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Abstract

Purpose: The contributions of the limbs to velocity and metabolic parameters in front-crawl swimming at different intensities have not been identified with the consideration of both stroke and kick rate. Consequently, velocity, oxygen uptake ($\dot{V}O_2$) and metabolic cost of swimming with the whole body (swim), the upper-limbs only (pull) and lower-limbs only (kick) were compared with stroke and kick rate controlled. **Methods**: Twenty elite swimmers completed six 200m trials; two swim, two pull and two kick. Swim trials were guided by underwater lights at paces equivalent to $65\pm3\%$ and $78\pm3\%$ of participants' 200m freestyle personal best pace; paces were described as 'low' and 'moderate', respectively. In the pull and kick trials, swimmers aimed to match the stroke and kick rates recorded during the swim trials, respectively. $\dot{V}O_2$ was measured continuously, with velocity and metabolic cost calculated for each 200m effort. **Results**: The velocity contribution of the upper-limbs (mean±SD: low $63.9\pm6.2\%$; moderate $59.6\pm4.2\%$) was greater than that of the lower-limbs to a large extent at both intensities (low ES=4.40; moderate ES=4.60). The $\dot{V}O_2$ utilized by the upper-limbs differed between the intensities (low $55.5\pm6.9\%$; moderate $51.4\pm4.0\%$; ES=0.74). The lower-limbs were responsible for a greater percentage of the metabolic cost compared to the upper-limbs at both intensities (low $56.1\pm9.5\%$, ES=1.30; moderate $55.1\pm6.6\%$, ES=1.55). **Conclusions**: Implementation of this testing protocol before and after a pull or kick training block will enable sports scientists to identify how the velocity contributions and/or metabolic cost of the upper- and lower-limb actions have responded to the training program.

Keywords: Stroke rate; kick rate; physiology; limb contributions; front-crawl

Introduction

In high performance swimming, coaches dedicate a substantial portion of the total training volume to training using the upper-limbs only (pull) and the lower-limbs only (kick) to ensure these muscle groups are able to produce propulsive forces in an energy-efficient manner. The distribution of pull and kick training is based on the coaches' perceptions of the relative importance of the upper- and lower-limbs in velocity production and their associated metabolic demands. Within the literature, it is generally accepted that the upper-limbs contribute approximately 90% to front-crawl swimming velocity.[1-3] However others have found that, when using the lower-limbs only, swimmers can achieve approximately 60-65% of the velocity attained during whole body swimming.[1] Thus, when the reported contribution of the upper-limbs (~90%) is summed with the contribution of the lower-limbs (~60%), the total far exceeds the velocity achieved during whole body swimming (100%). In lieu of agreeance on the relative importance of the upper- and lower-limbs on velocity production within the scientific literature, swimming coaches may be sub-optimally prescribing pull and kick training.

Furthermore, in studies where the anaerobic and aerobic capacities of swimming with the upper-limbs only, the lower-limbs only and the whole body have been estimated[4,5], the summation of pull and kick energy expenditure have exceeded the total energy expenditure observed in whole body swimming even when basal metabolic rate is accounted for. Authors have suggested that synergistic stabilizing muscles (e.g. trunk muscles) could be active in both the pull and kick trials. Additionally, muscular activity could be present and unaccounted for in actions such as pushing off from the wall after each lap and the isometric contractions required to hold a kickboard or pull buoy. As a result, these muscles require oxygen in both conditions and, when summing the net $\dot{V}O_2$ values from pull and kick trials, this energy overlap is not accounted for. While this may be true, the difference between whole body swimming net

$\dot{V}O_2$ and the sum of the net $\dot{V}O_2$ of swimming with the upper-limbs only and the lower-limbs only is likely too great to be solely attributed to the 'duplication' of $\dot{V}O_2$ requirements of the synergistic stabilizing muscle groups.[5]

Possible reasons for the discrepancy in previous findings, aside from the unaccounted costs associated with holding a kickboard and changes in body position and drag profiles between testing conditions, could relate to lack of control over stroke and kick rate across trials, as these parameters can influence swimming velocity and metabolic cost.[6,7] Recent research[8,9] has investigated the importance of the lower-limb actions on velocity and metabolic cost by analysis of whole-body and arms-only swimming at matched stroke rates. However, the contributions of the arm and leg movements to swimming velocity, and the associated energy expenditure, while controlling stroke and kick rate, is yet to be examined. Controlling these parameters will provide a closer match for the mechanical demands of swimming using the whole body versus swimming with the upper-limbs only or the lower-limbs only. Knowledge of how much of the total available energy in swimming is utilized by the upper-limbs compared to the lower-limbs, and to what extent the limbs contribute to velocity will enable coaches to make evidence-based decisions regarding the required volume and intensity of pull and kick training to stimulate physiological adaptations to enhance performance.

To extend upon recent research,[8,9] the aim of this cross-sectional study was to determine the velocity production and metabolic cost of swimming with the upper-limbs only and lower-limbs only relative to whole body swimming using the novel approach of controlling the stroke and kick rate among the testing conditions.

Methods

Participants

Eleven male and nine female elite swimmers who had competed in the 2014 Australian Swimming Championships and were currently training ≥ 7 swimming sessions in the pool per

week ($\geq$ 2 hr per session) volunteered to participate in this study. Participant characteristics are presented in Table 1; height, mass, arm span and sum of 7 skinfolds were measured by an accredited anthropometrist as previously described.[10] The study was approved by the Human Research Ethical Committee of The University of Queensland.

Design

Following an 800 m standardized warm up, participants completed 6 x 200 m swimming trials; two using the whole body (swim), two using the upper-limbs only (pull) and two using the lower-limbs only (kick). The two swim trials were standardized at 60% and 75% (described within the manuscript as 'low' and 'moderate', respectively) of the mean 200 m velocity for the male and female gold medalists from the 2012 Olympic Games (average velocity from the final 150 m to remove the influence of the dive). These paces were chosen following pilot testing that a) observed velocities commonly performed in aerobic training sets, and b) confirmed the submaximal nature of these velocities (classified by the absence of a slow-component $\dot{V}O_2$ response) in our participant group. The velocities, physiological responses and biomechanical parameters observed in the pilot testing were consistent with previous research[11,12] utilizing low-to-moderate exercise. Both swim trials were completed prior to the pull and kick trials, with the order of intensities and order of the pull and kick trials randomized and counterbalanced by a research assistant using an online number generator. Swimmers started each 200 m in-water by pushing off the wall and were guided by pre-programmed underwater pacing lights (Pacer2Swim, Portugal) to help maintain even pacing in both swim trials. The rates at which participants were required to stroke and kick in the pull and kick trials, respectively, were programed into an audible pacer (Tempo Trainer Pro, FINIS Inc.®, USA) inside the swimmer's cap. In the pull trials, swimmers matched the stroke rates (stroke cycles · min^{-1}) recorded during the swim trials (measured by the lead researcher and a research assistant (ICC 0.99, 95% CI 0.99-0.99, *P*<0.001) as previously described[8]). The lower-limbs

were supported by a pull buoy (buoyant force: 12 N), with the ankles fastened with a swimming band in both pull efforts, while the kick trials were completed with a kickboard. The kick rates (kick cycles $\cdot$ min^{-1}) observed in the swim trials (calculated by the primary researcher (Technical Error of Measurement: 2.2%) using a previously described calculation[8]) were matched in the kick efforts. All participants used the same pull buoy and kickboard within their testing sessions; equipment typically used during training sessions. Participants were requested to hold the kickboard with minimal force and to relax the legs as much as possible in the kick and pull trials, respectively. Trials were separated by five minutes of passive rest. Testing was conducted in a 25 m indoor swimming pool (mean±SD: water temperature 26.1±0.1°C, ambient air temperature 23.4±2.2°C, relative air humidity 59.7±11.8%) no sooner than 12 hours following a high intensity training session.

Outcome measures

All trials were filmed using two synchronized video cameras (Sony HXR-NX5P, Sony, Japan) positioned in a perpendicular plane 8.5 m from the swimmer at 5 m and 20 m from the starting wall of the pool (sampling rate 50 Hz). For all six trials, velocity (m $\cdot$ s^{-1}) was measured between 5 and 20 m of each lap from the video footage using Dartfish (Fribourg, Switzerland) and was computed as the distance divided by the time taken to cover the specified distance. Stroke rate was also verified through Dartfish analysis (ICC with average of lead researcher and research assistant: 0.996, 95% CI 0.995-0.997, $P<0.001$). With a total of eight measurements for each 200 m trial, the mean velocity and stroke rate value was used for data analysis. An underwater camera (GoPro® HERO4, San Mateo, California) was secured from a lane rope approximately 6 m from the wall of the pool (parallel to the direction of swimming) and recorded video footage at 50 Hz. The underwater footage was imported into Windows MovieMaker® (Microsoft Corporation, USA) for the frame-by-frame analysis of kick rate.

During each trial, oxygen uptake ($\dot{V}O_2$) and ventilation ($\dot{V}E$) were measured using a telemetric gas analysis system (Cosmed K4b[2], Rome, Italy) connected to the swimmer by a breathing tube and valve system (developed by the Queensland Academy of Sport and validated against the Cosmed Aquatrainer and the Cosmed Facemask: ICC for $\dot{V}O_2$: 0.98 (95% CI: 0.96–0.99, $P<0.001$). Participants were not able to tumble turn; instead open turns with minimal gliding were performed at the end of every lap, with participants pushing off from the wall at the beginning of the test and after each turn. Familiarization with the gas analysis equipment, turning strategy, pacing lights and metronome was included in the warm up. The gas analysis system was calibrated in accordance with the manufacturer's instructions prior to each 200 m trial. Breath-by-breath expired air was analyzed for $\dot{V}O_2$ ($mlO_2 \cdot kg^{-1} \cdot min^{-1}$) and $\dot{V}E$ ($L \cdot min^{-1}$)with the average of the final 30 seconds of data used for analysis.

Heart rate (HR; Polar T31, Polar®, USA) was recorded immediately after each 200 m trial. Ear lobe capillary blood lactate concentration ($[La^-]$) was measured before the first 200 m trial and again 1 and 3 minutes following each trial (Lactate Pro 2™, Tokyo, Japan). After converting the net $[La^-]$ to $\dot{V}O_2$ equivalents,[13,14] aerobic and anaerobic energy consumption were converted into SI units based on 1 mlO_2 being equivalent to 20.9 J [15,16] and then summed and divided by 60 to yield the total metabolic power ($\dot{E}_{Total}$; $J \cdot s^{-1}$). $\dot{E}_{Total}$ was then expressed relative to the swimmer's body mass ($J \cdot kg^{-1} \cdot s^{-1}$) and divided by the average velocity to obtain the total metabolic cost ($J \cdot kg^{-1} \cdot m^{-1}$).[16,17]

Each outcome measure (velocity, $\dot{V}O_2$ and metabolic cost) is expressed as an absolute value for each condition. For the pull and kick trials, data are also expressed relative to swim data ($Pull_{Relative}$ and $Kick_{Relative}$; %). Equations 3 and 4 were used to determine the percentage of swim velocity, $\dot{V}O_2$ and metabolic cost resulting from the actions of the upper- and lower-limbs when the pull and kick trials were normalized to the swim trial as 100% ($Pull_{Normalized}$, $Kick_{Normalized}$):

$$\text{Pull}_{\text{Normalized}} (\%) = \text{Pull}_{\text{Relative}} \cdot \sum(\text{Pull}_{\text{Relative}}, \text{Kick}_{\text{Relative}})^{-1} \qquad (3)$$

$$\text{Kick}_{\text{Normalized}} (\%) = \text{Kick}_{\text{Relative}} \cdot \sum(\text{Pull}_{\text{Relative}}, \text{Kick}_{\text{Relative}})^{-1} \qquad (4)$$

Statistical analyses

Data were analysed using SPSS (version 22.0, SPSS, Inc., Chicago, IL) to determine differences between swim, pull and kick at the two intensities. Normality of the distribution for outcome measures was tested using the Shapiro-Wilk test. Standard descriptive statistics for the measured biomechanical and physiological parameters for each 200 m swim were reported. A one-way repeated measures analysis of variance (ANOVA) was used to determine whether differences existed in the velocity, $\dot{V}O_2$ and metabolic cost observed in swim, pull and kick. A two-way ANOVA determined whether differences in the outcome measures of pull and kick relative to swim were evident between the two intensities and between males and females. The magnitude of the effect of sex on the outcome measures is described by partial eta squared (η_p^2) values and were interpreted following the Cohen's criteria[18] where η_p^2 of 0.01, 0.06 and 0.14 represent small, moderate and large effects, respectively. Where significant *F* ratios were identified from the ANOVA analyses, pairwise comparisons were made using the Bonferroni correction to locate the source of significant differences. The importance of the differences observed between the relative and normalized pull and kick data was assessed and reported using the Cohen effect size (ES) statistics[18], where 0.2, 0.5, and 0.8 were considered small, medium and large effects, respectively. Statistical significance was set at *P*<0.05. Results are reported as the mean ± SD, unless stated otherwise.

Results

When the outcome measures of pull and kick were expressed relative to swim velocity, $\dot{V}O_2$ and metabolic cost, a small effect of sex was observed on velocity (*P*=0.50, η_p^2=0.03) and $\dot{V}O_2$ (*P*=0.32, η_p^2=0.06), with sex having a moderate effect on metabolic cost (*P*=0.16,

$\eta_p^2=0.13$). Sex had a moderate effect on $\text{Pull}_{\text{Normalized}}$ or $\text{Kick}_{\text{Normalized}}$ velocity ($P=0.27$, $\eta_p^2=0.08$), and no effect on $\dot{V}O_2$ ($P=0.99$, $\eta_p^2=0.00$) or metabolic cost ($P=0.99$, $\eta_p^2=0.00$). The effect of sex on the outcome measures of interest was insignificant in all cases. Therefore, all results are reported as grouped data.

The low and moderate intensities equated to 65±3% and 78±3% of participants' personal best 200 m freestyle times. Participants used the same stroke rates in the swim (25.8±2.7 stroke cycles · min^{-1}) and pull efforts at the low intensity (25.6±2.5 stroke cycles · min^{-1}) ($P=0.32$). At the moderate intensity, the stroke rates used in the swim (33.5±3.1 stroke cycles · min^{-1}) and pull (32.9±3.6 stroke cycles · min^{-1}) differed ($P=0.01$), as did the kick rates between the swim and kick trials at low (63.8±18.1 and 65.2±18.4 kick cycles · min^{-1}, respectively; $P=0.03$). Kick rates in the swim and kick trials at the moderate intensity did not differ (89.5±22.7 and 88.6±19.1 kick cycles · min^{-1}, respectively; $P=0.87$). Velocity and $\dot{V}O_2$ in the swim efforts were higher than in pull and kick trials at both intensities (Figure 1; all $P<0.01$). At both intensities, metabolic cost of pull was lower than swim ($P<0.02$), while the metabolic cost of kick did not differ from that of swim ($P>0.01$). When the velocities of pull and kick were summed, the result was greater than swim velocity at both intensities (both $P<0.001$). The same pattern was observed for $\dot{V}O_2$ ($P<0.001$) and metabolic cost ($P<0.001$) with the sum of pull and kick exceeding swim at both intensities (Figure 1). Heart rate, ventilation and peak blood lactate concentration are reported in Table 2.

At both intensities, pull velocity expressed relative to swim velocity ($\text{Pull}_{\text{Relative}}$) was higher than the relative velocity of kick ($\text{Kick}_{\text{Relative}}$) (low $P<0.001$, ES=1.60; moderate $P<0.001$, ES=3.90), while the opposite was true for the metabolic cost (low $P=0.01$, ES=-0.86; moderate $P=0.01$, ES=-1.00). The difference between $\text{Pull}_{\text{Relative}}$ and $\text{Kick}_{\text{Relative}}$ $\dot{V}O_2$ was large at the low intensity ($P=0.02$, ES=0.93), while the difference was small and insignificant at the moderate intensity ($P=0.12$, ES=0.30).

When $Pull_{Relative}$ and $Kick_{Relative}$ were normalized to the swim trial as 100% (Figure 2), $Pull_{Normalized}$ velocity was greater than $Kick_{Normalized}$ velocity to a large extent at both the low ($P<0.001$, ES=4.40) and moderate ($P<0.001$, ES=4.60) intensities. The difference between $Pull_{Normalized}$ $\dot{V}O_2$ and $Kick_{Normalized}$ $\dot{V}O_2$ was large at the low intensity ($P=0.02$, ES=1.61) and of a medium magnitude at the moderate intensity ($P=0.02$, ES=0.68). There was a large difference between $Pull_{Normalized}$ metabolic cost and $Kick_{Normalized}$ metabolic cost at the low intensity ($P=0.01$, ES=-1.30) and moderate intensity ($P=0.04$, ES=-1.55).

Discussion

The present study compared the velocity, $\dot{V}O_2$ and metabolic cost of swim, pull and kick front crawl swimming at two intensities while controlling the stroke and kick rates. While previous studies have expressed pull and kick data relative to swim data (i.e. velocity, $\dot{V}O_2$ and metabolic cost), this study describes the relative contributions of the upper- and lower-limbs to velocity, $\dot{V}O_2$ and metabolic cost by normalizing the sum of pull and kick data, a method that has never been employed. Results show that, despite controlling the stroke and kick rate among conditions, the sum of pull and kick exceeded that of swim for velocity, $\dot{V}O_2$ and metabolic cost. Following the normalization process, the arms contributed ~62% of the velocity, utilized ~53% of the $\dot{V}O_2$ and were responsible for ~45% of the metabolic cost. Implementation of the testing protocol utilized in the present study could be used to assess specific energetic adaptations in the upper- and/or lower-limbs following a period of pull and/or kick training. Subsequently, these observations can be used to inform pull and kick training practices.

The majority of previous research investigating the upper- and lower-limb contributions to swimming performance have utilized maximal intensity efforts,[1,2,19] with relatively few investigations using submaximal intensities.[3,4] The physiological ($\dot{V}O_2$, heart rate and [La⁻]) and biomechanical (velocity and stroke rate) data observed at the low and moderate intensities in the present study are similar to those reported by others investigating the effects of intensity

on $\dot{V}O_2$ kinetics,[12] 3D kinematics,[11] and arm coordination and stroke parameters.[20] Despite the fact previous research has investigated the limb contributions to swimming performance at maximal intensity efforts, pull velocity was lower than swim velocity by ~10% at the low intensity. However, a difference of ~17% was observed between swim and pull velocities at the moderate intensity. This large (ES=3.90) difference between the intensities may be explained by the controlled stroke rate between swim and pull efforts in the present study compared to previous investigations. The stroke rates statistically differed between swim and pull (1.8% difference) at the moderate intensity in the present study, however a difference of less than 3.3% is within the typical error of measurement and is unlikely to have had a meaningful influence on arm-stroke parameters and performance.[21] While $\dot{V}O_2$ in the pull and kick trials was expected to be lower than the swim trial due to reduced velocities, the greater relative difference between swim and pull $\dot{V}O_2$ at the moderate intensity (~25.5%) compared to the low intensity (~7.3%) was not anticipated. Considering the relative velocity difference was also greater at the higher intensity, it is likely that $\dot{V}O_2$ responded proportionately.

While swimming intensity influenced the relative velocity and $\dot{V}O_2$ difference between swim and pull, the same result was not observed between swim and kick velocity, with kick velocity ~45% lower than swim velocity, regardless of intensity. This velocity difference is higher than previously reported (e.g. ~40%,[1] ~30%,[22] ~25-30% [23]), most likely due to the controlled kick rate in the present study. Without the control of kick rate during kicking efforts, swimmers may choose to kick at a faster rate than what was used during the swimming efforts, thus producing more propulsive actions over a given distance, resulting in a kicking velocity closer to swim velocity. Additionally, when kicking with a high frequency, the observed body position would be more hydrodynamic in comparison to kicking with a low frequency, thereby resulting in lower frontal surface area and greater propulsion. The role of the kick would also shift from being primarily responsible for buoyancy and balance at a low velocity, to a

relatively greater contribution to propulsion at a higher velocity. The relatively larger variance in the kick rates compared to the stroke rates used by swimmers in the swim trials is likely a reflection of the tendency for swimmers of different distance specialization inheriting different self-selected kick rates. The majority of participants specialized in events ≤ 100 m, while only two participants specialized in distance events ≥ 800 m; this uneven distribution of distance specialization among participants may have influenced the variance in self-selected kick rate.

Metabolic cost of pull and kick has not previously been expressed relative to swim data; most studies compare $\dot{V}O_2$ only.[4,5] In the present study, the metabolic cost of the kick expressed relative to swim was ~100% at the moderate intensity and was greater than 100% ($115.9 \pm 46.7\%$) at the low intensity, indicating that the kick had a higher metabolic demand despite being significantly slower than the swim. By controlling the kick rate during the kick trials, participants were required to kick with a frequency that may have been much slower than those typically used during kick sets in training, particularly for the swimmers (N=5) who used a two- or three-beat kick during the swim trials. As such, the efficiency with which the kick trials were completed may have been compromised due to the slower kick rates being less familiar to participants. Furthermore, a hydrodynamic body position is typically maintained by the kick during whole body swimming.[24] However, because the kick rates were quite slow, an increase in the kick depth was observed, but not quantified, in comparison to the kick depths during the swim trials, possibly resulting in a sub-optimal body position. With a poor body position, increased frontal surface area, increased drag forces and an increased metabolic cost are typically observed.[25] Previous research[7] has identified kick depth to have minimal impact on the internal mechanical power demands during whole body front crawl swimming and barefoot flutter kicking. However in these analyses, participants were able to use a self-selected kick rate. Thus it is likely that the kick pattern was inherently economical with reduced depth of the kicks, minimizing the internal mechanical power and metabolic cost. An increase in the intra-

cyclic velocity variation (IVV) and an imposition of an inefficient coordination pattern may have also been present during the kick trials considering the upper-limbs, which are generally considered to be the primary velocity generators, were restricted during the kick trials. If the IVV and coordination style were negatively affected by the absence of the upper-limb movements, there would have been a greater metabolic cost during the kick trials.

Despite controlling the stroke and kick rates among the testing conditions, the sum of pull and kick velocity, $\dot{V}O_2$, and metabolic cost still exceeded swim velocity, $\dot{V}O_2$, and metabolic cost. By controlling the stroke and kick rates, it was expected that the sum of pull and kick data would more closely align with swim data than previously reported,[4,5] as these parameters directly influence velocity[26] and metabolic cost.[7] Rather, it is evident that even when the stroke and kick rates are controlled among testing conditions, other factors (e.g. kinetic energy losses, drag forces, neuromuscular alterations, body position changes, and IVV) are likely to explain the significant differences observed in velocity, $\dot{V}O_2$ and the metabolic cost. Thus, utilizing the sum of pull and kick data to draw conclusions on the relative contributions of the upper- and lower-limbs is likely to be misleading. Following normalization of the present data, the upper-limbs were still responsible for the majority (~62%) of the velocity production. Despite being the dominant propulsion generators and utilizing a smaller portion of muscle mass, the normalized data indicate that the upper-limb movements are associated with a lower metabolic cost than the lower-limb movements. Consequently, prescribing training sets with the aim of decreasing the energy cost of the kick would result in more energy being available for the upper-limbs to produce the propulsive forces.

Practical Applications

The protocol utilized in the present study could be implemented in high performance training environments for identification of individual athlete velocity and metabolic contributions of the upper- and lower-limbs. Identification of individual upper- and lower-limb

contributions and associated energetic demands can help the coach, athlete and scientist to detect potential weaknesses in the efficiency of the upper-limbs or lower-limbs to produce velocity with minimal energy cost, thus informing targeted training practices. Furthermore, implementation of this testing protocol before and after a pull or kick training block will enable scientists to identify how the velocity contributions and/or metabolic cost of the upper- and lower-limb actions have responded to the training program. By obtaining insight into the relative contributions of the upper- and lower-limbs to velocity and understanding what proportion of the total available energy is used by limbs during whole body swimming, coaches can make informed decisions regarding the prescription of pull and kick training. Other potential applications from this research could involve the monitoring of stroke and kick rate during training efforts; this information could be used for subsequent training prescription for pull and kick sets. Waterproof accelerometers may provide a useful means of obtaining kick rate data when implementing this training strategy.

While stroke and kick rate were controlled throughout the pull and kick trials, the breathing frequency was unable to be controlled among the trials and as a result, small differences were observed in the breathing frequencies between the swim and kick trials at the moderate intensity. It is possible that differences in breathing frequency could influence the $\dot{V}O_2$ and metabolic cost, however the extent to which these differences have the potential to impact the data are unknown. It must be emphazised that only submaximal intensities were explored in the present study, thus it is still unknown whether the metabolic demands and velocity production of the upper- and lower-limbs during maximal swimming vary from the contributions reported here. As the size of the pull buoy used in the pull efforts in this study was very small (adding 12 N of buoyancy), the relative contributions may vary slightly when larger pull buoys are used, which is often the case during swimming training. It is possible that metabolic energy was used by the lower-limbs in the push-off in each turn. While this energy

was not accounted for in the data analysis, it is postulated that the energy expended by the lower-limbs in the push-off would be consistent among all three testing conditions, and therefore the subsequent influence on results would be minimal. Finally, it is likely that the upper- and lower-limbs are performing isometric work during the kick and pull trials, respectively. Due to restrictions in methodology, the energy used in these situations cannot be quantified. However, the portion of energy that would be utilized in these situations could be considered minimal in comparison to the energy utilized for moving the upper- and lower-limbs through the stroke-cycle and kick-cycle, respectively.

Conclusion

Normalizing the pull and kick data relative to the swim trial demonstrates that the legs contribute more to swimming velocity than previously reported. After normalization the upper- and lower-limbs appear to contribute equally to the $\dot{V}O_2$ during whole body swimming, with the upper-limbs using this energy more effectively.

Acknowledgments

Conflict of interest

The authors report no conflicts of interest.

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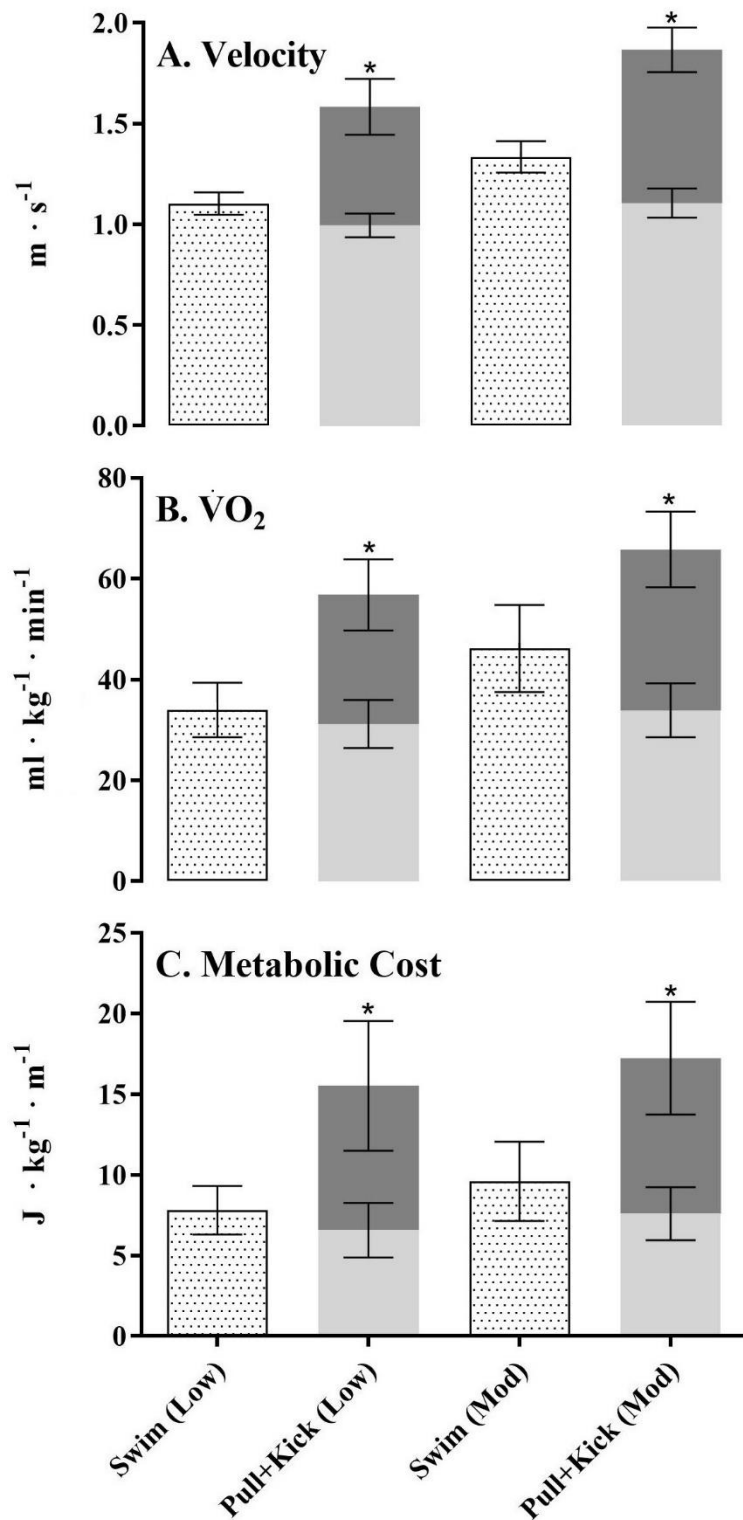
Figure 1. Group mean and standard deviation for (**A**) velocity (m · s^{-1}), (**B**) oxygen consumption (ml · kg^{-1} · min^{-1}) and (**C**) metabolic cost (J · kg^{-1} · m^{-1}) for swim (black dots), and the sum of pull (light grey) and kick (dark grey) for low and moderate intensities. * significantly different to the swim trial at the 0.05 level.
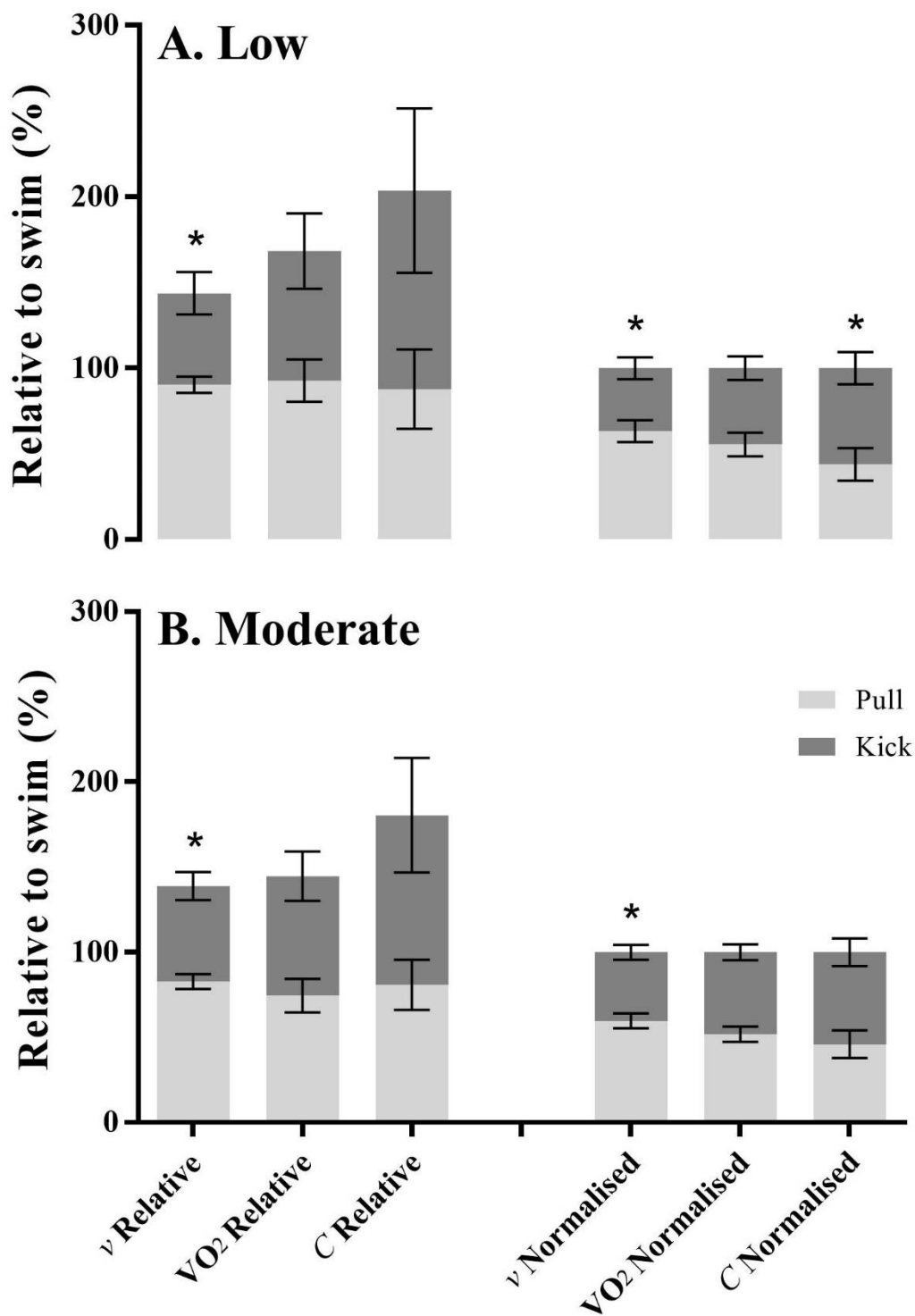
Figure 2. Velocity (*v*), oxygen consumption ($\dot{V}O_2$) and metabolic cost (*C*) of pull and kick swimming expressed relative to swim (%) and normalised to the swim trial as 100% (%) for the 'low' (A) and 'moderate' (B) intensities. Light and dark grey bars represent pull and kick data, respectively. * = significant difference (0.05) between pull and kick.

Table 1. Descriptive characteristics for male and female participants

	Age (y)	Mass (kg)	Height (cm)	Arm Span (cm)	Σ7SF (mm)	200 m PB (min:ss)
Male (n=11)	20.9 ± 2.1	78.8 ± 7.0	188.0 ± 4.3	194.8 ± 7.6	45.9 ± 9.5	1:53 ± 0:04
Female (n=9)	22.2 ± 3.9	65.7 ± 6.8	171.9 ± 6.1	175.2 ± 6.8	78.5 ± 19.0	2:00 ± 0:05
All (n=20)	21.5 ± 3.1	72.9 ± 9.5	179.9 ± 9.7	185.0 ± 12.3	62.2 ± 22.0	1:56 ± 0:06

Sum of 7 skinfold measures (Σ7SF); 200 m freestyle long course metres personal best time (200 m PB).

Table 2. Heart rate, ventilation and peak blood lactate concentration measured from the swim, pull and kick trials at low and moderate intensities. Data are displayed as mean ± SD.

	Low Intensity			Moderate Intensity		
	Swim	Pull	Kick	Swim	Pull	Kick
HR (bpm)	116±14	105±18	95±16*	155±17^	127±17*^	110±20*^
$\dot{V}$E (L · min^{-1})	60.8±14.3	56.3±11.5	44.1±16.4*	101.0±20.5	71.4±14.3*	60.2±16.8*
[La^-]$_p$ (mmol · L^{-1})	1.5±0.6	1.8±1.0	1.5±0.7	3.8±1.8^	2.4±1.3*^	1.8±0.9*

Heart rate (HR); Ventilation ($\dot{V}$E); peak blood lactate accumulation ([La^-]$_p$)

* = significantly different to the swim trial at the 0.05 level

^ = significantly greater than the 'low' intensity at the 0.05 level