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# Tethered Swimming: Historical Notes and Future Prospects

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**Definition:** Swimming coaches know that a swimmer's assessment must be specific and ecological. Thus, it is critical to select and employ adequate methodologies. The tethered swimming method can be useful and valid, in addition to being simple to apply. Regular use of this methodology can give coaches tools to intervene with their swimmers and increase performance. The main objective of this manuscript was to analyze the potential for measuring the propulsive forces exerted in water as a biomechanical tool for evaluating and training competitive swimmers. The key results demonstrated that this methodology allows (i) the assessment of upper limb bilateral kinetic asymmetries; (ii) the evaluation of the contribution of the upper and lower limb actions, inferring about the (un)balance between strength and coordination; (iii) the examination of the relationship between the intracyclic variations in speed and force; (iv) the evaluation of the effective application of force to the speed of high-level swimmers. Furthermore, this manuscript suggests advances using mathematical modeling and artificial intelligence (AI) that will provide significant insights into swimming performances. AI developments will promote its integration into sports optimization, and swimming will be no exception.

**Keywords:** force; performance; assessment; mathematical modeling; artificial intelligence

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## 1. Genesis and History

The term "tethered swimming" (TS) emerged in the 1970s by Magel [1]. Although he was the first to refer to this methodology, his work was based on ideas previously developed by Karpovich [2] and Mosterd [3]. In the 1930s, Karpovich moved forward with the first studies that aimed to analyze the relationship between force and resistance. In 1939, he presented an apparatus that consisted of using a kymograph to graphically represent the propulsive forces performed [4]. Although the intention was to better understand the magnitude of the applied force, the instrumentation used only allowed the estimation of the average forces exerted by a swimmer by inverse dynamics. Twenty years later, Mosterd [3] conducted his doctoral work at the University of Utrecht, arguing that

> "This research was carried out with the intention of contributing to the direct measurement of performance for a more scientific basis of swimming training in general and of the best swimmers in particular. By applying muscle training and interval training, the ability to apply force in swimming can increase considerably (...). It is necessary to first develop a good method for measuring propulsive forces and then determine from the research itself what influences your swimming training."

The used apparatus (a dynamometer) allowed for the recording of the forces exerted, the breathing events, and the beginning of the cycles of action of the upper and lower limbs. This idea served as the basis for Magel [1] to use a planimeter to estimate the propulsive forces in swimming, having used a three-minute test to characterize the production of force in the four swimming techniques. At that time, the curve average height (in millimeters) for each stroke was measured and then converted to average force values.

Knowing the relevance and validity of measurements performed in water, several studies have followed Magel by inferring the link between this test and swimming performances [5,6]. Yet, the technological limitations have inhibited the rapid achievement of results, blocking the determination of other variables and influences in swimming performances, as explained in previous literature reviews [7]. Therefore, the tethered swim was a methodology that was adopted poorly in its first years.

Another methodological issue was the duration of the test. This perception forced researchers to reduce the test time from 3 min to durations closer to those used in competition (e.g., 5, 10, 20, 30, 45, and 60 s). This reduction stimulated several perspectives on the duration of use in the tethered swim. Cortesi et al. [8] analyzed the relationship between performance in events of 50, 100, and 200 m with TS tests of 15, 30, 45, and 60 s, observing a greater relationship between the shorter distances (50 and 100 m) and the 30 s duration. Moreover, 30 s at maximum intensity is like the Wingate test protocol, allowing the acquisition of relevant physiological data for the swimmer's evaluation, namely, the anaerobic mechanisms of energy production [9]. Therefore, to bridge the gap between biomechanical and bioenergetic domains, physiological ecology must be ensured to guarantee results that provide an adequate interpretation.

## 2. Discovery

Regardless of the speed at which the research using TS has advanced, there has always been a concern in understanding the relationship between the force produced and the swimming performance [10]. Currently, there are different methodologies to do this, namely (i) a movement analysis using video [11]; (ii) active drag measurement systems [12]; (iii) pressure gloves [13]; (iv) full or partial TS [14,15]. Tethered swimming has been defined as the ergometer (equipment used in evaluation) most specific for swimming [14,16] since it implies the use of various body structures in a way that is very similar to a competitive reality, apart from some technical changes due to the non-existence of displacement [17]. Although TS has been pointed out as an ergometer suitable for studying swimmers [18], the fact that the swimmer exerts his forces without displacement of his body has questioned its ecology.

The tethered swim allows the evaluation of the force production exerted by the swimmer in a swimming situation, regardless of the technique used [19,20]. Nevertheless, most studies conducted to date have evaluated the front crawl technique, thus leaving a huge gap in the analysis of the other techniques. In one of the pioneering studies, Yeater et al. [6] studied the relationship between the swimming speed and the average maximum peak strength in front crawl, breaststroke, and backstroke, with only a significant relationship being found with the former. Without certainty, we can assume that front crawl had the greatest association, particularly given the fact that it is the most widely used technique, which led to several subsequent studies with this swimming technique [5,16,21].

Yet, at the time, and not being an easy-to-use methodology, different approaches have emerged. For example, Hopper et al. [22] measured the muscle mechanics that were exerted by the swimmer on an external resistance. Drawing a careful parallelism, the authors corroborated the inverse relationship between the developed muscle mechanics and the swimming performance (50 m) for the four swimming techniques. These results were reinforced by the study by D'Acquisto and Costill [23], who found a significant relationship between the muscle mechanics produced and the swimming performance. Examining the association between the produced forces in the tethered stroke and the swimming speed at 50, 100, and 200 m for all swimming techniques [20], the highest

correlation values were obtained for the breaststroke technique, followed by front crawl, butterfly, and backstroke, corroborating Hopper et al. [22]. In addition, the mean strength was the parameter with the greatest association with speed in the front crawl. Moreover, the correlation values decreased as the swimming distance increased, indicating the importance of the force exerted by the swimmer in the water for short-distance competitions regardless of the technique evaluated. Over longer distances, turns and technical improvements are likely to become more relevant.

Looking at the research conducted up to date, there are key considerations to be considered. In TS, heterogeneous samples (e.g., sex, age, and maturation) may raise some doubts about the validity of the results, and it is questionable whether it is appropriate to use heterogeneous samples for swimming studies [24,25]. In fact, cross-cutting considerations are more than relevant to the Sports Sciences, as described in [26]. In addition, the use of the biokinetic bench or cycle ergometer, using only the upper limbs, neglects the function of the lower limbs and the rotation of the body and its importance for body coordination. Moreover, it is not conducted in the swimmer's natural environment, the aquatic environment. Considerations that refer to the added value that the TS entails by focusing on the measurement of the forces exerted, maintaining the ecology of the movement.

## 3. Related Concepts or Principles

Competitive swimming is an inspiring and exciting process [27]: it involves continuous training efforts, a sense of accomplishment, and the relentless pursuit of improvement. Not surprisingly, a vast number of studies have been conducted in this field [28] since swimming is a high-interest sporting event, with records being frequently broken [29]. Research can be conducted in different domains (e.g., biomechanics, physiological, and psychological), but biomechanics and bioenergetics are the most susceptible areas to improve swimming performance [30], named the "biophysics of swimming". In fact, 5.6% of the papers presented at the *International Symposium on Biomechanics and Swimming Medicine* used a biophysical approach [28]. Undoubtedly, the importance, role, and assessment of strength in competitive swimming have long been topics for discussion.

It is undeniable that sports performance in swimming is related and interdependent on the swimmer's ability to invest and use his strength in an effective and efficient way in a fluid environment. This performance improves due to higher specificity and rigor in training processes [31]. Thus, the Sports Sciences can be used as a primary resource and a fundamental tool for the evaluation, prescription, and monitoring of swimmers' training.

TS can be a useful tool for coaches, making it possible to perform biomechanical and bioenergetic assessments with the swimmer replicating, with high proximity and competitive movements [32,33]. This instrumentation allows the measurement of the forces exerted by the swimmer in immersion, using its fixation at a solid point, usually the starting block. That is, by swimming in the same place, it is possible to create force–time curves that can characterize and compare the pattern of force application and its efficiency. According to the duration of the test (and its intensity), it is possible to draw conclusions about the mechanisms of energy production in both anaerobic [34] and aerobic [15] domains.

Based on the initial assumption that propulsion is an important factor influencing sports performance in swimming [35–37] and that the swimmer's goal is to cover a certain distance in the shortest possible time, the performance improvement is dependent on the acceleration that the swimmer can achieve through

$$F = m \cdot a, \tag{1}$$

where $F$ is the force, $m$ is the mass, and $a$ is the acceleration. In swimming, the force is dependent on the propulsive forces and resistance forces as opposed to the swimmer's

displacement (hydrodynamic drag). The mass of water must be added to the swimmer's mass in a fluid medium. This way, we can rewrite Equation (1):

$$a = \frac{P + D}{m_b + m_w}, \quad (2)$$

where $P$ refers to the propulsive forces, $D$ to the hydrodynamic drag forces, $m_b$ to the body mass, and $m_w$ to the mass of water.

It is in this sense that the measurement of propulsive forces can be an appropriate and useful tool for coaches to monitor the training process of their swimmers. Yet, locomotion in the aquatic environment is quite complex and makes it difficult to measure these forces. The tethered swim allows the measurement of the forces that (theoretically) correspond to the propulsive forces that the swimmer will have to produce to overcome the drag forces [6,38]. It is for this reason that the tethered swim has been described as one of the most specific ergometers for swimmers, simulating the characteristics of the surrounding environment (it is performed in an aquatic environment and not in the terrestrial environment) and the mechanics of swimming (with minor changes, according to [14,38]); this methodology is influenced by the anthropometric and physiological aspects of the swimmers, allowing an individual assessment [15].

The tethered swim, as its name implies, involves fixing the swimmer to a fixed point in the pool, as exemplified in Figure 1. Swimmers use a strap to which a high-rigidity steel cable is attached (with an elasticity that can be neglected), and the forces exerted are measured by means of a counterweight [1,22] or a load cell [20,39]. The load cell may be fixed to the ceiling wall of the pool, minimizing interferences with the swimmer technique and being aligned with the horizontal direction [40]. However, it will make the swimmer's feet touch the cable, inducing errors in assessed values. To overcome this last drawback, the load cell may be fixed to the starting block. This connection requires the creation of an angle between the cable and the surface of the water [20] that should be rectified [41,42] since it is aimed at estimating the forces of horizontal component:

$$F_x = cos\alpha \cdot F, \quad (3)$$

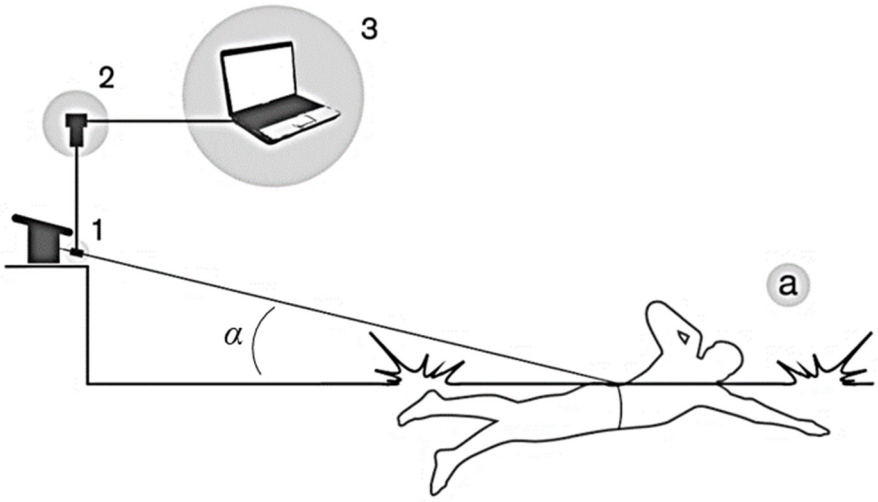



**Figure 1.** Representative design of a possible methodology to be adopted in the tethered swimming test (1—load cell; 2—data acquisition system; 3—personal computer). Republished from Morouço et al. [43], under Creative Commons Attribution License.

$Fx$ is the horizontal component of the measured force, $cos\ \alpha$ is the cosine of the angle between the cable and the water surface, and $F$ is the force exerted by the swimmer.

In our studies, the measuring system used uses a 3.5 m wire rope and a load cell with a sampling frequency of 100 Hz, with a maximum capacity of 500 kgf [33]. The load cell must be connected to a data acquisition system that allows it to be transferred to the computer, where it can be recorded and then analyzed [44].

Before data collection begins, swimmers should adopt the horizontal position with the rope at full length and perform two to three cycles of swimming at low intensity. From this moment on, the test can be started with the duration and intensity that is intended to be evaluated. Data acquisition should begin after the first action of the upper limb, thus avoiding the inertial effect caused by the cable maximum extension [20,45]; this usually occurs before or during the first action of the upper limb (Figure 2).




**Figure 2.** Photographs of assessments where it is possible to visualize the mechanism of attachment of the load cell to the block, the strap, the steel cable, the data acquisition console, and the location of the apparatus.

As exposed, the presented methodology allows the measurement of the forces exerted, and it is possible to represent an individual exerted force curves graph during swimming. Using it increases the likelihood of analyzing and comparing swimming technique profiles, thus permitting more accurate knowledge of the propulsive forces sequence [32]. The data can be exported to a laptop using an ergometer data acquisition system, converting the file to *.txt (Globus, Codognè, Italy). On the computer, they are introduced into the signal processing software (AcqKnowledge v.3.7; Biopac Systems, Santa Barbara, CA, USA) and filtered through an adequate filter. The cut-off value should be chosen according to the residual analysis (residual error vs. cut-off frequency). As previously mentioned, if there is an angle created between the wire rope and the horizontal, the data must be corrected by computing the horizontal component of the force, thus obtaining the individual force–time curves.

From each force–time curve, several parameters can be calculated: maximum force [5,18], mean maximal strength [6,21], medium strength [20,46], minimal force [38], impulse [33,39], and fatigue index [9,47] are the most common in the literature. There does not seem to be unambiguous evidence of which factor is more reliable. Taylor et al. [41] found that only average strength was a reliable parameter for estimating swimming performance, differing from the experiments of Dopsaj et al. [39], who stated that momentum was the most accurate parameter. The use of absolute values is coherent (e.g., [5,14,15]) to the detriment of relative values (normalized to body mass). Since the measurements are made in water, the effect of the thrust force relativizes the effect of body weight for a few kilograms [41,42], impairing the accuracy of the relationship between the variables [6,20].

Using the procedures presented, it is possible to evaluate swimmers in the aquatic environment in a practical way at a low cost and with quick results. Further research

may use a Reynold's number to understand the fluid dynamics involved in swimming, thereby aiding in the development of techniques and equipment that enhance performance by reducing drag and improving efficiency. It has been observed that the tethered stroke can induce some kinematic changes in the movement of the upper limbs compared to the freestyle stroke [17]. Yet, it is not known whether the force application is modified [44]. It can be evaluated by allowing swimmers to use their upper and lower limbs or restricting their use. It can be assessed using flaps and inducing different intensities and durations. It is, therefore, a methodology with a wide range of possibilities.

A major concern should be the fallibility of repeated measurements. Using the same equipment, properly calibrated, and ensuring the same preparatory conditions (e.g., standard heating) is critical. Throughout the hundreds of collections made, it was noticeable (subjectively) that verbal encouragement can and should be used. Using it in a certain collection and not using it in a subsequent one, where it is intended to analyze the evolution over time, can be misleading. Familiarization with the methodology is also crucial. Swimming while tethered is, sensorially, a challenge for some swimmers. Thus, allowing previous experiments with the methodology in the days prior to data collection may avoid the cancellation of tests that did not get the swimmer to commit properly.

## 4. Applications

One of the main concerns, and one of the most compelling, in the control and evaluation of athletes, results from the possibility of extracting key and privileged information (e.g., biomechanics). It allows for the optimization and monetization of the process chain, which involves training prescription and planning. To this end, the combination of several disciplines is assumed as a determining factor in the exact identification of the individual needs of the subject in view of the constraints and contexts in question. The presented methodology is based on the premise that the tethered swim has numerous potentialities in the measurement of the forces exerted by swimmers as an auxiliary indicator in the evaluation, prescription, and monitoring of swimmers' training, considering the biomechanical responses. In addition, it is an easy, operative, and low-cost methodology [7], convincing swimmers to produce more propulsive force to swim at higher speeds [32]. This association makes it possible to compare the swimmer's ability to produce increased muscle strength and technical ability. Nonetheless, the nature (linear or non-linear) and strength (small, moderate, large, or very large) of this correlation are not yet fully understood.

Last-decade advancements in technology have made it possible to recover the foundations of a methodology that remained obsolete, providing new functionalities. Currently, using a load cell to assess a swimmer's exerted forces (maintaining ecology) has become a useful method and auxiliary to the process of evaluation, prescription, and monitoring of training [7] in several variants, both in the aerobic domain [15] or anaerobic domain [9,34]. It is described as one of the most specific and reliable [14,38] ergometry measurements for swimming as it has strong similarities to the front crawl in terms of maximal oxygen uptake [48], muscle electrical activity [49], stroke rate, lactatemia, heart rate, and subjective perception of exertion [33]. Based on the identification of the sequences and their consequences of technically appropriate movements, TS allows obtaining, in a quick way, significant information about the conditions that directly influence and interfere with sports performance.

Swimming is undoubtedly a worldwide phenomenon that has been responsible for some of the greatest achievements in the history of the sport. Record breaks are frequent, indicating better and better levels of sports performance. These improvements are the result of a training process that has evolved, and research supported by Sports Sciences has contributed to this [12]. At the level of elite swimming, every detail is decisive and determines the color of the medals. Therefore, training with elite swimmers requires a process for multiple variables control (e.g., biomechanical, physiological, and psychological) that will manifest themselves, positively or negatively, in the four phases of a swimming event: the start, the swim itself, the turn(s), and the finish. Still, it is interesting to decompose

the performance in these phases, allowing us to identify the most key area of action for each swimmer.

By measuring sports performance parameters separately, it is possible to draw a swimmer profile, targeting an increase in his performance. Still, there are several questions that are posed to the coach, highlighting which, how, when, and how often should sports performance parameters be evaluated? Although the answer to these questions is intricate, it can lead to an increase in the training process efficiency [31,50] and predictions in sports performance [51]. As mentioned above, Barbosa et al. [30] indicated the synergy of bioenergetic and biomechanical fields as a "biophysical intervention" that may bring new conclusions about the training process.

Of the various parameters influencing sports performance in pure sport swimming, the measurement of the forces exerted by the swimmer can be a useful instrument for the identification of the weakest and strongest points of each swimmer [12]. Most studies consider the absolute values of force production [5,14,15]. This assumption is based on the principle that in the aquatic environment, and due to body position, there are other determining factors that produce propulsive force during swimming [32]. In fact, Yeater et al. [6] and Morouço et al. [20] normalized the values of strength by body mass, verifying that the normalization did not reveal a better estimate for sports performance. Thus, the relationship between strength capacity and muscle mass (and consequently, body mass) is affected by the swimmer's ability to apply force in the water (i.e., technical skill).

As previously mentioned, the methodology used allows a constant recording of the force values exerted by the swimmers. The analysis and characterization of the patterns of force production may allow greater precision in understanding the behavior of forces throughout the effort and comparing the different swimming techniques [32]. In a general analysis, we can indicate that the individual force–time curves—$F(t)$—(i) show a decline in all swimming techniques, suggesting the appearance of fatigue [52,53]; (ii) they present periodic peaks that indicate phases of greater and of lesser force production [47,53]; (iii) they show differences between swimming techniques, with simultaneous techniques (breaststroke and butterfly) presenting higher peaks and greater depressions in strength values [20]. TS is a sensitive methodology, with the best-level swimmers presenting higher maximum and average values [20,32,54]. Nonetheless, studies conducted with swimming techniques other than front crawl are scarce and do not allow these conclusions to be extrapolated to other techniques.

These studies show significant differences between the simultaneous and alternate techniques, with the breaststroke and butterfly presenting higher peaks and steeper slopes than the front crawl and backstroke. It corroborates the evidence that the simultaneous action of the upper and lower limbs increases the intracyclic variation in swimming speed [55,56], requiring greater energy expenditure [31,57]. Among the simultaneous techniques, we noticed that the breaststroke is the one that presents the highest peaks of force, which seems to correspond to the powerful movement of the action of the lower limb characteristics of this technique [31,56,58]. Still, it should be noted that it is common in this swimming technique for hip velocity to approach 0 m/s [57]. Contextualizing the tethered stroke, this deceleration in the movement may cause a decrease in the cable tension, which, when returning to maximum tension, may lead to value overestimation. Morouço et al. [20] tested 32 world-class swimmers during 30 s of TS, observing patterns for each swimming technique: breaststroke and butterfly obtained higher and lower force production values than front crawl and backstroke due to the limb's simultaneous actions, consequently leading to a greater intracyclic speed variation [55–57].

In front crawl and backstroke, the propulsive force production by the upper and lower limbs is alternated, i.e., the production of force stays more continuous during the stroke cycle. While one of the upper limbs performs underwater movements (propulsive phase), the other completes a recovery (aerial phase), and vice versa [58]; hence the name continuous techniques. In the tethered swim, this situation is observable by the minimum

values of the $F(t)$ curve not reaching close to the 0 N value and by the lower magnitude of variation in the force–time curve.

TS allows for the assessment of forces that are useful in a swimmer's evaluation and training control, regardless of the stroke. Assuming that more important than increasing a swimmer's strength is measuring his ability to effectively employ muscle force production in the water [18], the relationship between forces per tethered stroke and swim performance may provide the proper instrument for a precise assessment. As mentioned above, most research aiming to link forces with swimming speed has been conducted with the front crawl [5,16,21], leaving a lack of analysis in relation to other swimming techniques. A significant relationship (moderate to very large) between swim speed and tethered swim forces has been stated [5,16,18,21,33]. For instance, Christensen and Smith [5] evaluated 39 competitive swimmers (26 male and 15 female) at a maximum effort of 3 s, reporting a significant relationship ($r$ = 0.69 for males and $r$ = 0.58 for females), suggesting that sprint speed is related to the force a swimmer can generate. This assumption has been supported by subsequent studies (e.g., [20,21,39]), suggesting that swimmers should improve their maximum stroke strength to increase their maximum speed.

However, the above-mentioned investigations have assumed a linear relationship between swimming speeds and exerted forces. Nevertheless, if this association is not linear, variability in swimming speed may not be indicative of variability in force application. Keskinen et al. [18] analyzed the relationship of maximum velocity with maximum force and adjusted them to the second polynomial order ($y = -90 + 97.256x - 21.301x^2$; $r$ = 0.86, $p < 0.001$). This idea is supported by the principles of the force–velocity relationship of skeletal muscles [59], suggesting that, at a remarkably high speed, it is not easy to produce extremely high force values. Although an association is noticeable, the features and intensity of this relationship are uncertain. To help clarify this association, some studies aimed to examine the relationship of different parameters to performance [33]. Bearing in mind that propulsion happens during the propulsive phase of the stroke cycle [60,61], the effect of force regarding time must be reflected as follows:

$$I = \int_{t_1}^{t_2} F \cdot dt, \tag{4}$$

$I$ represent mechanical impulse and $F$ is the force applied from *time* $t_1$ to $t_2$ (beginning and end of the stroke cycle, respectively). Consequently, impulse calculations can be more accurate in interpreting forces in TS [39] since impulse depends on the force's magnitude, duration, and direction. While maximum force is a single point during the stroke cycle, it does not represent full TS potential. Indeed, if lower values of force are obtained over a longer time, a similar or even higher mechanical impulse can be achieved [62]. This idea was proven with the multiple regression model associating the impulse and stroke frequency, explaining 84% of the performance in the 50 m freestyle [33]. Theoretically, during the tethered swim, the impulse and stroke frequency should be able to explain 100% of the effort made against the transducer. If 16% is noticed, it suggests that the variation is due to the active drag that a swimmer must overcome during free swimming.

Another topic of research has been to evaluate the possible association between the forces that swimmers exert in dry conditions (commonly known as gym work) and those that are exerted during swimming in water. In the last three decades, dry force and power measurements have been performed using isokinetic or isometric conditions [63]. These evaluations may provide critical tools to improve training programs, explaining how much of a swimmer's performance depends on these parameters. One founding study demonstrated that upper limb power is strongly correlated with swim speed in the 25 m front crawl ($r$ = 0.90) [64]. The researchers used a biokinetic swim bench to assess 40 swimmers (22 females and 18 males). Afterward, these results were corroborated by experiments in cycle ergometers, namely when Hawley and Williams [65] evaluated the anaerobic power of the upper limbs of 30 swimmers (16 female and 14 male). These authors showed a moderate-to-strong relationship between peak power, average power, and the

fatigue index with the 50 m front crawl swim speed ($r$ = 0.82, 0.83, and 0.41, respectively). Also, the same research group observed that lower limb strength indices did not increase the estimations for performance in the 50 m and that upper limb power is also important in longer races [66]. From this perspective, the tethered swim can, and should, be a resource to infer the possible transfer of dry work to the ability to exert force in the water. Although it goes beyond the domains of this manuscript, we suggest reading the works of Morouço [67], Loturco et al. [68], and Ruiz-Navarro et al. [69] for a better understanding of the theme.

### *4.1. Bilateral Kinetic Asymmetries*

According to Equation (2), swimming speed is influenced by the circumstantial prevalence of propulsive or drag forces [58]. This influence is particularly important in short-distance races, and it is a critical factor in enhancing swimming performance [63]. Assuming that, for front crawl, upper limbs are the main responsible force for propulsion [70], a greater symmetry between the right and left may impact the swimming speed and promote more adequate postures by minimizing resistive drag [71]. Although this framework may seem unquestionable, the evidence for its acceptance is scarce, to say the least. In fact, hip and shoulder rotation tends to be more symmetrical in elite swimmers [72], but asymmetrical patterns have been stated in arm coordination [73] and strength–time profiles [62]. There seems to be, in practice, a leaning for swimmers to use one upper limb mostly for propulsion and the other mostly for support and control [74].

In a pioneering experiment in the 1970s with two male swimmers, asymmetries were found between the TS forces of the left and right strokes [75]. Kinetic asymmetries were later corroborated [44,62,76] and validated with kinematic asymmetries [73,77]. The existence of several experiments that demonstrate the inconsistency with the assertion that more symmetry is better should encourage further studies on the subject. Moreover, studies that analyzed asymmetries over a race or effort are sparse. As TS allows a constant measurement, further insights may be achieved in the coming years. Actually, a comparison of the forces exerted over time is useful to identify improvements that are effectively transformed into performance improvements.

From the various measurements made in the front crawl, it is easy to perceive asymmetries in the maximum force peaks (in most swimmers, they have a symmetry index greater than 10%), differentiating an upper limb used mainly for propulsion and the other mainly for support and body control [74]. These differences are clear in the first strokes, but they begin to attenuate during the test [76], with the dominant limb showing a greater decline in force production.

In TS evaluations, it is possible for the swimmer to perform the test and be faced with the $F(t)$ graph in real time. In this sense, a repeated evaluation throughout the season may allow for greater feedback effectiveness. The discussion with the coaches of the quantified (a)symmetries has had promising results for the improvement of the training process. We believe that the frequent use of this methodology can improve bilateral balance due to its ease of implementation.

Therefore, if most high-level swimmers have asymmetrical patterns, it is vital to wonder if those patterns influence the optimal function or if they are simply within the normal limits of variation.

### *4.2. Coordination and Deficit of Strength*

Another dimension of kinetic asymmetries can be observed in the relative contribution of limbs to a swimmer's propulsion. The importance of the lower limbs remains inconclusive for the various swimming techniques. Although their role has been overlooked and thought of as a minor factor [70,78–80], these results need to be quantified. Previous studies have performed an indirect measurement, i.e., they have calculated the contribution of lower limb action by subtracting the contribution of upper limb action from the value of the complete swim. Nevertheless, the results of Yeater et al. [6] and Swaine et al. [81] demonstrate that, measured in isolation, the sum of the forces of the lower limbs with the

upper limbs exceeds the value of the full swim. Moreover, Ogita et al. [82] also noticed this exceeding in energy consumption. Given that the reasons for this are unclear, researchers should deepen their findings by using variables that may explain the role of the lower and upper limbs in whole-body TS, particularly in alternating techniques.

Using a new ergometer (in a terrestrial environment), Swaine et al. [81] observed contributions to the upper limbs of 62.7 ± 5.1% and to the lower limbs of 37.3 ± 4.1%, contrasting with the assumption of 90% of propulsion obtained by the upper limbs [70,78–80]. As these data needed to be verified in water, Morouço et al. [43] idealized and performed evaluations with restrictions, as shown in Figure 3.

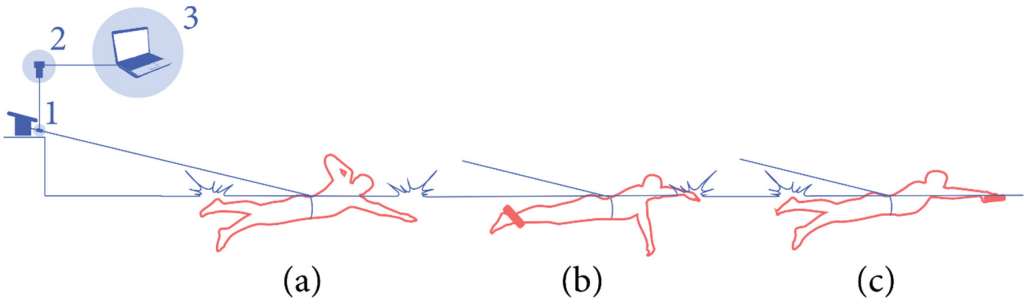



**Figure 3.** Experimental design to measure the forces produced in each test: (**a**) complete swim; (**b**) only with upper limbs; (**c**) only with lower limbs; 1—load cell; 2—data acquisition system; 3—Laptop. Republished from Morouço et al. [43], under Creative Commons Attribution License.

The obtained data showed a relative upper limb contribution of ~78% and ~35% of the lower limbs. These values reinforce the suggestion of Swaine et al. [81] that a greater proportion of the force exerted by swimmers in the water can be attributed to the role played by the action of the lower limbs. In addition, the fact that the sum of the contribution of the action of the upper and lower limbs is greater than the values of the full swim suggests that additional force may be achieved with correct synchronization between the upper and lower limbs [73]. Hence, the development of upper and lower limb strength must be attended to with proper coordination.

To this end, we propose the calculation of an index that could estimate irregular coordination. By calculating the percentage of the deficit between the forces exerted in the complete swim and the sum of the forces exerted with constraints, it is possible to diagnose effectiveness. It permits the assessment of coordination deficiencies or insufficient force indices [43]. These considerations are extremely relevant if used regularly throughout the season. Thus, the coach can perceive different scenarios:

- The swimmer can increase exerted forces when he performs the TS only with the upper limbs, but he is unable to increase it when he performs the full swim;
- The swimmer can increase exerted forces when he performs the TS with only the lower limbs, but he cannot increase it when he performs the full swim;
- The swimmer can increase exerted forces when he performs the full TS, but he cannot increase it when he performs the swim with only the upper or lower limbs.

The presented scenarios, associated with improvements in freestyle performance, may represent crucial diagnoses for improving coordination, arm strokes, or kicks. Knowing where to focus the main training sets is undoubtedly a specific factor for success throughout the planning structures.

### *4.3. Evaluation of Swimming Technique*

Theoretically, intracyclic variations in velocity result from the intracyclic variations in the net horizontal force ($dF$) applied by the swimmer to the water. If changes in the additional mass of the swimmer are neglectable, $dF$ will lead to variations in the acceleration and speed of the swimmers. Although higher intracyclic variations at an average maximum swimming speed led to decreased performance [58], it is still uncertain if and how variations in speed and strength

are related. Furthermore, their importance for reaching remarkably high sustainable speeds has not yet been clarified. This lack of explanation, if explored, could provide an innovative approach to understanding the ability of force application [83–85]. It was promising to show the adequacy of a novel parameter—the intracyclic variation in force:

$$dF = \frac{\sqrt{\frac{\sum_i (F_i - F)^{-2} \cdot f_i}{n}}}{\frac{\sum_i F_i \cdot f_i}{n}} \cdot 100 \quad (5)$$

This new parameter proved to be important for assessing the swimmer's ability to effectively apply force in the water [83–85]. Combining the variation in strength within a cycle with the maximum thrust a swimmer can get can explain high-level performance in short competitive events, such as the 50 m freestyle [83], where mechanical power, technique, and drag determine performance [30]. Intracyclic force and velocity patterns showed enormous similarities, meaning that there should be no relevant drag effect that alters the translation of force into velocity. Such a consideration implies that active drag force may be more associated with swimming speed than with swimming technique, corroborating the concept that passive drag is largely representative of active drag at different speeds [86]. It is, therefore, indisputable that it is more important for swimmers to increase their ability to effectively use muscle strength in the water than to increase their strength [18].

### *4.4. Development and Evolution*

It is undeniable that swimming performance is dependent on the swimmer's ability to apply force (effectively and efficiently) in a fluid environment [58]. It is dependent on the combination of several factors, namely biomechanical, energetic, tactical, and psychological factors [30], and success is highly related to the physical conditions of the swimmers, particularly in terms of muscle strength and power [87]. In addition, biomechanics has shown that training movements should be mechanical, like the ones used for competitions [30]. Thus, it can (and should) be used as a primary resource for the correct evaluation and prescription of swimmers' training.

Considering the multiplicity of competitive events in swimming, the influence of strength is more decisive in short-distance events [20,52]. Using a variety of testing equipment, it has been shown that upper limb musculature and corresponding muscle strength and power are strongly related to swimming speed [43,88,89]. Accordingly, improvements in strength, particularly in the upper limbs, may result in a greater maximum force exerted per swim cycle, aiming at a higher average swim speed [76,90].

Strength, force, and power are common terms in swimming scientific research. According to the objective of each investigation, all these characteristics proved to be determinants for swimming performance, and they can be trained in water. In addition, more important than the improvement of these characteristics is the ability to produce forces in the water, as this is the ultimate goal of increasing swimming speed. Thus, it was expected that the evaluation of propulsive forces in water would be one of the areas of scientific research in swimming. Still, the measurement of these forces in freestyle swimming is questionable, inducing that efforts should be made to improve existing methodologies and, consequently, increase the accuracy of measurements. From this perspective, the tethered swim allows reliable measurement of the forces exerted in the water by swimmers and has been used to ensure freedom of movement, considering the importance of replicating, in the most ecological way possible, the freestyle.

## 5. Future Directions

### *5.1. Mathematical Modeling*

It is evident that mathematics may play a pivotal role in understanding and optimizing various aspects of TS. For biomechanics analysis, mathematical models are used to describe the motion of swimmers during TS. Equations involving position, velocity, and acceleration

help analyze stroke efficiency and body movements. Furthermore, calculations involving Newton's laws of motion aid in understanding the forces applied during TS, determining resistance, drag forces, and the propulsion generated by the swimmer. From a fluid dynamics point of view, mathematical formulas may quantify the drag forces experienced by swimmers in the water, which is crucial for optimizing techniques to minimize resistance. On the training optimization side, mathematical models can help determine optimal training intensities, durations, and volume by analyzing performance data obtained from TS sessions, aiding in the periodization of training plans. This is of the utmost importance for performance predictions, using statistical regression models to predict swimmers' performances based on TS data, considering numerous factors, such as stroke rates, stroke lengths and resistance levels.

A component to which mathematical modeling has had a significant impact in recent years is the estimation of biomechanical dynamics from inertial data. One representative example is the estimation of Euler angles from inertial and magnetic sensor arrays. In the work by Madgwick et al. [91], a novel, computationally efficient algorithm based on gradient descent was proposed. It was designed for wearable human motion tracking based on data acquired using Inertial Measurement Units (IMUs) consisting of tri-axial accelerometers and gyroscopes and magnetic angular rate and gravity (MARG) sensor arrays also including tri-axial magnetometers. Due to the low computational load, the proposed approach can be implemented in resource-limited, low-power hardware and has already shown promising results in the context of stroke analysis during swim training [92].

Further approaches can be proposed, like mathematical relations related to oxygen consumption and energy expenditure, assisting in understanding the metabolic demands of TS and aiding in designing efficient training programs. Or mathematical algorithms helping to design smart TS systems that can dynamically adjust resistance levels based on predefined parameters or real-time data. If so, it will be possible to utilize optimization algorithms to find the most efficient stroke technique by considering multiple variables like stroke length, frequency, and force application. Mathematical modeling techniques, such as regression analysis or machine learning algorithms, may assist in analyzing large datasets obtained from TS testing to derive actionable insights for performance improvements.

There are several studies that, in recent decades, have revealed that in mathematical modeling, the use of fractional calculus (FC) can offer promising advantages over classical whole-order calculus, providing very consistent formulations that will allow the appropriate description of the physical phenomena involved [93,94]. Fractional calculus has been widely used in the mathematical modeling of evolutionary and dynamic systems with memory effects, allowing the incorporation of the variation history of certain variables in each time interval (finite or infinite), and is, therefore, one of the most effective mathematical tools for modeling real problems [95].

Fractional calculus is a recent branch of mathematical analysis that consists of the extension of the integer–order calculus that considers integrals and derivatives of any real or complex order [94,96]. In recent decades, in addition to the theoretical development of this area, there have been numerous studies that show its relevance due to its applicability in various areas, such as physics, mechanics, engineering, biology, or sports [97–99]. An example arises in the work of Couceiro et al. [100], where an approach using FC is presented to improve the accuracy of tracking methods that allow estimating the position of football players based on their trajectory and speed. In this study, the use of FC was compared with other traditional methods, concluding that FC has a classification accuracy for short sampling periods, allowing for an increase in the autonomy of the tracking systems used.

Currently, fixed-order FC is not always the best option when systems are dynamic, so it is beneficial to use non-constant order operators throughout the process, i.e., where the variable order is defined through a time-dependent function [94].

In this sense, to create mathematical models that can help improve the swimmer's performance, some important variables can be considered when using fractional calculus. For instance, force applied during the stroke, i.e., the variation in force throughout the

distinct phases of the stroke, can be analyzed to understand how it affects the efficiency of the movement. Furthermore, joint angular velocity, acceleration and deceleration patterns, and energy efficiency can help researchers understand how biomechanics influence swimming performance, indicating areas for improvement. By incorporating these variables into mathematical models, using FC and other analytical tools, it will be possible to gain a more comprehensive and detailed understanding of stroke movements. This can help identify specific areas that can be improved to increase the swimmer's overall efficiency and performance.

Another relevant dimension in TS is the need to maximize competitive swimming performances. Therefore, the calculus of variations can be a relevant tool to find workable solutions to optimization problems of this type. The calculus of variations focuses on determining minimizers or maximizers of a function that respects certain specific characteristics, and the problem may (or may not) be accompanied by one or more constraints, limiting the space in which the extrema (maxima or minima) of the problem are sought.

Recently, there have been many studies that reveal that the combination of the calculus of variations with the fractional calculus has potential in several areas. This allows finding extrema for functionals when it or the constraint conditions, or both depend on some fractional operator, i.e., integrals and/or derivatives of arbitrary order (not necessarily integer) [94,101]. In the last two decades, there have been numerous studies in areas such as classical and quantum mechanics, physics, and optimal control, which involve fractional calculus of variations, using diverse types of fractional operators, like the Riemann–Liouville, the Weyl, the Caputo, or the Hadamard fractional derivatives, determining necessary and sufficient conditions of optimality. According to the above, the use of non-local fractional operators in variational problems allows for a better adaptation to models that have memory effects.

In summary, the mathematical techniques may serve as the foundation for analyzing biomechanics, understanding fluid dynamics, optimizing training regimens, predicting performance outcomes, developing equipment, and deriving insights from data collected during TS testing. Its applications may further enable a deeper understanding and enhancement of various aspects related to TS for improved performance and training strategies.

### *5.2. Artificial Intelligence*

Complementary to the highlighted mathematical modeling, we do believe that artificial intelligence (AI) will play a key role in the integration of TS. Accordingly, various possibilities arise:

- Exploring AI-Assisted Analysis: investigating how AI technologies can be specifically integrated into TS setups for real-time stroke analysis, performance monitoring, and personalized feedback for swimmers and coaches.
- Personalized Training Plans: studying the development of AI-driven algorithms to create adaptive training plans based on individual swimmers' performance data obtained from TS testing.
- Refining Stroke Technique: further exploring how TS can be utilized to optimize stroke mechanics, body positioning, and efficiency, potentially using AI for more precise biomechanical analysis.
- Understanding Physiological Responses: investigating the physiological adaptations specific to TS training, focusing on endurance, strength development, and metabolic responses.
- AI Models for Performance Prediction: developing AI models that predict swimmers' performance based on TS data, considering stroke efficiency, resistance levels, and other key parameters.
- Enhanced Equipment Integration: researching the development of smart TS systems equipped with AI-driven functionalities to adjust resistance, provide feedback, and optimize training.
- Remote Coaching Platforms: exploring AI-powered platforms for remote coaching, allowing coaches to analyze TS sessions and provide guidance from a distance.

- Utilizing Big Data in Swimming: considering the aggregation and analysis of large datasets from TS testing to derive insights and trends beneficial for training and performance.

A recent example of the advantages of AI in swimming can be found in the work by Félix et al. [92], where the authors used Artificial Neural Networks (ANNs) for knowledge extraction from inertial data acquired in a dynamic setting, while swimmers performed backstroke, butterfly, breaststroke, and front crawl techniques. Based on the Euler angle analysis, novel parameters were extracted, such as body balance, body rotation, and trunk elevation, which provide valuable information for enhancing performance and preventing injuries. Furthermore, it was possible to automatically segment swim laps (with 100% precision) and classify the style; experimental results have shown a 100% precision in the recognition of the backstroke and an 89.60% precision for the three remaining swimming techniques (butterfly, breaststroke, and front crawl).

By delving deeper into these areas, researchers could contribute significantly to the advancement of TS as a training tool and performance evaluation method. Deeper expertise in swimming biomechanics and performance assessments could pave the way for innovative applications of AI technologies in optimizing training, refining techniques, and enhancing overall performance in TS contexts.

## 6. Conclusions and Prospects

Today, a load cell can continuously measure force–time curves and instantly present insightful feedback. Swimmers can quickly get inputs on their upper limb's kinetic asymmetries, the contribution of the different segments to coordination, and the effectiveness of applying force in the water. This work allowed us to recognize and describe the procedures for an adequate biomechanical evaluation. It provides the mandatory processes for training prescription, which should take place instantly after assessment (which should maintain ecology as high as possible).

Evidence found in the literature corroborates and validates the relevance and contribution that this methodology presents in the provision of critical and rapid information for the training prescription of high-level swimmers. In addition, this work also clarifies the importance of the effective application of force in the water for sports performance, reinforcing the advantages of including this approach in the training control and evaluation process.

Future suggestions are also addressed; with the integration of mathematical modeling and AI, significant improvements in training can be made in the coming years.

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