

Muscle power predicts freestyle swimming performance

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The purpose of this study was to determine the relationship between non-invasive laboratory measures of 'muscle power' and swim performance over sprint (50 m) and middle-distance (400 m) events. Twenty-two swimmers performed an upper and lower body Wingate Anaerobic Test (WAT) and a maximal sustained power output test (MPO) for the upper body. Peak power (*PP*) and mean power (*MP*) were determined for the WAT, while peak sustained workload (*WL_{peak}*) was determined for the MPO. Timed swims over 50 m and 400 m were undertaken by all swimmers during which the number of arm strokes per length was recorded. Highly significant relationships were found between sprint-swim speed (*S50*) and mean power of the arms (*MP_{arms}*) ($r = 0.63, P < 0.01$), between *S50* and mean power of the legs (*MP_{legs}*) ($r = 0.76, P < 0.001$) and between *S50* and the distance covered with each arm stroke (*DS*) ($r = 0.91, P < 0.001$). Multiple regression analyses revealed that WAT power indices for the legs did not significantly increase explained variance in *S50* above that of the arms. The relationship between *WL_{peak}* and *S400* was highly significant ($r = 0.70, P < 0.001$) and indicates the importance of arm power in the longer distance swim events.

Keywords: Anaerobic power, muscle power, performance prediction, swimming, Wingate Test

Recently a number of studies have emphasized the important role of 'muscular power' as a determinant of athletic performance¹⁻⁵. Correlations ranging from 0.71 to 0.90 have been reported between measures of short-term (<45 s) maximal upper body power and freestyle swimming speed⁶⁻⁹. With regard to running and cycling, it has been suggested that the primary variable that predicts endurance performance is the peak workload (or speed) an athlete can achieve during an incremental maximal test²⁻⁵.

The Wingate Anaerobic Test (WAT) has been utilized by a number of laboratories for the evaluation of short-term, high-intensity exercise^{7,10-12}. The validity and reliability of the WAT has been documented previously¹³. With respect to the rela-

tionship between this laboratory test and swimming performance, Inbar and Bar-Or⁷ found a correlation of -0.92 between mean power of the arms (*MP_{arms}*) and 25-m freestyle time in a small group ($n = 9$) of young swimmers. Recently, Hawley and Williams¹ reported highly significant relationships between *MP_{arms}* and swim speeds over 50 m ($r = 0.83, P < 0.001$) and 400 m ($r = 0.63, P < 0.01$) for male and female swimmers. To date only one study has assessed the relationship between the WAT for the lower body and swimming performance⁷.

We were interested in examining the role of muscle power and its relationship to swimming performance. Specifically, the aims of the current study were:

1. to assess the relationship between upper and lower body anaerobic power, as assessed by the WAT, and a 50-m sprint-swim performance;
2. to determine whether a combination of arm and leg power improves prediction of sprint-swim performance above that of arm or leg power alone;
3. to assess the relationship between the peak sustained workload (*WL_{peak}*) attained during a maximal sustained power output test (MPO) and swim performance over 400 m.

Materials and methods

Subjects and training

Twelve male and ten female swimmers participated in this investigation after giving informed consent in accordance with the guidelines outlined by the American College of Sports Medicine¹⁴. Swimmers were familiar with both physiological and anthropometric testing procedures, having served as subjects in several previous studies^{1,15,16}. Subjects had been training daily for the 3 months before this study, swimming on average 5000 m day⁻¹, 6 days a week. None of the subjects had participated in any formal strength-training programme for 6 months before investigation.

Physiological testing

Testing was undertaken over a 7-day period during the swimmers' competitive season. A mechanically braked Monark 818E cycle ergometer (Monark, Stockholm, Sweden), interfaced with an Apple IIE

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microcomputer, (Apple, Chicago, Illinois, USA) was employed for the lower body WAT. The warm-up protocol and determination of power outputs from the WAT have been described previously^{12,13}. The forces chosen for the lower body WAT were 0.070 kg kg⁻¹ body mass for males and 0.067 kg kg⁻¹ body mass for females¹⁷. For upper body testing a Monark 881E ergometer (Monark, Stockholm, Sweden) was interfaced with a microcomputer. Calculation of WAT indices for the upper body test and the warm-up protocol employed have been described elsewhere¹. Forces for the upper body WAT were 0.037 kg kg⁻¹ body mass and 0.029 kg kg⁻¹ body mass for males and females respectively¹⁰. The WAT data were not corrected for inertia of the flywheel¹⁸. However, power measurements were not initiated until swimmers had attained unresisted acceleration of the ergometer flywheel in accordance with the methodology of a previous study¹⁰.

The MPO consisted of arm cranking at 80 r.p.m. against a progressively increasing workload until volitional fatigue. The initial work rate was 24 W min⁻¹ for males and 16 W min⁻¹ for females. The power output was increased every 2 min by 16 W until subjects could no longer maintain a cadence of 70 r.p.m. For each test WL_{peak} was defined as the highest workload the subject completed. If a workload was not completed, WL_{peak} was determined from the following formula:

$$WL_{peak} (W) = WL_{com} + (t/120 \times \Delta WL) \quad (1)$$

where WL_{com} was the last workload which the subject completed for 120 s, t was the time(s) the final uncompleted workload was sustained and ΔWL was the final workload increment.

Subjects rested for 24 h before testing. During both the upper body tasks, subjects were instructed to remain seated, and during all laboratory tests they were given strong verbal encouragement.

Anthropometric data

Skinfold measurements were taken at the biceps, triceps, suprailiac, subscapular, mid-axilla, pectoral, abdominal, thigh and calf folds¹⁹. Lean body mass (LBM) and percentage body fat (% fat) were estimated from skinfold measurements²⁰. Arm length (AL) and leg length (LL) were also measured. AL was taken as the distance from acromion to stylium and LL was taken as the distance from trochanterion to sphyrium¹⁹.

Swimming performance

Timed swims were performed within 72 h of laboratory testing in a 25-m (short-course) pool. Subjects arrived at the pool and undertook a warm-up supervised by their coach. The 50-m time-trial was conducted first with a recovery period of 60 min before the 400-m swim. Subjects began the swim in the water with timing being started manually when their feet left the wall of the pool. Subjects were instructed to produce maximal effort. Three independent assessors recorded the swim times with the average of these being taken as representative of each

subject's performance. Times were subsequently converted to speeds (S) for the two swim distances. The number of strokes taken per length was also recorded in order to calculate the distance covered with each stroke (DS , m stroke⁻¹). Although this method overestimates DS by 4–5% due to the push off from the side of the pool²¹, this is a systematic overestimation which does not greatly influence subsequent comparisons between swimmers²². Therefore, in accordance with previous studies^{22,23} no attempt was made to derive a correction factor for DS . A stroke index (SI) was determined as previously described by Costill *et al.*²⁴.

Statistical analysis

Pearson product moment correlations and multiple linear regression analyses were performed using the computer software package SYSTAT (Systat, Evanston, Illinois). Results were considered significant where $P < 0.05$.

Results

The physical characteristics of the subjects are displayed in *Table 1*. With the exception of LBM there were no significant differences between male and female swimmers for the characteristics measured.

Table 2 shows the performance data for the 50-m and 400-m timed swims. Sprint-swim performances for 50 m ranged from 1.39 ms⁻¹ to 1.85 ms⁻¹ for males and from 1.42 ms⁻¹ to 1.79 ms⁻¹ for females, indicating a wide variation in sprint-swim ability. Both S50 and DS50 were significantly greater ($P < 0.05$) for males than females. There were, however, no significant differences with respect to S400 and DS400.

Table 3 displays the power output values for the upper and lower body WAT and MPO. Significant

Table 1. Descriptive characteristics of swimmers

Subjects	Age (years)	Body mass (kg)	LBM (kg)	Body fat (%)
Males ($n = 12$)	13.6(1.2)	54.4(7.6)	44.3(8.2)	18.6(4.9)
Females ($n = 10$)	13.2(1.9)	56.2(10.1)	41.9(6.6)	25.4*(4.1)

Values are mean(s.d.); LBM, lean body mass

*Significantly greater than for males, $P < 0.05$

Table 2. Performance characteristics of the sprint and middle-distance swims

Subjects	S50 (m s ⁻¹)	DS50 (m stroke ⁻¹)	S400 (m s ⁻¹)	DS400 (m stroke ⁻¹)
Males	1.69*(0.15)	1.26*(0.13)	1.34(0.12)	1.12(0.23)
Females	1.55(0.12)	1.11(0.13)	1.27(0.09)	1.08(0.07)

Values are mean (s.d.); S50, swim speed over 50 m; DS50, distance covered with each stroke during the 50-m swim; S400, swim speed over 400 m; DS400, distance covered with each stroke during the 400-m swim.

*Significantly greater than for females, $P < 0.05$

Table 3. Power outputs for the Wingate Anaerobic Test and the maximum sustained power output test

	Upper body			Lower body	
	PP	MP	WL _{peak}	PP	MP
Males	4.89*(0.59)	3.74*(0.36)	1.75(0.46)	10.75†(0.94)	8.26(0.97)
Females	3.65 (0.47)	2.82(0.29)	1.39(0.39)	9.51(0.96)	6.58(0.78)

All values, expressed in $W\ kg^{-1}$, are mean (s.d.) PP, peak power; MP, mean power; WL_{peak}, peak sustained workload

*Significantly greater than for females, $P < 0.001$

†Significantly greater than for females, $P < 0.01$

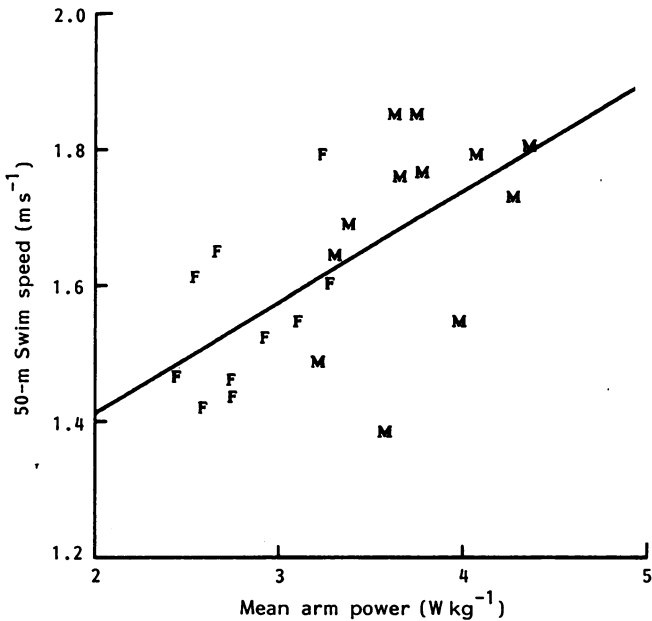


Figure 1. Relationship between sprint-swim speed (S50) and mean power of the arms (MP_{arms}) for male (M) and female (F) swimmers. $r = 0.63$; $y = 0.163x + 1.087$; s.e.e. = 0.121; $n = 22$

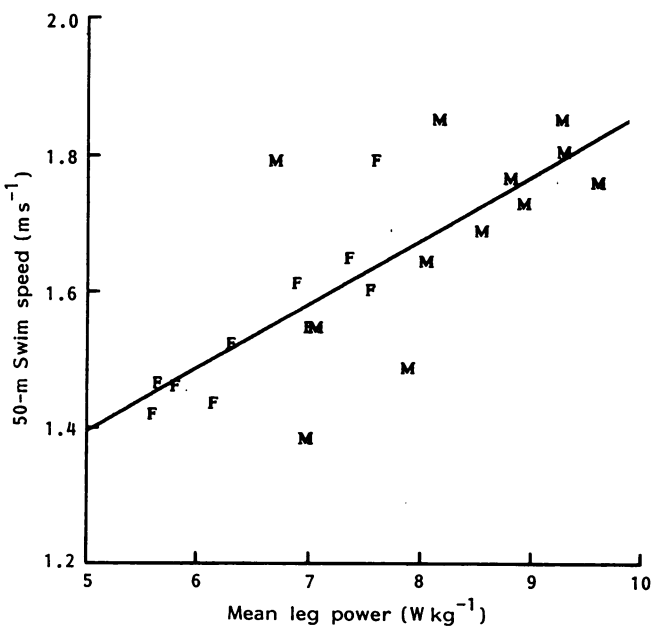


Figure 2. Relationship between sprint-swim speed (S50) and mean power of the legs (MP_{legs}) for male (M) and female (F) swimmers. $r = 0.76$; $y = 0.93x + 0.928$; s.e.e. = 0.100; $n = 22$

differences in power output were found between male and female swimmers for peak power of the arms (PP_{arms} ; $P < 0.001$), mean power of the arms (MP_{arms} ; $P < 0.001$), peak power of the legs (PP_{legs} ; $P < 0.01$) and mean power of the legs (MP_{legs} ; $P < 0.001$). There were no significant differences between male and female subjects with respect to WL_{peak}.

Figure 1 shows the relationship for S50 and MP_{arms} along with the associated regression equation, while Figure 2 displays the relationship between S50 and MP_{legs} . Multiple regression analysis revealed that WAT indices for the arms or the legs did not significantly increase the explained variance in S50 above that of each separately. Further, gender did not add significantly above WAT power indices in the prediction of sprint-swim speed and therefore single regression lines combining both males and females are displayed.

Step-wise multiple regression analysis revealed the best predictors of S50 were MP_{legs} , DS50 and AL ($r = 0.956$, $P < 0.001$; s.e.e. = 0.48).

Figure 3 displays the relationship between S400 and WL_{peak} for male and female subjects, along with the associated regression equation.

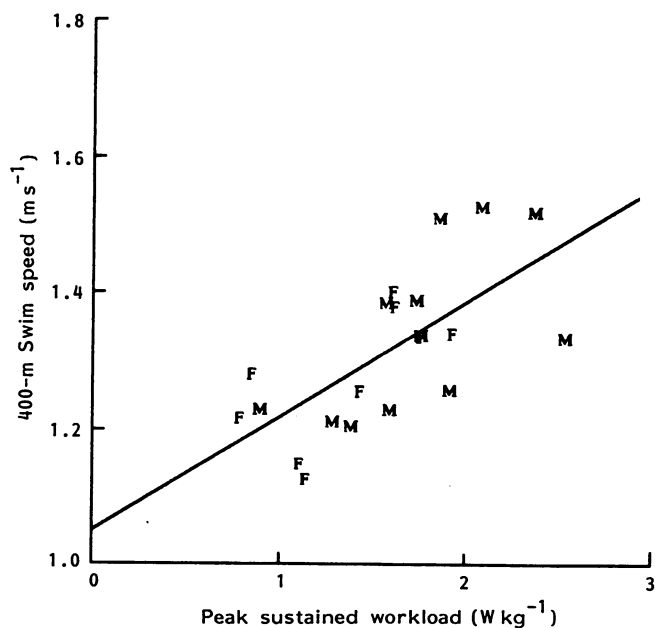


Figure 3. Relationship between middle-distance swim speed (S400) and maximal sustained workload (WL_{peak}) for male (M) and female (F) swimmers. $r = 0.70$; $y = 0.167x + 1.051$; s.e.e. = 0.086; $n = 22$

Discussion

This study shows that strong relationships exist between upper and lower body power output and both sprint (50 m) and middle-distance (400 m) freestyle-swim performance.

In the absence of longitudinal stature data, ancillary evidence of secondary sex characteristics and age of menarche, we cannot explain any variance in physiological and performance parameters which may be due to differences in the level of maturation of our swimmers¹⁹. Therefore, we have considered the data from the standpoint of the chronological age of our subjects only.

Our correlation of 0.63 between MP_{arms} and S50 is somewhat lower than previously reported^{1,7,15}. Further, Inbar and Bar-Or¹² found that for untrained children, anaerobic performance with the arms was 60–70% of that achieved by the legs; in the current study the corresponding figure was only 45%. Thus, there appears to have been a reduction in the ratio of arm to leg power in our subjects. This may, in part, explain why the relationships between the WAT power indices for the lower body and S50 were higher than those found for the upper body. The possibility also exists that the 'normal' arm:leg power ratio in untrained children¹² is different in swimmers.

Alternatively, the different ratio of arm:leg power found in the present study may be related to the long-distance swim-training our subjects were undertaking, which has a primary reliance on the arms²⁵ rather than the legs. As noted by Costill *et al.*²⁶, it is not uncommon for swimmers to experience a marked reduction in muscle power during periods of intense training, which can subsequently be reversed by a reduction in training volume.

Our correlation of 0.76 between MP_{legs} and S50 is also lower than the figure of 0.90 reported by Inbar and Bar-Or⁷. The discrepancy between the two correlations can probably be attributed to the different criterion swim distances to which power output was related. The study of Inbar and Bar-Or⁷ employed a 25-m sprint-swim, whereas a distance of 50 m was chosen for the current investigation. However, as noted previously¹, large subject numbers would be required to provide the statistical power necessary to detect small differences between correlation coefficients.

The highly significant relationship ($r = 0.70$, $P < 0.001$) found between WL_{peak} and S400 in the present study is notable. It has been suggested²⁻⁵ that the variable that best predicts endurance performance is the highest workload an athlete attains during a maximal test. Noakes *et al.*⁴ and Scrimgeour *et al.*⁵ found that for running, the peak treadmill speed achieved in a maximal test was a better predictor of performance than $\dot{V}O_{2max}$. Recently, Hawley and Noakes² reported a highly significant relationship ($r = 0.91$, $P < 0.001$) between the peak power a cyclist attained during an exhaustive laboratory cycling test and a 20-km cycle time-trial. Further, Costill *et al.*²⁴ report only a moderate relationship ($r = 0.43$) between a swimmer's time in an all-out 400 yard (365.8 m) swim, and $\dot{V}O_{2max}$. We have previously observed that the correlation between $\dot{V}O_{2max}$ deter-

mined during the MPO laboratory test and S400 is in the order $r = 0.42-0.48$ (Hawley *et al.*, unpublished observations), which is almost identical to the relationship found by Costill *et al.*²⁴ for $\dot{V}O_{2max}$ measured after a 400 yard maximal swim.

In our own preliminary studies we have noted that the fastest swimmers not only display high anaerobic power outputs but also high peak sustained power outputs, as determined by the WL_{peak} they achieve during a progressive, incremental maximal arm power test (Hawley and Williams, unpublished observations). In the present investigation the relationship between MP_{arms} and WL_{peak} was 0.55 ($P < 0.01$). Jones and McCartney²⁷ have previously reported a high relationship between $\dot{V}O_{2max}$ and total work output during 30 s of maximal isokinetic exercise. These workers suggested that 'changes in muscle function' could contribute to increases in maximal short-term work capacity evidenced after a period of training.

With respect to sprint-swimming speed and stroke mechanics, males were faster ($P < 0.05$) and covered a greater distance ($P < 0.05$) with each stroke than females. Correlations between DS50 and S50 were 0.93 for males and 0.82 for females. Other studies²²⁻²⁴ have indicated the importance of DS in determining a swimmer's speed.

The single best predictor of sprint-swim performance in the present study was the swimmer's stroke index (SI50; $r = 0.97$ for males, $r = 0.94$ for females). The SI ($S \times DS$) assumes that for a given speed the swimmer who has the greatest DS has the most efficient swimming technique²⁴. The SI is obviously sensitive to a swimmer's biomechanical and technical competence. Unfortunately, however, the SI cannot be considered an independent predictor of S50 since the derivation of this parameter incorporates S50.

With regard to middle-distance performance, there were no significant differences between males and females for S400 and DS400. Correlations between DS400 and S400 in the present study ($r = 0.42$ for males, $r = 0.43$ for females) are lower than those reported by Costill *et al.*²⁴. These workers found the single best predictor of swim performance over 400 yards (365.8 m) in male and female competitive swimmers was DS400 ($r = 0.88$). The best predictor of middle-distance swim performance in the present investigation was the peak workload the subject attained during the MPO test ($r = 0.70$, $P < 0.001$).

The relationship between S50 and S400 in the current study was strong ($r = 0.80$ for males, $r = 0.38$ for females), and illustrates that speed is still a large component of the 400-m event. Sharp *et al.*⁹ found an almost identical correlation ($r = 0.82$) between 25 yard (22.86 m) sprint velocity and 500 yards (457.2 m) time and suggested that 'arm power' was a necessary component for success in the longer distance event.

In summary, this study has demonstrated that significant relationships exist between laboratory measures of power and swim performance over both sprint and middle-distance events. Although our study cannot determine whether the relationship between our laboratory measures of power and swim performance are causal or merely coincidental, previous studies^{9,29} reveal that for the upper body

the relationship is likely to be causal²⁸. Further, previous investigations with swim-power tests have shown that small differences in muscle power are associated with measurable performance improvements in freestyle sprint-swimming²⁹⁻³¹. Therefore, swimmers in events up to 400 m may benefit from training which aims to improve arm and leg power. In those swimmers who possess a high level of arm and leg power, factors such as stroke mechanics may contribute more to the differences in performance seen between these individuals.

As the majority of individual swim events have a major reliance on anaerobic metabolism³², the necessity for large volumes (>10 000 m day⁻¹) of moderate intensity 'aerobic overload training' for these athletes must be seriously questioned. As recently noted by Costill *et al.*³³ 'it is difficult to understand how training at speeds that are markedly slower than competitive (race) pace for 3-4 h day⁻¹ will prepare the swimmer for the supramaximal efforts of competition'.

Taken collectively, the results of the current and other studies^{1,7,26,31} suggest that 'muscle power' is an important determinant of both sprint and middle-distance swimming performance. Although the mechanisms underlying the relationship between 'muscle power' and swimming performance cannot be explained by the current study, future investigations should focus on the examination of different training regimens and their influence on muscle contractility³. Such training studies will help elucidate those factors responsible for performance difference between individuals.

Acknowledgements

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