Review Article

Laboratory-based tests for swimmers: methodology, reliability, considerations and relationship with front-crawl performance

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ABSTRACT

Dalamitros, A.A., Manou, V., & Pelarigo, J.G. (2014). Laboratory-based tests for swimmers: methodology, reliability, considerations and relationship with front-crawl performance. *J. Hum. Sport Exerc., 9*(1), pp.172-187. Monitoring training process in swimming is essential for providing valuable information for both coaches and athletes. Among a large variety of laboratory-based tests used for the quantification of swimmers abilities and evaluation of fitness status, the most representative and easy to apply ones are chosen to be presented in this review. Furthermore, these tests reliability, methodology, referred considerations and relationship with front-crawl swimming performance are reported. Based on the previous mentioned criteria, the assessment of aerobic, anaerobic power and muscular strength, are analyzed. From the data examined, it is concluded that despite their reliability and efficacy in determining adaptations after a training period, as well as, detecting differences between athletes' training status, laboratory-based tests assessing aerobic, anaerobic power and muscular strength for swimmers does not meet the criterion of specificity and disregard the crucial role of technique. **Key words**: AEROBIC POWER, ANAEROBIC POWER, MUSCULAR STRENGTH, DRY-LAND TESTING, SWIMMING.

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INTRODUCTION

The assessment of swimmers performance is considered fundamental for the more accurate monitoring of the training process and is useful for talent identification (Smith et al., 2002). For an efficient performance assessment, testing should be held several times during a macrocycle (or a training period). The most common testing periods are at the begging of the preparation period and before the pre-taper phase. However, testing at the beginning and the end of each mesocycle has been also suggested (Gore, 2000).

Over the years, a variety of laboratory-based methods have been developed to assess the physiological parameters that influence front-crawl swimming performance and determine success such as the aerobic and anaerobic power (Gullstrand, 2000) and muscular strength (Zampagni et al., 2008).

Field-based procedures used for the measurement of aerobic power (portable telemetry system with snorkel device) and anaerobic power production (MAD system, fully or partially tethered swimming, underwater video analysis) during swimming (Toussaint et al., 1989; Keskinen & Komi, 1993; Kjendlie & Thorsvald, 2006; Baldari et al., 2013) correspond to the actual activity more closely as compared with laboratory-based tests. However, the cost of the above mentioned procedures is extremely high, as well as, time consuming and require specialized personnel.

It should be taken into consideration that swimming is separated from the other sports mainly because of the body's prone position, the controlled respiration caused by water immersion and the fluctuant environment in which forces are applied (Aspenes & Karlsen, 2012).

The purpose of this article is to provide evidence-based information upon the most commonly physiological laboratory-based tests for the assessment of swimmers' aerobic power, anaerobic power and muscular strength.

The reliability of all the procedures listed below is well documented and they can be applied regardless of age and performance level.

MATERIAL AND METHODS

Procedure

After developing the query, a systematic review of studies designed to correlate measurements conducted in a laboratory environment and performance during front-crawl swimming was carried out from February 2013 to July 2013. The author team searched independently the PubMed, Scopus, SPORTDiscus, Google Scholar and EBSCO host electronic databases. The articles and citations were separated into categories for each one of the parameters analyzed (aerobic power, anaerobic power and muscular strength) and the inclusion to review was decided through discussion. In addition, manual searches were conducted for proceedings from the Biomechanics and Medicine in Swimming series (volume IV, 1983 to volume XI, 2010), the on-line database of the European College of Sport Science (from 1994 to 2013), the website of the Journal of Swimming Research, and finally, relevant books, abstracts and thesis. When an abstracts' information was not sufficient to be taken under consideration, the full text was retrieved.

The identification of relevant work included the basic keyword "swimming", combined with the search items "correlation with performance", "physiological variables", "measurement", "laboratory testing", "dry-land testing”, “aerobic power”, “anaerobic power”, “vertical jumps”, “Wingate anaerobic test”, “muscular strength”, “isokinetic”, “biokinetic swim bench” and “hand grip test”.

The majority of the included studies concerned swimming performance from almost every competitive event, (50 to 800 m) and also swimming distances of 25 y (i.e., 22.9 m), 50 y (i.e., 45.8 m), 100 y (i.e., 91.4 m), 200 y (i.e., 182.9 m) and 400 y (i.e., 365.8 m). Two studies reported data obtained during 3 and 5 consecutive sets of 200 m (Bonen et al., 1980; Keskinen et al., 2007, respectively). One study examined the correlation with performance during a very short distance (14 m) (Guglielmo & Denadai, 2000), one study correlated values with performance during a much longer distance (2000 m) (Strzala et al., 2007), while two used distances not included in the competitive events program (30, 90, 360 and 366 m, respectively) (Reily & Bayley, 1988; Swaine & Reily, 1983).

Studies that correlated assessed values in a laboratory environment and performance during swimming with the individual medley, backstroke, breaststroke and butterfly techniques and in water-polo players were excluded. Only one study used participants from other aquatic sports (triathlonists and fin-swimmers) (Keskinen et al., 2007). Studies not written in English, Portuguese and English, unpublished data and case studies were also excluded. In contrast, studies examined all performance level, from recreational to high level and years of age, from childhood to masters, were included. The searches were not limited by date.

LABORATORY-BASED TESTS ASSESSING AEROBIC POWER

Aerobic power is considered to be a major component determining swimming performance for both endurance and sprint athletes (Olbrecht, 2000). For the oxygen uptake (VO_2) assessment, cycle ergometry, modified arm cycle ergometry (arm-cracking) and simulated swimming with the biokinetic swim bench (BSB) are mostly used (Swaine & Winter, 1999). The latter procedure appears to be preferred, since the activity of the arms involved during this test is more related to the actual swimming movement (Sharp et al., 1982), the shoulder’s adductors contributes to a bigger degree than during arm-cracking and manipulation of power output is allowed (Swaine, 1994). Mean maximal VO_2 values are reported to be higher for cycle ergometry, as larger muscle mass is involved, followed by simulated swimming and arm-cracking (Armstrong & Davies, 1981; Swaine & Winter, 1999).

The stationary gas analysis is proved to be accurate for measurement over a wide range of exercise levels and evaluate parameters like the energetic cost of exercise (Mookerjee et al., 2005), the slow component of VO_2 (Demarie et al., 2001), the VO_2 efficiency (Baba et al., 1996) and the ventilatory threshold (Fukuba et al., 1988).

The large number of protocols for the determination of VO_2peak/max during cycle ergometry includes differences in initial and work stage loadings and length, maximal and sub-maximal exercises, continuous and incremental protocols, as well as, alterations in body’s position or shoulder’s angle during arm cycle ergometry testing. The most common testing characteristics include incremental loadings of 12 to 25 W, two-to-three minutes stages and cycling cadence of 50 to 60 rpm^{-1} for upper and 70 rpm^{-1} for lower body testing (Franklin, 1985; Strzala & Tyka, 2009). Still, specifically for arm-cracking, cycling cadence between 70 to 80 arm rpm^{-1} (Smith et al., 2001) and greater elbow extension of 0^0 and 15^0 during testing (Smith et al., 2004) are recommended to elicit greater VO_2peak/max values. On the other hand, aerobic power assessment during exercise on the BSB comprises stroke frequency usually at 50 strokes per minute (Ogita & Taniguchi, 1995), or according to the strokes recorded during a 400 m swimming test performance (Swaine & Reilly, 1983) and initial intensity at 35 W, increased by 1 W every 6 s (Swaine, 1994).

Correlations of VO_2 peak/max values between simulated swimming, cycle ergometry arms or legs and front-crawl performance are reported in the studies presented in Table 1. These correlations tend to be higher as testing distance increases, consequently because of the enhanced aerobic energy contribution observed during longer distances (Obert et al., 1992). Alternatively, Strzala et al. (2007) found no significant correlation between performance over a 2000 m distance and VO_2max values assessed during arm-cracking and leg cycling in young swimmers.

Several limitations of the aerobic power evaluation during upper-body exercise in dry-land are presented, explaining differences in VO_2peak/max values obtained during swimming and ergometry in dry-land, including the bigger muscle mass involvement during free swimming (for example the torso muscle group) (Ogita & Tanigushi, 1995) and the inactive role of the legs (Swaine & Reily, 1983). Specifically for the BSB, forward movement through water is greater than the backward movement of the arms (Deschodt et al., 1999) and the limited chest expansion, due to the posture adopted, causes limited peak ventilation. Moreover, the breathing pattern used in similarity with the swimming technique leads to reduced ventilation (Swaine & Reily, 1983), providing some further explanations for the lower values presented in the literature. In the case of Ogita & Tanigushi (1995), VO_2max values during testing on the BSB in trained male college swimmers corresponded to 55% of that obtained during front-crawl in a swimming flume. Nevertheless, Gergley et al. (1984) suggest that training on the swimming bench causes local aerobic adaptations that can be transferred in swimming.

The limited number of studies assessing aerobic power in a laboratory environment can be attributed to the specific tests being designed and developed at the beginning of the 2000s. These testing procedures can offer breath by breath analysis while swimming and tend to be more valid after improvements made in reducing gas mixtures, air turbulence and resistance (Baldari et al., 2013; Keskinen at al., 2003; Rodriguez et al., 2008).

Table 1. *Correlation coefficient between laboratory tests assessing VO_2max/VO_2peak and front-crawl swimming performance*

Study	Instrumentation	Participants	Distance	Correlation
Bonen et al. (1980)	Arm-cracking	11 male swimmers (17.8, 12-32yr)	3x200 m	.97
Duche et al. (1993)	Leg cycling	25 swimmers (11.3±1.0yr)	50 m	.37
			400 m	.60
Obert et al. (1992)	Arm-cracking	5 male & 8 female swimmers (15-35yr)	100 m	-.61
			200 m	-.74
			400 m	-.76
Strzala et al. (2007)	Arm-cracking, leg cycling	15 swimmers (16.8±0.77yr) 15 swimmers (14.7±0.49yr)	2000 m	NS
Strazla & Tyka (2009)	Arm-cracking/leg cycling	26 swimmers (16.1±1.09yr)	25 m	.37/.53
			100 m	.47/.53
Swaine (1994)	Biokinetic swim bench	9 male swimmers (19.2, 15-23yr)	400 m	-.02
Swaine & Reily (1983)		5 males & 2 female swimmers (18.2±1.1yr)	366 m	.36

Note. NS=no significant.

LABORATORY-BASED TESTS ASSESSING ANAEROBIC POWER AND MUSCULAR STRENGTH

Anaerobic Power

Vertical Jumps

Vertical jumping as measured by the squat jump (SJ) and the countermovement jump (CMJ) are presented to be the most reliable from all dry-land tests for the estimation of explosive power (Markovic et al., 2004). SJ execution requires from the athlete to maintain a static semi-squatting and upright posture with the knees flexed at 90^0. During CMJ, athletes perform a fast counter-movement from the standing position prior to jumping, either with the arms remaining on the hips throughout the test to eliminate the influence of the arm swing (CMJ), or moving the arms backward –forward and upward (CMJa) (Gerodimos et al., 2008). During vertical jumping tests, height, maximum force and the rate of force development (RFD) are measured, by contact mats or force platforms (Markovic et al., 2004).

Swim trainers and coaches often assume that enhanced muscular power of the swimmers' lower body and improved jumping ability, may improve performance in the phases of fly / reaction time during the start and contact time / push-off / glide phase during the turn, as they are related to the explosive character of these two "non swimming elements" (Papadopoulos et al., 2009). In fact, time during start and turn can significantly influence the overall swimming performance (e.g., 10.5 and 20.5% respectively for the 50 yd distance) (Thayer & Hay, 1984).

In one of the first studies that involved vertical jumping and performance during start, Zatsiorsky et al. (1979) revealed a moderate correlation (r = .68) between the standing vertical jump and the time of flight including the glide and additionally between take-off horizontal velocity and the glide velocity (r = .60) in 60 swimmers of different levels. Similar results were obtained in the study of West et al. (2011) concerning start performance (15 m) and performance during a CMJ, measuring jump height (r = -.69), peak power (r = -.85) and relative power (r = -.66), but not for values of RFD (r = -.56) in 11 international sprint swimmers. De la Fuente et al. (2002), compared vertical peak forces exerted during a CMJ and the horizontal peak forces during the start, presenting not significant correlation for both male and female Physical Education students.

In a recent study, Sioutas et al. (2010) attempted to correlate performance during a simulated SJ test (the hands in a position similar to the block start), with the velocity values of the body just before entering the water in a sample of 43 young sprint swimmers of both genders. Results showed poor correlation (r = .29) between performance in vertical jump and the body's velocity during the phase of fly after the start. Moreover, performance during 25 and 50 m sprint performance was not associated with vertical jump height in 28 young competitive swimmers (r = .15 and .20 respectively) (Garrido et al., 2010). In addition, low to moderate correlations (r = .28 to .41) between leg power measurements produced by three different type of jumps (SJ, CMJ, CMJa) and initial velocity after the turn (velocity during the first 2 to 4 m) in 67 male swimmers are presented in the study of Croninn et al. (2007). The authors concluded that other parameters, such as reduced drag caused by an optimal streamline position, can affect swimming velocity during the glide phase and that the lack of correlation can be attributed to differences between the motor tasks of the two components that determine horizontal and vertical jumps. The results of these studies suggest that the usefulness of vertical jump testing is restricted to measuring performance on land and that other parameters, like the water phase (i.e., the glide), are more important for successful performance during the start. Also, improved performance of vertical jumping cannot be transferred directly to this task, regardless the technique used.

Alternatively, Keskinen et al. (2007), reported moderate correlation (r = .55) between vertical jumping height as measured by a CMJ and velocity during 5 sets of 200 m in both short (25 m) and long (50 m) pool swims in 11 swimmers of 3 different aquatic sports. Different results are presented in the study of Strzala & Tyka (2009) in 26 young swimmers. The authors observed high correlation between front-crawl velocity during 100 and 25 m distances and anaerobic power as exerted by a CMJ (r =.75 and .76 respectively). According to these studies, variables measured during the CMJ test are maybe useful parameters accounting for swimming velocity.

The dearth of homogeneity regarding to the training level and age of participants in the afore-mentioned studies, may partially explain the variation in data presented. This problem can be further compounded by the fact that the number of participants can influence the results and not all studies provide the necessary participants number in order to achieve acceptable statistical power.

Wingate Anaerobic Test

Numerous studies suggested that the estimation of peak power output enables accurate prediction of maximum speed during swimming, especially in short distances, since, as velocities become higher, necessity for greater power output is increased (Stager & Tanner, 2005). In front-crawl, about 90% of the total propulsive force is generated by the arm stroke, while the role of the legs is restricted to maintain the body in a proper posture in the water by reducing the trunk inclination (Hawley et al., 1992; Deschodt et al., 1999; Gourgoulis et al., 2013).

The Wingate anaerobic test (WAnT) is a classic laboratory tool and the most commonly used for the evaluation of anaerobic performance. The test determines values of peak and mean power with high reliability (Bar-Or, 1987). The typical protocol for implementing the WAnT includes maximal effort on a mechanically or electrically braked cycle ergometer for 30s. Resistance set varies from 0.029 to 0.065g·kg^{-1} of body mass for arm testing and from 0.050 to 0.075g·kg^{-1} for lower body testing, depending on subjects sex and age and is applied within the first 4 s. Peak and mean power values are determined from the 1, 3 or 5 s averages of power.

Correlation of upper body power values as measured by the WAnT and swimming performance, is presented in several studies. Specifically, performance during various distances (25 to 400 m) of front-crawl swimming, revealed a relationship with peak power (r = .82 to .86) and mean power values (r = -.68 to .92), while in other studies these type of correlations were of no significance for the same distances (Table 2). Studies examining the correlation of lower body power production with swimming performance have not draw the same attention. In the study of Hawley et al. (1992), performance of 50 m sprinting in male and female swimmers exhibited a significant correlation with mean power values of the legs (r = .76), while dissimilar results were demonstrated for female adolescent swimmers during a 30 m performance testing (r = .59 and .54 for peak and mean power, respectively) (Reily & Beyley, 1988).

Generally, peak and mean power values generated during the WAnT demonstrate decreasing correlations, as swimming distance increases and speed decreases. Still, the WAnT disregards the importance of body roll and coordination of upper and lower parts of the body.

Muscular Strength

Isokinetic Tests

When referring to isokinetic evaluation for swimmers, much interest is focused on abduction, adduction, internal and external rotation of the shoulder joint, as these movements seem to be more related to the biomechanics of swimming (Jobe & Pink, 1996). Specifically, swimming movement patterns mostly involve the adduction and internal rotation of the shoulder joint mainly used during the pull through phase, while the abduction and external rotation movement is essential for the recovery phase (Jobe & Pink, 1996; Alves et al., 2005). In addition, the extension of the knee joint has been investigated, due to the involvement of the specific muscular group in the flutter kick (Hawley et al., 1992).

The tests' objective is to provide information not only about the isolated muscles' peak torque, power and endurance values, but also informing about muscular asymmetry. The latter can be useful for preventing injuries such as the "swimmers shoulder" which consists the most common musculoskeletal problem in competitive swimming (Beach et al., 1992), with injury rates of 40 to 80% (Johnson et al., 1987), or the knee pain (Secchi et al., 2011). The quantification of these parameters is conducted via dynamometers during concentric testing with constant joint angular velocity and range of motion and the athlete placed in a supine or a sitting position. Angular velocities usually varying between 30 and 450 degrees per second (or 0.52 and 7.85 rad · sec^{-1}), depending on the joint (knee/shoulder) and variable measured (peak torque / power / endurance). Similarly, repetitions executed can also vary from 2 to 20. The elbow and the shoulder joint remains flexed at 90^0 to 120^0 throughout the tests (Miyashita & Kanehisa, 1979; Swanik et al., 2002). The range of motion limits for internal rotation is usually set at 40^0, for external rotation at 50^0 (Rupp et al., 1995), for shoulder horizontal adduction at 45^0, for abduction 90^0 (Perrin, 1993) and for the knee joint at 90^0 (Magnusson et al., 1995). The proposed agonist - antagonist strength ratio depends on the velocity and the position of the joint during testing (Aagaard et al., 1998).

The assumption that greater isokinetic peak torque values would conclude to greater propulsive force and, as a consequence, to greater velocity values, seems not to be accepted (Miyashita & Kanehisa, 1983; Reilly et al., 1990), due to the lack of specific reproducing of the swimming movements (Cardone et al., 1999) and the fact that the arm-pull phase during swimming is not an isokinetically action with constant velocity (Swaine & Reilly, 1983). Differences in peak torque values of upper extremities of elite compared with non-elite group of swimmers have been observed (Cardone et al., 1999). On the other hand, no differences in peak torque values were observed between asymmetric (freestyle, backstroke) and symmetric (butterfly, breastroke) swimming styles and between the right and the left side in young (Cardone et al., 1999; Mc Master et al., 1992; Secchi et al., 2009) and master swimmers (Magnusson et al., 1995; West et al., 2005). However, propulsive forces generated during swimming vary between the left and right arm-stroke, as they are influenced by factors, like the breathing side preference. According to Maglischo (2003), the more propulsive arm is usually the one on the breathing side.

The reliability of isokinetic dynamometers in measuring peak torque is presented to be high for muscle groups like the quadriceps. However, when the objective is to measure strength asymmetries, the intra-class correlation coefficients reliability appears to be low to moderate (Impellizzeri et al., 2008).

Apart from strength asymmetries indication, the relation with performance has not been studied extensively. Higher strength values of the internal rotator have been related with lengthened catch and pull phase (Tourney-Chollet et al., 2009) and performance during 10^0 m in boys ($r = .72$) and girls ($r = .51$) (Miyashita & Kanehisa, 1979). In the same study, peak torque values of the knee extension were negatively correlated ($r = -.58$) in boys, but not in girls. No significant correlations were obtained between values of maximal isokinetic strength (60^0), power (180^0) and endurance (300^0) of the shoulder joint with performance during a maximal swim test. The authors of the latter study conclude that maximal velocity during swimming is a combination of arm stroke and leg kicking and this kind of velocity cannot be generated by isokinetic devices (Reily et al., 1990). Based on these conclusions, Mookerjee et al. (1995) used two different velocities, (360^0 and 450^0) on knee joint exercise to reproduce the highest possible velocity generated during flutter kicking speed, as well as a lower one (180^0), to allow comparisons between female collegiate swimmers. The authors suggested a correlation between swimming performance in 25 and 50 y distance (r = .82 and .72 respectively) and also the presence of a plateau in peak torque between middle and high test velocities (360^0 and 450^0), recommending that testing velocity during isokinetic evaluation of the lower extremities should be above 330^0.

Biokinetic Swim bench test

The biokinetic swim bench test (BSB) is considered to be the most widely used swimming test in dry-land, with high reliability values (r = .93) (Sharp et al., 1982; Sharp, 1986) and provides the highest stimulus for arm stroke (Ogita & Taniguchi, 1995). It is executed with the swimmer in a prone position and the hands placed in paddles attached to pull ropes. During execution, the swimmer pulls quickly backwards through a complete range of motion with his arms moving in parallel or with an alternate pulling. For a better simulation of the front-crawl, athletes are instructed to duplicate the recovery phase of the arms. Velocity during the test ranges approximately between 0.50 and 3.70 m s^{-1}.

Correlations between peak torque, as measured by the BSB with short (25 y to 100 m) and middle distances (200 y to 500 y), as well as the endurance work output with the 100 m front crawl performance, were rather high, especially for males (r = .74 to .90) (Table 2). Contrary, Costill et al. (1986) presents a correlation of .24 for 25 m sprint performance, attributing this low relationship to the heterogeneous sample of swimmers tested and, more specifically, regarding the wide range of age, sprint velocities and strength applied in the previous studies. BSB has also been used for the bilateral comparison of the power output of injured and non-injured arms of swimmers. In general, maximum power generated by the arms measured on a BSB and its relationship with swimming performance is reduced when increasing distance (Reily & Bayley, 1988; Sharp, 1986).

It should be noted that the inadequacy of controlling the elbow position, observed during testing with the BSB, can lead to inaccurate findings and prescriptions for strength training, especially in high lever sprinters (Strass et al., 1990). Similarly with the isokinetic dynamometer, biokinetic swim bench does not replicate fully the swimming motion, and the contribution of legs is exceptionally measured with the addendum of leg-kicking ergometers (Swaine, 2000). Electromyographic and kinematic analyses have revealed differences between the arms movements during swimming and testing on the BSB (Olbrecht & Clarys, 1983). In addition, when the power production exceeds the level of ~500 W, the correlation between power measured by the BSB and swimming performance follows a non-linear relationship, indicating that other factors related to propulsion and active drag reduction effect sprint performance (Sharp, 1986). However, the limited contribution of lower extremities to swimming speed, especially during long swimming distances, indicate that arms-only measurement can accurate assess swimmers' anaerobic power (Hollander et al., 1988).

Isometric Hand Grip Test

The isometric hand grip consists a strength parameter that has been used for testing several swimming populations, from childhood (talent identification), to master swimmers (highlight differences among them). The tests' reliability is presented high for the measurement of hands' strength (Mathiowetz et al., 1985). Hand grip strength seems to reflect the overall body strength (Foo, 2007) and has been positively correlated with parameters like the muscle and body mass (Hewitt, 1997). The test is usually conducted with mechanical or digital hand dynamometers on the dominant side, with a fully extended elbow and no other body movement, while the produced maximal isometric strength is maintained at least for 3 to 5 s (Douda et al., 2010).

According to Geladas et al. (2005), grip strength consist a significant predictor of 100 m front-crawl performance in male and female young competitive swimmers. However, most of the studies examining the relationship between hand grip strength and front-crawl performance for distances from 25 to 800 m showed negative poor to moderate correlations, especially in the longer distances (r = -.18 to -.73) (Table 2).

As a remark for studies regarding children and adolescents which simply correlate strength with performance, Sharp (1986) supports that they do not take into account physical maturity and therefore this relationship can be coincidental, suggesting the determination of the nature of this relationship. Moreover, for high-level athletes enhanced muscular power performance does not correspond to faster sprint velocities.

Table 2. *Correlation coefficient between laboratory tests assessing muscular power, strength and front-crawl swimming performance.*

Study	Instrumentation	Participants	Distance	Correlation
Blanksby et al. (1986)	Hand grip	82 swimmers (9-13yr)	100 m	-.36
Costil et al. (1986)	Biok. swim bench	46 male & 30 female collegiate swimmers (17-22yr)	25 y	.24
Douda et al. (2010)	Hand grip	30 pre-pubertal (10.5±0.5yr) &	50 m	-.60
		42 pubertal (13.7±1.5yr) male & female swimmers		
Duche et al. (1993)	WAnT (legs)	25 male swimmers (11.3±1.0yr)	50 m	.57/.35(PP/MP)
			400 m	.51/.15(PP/MP)
Garrido et al. (2010)	CMJ	16 boys & 12 girls (12.0±0.6yr)	25 m	-.15
			50 m	-.20
Garrido et al. (2012)	Hand grip*	Females	100 m	
		10 juvenile (12.5±0.5yr)		.82
		14 junior (14.6±0.5yr)		.62
		15 senior (18.6±2.3yr)		.54
			200 m	.65
				.21
				.59
		Males	100 m	
		11 juvenile (15.0±0.5yr)		.63
		10 junior (16.4±0.5yr)		.49
				.31
			200 m	-.01
				-.18
				.26
Guglielmo & Denadai (2000)	WAnT (arms)	9 male swimmers (18.1±2.2yr)	14 m	.40(PP)/.64/(MP)
			25 m	.28(PP).39/(MP)

			50 m	.03(PP)/.09/(MP)
			400 m	-.52(PP) -.37/(MP)
Geladas et al. (2005)	Hand grip	178 boys (12.8±0.1yr) 85 girls (12.7±0.1yr)	100 m	-.73 -.18
Hawley &Williams (1991)	WAnT (arms)	14 male & 16 female swimmers	50 m	.82 (PP)
				.83 (MP)
Hawley et al. (1992)	WAnT (legs)	12 male (13.6±1.2yr) & 10 female swimmers (13.2±1.9yr)	50 m	.76 (MP)
	WAnT (arms)			.63(MP)
Inbar & Bar-Or (1977)		9 young swimmers (8-12yr)	25 m	-.92(MP)
Johnson et al. (1993)	Biok. swim bench	20 collegiate & 9 high school swimmers (18±2yr)	25 y	.74
Keskinen et al. (2007)	CMJ	11 male: 3 swimmers, 6 triathlonists & 2 fin-swimmers (24.7±5.0yr)	5x200 m	.55
Miyashita & Kenehisa (1979)	Isokinetic (arms)†	35 boys/girls (11-21yr)	100 m	.73/.52
	Isokinetic (knee)			-.58/NS
Mookerjee et al. (1995)		20 female collegiate swimmers (19.8±1.1yr)	25 y	.82
			50 y	.70
Morouco et al. (2011)	CMJ	10 male international swimmers (14.9±0.7yr)	50 m	.04 (height)
				.33 (work)
Reily & Bayley (1988)	WAnT (legs)	12 female swimmers (13-16yr)	30 m	.59(PP)/.54(MP)
			90 m	NS
			360 m	NS
	WAnT (arms)		30 m	.86(PP)/.83(MP)
			90 m	.57(PP)/.63(MP)
			360 m	NS
	Biok. swim bench‡§		30 m	.92(PP)/.93(MP)
			90 m	.89(PP/MP)
			360 m	.73(PP/MP)
Saavedra et al. (2010)	Hand grip	66 male swimmers (13.6±0.6yr)/ 67 female swimmers (11.5±0.6yr)	3 PBE	.51/.54
Sharp et al. (1982)	Biok. swim bench	18 male (15.8±0.4yr) 22 female (14.7±0.3yr) competitive swimmers	25 y	.90
			100 y	.86
			200 y	.85
			500 y	.76
Strazla & Tyka (2009)	CMJ	26 swimmers (16.1±1.1yr)	25 m	.76
			100 m	.75
Strohm (1990)	WAnT (arms)	9 male & 6 female well-trained swimmers		.82(PP)
				.77(MP)
	Biok. swim bench			.90

Rohrs & Stager (1991)	WAnT (arms)	39 male competitive swimmers (15.9±1.0yr)	25 y	.50(PP)/.41(MP)
			50 y	.53(PP)/.47(MP)
			100 y	.41(PP)/.44(MP)
Rohrs et al. (1990)		13 male (20.1±1.0yr)/	25 y	.64/.09 (PP)
		19 female (19.4±1.1yr) swimmers		.49/.37 (MP)
			50 y	.53/-.14 (PP)
				.45/.30(MP)
			100 y	.54/.04 (PP)
				.32/.43(MP)
	Vertical jump		25 y	.59/.07
			50 y	.66/-.13
			100 y	.62/.12
	Biok. swim bench‡		25 y	.86/.31
			50 y	.89/.30
			100 y	.88/.42
	Biok. swim bench||		25 y	.74/.33(R)
				.66/-.03(L)
			50 y	.61/.30(R)
				.61/-.15(L)
			100 y	.47/.32(R)
				.49/-.07(R)
Zampagni et al. (2008)	Hand grip	261 master (40-80yr) male & female swimmers	50 m	-.72
			100 m	-.57
			200 m	-.58
			400 m	-.57
			800 m	-.39

Note. WAnT = Wingate anaerobic test; CMJ = counter movement jump; PP = peak power; MP = mean power; 3 PBE=3 personal best events; NS=no significant.

* = dominant hand

† = internal rotation

‡ = modified WAnT

§ = most significant from three different speeds setting

||= single pull

CONCLUSIONS

Testing swimmers in a laboratory environment is a reliable and non-invasive procedure. The tests, previously analyzed, can be conducted in most of exercise testing laboratories and can be used to evaluate training-induced changes in competitive swimmers, provide valuable feedback for swimmers and coaches and determine weaknesses that could lead to potential injuries, until the field-baed testing procedures become more accessible.

The lack of specificity with the swimming movement observed during laboratory testing consist a crucial drawback and furthermore, technique, along with the spatial-temporal parameters and other kinematic and kinetic variables, are consider to be the most important factors determining success in competitive swimming and these cannot be measured by dry-land tests.

Finally, the variety of different execution protocols and the lack in standardization of methods used can modify the results between different laboratories, concluding in making the comparison difficult.

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Furthermore, methodological frameworks are presented to perform a comprehensive HRA, including shut-down conditions, to study reliability of decision making, and to study the effects of wrong human actions.Â Paper [VI] presents a detailed methodological framework for performing such an HRA, together with an application. Swimming performance All the swimmers performed two maximal freestyle trials in both 25 m and 50 m, with a 15 min active recovery period between the two trials. The tests took place with two days interval, starting with the 25 m test and were always preceded by the same warm-up routine. The data collection was conducted in a 25 m indoor swimming pool.Â Laboratory-based tests for swimmers: methodology, reliability, considerations and relationship with front-crawl performance. By Athanasios Dalamitros. The Relationship Between Front Crawl Swimming Performance And Swimming Technique In Young Swimmers. By Aldo Costa. Issues of research reliability and validity need to be addressed in methodology chapter in a concise manner. Reliability refers to the extent to which...Â Reliability refers to the extent to which the same answers can be obtained using the same instruments more than one time. In simple terms, if your research is associated with high levels of reliability, then other researchers need to be able to generate the same results, using the same research methods under similar conditions. It is noted that â€œreliability problems crop up in many forms. Reliability is a concern every time a single observer is the source of data, because we have no certain guard against the impact of that observerâ€™s subjectivityâ€ (Babbie, 2010, p.158).