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# Elite swimmers do not exhibit a body mass index trade-off across a wide range of event distances

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There is a trade-off reflected in the contrasting phenotypes of elite long-distance runners, who are typically leaner, and elite sprinters, who are usually more heavily muscled. It is unclear, however, whether and how swimmers' bodies vary across event distances from the 50 m swim, which is about a 20–30 s event, to the 10 000 m marathon swim, which is about a 2 h event. We examined data from the 2012 Olympics to test whether swimmers' phenotypes differed across event distances. We show that across all swimming event distances, from the 50 m sprint to the 10 000 m marathon, swimmers converge on a single optimal body mass index (BMI) in men's and women's events, in marked contrast with the strong inverse relationship between BMI and event distance found in runners. The absence of a speed–endurance trade-off in the body proportions of swimmers indicates a fundamental difference in design pressures and performance capability in terrestrial versus aquatic environments.

## 1. Background

In running, short events favour strength and speed, whereas long-distance events favour economy and endurance. Consequently, elite runners vary phenotypically among events [1,2]. Marathoners are typically thinner than sprinters because maximum speed is constrained by the runner's capacity to generate ground forces, and thus increases with muscle mass [1,2]. By contrast, the metabolic cost of running, which affects endurance, increases directly with body mass and inversely with leg length [3,4]. Indeed, the body mass index (BMI; kg $m^{-2}$) of elite runners correlates with race distance and speed, and the ratio of BMI/ground force generation is invariant across a range of events [2]. This speed versus endurance trade-off is also evident within multi-event sports: decathletes performing well in the 100 m sprint do relatively poorly in the 1500 m run [5].

In swimming, however, an activity where the fundamental mechanical constraint on speed is the propulsive work performed per unit of drag [6], it is not clear how or whether the trade-off in body size and proportions applies. In water, muscular effort to support body mass is negligible, because the body displaces water and is nearly neutrally buoyant. However, a larger body and increased surface area will increase drag, which will decrease racing speed for a given amount of mechanical power [7]. Results from previous studies examining the anthropometrics of elite swimmers have been mixed, with no clear pattern governing body shape and size across sprint and endurance events [8–10].

Here, we test the hypothesis that human swimmers will have an optimal BMI that does not vary with event distance. Our hypothesis follows a simple model: muscular power output by swimmers is a function of muscle mass, and thus proportional to body mass; drag is proportional to surface area [7], and thus to height$^2$ under the assumption of isometric scaling. Therefore,

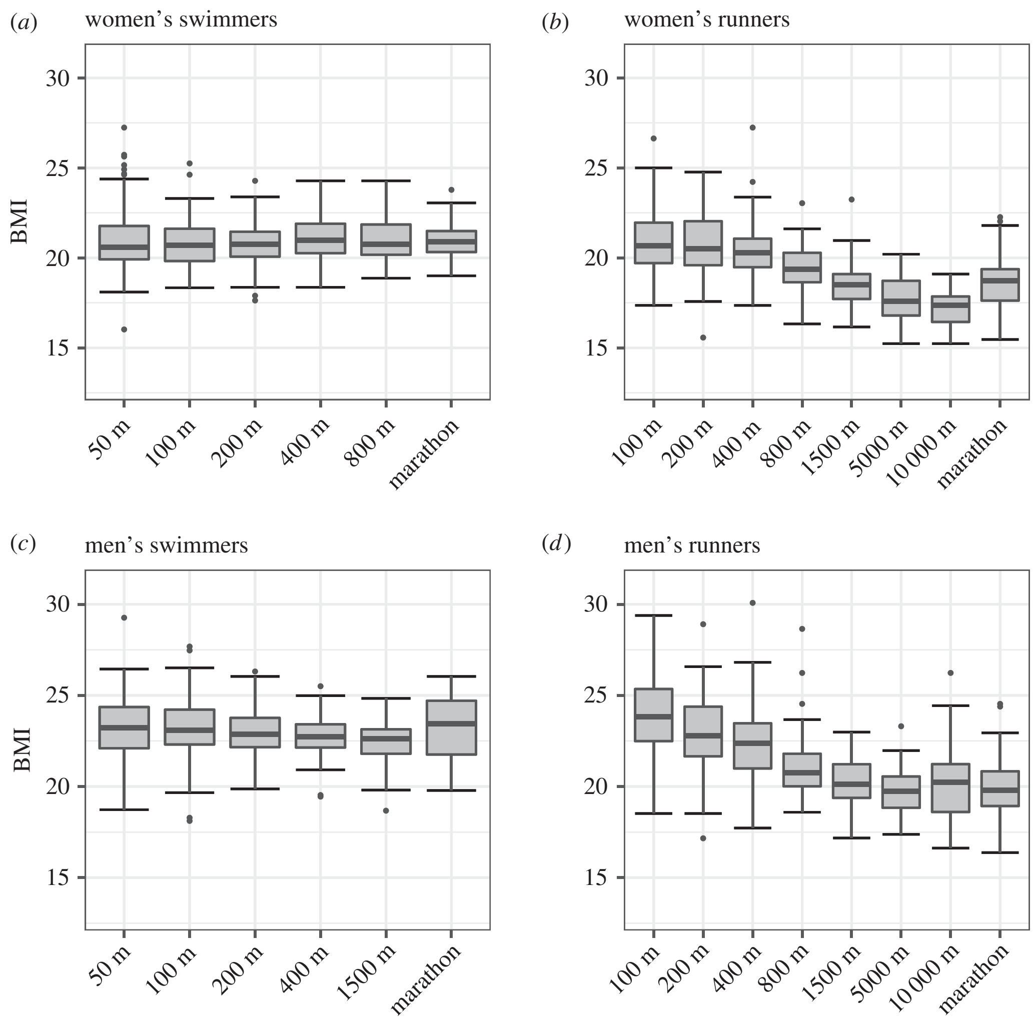


**Figure 1.** Relationship between race distance and BMI in runners and swimmers in men's and women's events. Full model results in table 1. The boxplot centre line is the median. The lower and upper margins of the box are the first and third quartiles, respectively. The upper whisker is the third quartile plus 1.5 times the interquartile range. The lower whisker is the first quartile minus 1.5 times the interquartile range. Outliers appear as points.

under the assumption that BMI variation in elite athletes chiefly reflects differences in muscle mass, we predict that BMI, the ratio of mass to height$^2$, should determine the ratio of power output to drag, and thus speed. Critically, because a swimmer's mass is less costly in water, this model predicts the optimal BMI will not vary with race distance—a fundamental difference from running. We predict that elite swimmers will converge on a single BMI regardless of event distance. We tested these predictions using data on height, mass and BMI for runners and swimmers competing in the 2012 Olympic Games in London. Given that trade-offs seem to emerge only at the extremes of ability [5,11,12], we contend that the study of these elite Olympic athletes will be especially insightful for understanding the patterns of trade-offs in running and swimming.

## 2. Methods

The 2012 London Olympian height and mass data were obtained from *The Guardian* [13]. Event times were compiled from official Olympics sources [14]. The height and mass dataset was trimmed to include only swimmers (270 competitors in men's and 252 in women's events) and runners (544 competitors in men's and 516 competitors in women's events). No information was given regarding the methods for measuring mass or height. After careful examination of the data, seven height and mass estimates were discarded as probably incorrect. Other factors, such as athlete age—which was found to have a role in performance trade-offs in decathletes and heptathletes who perform in multiple events [15]—were not considered in this study. Athletes were included in every event in which they participated. BMI was calculated as mass in kilograms divided by (height in metres)$^2$. We reasoned that in elite athletes, differences in BMI chiefly reflect differences in muscle mass, rather than differences in other tissues, such as fat, following Weyand & Davis [2]. Relays were used according to their leg distance, hurdlers were excluded from the running events and only freestyle events were included for swimmers. We used single-predictor linear regression to test whether height, mass and BMI were related to log-transformed event distances within men's and women's events and also event type (swimming versus running). Statistical analyses were conducted in R [16] with $p < 0.05$ used to indicate statistical significance.

## 3. Results

As predicted, BMI was not significantly related to event distance in men's or women's swimming events: elite swimmers converge on a common BMI (figure 1 and table 1). Specifically, our linear models found that BMI was not a predictor for race speed in competitors in men's ($p = 0.224$) or women's ($p = 0.778$) events (table 1). Indeed, within both men and women, the median BMI for swimmers competing

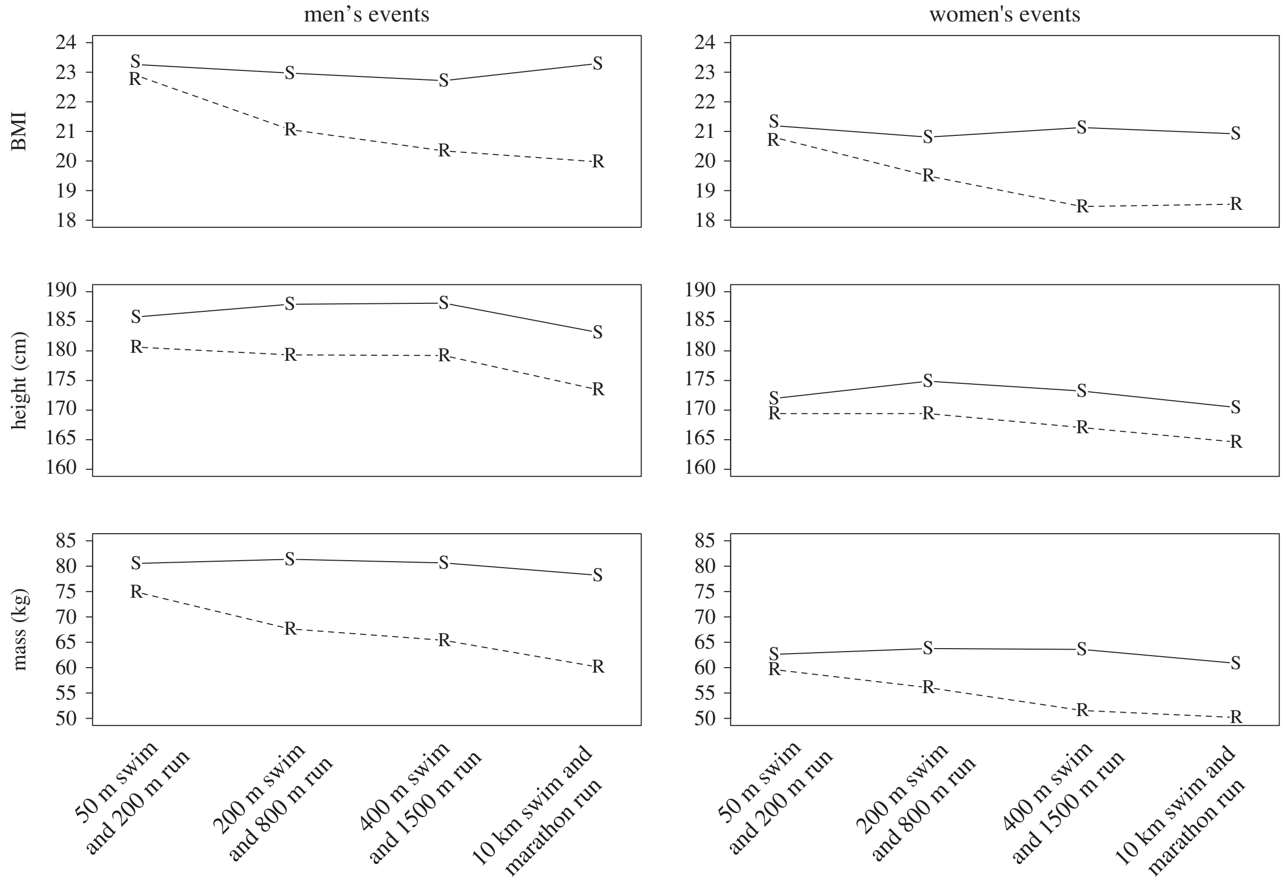


**Figure 2.** Interaction plot for four sets of events matched by duration. Mean BMI, mass and height are given for each set. S, swimmers; R, runners.

**Table 1.** Univariate linear regression results of three predictors (BMI, height and mass) each individually tested against one response (log(event distance)) for analyses of four datasets (men's and women's running and swimming). $\beta$ indicates the $\beta$ coefficient, which is the increase in the response variable (log event distance) for every 1-unit change in the predictor variable. Italic *p*-values are significant.

| | | men's events | | | women's events | | |
|---|---|---|---|---|---|---|---|
| | predictor variable | $\beta$ | adj. $R^2$ | *p*-value | $\beta$ | adj. $R^2$ | *p*-value |
| running | BMI | −0.53 | 0.35 | *<2.2 × 10^−16^* | −0.64 | 0.30 | *<2.2 × 10^−16^* |
| | height (cm) | −0.07 | 0.06 | *3.1 × 10^−9^* | −0.09 | 0.06 | *4.0 × 10^−9^* |
| | mass (kg) | −0.15 | 0.41 | *<2.2 × 10^−16^* | −0.19 | 0.34 | *<2.2 × 10^−16^* |
| swimming | BMI | −0.06 | 0.00 | 0.224 | −0.01 | 0.00 | 0.778 |
| | height (cm) | −0.03 | 0.02 | *0.009* | −0.02 | 0.01 | 0.053 |
| | mass (kg) | −0.03 | 0.02 | *0.004* | −0.02 | 0.01 | 0.111 |

in the 50 m sprint (an approx. 20–30 s event) was indistinguishable from those competing in the 10 000 m marathon swim (an approx. 2 h event) (table 1; electronic supplementary material, table S1 and figure S1). For height and mass, there was a significant difference for competitors in men's events, but only a very small amount of the variance was explained by these predictors (2%) (table 1; electronic supplementary material, figure S1). This result in swimmers stands in marked contrast with the highly significant negative correlation between BMI and event distance among the Olympic runners (figure 1 and table 1), which is in accordance with earlier findings [2]. Furthermore, in runners, BMI explained 35% and 30% of the variation in race distance in men's and women's events, respectively. While substantially higher than the amount explained in swimmers (0%), this still indicates that in runners 60–65% of the variance in race distance is due to factors other than BMI.

We further examined whether swimmers paid the same performance cost for increased body mass as runners by examining four pairs of swimming and running events that were matched by duration (50 m swim matched with 200 m run, 200 m swim matched with 800 m run, 400 m swim matched with 1500 m run and 10 km swim matched with 26.1 mile (42 165 m) marathon run). Three responses (BMI, height and mass) were examined along with two categorical predictor variables (the four duration pairs and event type (swim or run)). Using ANOVA, we compared a model that did not allow interaction between event type and duration, with a more complex model that allowed interaction. For BMI and mass, there is a significant interaction in both men's and

**Table 2.** Multivariate regression of multiple predictors on race speed. Multivariate regression results of the following predictors: event distance (log-transformed), event type (swim and run) competitors (men and women), and an interaction of competitor and event type on race speed (log-transformed). *F*-statistic: 9510 on 4 and 320 d.f. *p*-value: less than $2.2 \times 10^{-16}$. Adjusted $R^2 = 0.99$. For each predictor, significant *p*-values in italics.

| | estimate | s.e. | *t* | $Pr(>\|t\|)$ |
|---|---|---|---|---|
| (intercept) | 6.770 | 0.015 | 445.934 | *$<2 \times 10^{-16}$* |
| log event distance | −0.094 | 0.002 | −53.443 | *$<2 \times 10^{-16}$* |
| event type (swim/run) | −1.469 | 0.010 | −142.877 | *$<2 \times 10^{-16}$* |
| competitors (men/women) | −0.112 | 0.009 | −12.849 | *$<2 \times 10^{-16}$* |
| interaction: event type × competitors | 0.017 | 0.014 | 1.168 | 0.244 |

women's events, demonstrating that the relationship of these variables is different for swimming and running (figure 2; electronic supplementary material, tables S2 and S3). This can be seen by comparing the relatively flat line in the swimmers and the negatively sloping line in runners (figure 2). This indicates that runners generally decrease in both BMI and mass with increased event duration, whereas there is no such decrease in swimmers.

## 4. Discussion

Our study supports the hypothesis that swimmers do not incur the same cost for added mass that is seen in runners. In other words, the speed versus endurance trade-off in BMI, which is clearly evident in the phenotypes of elite runners [1,2], is absent in the phenotypes of swimmers. Across all swim event distances, swimmers' BMIs are most similar to those of sprint runners. Our results have broader implications for the debate over trade-offs between speed and endurance in animal locomotion. As such, our work demonstrates the potential for insights that can be drawn from exploring the connections between human performance, sports science and evolutionary biology, a point recently made by Wilson *et al.* [17]. Trade-offs are a common and appealing idea in biology and beyond (e.g. economics) [11], yet results have been varied as to whether the speed/endurance trade-off widely applies to animal locomotion (e.g. [5,18–29]). We show no evidence for broad phenotypic trade-offs between elite sprint and endurance swimmers and we propose that this is due to the unique biomechanical demands of swimming. Studies of fish shed light on this finding in humans. For example, cod show a burst/endurance performance trade-off [29] and moquitofish show a steady/unsteady swimming performance trade-off [28], though such trade-offs are not universally found in fish (e.g. [25–27]). Interestingly, in cod, there were no broad morphological differences between individual codfish that correlated with performance [29], a similar finding to ours. Mosquitofish specialists, on the other hand, are morphologically distinct from one another [28]. Additional research is needed to better understand the physiological mechanisms and finer-scale anthropometric variables underlying the sprint/endurance performance trade-off in human swimmers. In a confirmation of earlier findings in runners [30], one recent study showed, for example, that the muscle fibre-type composition of athletes varied based on the length of their event in swimmers, in addition to runners and other athletes [31].

Notably, within each swimming and running event, the mean difference between men and women competitors' BMI corresponded nearly exactly with the mean difference in race speed (both are 11% different; electronic supplementary material, table S1). Debate has focused on whether differences in running speeds of men and women are related to differences in average pelvic dimensions [32–35], but our results challenge this idea. Compared with running, differences relating to pelvic dimensions are likely to be more limited in swimming, where the legs and pelvis do not bear weight. Multivariate analysis of racing speed finds no significant interaction between men's and women's competitors and whether the event is running or swimming (table 2), suggesting that pelvic dimensions have no additive effect on the differences in running performance between men and women competitors. Together with recent work showing no effect of pelvic width on the energy cost of running [34], our results strongly imply that differences in muscle mass between men and women (and thus in power and maximal oxygen uptake) are a primary cause of differences in race performance in elite athletes in these events [36–39].

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Authors' contributions. All authors contributed to conceptualization, formal analysis and writing.

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