Journal of Advanced Research 21 (2020) 65–70

Contents lists available at ScienceDirect

Journal of Advanced Research

journal homepage: www.elsevier.com/locate/jare

Human thrust in aquatic environment: The effect of post-activation potentiation on flutter kick

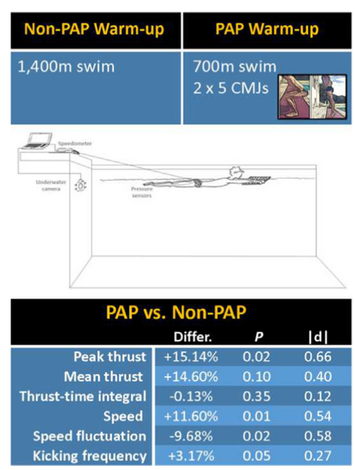
Felicia Ng [a], Jia Wen Yam [a], Danny Lum [a,b], Tiago M. Barbosa [a,c,d,*]

[a] Physical Education and Sport Science Academic Group, National Institute of Education, Nanyang Technological University, Singapore 637616, Singapore
[b] Singapore Sports Institute, Sport Science and Medicine Centre, Singapore 397630, Singapore
[c] Department of Sports Sciences, Polytechnic Institute of Bragança, Bragança 5300-252, Portugal
[d] Research Center in Sport, Health and Human Development, CIDESD, Vila Real 5001-801, Portugal

HIGHLIGHTS

- This is the first experimental study on the thrust of flutter kick by humans.
- The thrust by humans is lower than what is reported in aquatic animals.
- The study reports the relationship between post-activation potentiation and kicking performance.
- Post-activation potentiation increases thrust, which is going to enhance the kicking kinematics.
- Kicking kinematics will thereby improve performance.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 June 2019
Revised 23 September 2019
Accepted 1 October 2019
Available online 4 October 2019

Keywords:
Human locomotion
Swimming
Post-activation potentiation
Kinetics
Kinematics
Propulsion

ABSTRACT

Herein, we analyse by experimental techniques the human kicking thrust and measure the effect of a warm-up routine that includes post-activation potentiation (PAP) sets on front-crawl flutter kick thrust, kinematics, and performance. Sixteen male competitive swimmers with 22.13 ± 3.84 years of age were randomly assigned in a crossover manner to undergo a standard warm-up (non-PAP; control condition) and a warm-up that included PAP sets (PAP; experimental condition) consisting in 2 × 5 repetitions of unloaded countermovement jump. Participants performed a 25 m all-out trial in front-crawl with only flutter kicks eight min after each warm-up. Kinetics (i.e., peak thrust, mean thrust, and thrust-time integral) and kinematics (i.e., speed, speed fluctuation and kicking frequency) were experimentally collected by an in-house customized system composed of differential pressure sensors, speedo-meter, and underwater camera. Peak thrust ($P = 0.02$, $d = 0.66$) and mean thrust ($P = 0.10$, $d = 0.40$) were increased by 15% in PAP compared to non-PAP. Large and significant differences were noted in speed ($P = 0.01$, d = 0.54) and speed fluctuation ($P = 0.02$, d = 0.58), which improved by 10% in PAP compared with non-PAP. In conclusion, a warm-up that includes PAP sets improves kicking thrust, kinematics and performance.

Peer review under responsibility of Cairo University.

* Corresponding author.
E-mail address: tiago.barbosa@nie.edu.sg (T.M. Barbosa).

https://doi.org/10.1016/j.jare.2019.10.001
2090-1232/

Introduction

Human beings encounter numerous challenges to move in water as compared to aquatic animals. Swim acceleration is the net resultant of drag and propulsive forces acting on a body. Several aquatic specimens, such as dolphins, are fully adapted to maximize propulsion and minimize drag [1]. Since a long time ago, substantial research using different experimental techniques, simulations, and modelling procedures have been conducted on the thrust of aquatic specimens [2–7]. In comparison with the body of evidence on aquatic animals thrust, the knowledge on human thrust in water is very limited. Human locomotion in water depends on the amount of propulsion produced by both upper- and lower-limbs while performing arm-pulls and kicks simultaneously. Noteworthy, human kicking resemble to the tail movements of cetaceans [8,9].

Human kicking contributes to approximately 10–15% of overall speed during full swimming (i.e., arm-pulls and kicks simultaneously) [10,11]. Previous research has focused on the thrust produced by upper-limbs during each arm-pull due to its larger contribution to overall swim speed [12]. Recently, there has been an increasing interest to understand the role of human kicking. However, the majority of research studies investigated the physiological responses [13,14], kinematics and nonlinear behaviour [12] of flutter kick, with few studies on human flutter kick thrust. Most studies selected computational simulations [15] and analytical modelling [16]. A couple of reports conducted experimental tests but in tethered flutter kicking [17] and a case study of stationary flutter kicking against a wall [18]. However until this date, there is no evidence on flutter kick thrust using experimental methods in a more ecologic valid setting (i.e., unrestricted swimming with swimmers displacing in water). Therefore, remains in question if the results from aforementioned studies using simulations, modelling, and preliminary experiments would be representative to those conducted using experimental methods in a more ecological valid setting. Reliable data on human flutter kick thrust can provide deeper insights into flutter kick mechanisms, which in turn can have a significant impact on the performance of competitive swimmers.

Post-activation potentiation (PAP) refers to the increase in muscle isometric twitch and low frequency tetanic after a conditioning activity [19,20]. To induce PAP, athletes perform a high intensity resistance exercise that causes muscle contractions prior to a main bout of exercise (e.g. a race) [21]. Once the muscles have experienced a maximal contraction, potentiation occurs and would enhance athletes' muscle performance [22]. Fatigue and potentiation are muscles' mechanic responses after contraction, and PAP is the prevalence of potentiation over fatigue [23]. Recently, there has been a growing interest in determining if incorporating PAP conditioning exercises into athletes' warm-up will be beneficial in improving their performance.

Previous studies demonstrated that PAP could improve plyometric jumping performance [24–26], sprinting [27,28], throws, other upper-body ballistic skills [26], and sport-specific skills [29]; one of which was swimming. In competitive swimming, PAP may help to enhance sprinting performance [29–31]. Plenty of researches have been conducted on the effects of warm-up in swimming [32,33]. It is possible to include PAP sets in the warm-up routines of swimmers. However, the mechanism by which PAP enables swimmers to deliver better performances is unclear. As far as kicking is concerned, an enhancement in the magnitude of the thrust produced may exist, which may have an effect on kicking kinematics and therefore in performance. However, there is no evidence on this in the literature. Thence, the aim of this study was to analyse by experimental techniques the human kicking thrust and measure the effect of a warm-up routine that includes PAP sets on front-crawl flutter kick thrust, kinematics and performance. It was hypothesised that following PAP sets the kicking thrust and kinematics would improve and, therefore a performance enhancement should be expected.

Subject and methods

Design

A randomised crossover research design was selected to compare the differences between a standard warm-up without a PAP set (non-PAP; control condition) and another with PAP sets (PAP; experimental condition). All participants were required to attend three sessions (one familiarisation and two testing sessions). During the first session, participants were familiarised with the testing procedures. The first testing session took place 48 h after familiarization and second testing session one week after the first testing session. For each testing session, participants randomly performed one of the two warm-ups (non-PAP or PAP) followed-up by a 25 m all-out bout in front-crawl flutter kick with a push-off start from the headwall. Latency period between end of warm-up routines and all-out time trial was set at 8 min, as reported elsewhere [34].

Participants

Sixteen male competitive swimmers were recruited for this study (22.13 ± 3.84 years, 72.50 ± 7.21 kg of body mass, 1.77 ± 0.04 m tall, 7.44 ± 4.11 years of competitive experience). All swimmers raced in local competitions in the previous year. The inclusion criteria to recruit the subject were as follows: (i) males; (ii) competitive swimmers; (iii) competing at local, national or international competitions in the past. Exclusion criteria included: (i) non-competitive swimmer (e.g. water polo players); (ii) suffering from any injury or disease in the past six months; (iii) unable to attend the three scheduled sessions of this study. *The Institutional Review Board of the Nanyang Technological University approved the study (IRB-2018-04-005). All participants had been briefed about their rights before signing a written informed consent form. Parental and/or guardians consent were sought for under-age participants.*

Warm-up routines

Participants were randomly assigned to perform two different warm-ups in a crossover manner: (i) non-PAP (control condition) and (ii) PAP (experimental condition). Latency period between each warm-up and running in-water testing was set at 8 min [29,35]. The customized warm-up (PAP; experimental condition) was designed based on a mix of coaches' experience and evidence found in the literature [32,33,36].

The total mileage for non-PAP warm-up was set at 1,400 m. The warm-up consisted of swimming 400 m in self-selected stroke and pace (i.e., any stroke and speed of choice), 200 m of front-crawl drills (25 m steady/25 m fast), 200 m of flutter kick drills using a kickboard (15 m fast/35 m steady), 4×100 m (2 front-crawls and 2 individual medleys with 10 s rest in between), 100 m (easy) and 2×50 m (dive followed by 15 m fast/35 m easy) of front-crawl drills.

In the PAP warm-up, participants were required to perform 700 m plus PAP sets to match the overall workload of non-PAP condition. The warm-up consisted of swimming 200 m in self-selected stroke and pace, 100 m of front-crawl drills (25 m steady/25 m fast), 100 m of flutter kick drills using a kickboard (15 m fast/35 m steady), 2×100 m (1 front-crawl and 1 individual medley with 10 s rest in-between), 50 m (easy) and 50 m (dive followed by 15 m fast/35 m easy) of front-crawl drills. To induce PAP, in-

Table 1
The effect of post-activation potentiation sets on kicking kinetics.

	Non-PAP Mean ± SD (95CI)	PAP Mean ± SD (95CI)	Worthwhile change (% of Non-PAP)	Δ	*P*	|d|
Peak thrust [N]	92.7 ± 15.8 (84.3–100.2)	105.2 ± 21.1 (94.8–115.9)	7.94 N (8.56%)	15.14%	0.02	0.66
Mean Thrust [N]	35.52 ± 7.42 (32.02–36.68)	39.56 ± 12.44 (34.05–46.44)	3.71 N (10.45%)	14.60%	0.10	0.40
Thrust-time integral [N.s]	9.89 ± 1.71 (9.04–10.67)	9.63 ± 2.44 (8.44–10.84)	1.22 N.s (12.67%)	0.13%	0.35	0.12

PAP - post-activation potentiation, SD – standard deviation, 95CI – bootstrapped 95% confidence interval, Δ – percentage of individual change, *P* – P-value, d – Cohen's d.

water warm-up was followed-up by 5 min of rest before performing two sets of five maximal repetitions (two min rest between sets) of unloaded countermovement jumps on-land [34,37].

In-water testing

All participants performed in-water testing eight min upon completing each warm-up. The in-water testing was a 25 m all-out trial, with water temperature at 27.5 °C, using front-crawl with only flutter kicks while holding on to a kickboard (dimensions: 42 × 29 cm) by the front edge. Participants were instructed to execute a gentle push-off start from the headwall in order to minimise gliding and not performing dolphin kicks.

Kinetics and kinematics were collected by an in-house customised system composed of differential pressure sensors (Aquanex, Swimming Technologies, Florida, USA), speedo-meter (Swim speedo-meter, Swimsportec, Hildesheim, Germany) and underwater camera (Aquanex, Swimming Technology Research, Inc., USA). Differential pressure sensors were placed between 2nd and 3rd metatarsus of each foot. These sensors measure the change in pressure between inlet and outlet (dorsal and plantar foot) and then force is derived. The speedo-meter was set on the headwall of the swimming pool, about 0.2 m above water surface. The string of the speedo-meter was attached to the back of a belt worn at participants' hip. Underwater camera was set-up 0.5 m deep on the headwall, providing an underwater view in the transverse plane.

A customised software (LabVIEW®, v. 2017) was used to collect ($f = 50\ Hz$), streaming and playback time-series data, as well as, video signal of each trial. Data was transferred from hardware components (pressure sensors, speedo-meter and underwater camera) to interface by a 14-bit resolution acquisition card (NI-6001, National Instruments, Austin, Texas, USA). Afterwards, the data from the customised software was imported into a signal processing software (AcqKnowledge v. 3.9.1, Biopac Systems, Santa Barbara, USA). Eighteen flutter kicks by each lower limb (a total of 36 flutter kicks for both lower limbs) in the mid-section of the pool (between the 10 and 20 m marks, to eliminate the effects of push-off start and decrease in speed at the end of the effort) were analysed and mean values for the following kinetic and kinematic parameters were calculated for further analysis.

Kinetic variables that were analysed included the peak thrust (i.e., the maximal value, in N), mean thrust (in N) and thrust-time integral (in N.s). Kinematic variables included speed (in m/s), speed fluctuation (dimensionless) and kicking frequency (in *Hz*) following the procedures reported elsewhere [12]. Speed fluctuation can also be deemed as a proxy of energy cost, because it was noted that there is an inverse relationship between the two variables, specifically when swimming the full stroke [38,39].

Statistical analysis

Mean ± standard deviation (SD) and mean percentage of individual change (Δ = PAP/NPAPx100) is reported for all dependent variables. Uncertainty in each condition was computed by bootstrapping 95% confidence intervals (95CI) (1,000 samples). Randomisation test was run to compare differences between conditions (paired samples, 20 permutations, 1,000 repetitions, $P \le 0.05$). Cohen's d was selected as standardised effect size of mean differences and deemed as: (i) $|d| \le 0.2$ trivial; (ii) $0.2 < |d| \le 0.5$ medium; (iii) $|d| > 0.5$ large. Statistical analyses were run on R. Between-subjects worthwhile changes in control condition (non-PAP) were computed to examine the smallest meaningful improvement required when undergoing PAP. Worthwhile change was calculated by having $d = 0.2$ as the smallest standardized effect size in sports performance [40]. Worthwhile change was then converted into smallest partial improvement to be expected having as reference the mean value of non-PAP (i.e., the smallest meaningful percentage of change from control to experimental conditions; % change = mean × worthwhile changes).

Results

Overall, there was a medium-large enhancement of the kicking thrust undergoing the warm-up that includes PAP sets (Table 1). Worthwhile change between subjects was expected to be 8.56% and 10.45%, for peak thrust and mean thrust, respectively. Peak ($P = 0.02$, $d = 0.66$) and mean ($P = 0.10$, $d = 0.40$) thrust increased by 15.14% and 14.60%, respectively. Thus, above the 8.56% and 10.45% smallest worthwhile change thresholds. The bootstrapped 95CI of the peak thrust shifted from 84.3 to 100.2 N band to 94.8–115.9 N. Likewise, the bootstrapped 95CI of the mean thrust shifted from 32.02 to 36.68 N to 34.05–46.44 N. Trivial changes were noted in thrust-time integral. Therefore, there is a meaningful improvement in kicking thrust after undergoing PAP sets.

There was also a meaningful change in kicking kinematics. Large and significant differences were noted in speed ($P = 0.01$, d = 0.54) and speed fluctuation ($P = 0.02$, $d = 0.58$) (Table 2). Both variables improved by 10%, which is very close to (in the speed fluctuation case) or above (in the speed case) the expected smallest worthwhile changes. Participants were faster with a 95% confidence interval after PAP sets (from 0.54 to 0.64 m/s to 0.59–0.72 m/s). Speed fluctuation was reduced from 0.10 to 0.13 to 0.08–0.10 bootstrapped 95CI after PAP. Kicking frequency had a medium and significant increase by 3.17% ($P = 0.049$, $d = 0.27$) from bootstrapped 95CI of 2.26–2.52 *Hz* to 2.31–2.63 *Hz*. So, after a warm-up that included PAP sets, participants became faster and decreased the speed fluctuation.

Discussion

This study aimed to analyse the effect of a warm-up routine that includes PAP sets on front-crawl flutter kick thrust, kinematics and performance. There were significant and large improvements in flutter kick thrust, kinematics and performance, when participants performed a warm-up that features PAP sets. Flutter kick

Table 2
The effect of post-activation potentiation sets on kicking kinematics.

	Non-PAP Mean ± SD (95CI)	PAP Mean ± SD (95CI)	Worthwhile change (% of Non-PAP)	Δ	*P*	|d|
Speed [m/s]	0.59 ± 0.10 (0.54–0.64)	0.66 ± 0.13 (0.59–0.72)	0.06 m/s (9.80%)	11.60%	0.01	0.54
Speed fluctuation [dimensionless]	0.11 ± 0.04 (0.10–0.13)	0.09 ± 0.02 (0.08–0.10)	0.01 (9.61%)	9.68%	0.02	0.58
Kicking frequency [*Hz*]	2.40 ± 0.24 (2.26–2.52)	2.48 ± 0.32 (2.31–2.63)	0.16 *Hz* (6.47%)	3.17%	0.05	0.27

PAP - post-activation potentiation, SD – standard deviation, 95CI – bootstrapped 95% confidence interval, Δ – percentage of individual change, *P* – P-value, d – Cohen's d.

thrust improved by 15%, whereas kinematics and performance improved by 10%.

There is a paucity of studies investigating human flutter kick thrust by experimental testing. In a study on tethered swimming, in male swimmers, it was reported that peak and mean thrust were 100.1 ± 28.2 N and 35.1 ± 7.6 N, respectively [17]. Just one qualitative case study of a college swimmer reported the pressure on plantar and dorsal surfaces of the feet kicking in front-crawl at 1.03 m/s, 1.10 m/s and 1.14 m/s [41]. In another case study, it was reported that a world-record holder, performed flutter kicks against a force plate mounted on a headwall delivered a peak force of 90–113 N [18]. Computational fluid dynamics of human dolphin kick suggested a mean thrust of 100 N at 2.2 *Hz* [15]. Based on an analytical procedure, mean flutter kick thrust was reported as 42 ± 4 N [16]. When fins were used, the tethered flutter kick thrust ranged between 130 ± 23 N and 178 ± 30 N, depending on the fins' model [42]. Peak and mean thrust data from the present study shows a good adherence to aforementioned results. A study conducted on the thrust of aquatic animals suggested that the mean thrust by dolphins is approximately 80 N [3]. In another study, conducted in still water, the thrust generated by great white sharks was modelled by computational fluid dynamics to be 295 N [7]. Unsurprisingly, the magnitude of human thrust was far lower as compared to aquatic animals.

Previous research noted that PAP can help to enhance sprinting performance [29–31]. However, until now, the underlying mechanism that led to performance improvements after performing PAP sets remains unclear. There was a meaningful improvement in flutter kick thrust after performing PAP as compared to non-PAP. Between-subjects worthwhile change was computed as 8.56% and 10.45% for peak thrust and mean thrust, respectively; both improved by 15% in PAP in comparison with non-PAP. Regrettably, the assessment of neuromuscular response concurrent to this data collection set-up was not possible. As such, it is uncertain the neuromuscular mechanism by which PAP led to an increase of thrust. However, literature points out three main neuromuscular mechanisms explaining the PAP phenomenon. The first is the phosphorylation of myosin regulatory light chains. This causes the actin-myosin to be more sensitive to calcium released from the sarcoplasmic reticulum, during subsequent muscle contractions. Thus, the force of each consecutive twitch contraction is increased [43]. The second is the increased synaptic excitation within the spinal cord. It results in increased post-synaptic potentials and subsequent increased force [44]. The last mechanism is the decrease of the pennation angle, enhancing the mechanical advantage and increasing the force transmission to tendons and bones [22]. The conditioning activity may also increase connective tissue and tendons compliance [22].

The findings from the present study provide evidence that PAP can enhance the magnitude of flutter kick thrust, which translated into faster swim speed. The procedures reported in previous studies to elicit PAP used heavy dry-land equipment that is not available in swimming pools and is not convenient to carry. Sarramian et al. [31] utilised medicine balls and weights to perform pull-ups together with weighted vests and boxes to perform countermovement jumps. Cuenca-Fernández et al. [29] investigated the influence of PAP protocols utilising multipower machines and flywheel devices. Hence, the question on whether PAP can be induced by performing exercises with minimal and light equipment or, only the body weight, was raised. Our findings suggest that using just participants' body weight and performing two sets of five maximal repetitions of unloaded countermovement jumps is a simple, convenient and effective way to achieve better performance.

Speed fluctuation decreased significantly after performing PAP as compared to non-PAP. The improvement was 9.68%, near the 9.61% smallest worthwhile change estimated. Bootstrapped 95CI bands ranged between 0.10 and 0.13 and 0.08–0.10, which is within the 0.09–0.13 interval reported elsewhere using the same measurement technique [12]. Speed fluctuation is strongly related to energy cost of swimming, at least swimming full stroke (i.e. arm-pull synchronised with kicking). Energy cost is inversely related to swimming efficiency [45]. As such, smaller speed fluctuation is related to less energy cost while swimming [38,39]. Despite these findings, whether such relationship shows the same magnitude if assessed the energy cost of kicking and its speed fluctuation, remains inconclusive. Nonetheless, one can argue that undergoing PAP, participants became more efficient. However, swimming efficiency is not as determinant in sprinting as in middle- or long-distance events. It was reported that among the US National Team, sprinters, middle-distance swimmers and long-distance counterparts had a propelling efficiency of 47.8 ± 8.1%, 55.9 ± 10.1% and 61.5 ± 10.2%, respectively [46].

Gatta et al. [16] noted a kicking frequency of 2.4 ± 0.2 *Hz* swimming at 1.2 m/s; whereas, Zamparo et al. [47] 1.29 ± 0.14 *Hz* at 0.6 m/s. National-level swimmers performing dolphin kicks fully submerged at 1.13 m/s had a kick frequency of 1.76 *Hz* [48]. The present study found that kicking frequency increased from 2.26 to 2.52 *Hz* to 2.31–2.63 *Hz* (Δ = 3.17%). However, this improvement was lower than the worthwhile change needed (6.47%). Consequently, *P*-value falls very near to the rejection threshold ($P = 0.049$) and in the lower end of a medium effect size ($d = 0.27$). The magnitude of these variations in kicking frequency might have led to trivial changes in the thrust-time integral. In the first of two 100 m dash trials, the stride frequency showed a larger effect size after PAP [49]. It has been reported that kicking frequency has an effect on metabolic response [50]. The increase in speed due to higher kicking frequency can have the detrimental effect of a larger internal mechanical work. Increased energy cost is a consequence of a higher internal mechanical work. Therefore, the increase in kicking frequency as a mechanical strategy to swim faster might be suitable in events where energy cost is not a key-determinant, such as short sprints. Conversely, in longer sprints, speed increase should be done based on a different strategy.

Participants were faster after performing PAP (bootstrapped 95CI: from 0.54 to 0.64 m/s to 0.59–0.72 m/s). Speed improved by 11.60%, which was above the 9.80% worthwhile change expected. Previous studies demonstrated that the contribution of arm-pulls to full swim speed (i.e., arm-pulling synchronised with kicking) speed is 85–90% [10–14]. Thus, the overall contribution of flutter kicks is 10–15%. Interestingly, at least in young participants, kicking accounts for 60% of the speed performing the full stroke [12]. In another study, the sum of arms-only and legs-only swimming also exceeded that of whole body for velocity, VO_2 and metabolic cost [14]. A possible explanation for this decrease from 60% to 10–15% is a counteract effect of kicking thrust by tangential drag force. The latter will increase over the stroke cycle, due to an increase in speed that is related to arm-pull. According to a simulation, such increase in tangential drag cancels out the thrust effect [51]. Therefore, a 10% improvement in kicking thrust, after performing PAP, may allow swimmers to be faster by 1.0–1.5% during a swim race, provided energy cost remains the same. An improvement of 1% in a swim race that takes about 50 s, such as for instance the 100 m freestyle, means less 0.5 s in the final race time. Sarramian et al. [31] reported a mean improvement of 1.81% in a 50 m freestyle trial in male swimmers, after performing upper-limbs PAP. The 1.81% improvement is in tandem with the current findings of about 1.0–1.5%. Moreover, a standardised effect size of $d = 0.54$ translates into a percentile gain of 21 places. For instance, if one is ranked 50th in the top-100, going under PAP and everything else being equal, moves the swimmer up to position 29th. Altogether, in elite sports, an enhancement by 1.0–1.5% is deemed as meaningful.

Overall, the inclusion of PAP sets at the end of the warm-up routine can elicit a performance enhancement. Five min after the in-water warm-up, swimmers can perform two sets of five maximal unloaded countermovement jumps with two min rest between sets. This is expected to improve the kicking performance by 10% and the overall swim performance in 1.0–1.5%. The warm-up mileages selected are within the common practice among swimmers of this level [32,33,36]. A review of the literature suggested a mileage of 1.0–1.5 km [36]. Different in-water mileages in the two warm-ups aimed to match the overall workload in both condition. However, one can argue that by applying the same warm-up mileage (e.g., 1.4 km) in the control and experimental conditions, PAP might as well be seen as a strategy able to change performance on that particular moment or state of fatigue. Most selected variables increased the coefficient of variation (CV = SD/mean) from non-PAP to PAP. The increased variability can be related to different magnitudes of response to PAP from individual to individual, as well as, to each one of them having an optimal latency period that can be different to the 8 min selected for this research. As such, swimmers are advised to determine their own optimal latency period.

While this research has shown that PAP improves kicking kinetics, kinematics and performance, some limitations can be pointed out: (i) it is still unknown if different latency periods between PAP sets and in-water testing will yield similar results; (ii) future studies can be conducted to provide insight on the hypothetical changes in kicking efficiency (Strouhal number) after performing PAP; (iii) it is still unknown if similar PAP effect can be observed in other swim strokes (e.g., backstroke kick, dolphin kick and breaststroke kick); (iv) it is not yet known if PAP will have the same effect on arm-pull; and (v) experiments were conducted over 25 m, and might not be representative of the swimmer's acute response in longer distances.

Conclusions

In conclusion, there are meaningful improvements in kicking thrust, kinematics and performance after undergoing a warm-up that includes PAP sets. PAP exercise in the form of body-weighted countermovement jump can elicit an increase in thrust, which in turn is going to enhance the kicking kinematics and performance.

Compliance with ethics requirements

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008 (5). Informed consent was obtained from all patients for being included in the study.

Acknowledgements

This research was funded by NIE AcRF Grant (RI 6/17TB).

Declaration of Competing Interest

The authors have declared no conflict of interest.

References

[1] Fish FE, Hui CA. Dolphin swimming–a review. Mammal Rev 1991;21 (4):181–95.
[2] Johnson W, Soden PD, Trueman ER. A study in jet propulsion: an analysis of the motion of the squid, Loligo vulgaris. J Exp Biol 1972;56(1):155–65.
[3] Videler JO, Kamermans PA. Differences between upstroke and downstroke in swimming dolphins. J Exp Biol 1985;119(1):265–74.
[4] O'dor RK, Wells J, Wells MJ. Speed, jet pressure and oxygen consumption relationships in free-swimming Nautilus. J Exp Biol 1990;154(1):383–96.
[5] Drucker EG, Lauder GV. Locomotor function of the dorsal fin in teleost fishes: experimental analysis of wake forces in sunfish. J Exp Biol 2001;204 (17):2943–58.
[6] Fish FE, Legac P, Williams TM, Wei T. Measurement of hydrodynamic force generation by swimming dolphins using bubble DPIV. J Exp Biol 2014;217 (2):252–60.
[7] Ogami Y. A three-dimensional source-vorticity method for simulating incompressible potential flows around a deforming body without the Kutta condition. Comput Fluids 2017;154:184–99.
[8] Ungerechts BE. A comparison of the movements of the rear parts of dolphins and butterfly swimmers. Biomech Med Swimming 1983:215–21.
[9] von Loebbecke A, Mittal R, Fish F, Mark R. Propulsive efficiency of the underwater dolphin kick in humans. J Biomech Eng 2009;131(5):054504.
[10] Deschodt VJ, Arsac LM, Rouard AH. Relative contribution of arms and legs in humans to propulsion in 25-m sprint front-crawl swimming. Eur J Appl Physiol Occup Physiol 1999;80(3):192–9.
[11] Gourgoulis V, Boli A, Aggeloussis N, Toubekis A, Antoniou P, Kasimatis P, et al. The effect of leg kick on sprint front crawl swimming. J Sport Sci 2014;32 (3):278–89.
[12] Bartolomeu RF, Costa MJ, Barbosa TM. Contribution of limbs' actions to the four competitive swimming strokes: a nonlinear approach. J Sport Sci 2018;36 (16):1836–45.
[13] Ribeiro J, Figueiredo P, Sousa A, Monteiro J, Pelarigo J, Vilas-Boas JP, et al. VO2 kinetics and metabolic contributions during full and upper body extreme swimming intensity. Eur J Appl Physiol 2015;115(5):1117–24.
[14] Morris KS, Osborne MA, Shephard ME, Skinner TL, Jenkins DG. Velocity, aerobic power and metabolic cost of whole body and arms only front crawl swimming at various stroke rates. Eur J Appl Physiol 2016;116(5):1075–85.
[15] Cohen RC, Cleary PW, Mason BR. Simulations of dolphin kick swimming using smoothed particle hydrodynamics. Hum Mov Sci 2012;31(3):604–19.
[16] Gatta G, Cortesi M, Di Michele R. Power production of the lower limbs in flutter-kick swimming. Sports Biomech 2012;11(4):480–91.
[17] Morouço PG, Marinho DA, Izquierdo M, Neiva H, Marques MC. Relative contribution of arms and legs in 30 s fully tethered front crawl swimming. BioMed Res Int 2015.
[18] Wei T, Mark R, Hutchison S. The fluid dynamics of competitive swimming. Annl Rev Fluid Mech 2014;46:547–65.
[19] McGowan CJ, Pyne DB, Thompson KG, Rattray B. Warm-up strategies for sport and exercise: mechanisms and applications. Sports Med 2015;45 (11):1523–46.
[20] Sasaki K, Tomioka Y, Ishii N. Activation of fast-twitch fibers assessed with twitch potentiation. Muscle Nerve 2012;46(2):218–27.
[21] Gago P, Marques MC, Marinho DA, Ekblom MM. Passive muscle length changes affect twitch potentiation in power athletes. Med Sci Sports Exerc 2014;46 (7):1334–42.
[22] Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. Sports Med 2009;39 (2):147–66.

[23] Rassier DE, Macintosh BR. Coexistence of potentiation and fatigue in skeletal muscle. Brazilian J Med Biol Res 2000;33(5):499–508.
[24] Gourgoulis V, Aggeloussis N, Kasimatis P, Mavromatis G, Garas A. Effect of a submaximal half-squats warm-up program on vertical jumping ability. J Strength Cond Res 2003;17(2):342–4.
[25] Ruben RM, Molinari MA, Bibbee CA, Childress MA, Harman MS, Reed KP, et al. The acute effects of an ascending squat protocol on performance during horizontal plyometric jumps. J Strength Cond Res 2010;24(2):358–69.
[26] Seitz LB, Haff GG. Factors modulating post-activation potentiation of jump, sprint, throw, and upper-body ballistic performances: A systematic review with meta-analysis. Sports Med 2016;46(2):231–40.
[27] Smith JC, Fry AC, Weiss LW, Li Y, Kinzey SJ. The effects of high-intensity exercise on a 10-second sprint cycle test. J Strength Cond Res 2001;15(3):344–8.
[28] Yetter M, Moir GL. The acute effects of heavy back and front squats on speed during forty-meter sprint trials. J Strength Cond Res 2008;22(1):159–65.
[29] Cuenca-Fernández F, López-Contreras G, Arellano R. Effect on swimming start performance of two types of activation protocols: lunge and YoYo squat. J Strength Cond Res 2015;29(3):647–55.
[30] Hancock AP, Sparks KE, Kullman EL. Postactivation potentiation enhances swim performance in collegiate swimmers. J Strength Cond Res 2015 Apr 1;29(4):912–7.
[31] Sarramian VG, Turner AN, Greenhalgh AK. Effect of postactivation potentiation on fifty-meter freestyle in national swimmers. J Strength Cond Res 2015;29(4):1003–9.
[32] Neiva HP, Marques MC, Barbosa TM, Izquierdo M, Viana JL, Teixeira AM, et al. The effects of different warm-up volumes on the 100-m swimming performance: a randomized crossover study. J Strength Cond Res 2015;29(11):3026–36.
[33] Neiva HP, Marques MC, Barbosa TM, Izquierdo M, Viana JL, Teixeira AM, et al. Warm-up for sprint swimming: Race-pace or aerobic stimulation? A randomized study. J Strength Cond Res 2017;31(9):2423–31.
[34] Lum D. Effects of various warm-up protocol on special judo fitness test performance. J Strength Cond Res 2019;33(2):459–65.
[35] Kilduff LP, Cunningham DJ, Owen NJ, West DJ, Bracken RM, Cook CJ. Effect of postactivation potentiation on swimming starts in international sprint swimmers. J Strength Cond Res 2011;5(9):2418–23.
[36] Neiva HP, Marques MC, Barbosa TM, Izquierdo M, Marinho DA. Warm-up and performance in competitive swimming. Sports Med 2014;44(3):319–30.
[37] Baker D. Increases in bench throw power output when combined with heavier bench press plus accommodating chains resistance during complex training. J Aust Strength Cond 2009;16:10–8.
[38] Barbosa TM, Keskinen KL, Fernandes R, Colaço P, Lima AB, Vilas-Boas JP. Energy cost and intracyclic variation of the velocity of the centre of mass in butterfly stroke. Eur J Appl Physiol 2005;93(5–6):519–23.
[39] Barbosa TM, Bragada JA, Reis VM, Marinho DA, Carvalho C, Silva AJ. Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. J Sci Med Sports 2010;13(2):262–9.
[40] Bucheit M. Chasing the 0.2. Int J Sports Physiol Perf 2016;11:417–8.
[41] Ichikawa H, Kuriki A, Taba S, Taguchi M. Difference of hydrodynamic force on foot between front crawl six-beat and flutter kicking. In: Mason B, editor. Biomechanics and Medicine in Swimming XII. Canberra, Australia: Australia Sports Institute; 2014. p. 152–7.
[42] Pendergast DR, Mollendorf J, Logue C, Samimy S. Evaluation of fins used in underwater swimming. Undersea Hyperbaric Med Soc 2003;30:55–71.
[43] Vandenboom R, Grange RW, Houston ME. Myosin phosphorylation enhances rate of force development in fast-twitch skeletal muscle. Am J Physiol 1995;268:C596–603.
[44] Rassier DE, Herzog W. Force enhancement following an active stretch in skeletal muscle. J Electromyogr Kinesiol 2002;12(6):471–7.
[45] Zamparo P, Lazzer S, Antoniazzi C, Cedolin S, Avon R, Lesa C. The interplay between propelling efficiency, hydrodynamic position and energy cost of front crawl in 8 to 19-year-old swimmers. Eur J Appl Physiol 2008;104(4):689.
[46] Cappaert J, Franciosi P, Langhand G, Troup J. Indirect calculation of mechanical and propelling efficiency during freestyle swimming. In: MacLaren D, Reilly T, Lees A, editors. Biomechanics and Medicine in Swimming VI. London: E & FN SPON; 1992. p. 53–6.
[47] Zamparo P, Pendergast DR, Termin B, Minetti AE. How fins affect the economy and efficiency of human swimming. J Exp Biol 2002;205(17):2665–76.
[48] Arellano R, Pardillo S, Gavilán A. Underwater undulatory swimming: Kinematic characteristics, vortex generation and application during the start, turn and swimming strokes. In: Proceedings of the XXth international symposium on biomechanics in sports. Caceres, Spain: Universidad de Extremadura; 2002. p. 29–41.
[49] Gil MH, Neiva HP, Garrido ND, Aidar FJ, Cirilo-Sousa MS, Marques MC, et al. The effect of ballistic exercise as pre-activation for 100 m sprints. Int J Envior Res Public Health 2019;16(10):1850.
[50] Morris KS, Osborne MA, Shephard ME, Jenkins DG, Skinner TL. Velocity, oxygen uptake, and metabolic cost of pull, kick, and whole-body swimming. Int J Sports Physiol Performance 2017;12(8):1046–51.
[51] Nakashima M. Mechanical study of standard six beat front crawl swimming by using swimming human simulation model. J Fluid Sci Technol 2007;2(1):290–301.