ENERGETICS OF SWIMMING WITH HAND PADDLES OF DIFFERENT SURFACE AREAS

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ABSTRACT

Crocker, GH, Moon, JF, Nessler, JA, and Newcomer, SC. Energetics of swimming with hand paddles of different surface areas. *J Strength Cond Res* 35(1): 205–211, 2021—Hand paddles are one of the most common training aids used by the competitive swimmer, yet little is known regarding how hand paddle surface area affects the metabolic cost of transport (COT) while swimming. The purpose of this study was to determine how altering hand paddle size affects energy use during submaximal, front-crawl (i.e., freestyle) swimming. Twenty-six proficient, adult swimmers (13 men and 13 women) completed six 3-minute trials in a flume at a constant pace (102 $cm \cdot s^{-1}$; 1:38 per 100 m). Trials were performed in random order, using 1 of 5 pairs of hand paddles of different sizes or no paddles at all. Paddle surface areas were 201, 256, 310, 358, and 391 cm^2 per hand. Without paddles, COT, arm cadence, and distance per stroke were 7.87 ± 1.32 $J \cdot kg^{-1} \cdot m^{-1}$, 29.4 ± 4.9 min^{-1}, and 2.13 ± 0.34 m, which corresponded to a rate of oxygen consumption ($\dot{V}O_2$) of 23.3 ± 3.7 $ml \cdot kg^{-1} \cdot min^{-1}$ and a heart rate (HR) of 118 ± 17 $b \cdot min^{-1}$. The use of larger hand paddles decreased COT, cadence, $\dot{V}O_2$, and HR and increased distance traveled per stroke (all $p < 0.001$). However, the magnitude of the change of COT decreased as paddle size increased, indicating diminishing marginal return with increasing paddle surface area. The largest sized paddles increased COT per stroke compared with swimming without paddles ($p = 0.001$). Therefore, results from this study suggest that an optimal hand paddle size exists (210–358 cm^2) for proficient, adult swimmers, which reduces COT without increasing COT per stroke.

KEY WORDS cost of transport, efficiency, aquatics, ergogenic aids

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INTRODUCTION

Hand paddles are common training tools for competitive swimmers. Most swim coaches instruct their swimmers to use hand paddles during training, despite limited evidence on how wearing hand paddles alters swimming energetics (9,14) and a lack of research in optimal sizing of hand paddles. In addition, many manufacturers produce hand paddles in various shapes and sizes, yet these designs are based largely on anecdotal evidence. This lack of empirical evidence on how different sized hand paddles affect swimming efficiency may lead to improper sizing of hand paddles, which may slow the swimmer's progression and may lead to shoulder injuries (5,10).

Optimal hand paddle size may vary among individuals, and this variation may be based on a number of personal characteristics, including body size, experience, proficiency, and other anthropometric measurements. Although there has been little scientific investigation into these factors to date, an argument can be made for the influence of an individual's anthropometric characteristics on optimal hand paddle size. Anthropometric measurements have been shown to affect cost of transport (COT; the energy required to move 1 kg of body mass 1 m) in both swimming (2) and running (1,11,13). When comparing swimming with running, COT for swimming is greater than COT for running the same distance (12). Therefore, factors that alter swimming economy may have a relatively larger effect and greater importance in a competitive swimmer when compared with factors that improve running economy in a competitive runner. This is particularly relevant to the use of hand paddles, as previous research has shown that swimmers with larger propelling surface areas (i.e., larger hands, forearms, and feet) have reduced COT in swimming compared with those with smaller propelling surface areas (6).

Hand paddles artificially increase the propelling surface area of the swimmer's hand and reduce COT while swimming (9,14). By definition, swimmers with lower COT have lower rates of energy expenditure (EE) relative to their body mass compared with less efficient swimmers at the same swimming velocity. Previous research has reported that wearing hand paddles increases swimming efficiency through either a reduction in the swimmer's rate of oxygen consumption ($\dot{V}O_2$) at the same

Table 1. Demographics, proficiency, training amount, and swimming history for the subjects in this study.*†

	N	Age (y)	Height (cm)	Mass (kg)	BMI ($kg \cdot m^{-2}$)	500-yd time	Volume ($h \cdot wk^{-1}$)	HS (%)	COL (%)	Coached workout (%)	Paddles (%)
Men	13	38.4 ± 11.6	182 ± 5	88.3 ± 10.3	26.7 ± 3.5	5:34 ± 0:20	4.8 ± 2.1	69	38	92	62
Women	13	39.2 ± 12.0	169 ± 5	64.7 ± 11.7	22.5 ± 3.4	6:03 ± 0:48	4.4 ± 2.0	77	69	77	69
Total	26	38.8 ± 11.6	176 ± 8	76.5 ± 16.2	24.6 ± 4.0	5:48 ± 0:39	4.6 ± 2.0	73	54	85	65

*BMI = body mass index; HS = high school; COL = college.
†Values reported are mean values (*SD*). Height and mass were measured. Subjects self-reported their current 500-yd freestyle time, current training volume, whether they swam on their high-school or college swim teams, whether they currently attend a coached workout (United States Masters Swimming or equivalent), and whether they currently use hand paddles during training.

swimming speed or an increase in swimming velocity at the same $\dot{V}O_2$ (9,14). However, these studies are limited because they only compare one size of hand paddles to wearing no paddles at all. Therefore, based on previous research, it is difficult to determine how altering the size of the swimmer's hand paddles affects their COT.

The primary purpose of the present study was to determine how the energetics of submaximal front-crawl (i.e., freestyle) swimming change across 5 different sized, but similarly shaped, hand paddles. We hypothesized that larger hand paddles will reduce COT by increasing distance per stroke and slowing arm cadence at the same swimming speed. The secondary purpose was to determine if an individual's anthropometric measurements could predict the hand paddle size that minimizes COT (i.e., optimizes swimming efficiency). We hypothesized that swimmers with larger hands and longer forearms (i.e., upper-body propelling surface areas) would swim most efficiently with larger paddles than those with smaller hands and shorter forearms.

Methods

Experimental Approach to Problem

This study characterized how altering hand paddle size affects the energetics of front-crawl swimming. This was accomplished by asking athletes to swim in a flume at a constant velocity while wearing 1 of 5 different sized hand paddles and without paddles. The most efficient paddles would be the pair that resulted in the lowest COT ($J \cdot kg^{-1} \cdot m^{-1}$). Anthropometric measures were taken to assess whether any of these measurements correlated with the most efficient size hand paddles for the cohort of swimmers. This experimental approach allowed us to describe how COT changes among hand paddles and relate optimal hand paddle size to anthropometric measurements, which would aid in sizing hand paddles for the competitive swimmer.

Subjects

Twenty-six adult, masters-level swimmers (13 men and 13 women) participated in this study. The inclusion criterion was the ability to swim for 3 minutes at a 1:38 pace per 100 m (1:30 pace per 100 yd) without paddles, which limited subjects to only proficient, experienced swimmers (Table 1). Subjects were swimming 4.6 ± 2.0 $h \cdot wk^{-1}$ at the time of the study and ranged in age from 21 to 59 years old (men, 38.4 ± 11.6 years old; women, 39.2 ± 12.0 years old). The male subjects were 182 ± 5 cm tall and weighed 88.3 ± 10.3 kg. The female subjects were 169 ± 5 cm tall and weighed 64.7 ± 11.5 kg. These height and mass measurements corresponded to body mass indexes of 26.7 ± 3.5 and 22.5 ± 3.4 $kg \cdot m^{-2}$ for men and women, respectively. The mass, height, and age of subjects

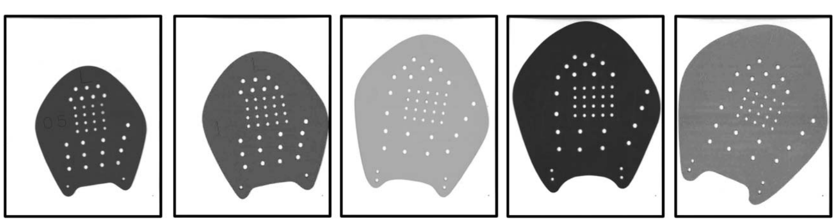

Figure 1. Digital scans of the hand paddles used in this study. For scale, each rectangle box represents an 8.5 × 11" (21.6 × 27.9 cm) sheet of paper. Hand paddle surface areas were 201, 256, 310, 358, and 391 cm^2.

Figure 2. The custom built snorkel used for this study. Subjects wore a nose clip and breathed through a mouthpiece connected to a 2-way nonrebreathing valve that was affixed to the subject's forehead using an aluminum bracket. A fin was mounted to the base of the snorkel to stabilize the snorkel in the water.

were measured standard deviation. Subjects were informed of the risks and benefits of the study and then gave written informed consent to participate. The California State University, San Marcos Institutional Review Board (protocol #813366) approved this study.

Procedures

Before the experimental protocol, subject's height, mass, and wingspan and the length of their leg, torso, forearm, and hand were measured. Leg length was measured as the vertical distance from the greater trochanter to the floor. Torso length was defined as the vertical distance from the acromioclavicular joint to the greater trochanter. Forearm length was measured as the distance between the elbow and the wrist measured during hand flexion. Hand length was measured as the distance from the wrist to the longest finger also measured during hand flexion. Length measurements were made using a cloth measuring tape or a 6-ft measuring stick. Digital photographs (iPhone 6; Apple, Cupertino, CA) of each subject's right hand and a reference ruler were acquired for measurements of surface area using ImageJ software (National Institutes of Health).

Commercial, two-dimensional (i.e., flat) hand paddles were used for this study (Strokemakers, Scottsdale, AZ sizes 0.5, 1, 2, 3, and 4). Digital images of the right-hand paddle were acquired using a scanner (HP Inc., Deskjet 3050, Palo Alto, CA) at 300 pixels per inch (Figure 1), and ImageJ software (National Institutes of Health, Bethesda, MD) was used to determine paddle surface area. Right and left paddles were mirror images of each other, and each paddle had 38–45 holes depending on the size (larger paddles had more and larger holes). Surface area measurements factored out the holes in each paddle (i.e., paddle surface area would have been greater had the surface areas of each hole been included in the measurement). However, some holes on paddles were covered by the subject's hand and others anchored the elastic straps that held the paddles to the subject's wrist and third finger.

The entire study was conducted in a 4.88 × 2.74-m (16 × 9-ft) swimming flume (Endless Pools Elite, Aston, PA). The water depth was 1.14 m (45 in). Subjects swam in the flume using a commercial swimming snorkel (Speedo, Hydralign Center Snorkel, Nottingham, United Kingdom) to warm-up and to become familiar with flume swimming. This warm-up period lasted for at least 3 minutes but not longer than 6 minutes. During the study, subjects wore a snorkel fabricated from a 2-way nonrebreathing valve (Hans Rudolph, Shawnee, KS; "F" shape 2750), copper pipes, and plastic connectors (Figure 2). Respiratory valves used in swimming studies have been shown to have low air-flow resistance and small dead space, without affecting the swimmer's total body drag (15). A small, rigid fin was fabricated and attached to this snorkel to stabilize the snorkel and reduce side-to-side head/snorkel movement. Expired gas was collected and analyzed with a metabolic cart (ParvoMedics, TrueOne 2400, Sandy, UT) via 15′ of tubing suspended above and in front of the swimmer. Heart rate (HR) was measured using a chest strap and watch (Polar Electro, RX5,

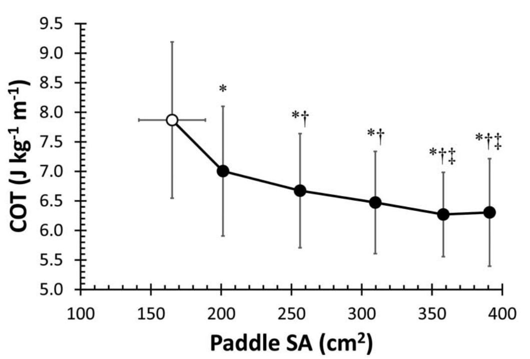

Figure 3. Cost of transport (COT) vs. hand paddle surface area (SA). Values reported are mean ± *SD*. The open circle denotes swimming without hand paddles and closed symbols denote the 5 different size hand paddles. The mean hand SA was 165 cm^2, and the horizontal error bars denote *SD* for hand size among subjects. *Denote significantly different from without paddles; †denote significantly different from smallest (201 cm^2) hand paddles; ‡denote significantly different from next smallest (256 cm^2) hand paddles.

Kempele, Finland). Subjects were also given 1–2 minutes to swim in the flume to become familiar with the experimental snorkel setup before the first experimental trial.

Swimmers were fitted with 2 buoys (Sporti, Pull Bouy, Esbjerg, Denmark), one between their thighs and the other between their ankles. The ankle buoy was strapped between their ankles using an ankle strap (Finis, Pulling Ankle Band, Livermore, CA), and the thigh buoy was held in place through adduction of the swimmer's legs. The experimental protocol consisted of 6 rounds, each of which included 3 minutes of seated rest followed by 3 minutes of swimming. The subjects performed each swimming bout with 1 pair of 5 different sized hand paddles or without paddles (6 trials total) at a constant pace ($1.02\ m\cdot s^{-1}$; 1:38 per 100 m; 1:30 per 100 yd) in the flume. The order of the 6 trials was randomized for each subject. Subjects reported their rating of perceived exertion and shoulder pain on a 0–10 scale immediately after each swim. For this scale, "0" corresponds to no pain/fatigue, "5" is moderate pain/fatigue, and "10" is the worst pain/fatigue possible.

A flowmeter (JDC Electronics Flowatch Flowmeter) constantly measured water speed during the experimental protocol. The metabolic cart and HR monitor measured $\dot{V}O_2$, respiratory exchange ratio (RER), and HR in real time and recorded values to a PC computer at 5-second intervals. The rate of EE was calculated from the average $\dot{V}O_2$ and RER measurements for the last minute of each trial. Dividing EE by the constant swimming speed ($1.02\ m\cdot s^{-1}$) determined COT. The average values for the last minute of each 3-minute swim were used for analyses. Each trial was video recorded at 30 frames per second using an underwater camera (GoPro Hero 4, San Mateo, CA). Arm cadence was determined from these videos as the time it took for the swimmer's right arm to complete 10 cycles. Distance traveled with each arm cycle was calculated as the constant swimming speed ($1.02\ m\cdot s^{-1}$) divided by arm cadence. The energy expended with each arm stroke (COT/stroke) was calculated as EE divided by arm cadence.

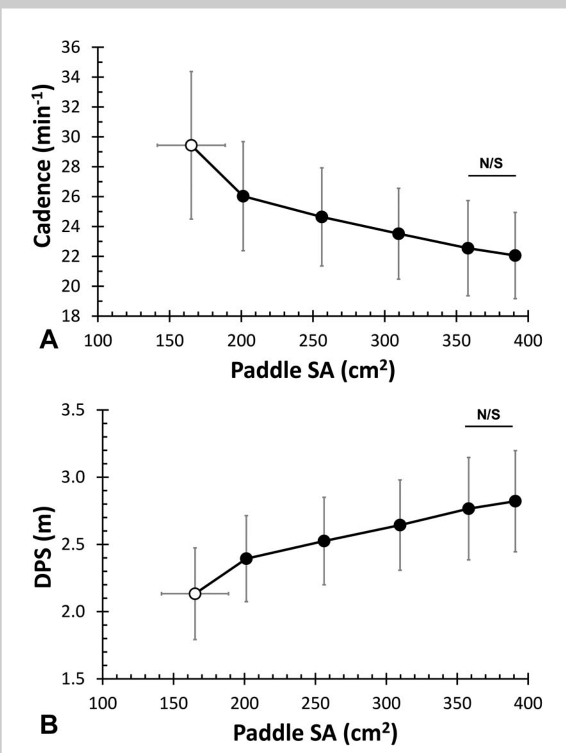

Figure 4. Arm-stroke cadence (A) and the distance traveled per arm stoke (DPS; panel B) vs. hand paddle surface area (SA). Values reported are mean ± *SD*. The open circle denotes swimming without hand paddles and closed symbols denote the 5 different size hand paddles. The mean hand SA was 165 cm^2, and the horizontal error bars denote the *SD* for hand size among subjects. For both panels, all trials differed from all others with the exception of the 2 largest paddles (N/S denotes "not significant").

Statistical Analyses

Values reported are mean values and *SD* for each pair of hand paddles and without paddles. Repeated-measures analysis of variance was used to determine whether significant differences existed among hand paddles and Bonferroni's multiple pairwise comparison procedure to compare between 2 paddles. Pearson's correlation coefficient was used to determine relationships between anthropometric measurements and optimal hand paddle size or COT. Forward stepwise linear regression was used to determine which independent variables significantly predicted COT. The alpha value for all tests was 0.05. All statistical analyses were performed in Microsoft Excel, Redmond, WA or IBM SPSS Statistics for Windows, Armonk, NY, version 20.

Results

The surface areas of the hand paddles used in this study were 201, 256, 310, 358, and 391 cm^2. One female swimmer was

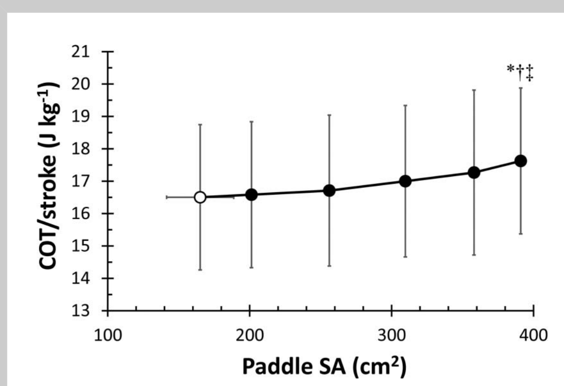

Figure 5. Cost of transport per arm stroke (COT/stroke) vs. hand paddle surface area (SA). Values reported are mean ± *SD*. The open circle denotes swimming without hand paddles and closed symbols denote the 5 different size hand paddles. The mean hand SA was 165 cm^2, and the horizontal error bars denote the *SD* for hand size among subjects. *Denote significantly different from without paddles; †denote significantly different from smallest (201 cm^2) hand paddles; ‡denote significantly different from the next smallest (256 cm^2) hand paddles.

TABLE 2. Mean values (*SD*) of anthropometric measurements for the subjects in this study.*

	Men ($N = 13$)	Women ($N = 12$)	Total ($N = 25$)
Leg length (cm)	92.9 ± 4.6	86.9 ± 3.1	90.0 ± 4.9
Torso length (cm)	58.5 ± 2.9	53.6 ± 4.3	56.2 ± 4.4
Forearm length (cm)	29.9 ± 1.3	27.7 ± 1.1	28.8 ± 1.7
Hand length (cm)	20.1 ± 1.2	18.5 ± 1.0	19.3 ± 1.3
Hand width (cm)	9.9 ± 0.4	8.6 ± 0.5	9.3 ± 0.8
Hand SA (cm^2)	184 ± 14	147 ± 13	166 ± 23
Wingspan (cm)	183 ± 6	169 ± 7	176 ± 10

*SA = surface area.

omitted because of technical difficulties during her measurements; therefore, 25 swimmers (13 men and 12 women) were used for analyses. Mean $\dot{V}O_2$, RER, and HR were 23.3 ± 3.7 $ml \cdot kg^{-1} min^{-1}$, 0.90 ± 0.07 and 118 ± 17 $b \cdot min^{-1}$, respectively, for all swimmers without hand paddles. Cost of transport averaged 7.87 ± 1.32 $J \cdot kg^{-1} \cdot m^{-1}$ for all subjects swimming without hand paddles and decreased with increasing paddle size (Figure 3). All paddles significantly lowered COT compared with swimming without hand paddles. However, the magnitude of the change in COT decreased as paddle size increased–COT decreased 0.86 $J \cdot kg^{-1} \cdot m^{-1}$ between the smallest paddles and no paddles, whereas COT remained unchanged between the 2 largest paddles.

Arm cadence averaged 29.4 ± 4.9 strokes per minute without paddles and decreased when swimming with larger hand paddles (Figure 4A). Arm cadence differed significantly among all paddles with the exception being between the 2 largest paddles. Among the 5 paddles, there was a linear decrease in arm cadence with increasing hand paddle surface area ($r = -0.997$; $p < 0.001$). The difference in cadence between no paddles and the smallest pair of hand paddles was larger than any difference among paddle sizes. Distance traveled per arm stroke averaged 2.13 ± 0.34 m without paddles and increased with increasing paddle surface area to a maximum of 2.82 ± 0.38 m with the largest paddles (Figure 4B). Similar to arm cadence, there was no difference in distance per stroke between the 2 largest paddles.

The energy expended with each arm stroke without hand paddles was 16.5 ± 2.2 $J \cdot kg^{-1}$. Only the largest sized hand paddle significantly increased the energy expended with each arm stroke compared with swimming without paddles (Figure 5). The energy cost per arm stroke with the largest paddles was 17.6 ± 2.3 $J \cdot kg^{-1}$.

Optimal paddle size was determined as the paddle size that resulted in the lowest COT for each individual. More than half of the swimmers (18 of 25; 72%) swam most efficiently with one of the largest 2 pairs of hand paddles, whereas none of the individuals were most efficient with the smallest size paddles or without paddles. The remaining 7 subjects (28%) were most efficient with one of the remaining 2 paddles. No differences existed between shoulder pain or rating of perceived exertion among hand paddles. For all subjects wearing all paddles, the highest reported shoulder pain was 5 and the highest rating of perceived exertion was 6 on a 0- to 10-point scale.

Anthropometric measurements for the 25 subjects are in Table 2. Although none of the anthropometric measurements were directly correlated with optimal paddle size, subjects who were heavier ($r = -0.429$; $p = 0.023$) and those with a higher body mass index (BMI) ($r = -0.454$; $p = 0.013$) had lower COT when swimming with their most optimal sized hand paddles. Comparison among all subjects swimming without paddles showed that heavier individuals were more efficient swimmers as they had lower COT (Table 3). Although many anthropometric variables correlated with lower COT, none significantly improved the ability to predict COT once the body mass (the strongest predictor) was included in the forward stepwise regression model.

TABLE 3. Correlation analysis for the subject demographics and anthropometrics with cost of transport ($J \cdot kg^{-1} \cdot m^{-1}$) for all 25 subjects (13 male and 12 female subjects) swimming without hand paddles.*†

	r	*p*
Mass	−0.628‡	0.001
BMI	−0.611‡	0.001
Hand length	−0.578‡	0.002
Torso length	−0.557‡	0.004
Hand SA	−0.535‡	0.006
Hand width	−0.474‡	0.017
Wingspan	−0.471‡	0.017
Height	−0.427‡	0.033
Age	0.318	0.121
Forearm length	−0.203	0.331
Leg length	−0.202	0.333

*BMI = body mass index; SA = surface area.
†Variables are ranked in order from strongest to weakest correlation.
‡Denote significant relationships with cost of transport.

Discussion

The primary purpose of this study was to determine how COT changes in swimmers wearing 5 pairs of different sized but similarly shaped hand paddles compared with swimming without hand paddles. It was hypothesized that larger hand paddles would reduce COT by increasing distance per stroke and slowing arm cadence during constant velocity swimming. Results from this study show that COT was reduced when swimmers wore hand paddles of any size (Figure 3). Swimming with larger hand paddles also resulted in slower arm cadence and increased distance traveled with each arm stroke (Figure 4). Taken together, these data support the hypothesis that COT is reduced in conjunction with slower arm cadence and increase distance per stroke when wearing larger hand paddles. These findings corroborate with previous research showing decreased COT when swimming with hand paddles compared with swimming without paddles (9,14). However, the present study is the first to show how COT changes over a range of hand paddle sizes (201–391 cm^2).

We also noted a diminishing marginal return for COT with the increase in hand paddle surface area. The smallest hand paddles (201 cm^2) reduced COT compared with wearing no hand paddles, whereas there were no differences in COT between the 2 largest hand paddles (358 and 391 cm^2; Figure 3). The manufacturer produces one smaller and one larger pair of hand paddles than the range of paddles used in this study. The smallest size was not used here because the surface area of those paddles would have been too similar to the size of the swimmers' hands. For reference, subjects' hand surface areas ranged from 127 to 204 (165 $\pm$ 24) cm^2. However, the present study found the greatest increase in swimming efficiency from no hand paddles to the smallest size hand paddles. Therefore, it would have been informative to use smaller paddles than the smallest size hand paddles used in this study. Future research should compare COT between wearing very small paddles to swimming without paddles.

We also hypothesized that swimmers with larger pulling surface areas (i.e., longer forearms and larger hand surface areas) would have a larger optimal hand paddle size than those with smaller pulling surface areas. We defined optimal hand paddle size as the pair of hand paddles that had the lowest COT for each individual. This hypothesis was not supported as no anthropometric measurement correlated with optimal hand paddle size. However, swimmers with a higher BMI had a reduced COT when swimming with their optimal size hand paddles. Body mass, but not height, was correlated with lower COT, indicating that heavier individuals swim more efficiently when wearing their optimal size hand paddles. In addition, many anthropometric measurements correlated with COT when swimming without paddles. However, multiple linear regression showed that COT can be best predicted by body mass alone, independent of the anthropometric measurements in this study. Similarly, comparison of COT among marine mammals show that heavier mammals have lower COT (12,16).

All swimmers wore buoys between their thighs and ankles that floated their legs and prevented them from kicking. A previous study altered arm cadence in swimmers without paddles or buoys and found that swimmers increased their kick rate and propulsive force per kick when arm cadence was slowed with a metronome (8). One can speculate that if swimmers in the present study were allowed to kick, they may have changed their kick rate or propulsive force per kick to compensate for different size hand paddles. The use of a pull buoy and ankle strap is consistent with previous studies using hand paddles (9,14).

Hand paddles have also been researched during sprint performance and have been shown to reduce arm cadence during maximal intensity swimming (4,7). In addition, biomechanical analyses have shown that the resultant force in both pull and push phases of the arm stroke are greater with large paddles (268 cm^2) but not with the small paddles (116 cm^2) compared with swimming without paddles during maximal intensity swimming (4). This finding corroborates with the present study in that only the largest size hand paddle (391 cm^2) significantly increased COT per stroke, suggesting an increased muscular work needed to pull and push the largest size hand paddles.

All subjects swam at the same velocity for all trials (1.02 $m\cdot s^{-1}$; 1:38/100 m [1:30/100 yd]) as opposed to scaling the velocity to each individual's ability. This constant speed was selected because it was fast enough to limit the subjects to only proficient swimmers, yet not too fast as to hinder our ability to recruit masters-level swimmers (3). Furthermore, the subjects needed to swim at a submaximal pace because indirect calorimetry only measures the energy expended via oxidative metabolism. Any energy from anaerobic metabolism would be missed by the metabolic cart and would make the swimmers appear to have a lower COT than in reality. Blood lactate concentrations (a byproduct of anaerobic metabolism) were not measured in this study. However, the metabolic cart calculated RER (the ratio of CO_2 produced to O_2 consumed), and it was less than 1.00 for all subjects with all paddles, except for 4 subjects who had RER values slightly above 1.00 only during the no hand paddles trial. For these individuals, we used an RER of 1.00 for COT determination, noting that the COT we report may be slightly less than their actual COT for these 4 individuals. However, this methodological consideration would not affect the conclusions from this study because the differences between any paddle size and no hand paddles would be slightly larger than we report; yet COT with all pairs of hand paddles were significantly different from without paddles. Subjects also reported their fatigue on a 10-point scale and range from 0 to 6 (2.6 $\pm$ 1.7) for the without hand paddle trials, suggesting submaximal (i.e., almost exclusively aerobic) exercise intensities.

The paddles used in this study were selected because they are flat (2D), commonly used by collegiate and masters-level swimmers, and come in a wide range of sizes. All sizes of the paddles are similarly shaped (Figure 1). Therefore, hand paddle size was the independent variable for this study. The range of hand paddle sizes used in this study was greater than those used in previous investigations on hand paddle use (4,7,9,14). The paddles in the present study also had holes that were not included in the surface area measurements. However, the swimmer's hands would obstruct some holes and, therefore, the size of their hands would affect how many holes were occluded. We know of no studies on the metabolic or biomechanical effects of the presence/absence of the holes in the hand paddles.

In summary, wearing larger hand paddles reduces COT by both reducing arm cadence and increasing distance per stroke at the constant swimming speed used in this study (1:38 per 100 m). We observed diminishing marginal return with increasing paddle size on the reduction in COT. Rather, it seems that COT is improved with hand paddles as small as 201 cm^2. The largest paddles tested here (391 cm^2) increase the metabolic cost per arm stroke compared with swimming without paddles, whereas paddles less than 356 cm^2 did not. No anthropometric measurements predicted the hand paddle size that resulted in the lowest COT for each individual. Results from this study may lead to a better understanding of sizing of hand paddles during swim training, possibly increasing rate of progression or reducing injury risk. However, future research is needed with smaller and larger hand paddles, paddles of different shapes, and at a range of swimming speeds.

Practical Applications

Hand paddles are one of the most commonly used training aids for the competitive, masters-level swimmer. The use of hand paddles reduces the energy cost of swimming compared with swimming without paddles with the greatest reduction in energy cost between the smallest sized paddles and no paddles. This result indicates that even very small paddles (210 cm^2) can increase distance per stroke, slow arm cadence, and reduce the energetic cost of constant velocity swimming. In general, paddles with surface areas in the range of 210–358 cm^2 seem well suited for male and female masters-level swimmers capable of swimming aerobically at a pace of 1:38 per 100 m (1:30 per 100 yd). However, no anthropometric measurements correlated with optimal hand paddle size, indicating sizing of hand paddles may be more complicated than simple anthropometric measurements.

Acknowledgments

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References

1. Anderson, T. Biomechanics and running economy. *Sports Med* 22: 76–89, 1996.
2. Chatard, JC, Lavoie, JM, and Lacourl, JR. Analysis of determinants of swimming economy in front crawl. *Eur J Appl Physiol Occup Physiol* 61: 88–92, 1990.
3. Ferreira, MI, Barbosa, TM, Costa, MJ, Neiva, HP, and Marinho, DA. Energetics, biomechanics, and performance in masters' swimmers. *J Strength Cond Res* 30: 2069–2081, 2016.
4. Gourgoulis, V, Aggeloussis, N, Vezos, N, Kasimatis, P, Antoniou, P, and Mavromatis, G. Estimation of hand forces and propelling efficiency during front crawl swimming with hand paddles. *J Biomech* 41: 208–215, 2008.
5. Hawkins, RJ and Kennedy, JC. Impingement syndrome in athletes. *Am J Sports Med* 8: 151–158, 1980.
6. Kjendlie, PL and Stallman, R. Morphology and swimming performance. In: *World Book of Swimming: From Science to Performance.* L Seifert, D Chollet, and I Mujika, eds. Hauppauge, NY: Nova Science Publishers, 2011. pp. 203–219.
7. López-Plaza, D, Alacid, F, López-Miñarro, PA, and Muyor, JM. The influence of different hand paddle size on 100-m front crawl kinematics. *J Hum Kinet* 34: 112–118, 2012.
8. McLean, SP, Palmer, D, Ice, G, Truijens, M, and Smith, JC. Oxygen uptake response to stroke rate manipulation in freestyle swimming. *Med Sci Sports Exerc* 42: 1909–1913, 2010.
9. Ogita, F and Tabata, I. Effect of hand paddle aids on oxygen uptake during arm-stroke-only swimming. *Eur J Appl Physiol Occup Physiol* 66: 489–493, 1993.
10. Richardson, AB, Jobe, FW, and Collins, HR. The shoulder in competitive swimming. *Am J Sports Med* 8: 159–163, 1980.
11. Saunders, PU, Pyne, DB, Telford, RD, and Hawley, JA. Factors affecting running economy in trained distance runners. *Sport Med* 34: 465–485, 2004.
12. Schmidt-Nielsen, K. Locomotion: Energy cost of swimming, flying, and running. *Science* 177: 222–228, 1972.
13. Scholz, MN, Bobbert, MF, van Soest, AJ, Clark, JR, and van Heerden, J. Running biomechanics: Shorter heels, better economy. *J Exp Biol* 211: 3266–3271, 2008.
14. Toussaint, HM, Janssen, T, and Kluft, M. Effect of propelling surface size on the mechanics and energetics of front crawl swimming. *J Biomech* 24: 205–211, 1991.
15. Toussaint, HM, Meulemans, A, de Groot, G, Hollander, AP, Schreurs, AW, and Vervoorn, K. Respiratory valve for oxygen uptake measurements during swimming. *Eur J Appl Physiol Occup Physiol* 56: 363–366, 1987.
16. Williams, TM. The evolution of cost efficient swimming in marine mammals: Limits to energetic optimization. *Philos Trans R Soc Lond B Biol Sci* 354: 193–201, 1999.