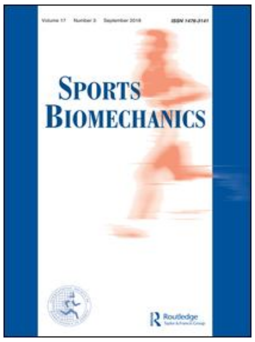

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The transfer of dry-land strength & power into thrust in competitive swimming

Julian Q.J. Tan [a,b], Marcus J.C. Lee [c], Desmond Boey [c], Danny Lum [a,c] and Tiago M. Barbosa [a,d,e]

[a]Physical Education and Sport Science Academic Group, National Institute of Education, Nanyang Technological University, Singapore, Singapore; [b]Temasek Polytechnic, Singapore, Singapore; [c]Sport Science and Sport Medicine, Singapore Sport Institute, Singapore, Singapore; [d]Department of Sport Sciences, Polytechnic Institute of Bragança, Bragança, Portugal; [e]Research Centre in Sports, Health and Human Development, Vila Real, Portugal

ABSTRACT

The aim was to compare the transfer of dry-land strength and power (S&P) of the shoulder into thrust in front-crawl between swimmers of different competitive levels. Four elite and six sub-elite swimmers were selected to perform a dry-land or an in-water test in random order. The dry-land S&P measurements comprised mean torque, peak torque and mean power of the shoulder rotators of the dominant and non-dominant upper-limbs that were assessed on an isokinetic dynamometer at 90°/s and 180°/s. In-water mean thrust, peak thrust and peak power were collected using an in-house customised system composed of differential pressure sensors and an underwater camera during a 25 m freestyle swim at three different paces (400 m pace, 200 m pace, all-out). There were non-significant and trivial variations in dry-land S&P between elite and sub-elite swimmers. The variations were non-significant but mostly large in the case of thrust. Correlation coefficients of elite swimmers were significantly larger than sub-elite counterparts. In conclusion, elite swimmers seem to be more efficient than sub-elite swimmers at transferring dry-land S&P into thrust.

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Torque; propulsion; performance; technique; front-crawl

Introduction

It is a mainstream procedure for swimmers to undergo strength and conditioning programmes. Swimmers undergo dry-land strength and conditioning training on a weekly daily basis to improve their fitness and performance and, prevent musculoskeletal injuries (Crowe et al., 1999; Zatsiorsky & Kraemer, 2006).

Upper-body strength has been shown to correlate significantly with swimming velocity (Aspenes et al., 2009; Costill et al., 1986; Sharp, 1982; Tanaka & Swensen, 1998; Toussaint & Vervoorn, 1990). However, trivial-moderate relationship between dry-land strength and in-water performance were reported elsewhere too (Crowe et al., 1999; Garrido et al., 2012; Johnson, 1993). Two main explanations can be put forward: (1) most studies assessed the maximal load and all-out trials, with the latter more related to power (González-Badillo &

CONTACT Julian Q.J. Tan tanq0038@e.ntu.edu.sg

Sánchez-Medina, 2010; Tanaka & Swensen, 1998); (2) dry-land strength does not relate directly to performance (Barbosa et al., 2010).

Dry-land strength & power (S&P) seems to be on one end of the deterministic model in swimming, whereas performance is on the opposite end. In between, there are several variables (e.g., biomechanics) serving as mediators of the strength-performance relationship. A 20% to 40% improvement in strength after a training programme has been reported to result in 4.4% to 2.1% improvements in swim times (Strass, 1988). But has also been reported to yield no improvements in swim times (Young, 2006). It is evident that not all improvements in S&P translates to performance enhancement. Maybe an increase in the ratio of transfer between dry-land and in-water S&P can lead to an enhanced swimming performance. However, there is scarce evidence on the transfer of dry-land S&P into in-water thrust.

The tests selected to monitor dry-land and in-water S&P could affect whether transference is observed. Dry-land S&P tests should, as much as possible, mimic the limbs′ actions during swimming (i.e. main joints and muscles activate when swimming) (Swaine, 1997). Arm-pull is the main source of thrust in swimming (Barbosa et al., 2010). The shoulder joint, its internal and external rotators play a key-role in the arm-pull (Batalha et al., 2013). Movements during tests such as the squat jump, bench press, may not be representative of the limb's actions during swimming. Another example of this mismatch is the handgrip test that is used in several talent identification and development programmes in swimming (Geladas, 2005; Silva et al., 2007). The handgrip test does not biomechanically mimic swimming, and thus was reported to only have a trivial-moderate correlation with swimming times (Garrido et al., 2012). Some researchers propose that dry-land tests run on isokinetic devices (such as, swim bench or isokinetic dynamometer) yield S&P measurements that have a stronger correlation with swimming performance (Sharp, 1982; Swaine, 1997).

Most researchers have used tethered swimming tests to assess in-water S&P (Cuenca-Fernández et al., 2020; Dominguez-Castells et al., 2012; González Ravé et al., 2018; Magel, 1970; Morouço et al., 2011). The swimmer is tethered by a cable or string on the starting block and a strain gauge is used to measure the force produced. Tethered swimming tests have a couple of limitations (Maglischo et al., 1984 ; Psycharakis, 2011): (1) the fluid flow around a stationary body is different to what happens in free swimming; and therefore (2) the kinematics of the swim stroke changes. Assessing in-water thrust during free swimming trials instead of tethered swimming could be beneficial. Altogether, it is unclear on the transfer of dry-land S&P into in-water thrust and how this relationship could be differentiated between swimmers across different expertise levels. Being able to maximise the efficiency of this transfer can provide an advantage to swimmers. As such, it is expected that swimmers of better competitive level will be able to display a larger association between dry-land and in-water S&P. However, there is no evidence on this yet. Dry-land and in-water testing should be ecologically valid, resembling as much as possible swimming actions and eliciting the same main joints and muscles as swimming.

The main aim was to analyse the transfer of dry-land S&P of the shoulder into in-water thrust in front-crawl between swimmers of different competitive levels using testing protocols that mimic the biomechanical demands of swimming. Dry-land S&P of the shoulder was assessed isokinetically, while in-water S&P was assessed during free-swimming. It was hypothesised that swimmers of higher competitive levels would be more efficient in transferring dry-land S&P to in-water thrust than their lower-level counterparts.

Methods

Experimental approach to the problem

This study adopted a randomised crossover and cohort research design. Participants attended two separate testing sessions. Participants of different competitive levels (elite vs. sub-elite) were randomly selected to undergo first either under dry-land or in-water testing. Each testing session included trials at different speeds. Analyses of variance in dry-land strength and in-water thrust between competitive levels and speed were carried out. Associations between dry-land strength and in-water thrust were also computed.

Participants

Four elite (two males and two females, 21.3 ± 4.0 years, 1.76 ± 0.06 m tall, 70.41 ± 9.0 kg of body mass, 12.3 ± 4.2 years of training and competition experience) and six sub-elite swimmers (five males and one female, 21.8 ± 3.2 years, 1.74 ± 0.07 m tall, 71.1 ± 8.5 kg of body weight, 6.7 ± 7.0 years of training and competition experience) were recruited to take part in this research. Elite swimmers are defined as those who have competed at international events, whereas sub-elite at national level.

The study was approved by the Institutional Review Boards of Nanyang Technological University and Singapore Sport Institute. Participants, and whenever needed parents or legal guardians, provided written consent.

Procedures

Dry-land testing

Shoulder internal rotators and shoulder external rotators strength of the dominant and non-dominant upper limbs were tested (f = 100 Hz) on an isokinetic dynamometer (Biodex System Pro 3; Biodex Corp., Shirley, NY, USA).

Participants underwent a 15-min dynamic stretching protocol of their choice, followed-up by a familiarisation set (one set of three repetitions at both 90°/s and 180°/s angular velocities each). Subsequently, data were collected from two sets of three repetitions at both angular velocities with 2-min of rest between sets (ICC = 0.98 ± 0.02) (Batalha et al., 2013). Each subject was positioned on the equipment so that the shoulder axis was aligned with the axis of the dynamometer. The arms were in the scapular plane at 90 degrees of abduction, 90 degrees of elbow flexion, and the range of motion of 0 to 90 degrees as reported elsewhere (Batalha et al., 2013). At the start of each test, the subject was advised to relax the shoulder so that passive determinations of the effects of gravity on the limb could be determined and used as a correction factor for the final results. Testing protocol was afterwards repeated for the opposite shoulder. Data extracted were: (1) mean torque, (2) peak torque and (3) mean power. These data were expressed from the average values of two sets of three repetitions of shoulder internal and external rotations at both 90°/s and 180°/s angular velocities each.

In-water testing

Thrust was collected by an in-house customised system composed of differential pressure sensors and underwater camera. Sensors were placed between 3rd and 4th proximal phalanges of each hand (f = 50 Hz). The underwater camera was set on the headwall of the pool streaming images of the swimmer in the transverse plane (f = 50 Hz).

Swimmers were required to perform a 15-min general warm-up that included dynamic stretches, typical race-day routine, followed-up by familiarisation with the equipment. Then, data were collected at three different speeds (400 m race pace, 200 m race pace, all-out) with a 5-min rest interval between each bout (ICC = 0.90 ± 0.06) (Johnson, 1993). Data were exported to a signal processing software (AcqKnowledge v3.9.1, Biopac Systems, Santa Barbara, CA, USA), where it was smoothed using a low-pass filter at 6 Hz after residual analysis. The dependent variables were: (1) mean thrust; (2) peak thrust; and (3) peak power. These data were expressed from the average values of five left and right strokes each, at slow, moderate and all-out pace.

Statistical analyses

Normality of data was assessed by Kolmogorov-Smirnov and Shapiro-Wilk tests ($P > 0.05$). Data is reported as mean±SE and 95% of confidence interval (95 CI). Mixed ANOVA (Competitive Level x Speed) was used to analyse the variations in both dry-land and in-water variables ($P < 0.05$). Whenever needed, this was followed-up by Bonferroni as post-hoc test. Interaction and main effect size was computed by eta-squared (η2) and deemed as without effect if 0< η2 ≤ 0.04, minimum if 0.04< η2 ≤ 0.25, moderate if 0.25< η2 ≤ 0.64, and strong if η2 > 0.64 (Ferguson, 2009).

Pearson product-moment correlation coefficient was computed to assess associations between dry-land and in-water variables ($P < 0.05$). Correlation effect sizes were deemed as null if 0<|r|<0.1, small 0.1<|r|<0.3, moderate 0.3<|r|<0.5, and strong |r|>0.5 (Cohen, 1988).

Comparison of Pearson product-moment correlation coefficient between elite and sub-elite swimmers (18 pairs of correlations: 3 swim speeds × 2 dry-land speeds × 3 pairs of dry-land and in-water outcomes) was done running independent student's T-test ($P < 0.05$). Cohen´s d was selected as standardised effect size of mean differences and deemed as trivial when |d|<0.2, medium 0.2<|d|≤0.5, and strong |d|>0.5 large (Cohen, 1988).

Results

Dry-land testing

Non-significant interaction between Competitive Level × Isokinetic Speed were found for peak torque ($P = 0.007$, η2 = 0.35), mean torque ($P = 0.089$, $\eta^2 = 0.01$) and mean power ($P = 0.053$, $\eta^2 = 0.05$) (Table 1). However, significant and strong main effects of the speed were noted in peak torque ($P < 0.001$, $\eta^2 = 0.79$), mean torque ($P = 0.005$, $\eta^2 = 0.79$) and mean power ($P = 0.001$, $\eta^2 = 0.70$). Peak and mean torques were larger at slower speeds, and mean power was larger at faster speeds. Non-significant and minimum main effects were noted in these three variables between elite and sub-elite participants (0.23 < P < 0.49; 0.06< η2 < 0.17). Altogether, there were trivial differences in dry-land S&P between competitive levels.

Table 1. Analysis of variance of the dry-land variables.

Variable		Condition	Mean diff.	SE	95 CI-LB	95 CI-UB	P	η^2 or d
Peak Torque [Nm]	Interaction	E × 90°/s	41.47	5.45	28.91	54.03	0.007	0.35
		E × 180°/s	35.18	6.06	21.21	49.15		
		SE × 90°/s	33.00	4.45	22.74	43.25		
		SE × 180°/s	30.15	4.95	18.74	41.56		
	Main Effect	E vs. SE	6.75	7.39	−10.29	23.79	0.039	0.09
		90°/s vs. 180°/s	4.57	0.83	2.66	6.48	<0.001	0.79
Mean Torque [Nm]	Interaction	E × 90°/s	35.98	4.64	25.29	46.68	0.089	0.01
		E × 180°/s	32.18	4.08	22.77	41.60		
		SE × 90°/s	28.73	3.79	19.99	37.46		
		SE × 180°/s	25.38	3.33	17.70	33.07		
	Main Effect	E vs. SE	7.03	5.43	−5.5	19.55	0.023	0.17
		90°/s vs. 180°/s	3.57	1.53	0.05	7.09	0.005	0.79
Mean Power [W]	Interaction	E × 90°/s	42.90	5.36	30.54	55.27	0.053	0.05
		E × 180°/s	53.31	9.40	31.64	74.98		
		SE × 90°/s	34.11	4.38	24.01	44.21		
		SE × 180°/s	48.25	7.67	30.56	65.95		
	Main Effect	E vs. SE	6.93	9.45	−14.87	28.72	0.049	0.06
		90°/s vs. 180°/s	−12.28	2.87	−18.9	−5.66	0.001	0.70

E—elite swimmers
SE—sub-elite swimmers
η^2—standardised effect sizes of interactions & main effects
d—standardised effect sizes of simple effects

In-water testing

Non-significant interaction Competitive Level × Swim Speed were found in peak thrust (P = 0.065, η^2 = 0.05), mean thrust (P = 0.030, η2 = 0.14) and mean power (P = 0.083, η^2 = 0.01) (Table 2). Significant and strong main effects of the speed were noted in peak thrust ($P < 0.001$, $\eta^2 = 0.65$), mean thrust ($P < 0.001$, $\eta^2 = 0.84$) and mean power ($P < 0.001$, η^2 = 0.85). Follow-up post-hoc tests (i.e. simple effects) yielded significant differences between all pairwise conditions, except the peak thrust comparing moderate pace against all-out trial. Mean thrust, peak thrust and mean power increased with speed. There was a non-significant ($0.06 < P < 0.24$) and minimum-moderate main effect of the competitive level ($0.17 < \eta^2 < 0.37$). The η^2 interval for in-water testing was larger than for dry-land testing. Referring to 95 CI of the differences between elite and sub-elite swimmers, the lower-boundary of the 95 CI was very close to zero. This suggests that there was a substantial difference in the in-water thrust between both groups.

Table 2. Analysis of variance of the in-water variables.

Variables	Comparison	Condition	Mean diff.	SE	95 CI-LB	95 CI-UB	*P*	η^2 or d
Peak Thrust [N]	Interaction	E × Slow	65.21	5.13	53.38	77.04	0.065	0.05
		E × Mod	73.70	4.35	63.67	83.73		
		E × All-out	75.94	4.24	66.16	85.72		
		SE × Slow	53.92	4.19	44.26	63.58		
		SE × Mod	59.69	3.55	51.51	67.88		
		SE × All-out	65.81	3.46	57.82	73.80		
	Main effect	E vs. SE	11.81	5.41	−0.66	24.28	0.006	0.37
		Swim Speeds					<0.001	0.65
	Simple effect (speed)	Slow vs. Mod	−7.13	1.92	−12.91	−1.35	0.002	0.62
		Mod vs. All-out	−4.18	1.56	−8.88	0.52	0.008	0.44
		Slow vs. All-out	−11.31	2.67	−19.36	−3.26	0.001	1.09

(*Continued*)

Table 2. (Continued).

Variables	Comparison	Condition	Mean diff.	SE	95 CI-LB	95 CI-UB	P	η^2 or d
	Interaction	E × Slow	18.77	1.31	15.75	21.79	0.030	0.14
		E × Mod	22.14	1.81	17.96	26.33		
		E × All-out	31.76	2.85	25.18	38.35		
		SE × Slow	17.15	1.07	14.69	19.62		
		SE × Mod	19.96	1.48	16.54	23.37		
		SE × All-out	26.45	2.33	21.08	31.82		
Mean Thrust [N]	Main effect	E vs. SE	3.04	2.28	−2.22	8.30	0.022	0.18
		Swim Speeds					<0.001	0.84
	Simple effect (speed)	Slow vs. Mod	−3.09	0.55	−4.75	−1.43	0.001	0.97
		Mod vs. All-out	−8.06	1.39	−12.25	−3.86	0.001	1.56
		Slow vs. All-out	−11.15	1.58	−15.91	−6.38	<0.001	2.32
	Interaction	E × Slow	25.96	2.07	21.17	30.74	0.083	0.01
		E × Mod	33.47	3.36	25.72	41.22		
		E × All-out	54.47	6.53	39.40	69.53		
		SE × Slow	20.94	1.69	17.03	24.84		
		SE × Mod	28.17	2.74	21.84	34.49		
		SE × All-out	47.42	5.33	35.12	59.72		
Mean Power [W]	Main effect	E vs. SE	5.79	4.55	−4.70	16.28	0.024	0.17
		Swim Speeds					<0.001	0.85
	Simple effect (speed)	Slow vs. Mod	−7.372	1.287	−11.254	−3.489	<0.001	1.24
		Mod vs. All-out	−20.126	3.147	−29.618	−10.635	<0.001	1.93
		Slow vs. All-out	−27.498	3.841	−39.083	−15.913	<0.001	2.82

E—elite swimmers
SE—sub-elite swimmers
η^2—standardised effect sizes of interactions & main effects
d—standardised effect sizes of simple effects

Associations between dry-land and in-water testing

There were positive correlations between all dry-land and in-water variables (Table 3). Majority of the associations were moderate-strong (i.e. $|r|>0.3$). The largest correlation was in the elite group between mean thrust during all-out swim and mean torque at 180°/s (R = 0.95, $P = 0.003$). Elite swimmers showed larger coefficients than sub-elite counterparts in 16 out of 18 correlations. The pool of correlation coefficients of elite swimmers was significantly larger than sub-elite counterparts (sub-elite: R = 0.42 ± 0.13, elite: R = 0.67 ± 0.18, $P < 0.001$, d = 1.59). Hence, elite swimmers were more efficient transferring dry-land S&P into in-water thrust than sub-elite swimmers.

Discussion and implications

The aim was to compare the transfer of the dry-land strength and power (S&P) of the shoulder into thrust in front-crawl between elite and sub-elite swimmers. There were non-significant and trivial variations in dry-land S&P between elite and sub-elite swimmers. Conversely, the variations were non-significant but large in the case of the thrust. Correlation coefficients of elite swimmers were significantly larger than their sub-elite counterparts, suggesting that elite swimmers might be better than sub-elite in transferring dry-land S&P into thrust.

Non-significant interaction Competitive Level × Isokinetic Speed were found in the three dry-land parameters selected. However, significant, and strong main effects of the speed were noted ($0.001 < P < 0.05$, $0.70 < \eta^2 < 0.79$). Dry-land peak and

Table 3. Correlation between dry-land and in-water variables.

		Peak Torque-Peak Thrust				Mean Torque-Mean Thrust				Mean Power-Mean Power			
		Sub-Elite		Elite		Sub-Elite		Elite		Sub-Elite		Elite	
Swim Pace		90°/s	180°/s	90°/s	180°/s	90°/s	180°/s	90°/s	180°/s	90°/s	180°/s	90°/s	180°/s
Slow	R	0.370	0.410	0.490	0.650	0.210	0.170	0.630	0.190	0.360	0.420	0.650	0.700
	P	0.023	0.021	0.025	0.018	0.034	0.038	0.019	0.040	0.024	0.020	0.018	0.015
Moderate	R	0.540	0.570	0.520	0.540	0.450	0.350	0.870	0.500	0.670	0.650	0.860	0.850
	P	0.014	0.012	0.024	0.023	0.019	0.025	0.007	0.025	0.007	0.008	0.007	0.008
All-out	R	0.350	0.420	0.630	0.560	0.330	0.350	0.800	0.950	0.420	0.430	0.860	0.720
	P	0.025	0.020	0.018	0.022	0.026	0.025	0.010	0.003	0.020	0.020	0.007	0.014

R—correlation coefficient
P—*p*-value

mean torques were larger at slower speed, and mean power was larger at faster speed. Peak torque at 180°/s is within the values reported elsewhere (Batalha et al., 2013). The torque also decreased at faster speeds in that same study (Batalha et al., 2013). Results are also in tandem with the typical force-speed relationship reported for the musculoskeletal system. As concentric speed increases, the torque produced decreases. As the relative filament speed increases (i.e., as muscle velocity becomes faster), less cross-bridges have time to attach and to generate tension, and thus force decreases (Fenwick et al., 2017). On the other hand, the increase in the mean power is strongly related to increase in speed, as expected. Elite swimmers exhibited superior lower-limb S&P for the swimming turn compared to younger and less experienced swimmers (Jones et al., 2018). A cluster analysis of young swimmers over a full season noted that the cluster of best performers (talented swimmers) was always characterised by parameters related to dry-land S&P, but not in the cluster of mid-tier swimmers (proficient swimmers) and low-tier counterparts (non-proficient swimmers) (Morais et al., 2016a). Strong correlations (R = 0.93) have been reported between upper body muscular strength and swimming performance (Smith, 2002). As far as competitive level main effect is concerned, non-significant and minimum variations were noted ($0.23 < P < 0.49$; $0.06 < \eta 2 < 0.17$). Therefore, dry-land S&P seems to be less sensitive to discriminate swimming expertise. In summary, our results suggest that there were trivial differences in dry-land S&P between elite and sub-elite swimmers.

Non-significant interaction for Competitive Level × Swim Speed were found in all in-water variables ($0.30 < P < 0.83$; $0.01 < \eta^2 < 0.14$). Significant and strong main effects of the speed were noted in these variables ($P < 0.001$, $0.65 < \eta^2 < 0.85$). Mean thrust, peak thrust and mean power increased with swim pace. To swim faster, the magnitude of the thrust must overcome the intensity of the drag force. Even though both drag and thrust increase with speed, thrust must be higher than drag to displace faster and to prevent negative acceleration. There would be an increase in thrust with increasing swim speed as reported previously in empirical (Berger et al., 1995) and computational fluid dynamics studies (Rouboa et al., 2006). Although the effect of competitive level was non-significant ($0.06 < P < 0.24$), there was a minimum-moderate main effect. Interestingly, the η2 interval for in-water testing was larger than for dry-land testing (in-water: $0.17 < \eta^2 < 0.37$ vs dry-land: $0.06 < \eta 2 < 0.17$). The lower-boundary of the 95 CI of mean thrust, peak thrust and mean power were very close to zero and the upper boundary positive, indicating that elite swimmers were always prone to produce more thrust than sub-elite counterparts. However, in the case of the dry-land variables, the middle of the confidence interval is around zero. This indicates that there is no clear trend for elite or sub-elite swimmers to produce more dry-land S&P. 1991 World and 1992 Olympic champion swimmers produced great thrust, power and efficiency as compared to remaining swimmers (Cappaert et al., 1995). Altogether, effect sizes and confidence intervals suggest some difference exists in the in-water thrust between elite and sub-elite swimmers.

All dry-land and in-water correlations were positive, pointing out that increases in dry-land S&P were met with an increase in thrust produced in-water. Most associations were moderate or strong and, pooling 18 pairs of correlation, the coefficients of elite swimmers were significantly larger than sub-elite counterparts. 44% of the variance in thrust produced by elite swimmers can be explained by dry-land scores. Average sub-elite correlation coefficients were R = 0.42 ± 0.13 (i.e. R^2 = 0.18 ± 0.02) whereas, elite R = 0.67 ± 0.18 (i.e. R^2 = 0.44 ± 0.03). Based on the coefficients of determination obtained, elite swimmers transferred 45–50% of the dry-land S&P into thrust. However, this transfer by sub-elite swimmers is at a lower percentage of 15–20%. This seems to suggest that the transfer of dry-land S&P into in-water thrust is higher in elite than sub-elite swimmers. We are unaware of a similar analysis in aquatic and water sports (swimming, canoeing, rowing, etc.). Isokinetic forearm flexion and extension at 180°/s were retained as two of the main predictors of propulsion of male swimmers aged 12.4 ± 2.7 years old (Cochrane et al., 2015). As this is the first attempt to relate dry-land S&P to in-water thrust in adult swimmers, we could not find data in the literature to benchmark our findings. Nevertheless, the overall swim efficiency (defined as the ratio between total external mechanical work and total energy expenditure) of national level Dutch swimmers has been reported as being by 50–60% (Toussaint et al., 1988). This amount is reasonably similar to the coefficient of determination between dry-land and in-water parameters of the elite swimmers recruited.

Elite and sub-elite swimmers displayed the same dry-land scores. However, variations in the production of in-water thrust were large and had minimal overlap of the 95% confidence intervals (i.e., the main difference between competitive groups was not in the dry-land testing but in the in-water assessment). Despite having the same amount of dry-land S&P, sub-elite swimmers are unable to produce as much in-water thrust as their elite counterparts. This suggests that sub-elite swimmers might have a lower propelling efficiency. Propelling efficiency is a ratio between mechanical power needed to overcome drag and external mechanical power. External mechanical power accounts the aforementioned power to overcome drag and the power to transfer kinetic energy to water. World and Olympic champions (Cappaert et al., 1996) and Olympic medallists (Huang et al., 2010) were reported as having larger propelling efficiency than other contenders. Hence, one can speculate that elite swimmers are able to transfer more kinetic energy to the water than sub-elite swimmers. This is supported by the larger correlation between dry-land and in-water strength measurements for the elite swimmers. Structural equation modelling studies on 12-year-old swimmers reported that dry-land S&P were important in the generation of power to overcome drag, swim speed, propelling efficiency and performance in the 100 m freestyle event (Morais et al., 2016b). As such, needing to enhance thrust in sub-elite swimmers, coaches are advised to do a preliminary assessment if the optimal solution is to undergo a dry-land S&P programme and/or an in-water programme to enhance swimming technique.

Main limitations of this study include: (1) thrust was only assessed in front-crawl, therefore, the current findings cannot be generalised for other swim strokes; (2) isokinetic swim bench is a feasible option to provide dry-land S&P of multi-joint actions; (3) in-water system selected is only able to record the thrust produced by the hand, not being able to measure the thrust by forearm and upper-arm; (4) future studies might consider to synchronise IMUs and differential pressure sensors to compute the effective propulsive force (i.e. propulsion in the direction of the body´s displacement).; (5) future research projects can also furnish insights on the degree of transfer of thrust by various muscle groups and/or joints.

In conclusions, there were trivial variations in dry-land S&P between elite and sub-elite swimmers; albeit, the thrust variations were large with minimal overlap of the 95% confidence intervals. Correlation coefficients of elite swimmers were significantly larger than sub-elite counterparts. Thus, elite swimmers seem to be more efficient than sub-elite at transferring dry-land S&P into thrust.

Having said so, as a practical application, swimmers are advised to undergo S&C programmes and should not overlook the importance of improving their swim technique to enhance the efficiency of the transfer of dry-land strength and power into useful thrust, which may contribute to fine advantageous margins in the pool.

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ORCID

Julian Q.J. Tan http://orcid.org/0000-0002-9985-7770
Danny Lum http://orcid.org/0000-0002-8908-3791
Tiago M. Barbosa http://orcid.org/0000-0001-7071-2116

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