This thesis also investigated the intra-day reliability of the Smart Paddle™ over various intensities and swimming strokes. However, this thesis did not establish the inter-day reliability of the

Smart Paddle™. This should be a consideration for long-term kinetic variable analysis which would be important to determine whether Smart Paddle™ could be used for monitoring performance progression across a season. Inter-day reliability was not overlooked in this study protocol. However, due to the collaboration with high-performance athletes and coaches during their peak competition season, the assessment of inter-day reliability would have interfered with their training schedule beyond the single testing session required for the present design. A final limitation of this thesis is the unbalanced sample size of participants within each stroke category. The lower sample size for backstroke and butterfly compared to freestyle could have influenced the results obtained in this study.

SECTION 6

CONCLUSION

6.1 Conclusion

The aim of this thesis was to investigate the efficacy of the Smart Paddle™ PS for measuring kinetic force variables in free-swimming performance of high-performance level swimmers. This study concludes that the Smart Paddle™ is valid for the determination of accurate kinetic variables. This was determined by the investigation of construct validity, criterion validity, and objective validity in stroke rate. This study identified and acknowledged the validity challenges and developed an overview image of the validity of Smart Paddle™ to evaluate and support the accuracy of the kinetic results produced from the devices. The findings in this study indicate Smart Paddle™ is reliable, referencing the strong intra-day absolute and relative reliability identified in this study, demonstrating that Smart Paddle™ can be used for kinetic force analysis in free-swimming performance repeatedly for freestyle, backstroke, and butterfly at a range of intensities (low – high). This study identified that Smart Paddle™ can identify confidently small significant differences in all kinetic variables between low and high intensities for freestyle but not as confidentially for peak force and hand velocity in backstroke and butterfly, identifying that Smart Paddle™ is sensitive for all strokes measuring average force, impulse and efficiency.

This thesis has identified that PS may be the preferred choice for in-water force analysis due to its ability to measure force between limbs rather than sum of whole body. There have been mixed findings of the use of wired external devices on PS and whether it causes an impairment to swimming performance (Koga et al., 2022; Santos et al., 2022b; Yeater et al., 1981), coming to the conclusion that wireless devices would be preferred to wired to minimise performance interference. The Smart Paddle™ eliminates the issue of wired connections as all data collection and storage is collected, processed and stored wirelessly, making this ideal analysis protocol compared to other prior methodologies.

Overall, Smart Paddle™ can confidently be used for practical applications in training for kinetic analysis in freestyle, backstroke and butterfly over a range of training intensities, providing coaches and practitioners with creative freedom for kinetic analysis purposes in high-performance swimming analysis using the Smart Paddle™.

SECTION 7
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