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Title: Added mass in human swimmers: age and gender differences.

Keywords: Swimming, added mass coefficient, gender, shape and body size.

Abstract

In unstationary swimming (changing velocity), some of the water around the swimmer is set in motion. This can be thought of as an added mass (Ma) of water. The purpose of this study was to find added mass on human swimmers and investigate the effect of shape and body size. Thirty subjects were connected to a 2.8m long bar with handles, attached with springs (stiffness k=318N/m) and a force cell. By oscillating this system vertically and registering the period of oscillations it was possible to find the added mass of the swimmer, given the known masses of the bar and swimmer. Relative added mass (Ma%) for boys, women and men were, respectively, 26.8±2.9%, 23.6±1.6% and 26.8±2.3% of the subjects total mass. This study reported significantly lower added mass ($p<0.001$) and relative added mass ($p<0.002$) for women compared to men, which indicate that the possible body shape differences between genders may be an important factor determining added mass. Boys had significantly lower ($p<0.001$) added mass than men. When added mass was scaled for body size there were no significant differences ($p=0.996$) between boys and men, which indicated that body size is an important factor that influences added mass. The added mass in this study seems to be lower and within a smaller range than previously reported (Klauck, 1999; Eik et al., 2008). It is concluded that the added mass in human swimmers, in extended gliding position are approximately ¼ of the subjects' body mass.

Introduction

Maximization of human swimming performance is dependent on three main goals: the ability to create propulsion, reduction of drag and the restraint of physiological cost. Within all three areas there have been many studies, however there are still unknown features of drag and propulsion. In research on both drag and propulsion of human swimming, unsteady effects have received relatively little attention. Drag is defined as “the force on an object moving in a fluid due to the rate of change in momentum of the fluid influenced by the object moving through the fluid” (Vogel, 1996), and is explained by physical characteristics of the water such as density, viscosity and pressure. In addition, the swimmer’s size, shape, frontal area and velocity affect drag. This can be expressed in the drag equation:

$$F_D = \frac{1}{2}\rho C_D U^2 A \qquad \text{(Equation 1)}$$

where F_D is pressure drag force, ρ is density of the water, C_D is the drag coefficient, U is the swimmers velocity relative to the water flow and A is total cross-section area of the swimmer in the moving direction. Most research has been done during stationary swimming, but drag during unstationary swimming should also be taken into account. In unstationary motion, the flow pattern changes with time. A swimmer decelerates after starts and turns and within a swimming cycle there are velocity variations. In unstationary swimming, some of the water around the swimmer is set in motion. This can be thought of as added mass (Ma) of water, and is the water a swimmer has to accelerate in addition to body mass during a change in velocity. Added mass is important when determining the energy expenditure and drag for a swimmer. Added mass can be represented as a dimensionless factor (C_a) that is defined as added mass divided on the mass of fluid as the object is moving (Stager & Tanner, 2005), and is expressed as:

$$Ma = C_a V\rho \qquad \text{(Equation 2)}$$

where C_a is added mass coefficient, V is body volume of the swimmer and ρ is water density (Vogel, 1996).

The additional force that exists when an object is accelerating in an ideal fluid is called the acceleration reaction. It indicates "the force needed to accelerate the added mass of fluid backwards" (Vogel, 1996). The acceleration reaction inertia is added to an object during accelerations in a fluid and is one of the dominant hydrodynamic forces that counteract the movement on a human swimmer. The amount of fluid that is accelerated depends on the shape of the body and the pattern of the water flow around the body. Various equations can estimate the acceleration reaction depending if the water is accelerating and the object is stationary, or opposite (Vogel, 1996).

The effect of added mass is well documented in theoretic hydrodynamics, in research of the shipbuilding industry and in marine biology (e.g. Brennen, 1982; Daniel, 1985). Previously only two other studies have investigated added mass on swimmers during passive gliding (Klauck, 1999; Eik et al., 2008). On the basis of data reported by Klauck (1999) and by using a conservative added mass coefficient of 0.5, Kjendlie & Stallman (2008) estimated added mass and found a 34% increase of drag when added mass was taken into account. This exemplifies the importance of knowing more about the added mass of human swimmers. The purpose of this study was to (a) find added mass on human swimmers, (b) investigate the effect of shape and body size and (c) to establish predictive linear regression equations for future added mass calculations. This study examined added mass on swimmers in a submerged position, where wave drag (D_w) have lower influence on total drag (Pendergast, et al., 2005).

Methods

Subjects

Thirty subjects where recruited into three groups; boys (n=9), women (n=10) and men (n=11). Anthropometrical measurements for all subjects were collected for body height, reaching height, shoulder width (in an upright streamlined position), body mass, age and frontal area (FA) is reported in Table 1. A vertical oscillation test was performed to estimate added mass in the ocean laboratory at Norwegian Marine Technology Research Institute (MARINTEK). Written and informed consent was obtained from the participants. The study was approved by the Regional Committee for Medical Research Ethics, Oslo, Norway.

Table 1. *Anthropometrical measurements and age for boys, women and men. Mean and standard deviation (SD).*

	Boys (n=9)	Women (n=10)	Men (n=11)	Total (n=30)
Body height (cm)	163.6 (8.2)	167.5 (4.8)	182.4 (6.4)	171.8 (10.5)
Reaching height (cm)	222.2 (13.6)	225.3 (7.1)	245.7 (9.1)	231.8 (14.6)
Body mass (kg)	50.2 (8.1)	63.9 (5.3)	78.2 (6.3)	65.0 (13.2)
Shoulder width (cm)	33.0 (2.2)	36.5(2.0)$^{-2}$	41.7 (2.3)$^{-1}$	37.3 (4.3)$^{-3}$
Age (years)	13.7 (0.9)	22.2 (3.3)	25.2 (4.9)	20.7 (6.0)
Frontal area (m^2)	0.065 (0.008)	0.080 (0.015)	0.089 (0.006)	0.079 (0.014)

The numbers in superscript indicates the number of subjects that were excluded from the specific test.

Procedures

The subjects were connected to a 2.8m long bar (1.975kg) in a vertical equilibrium position under water (15°C). Three moveable handles (415g) were attached to the bar to keep the subject in a streamlined position. The vertical oscillation was set in motion by pulling the spring system upwards.

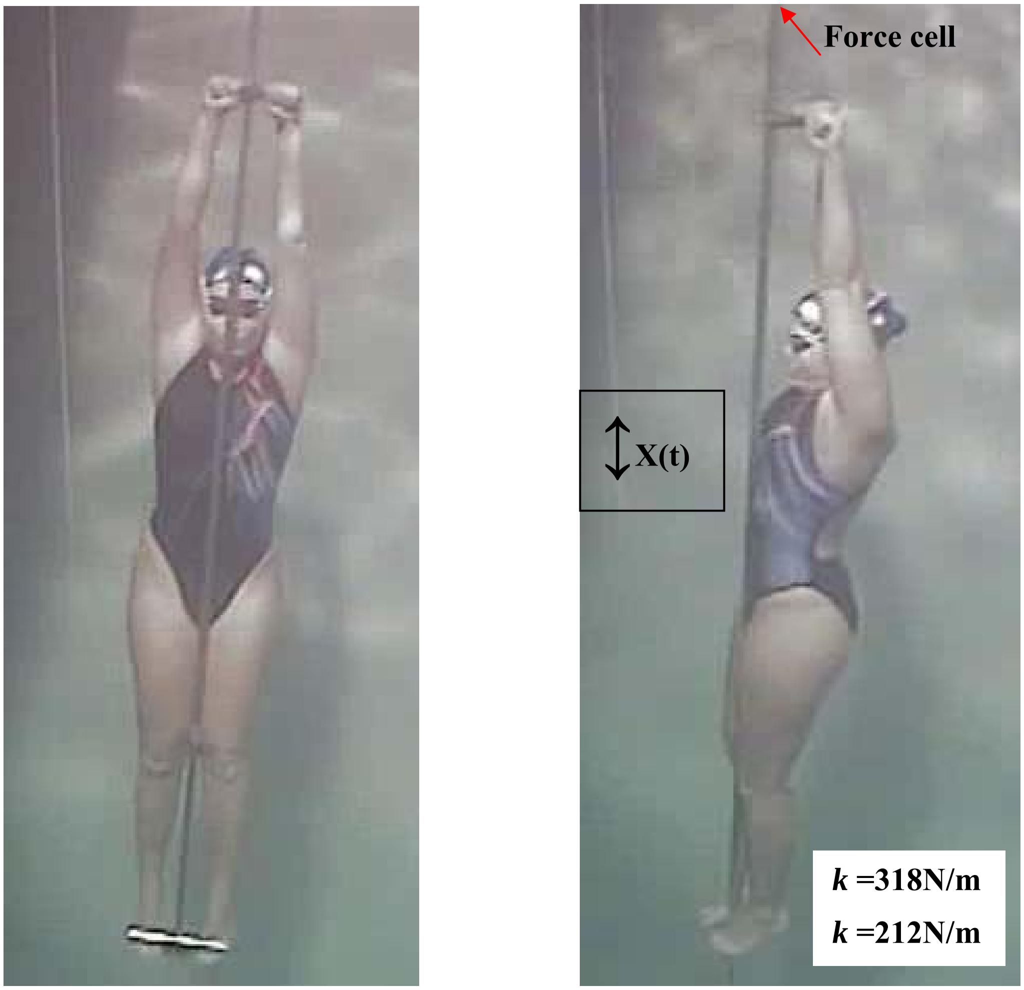

Figure 1: *A swimmer attached to the bar during vertical oscillations.*

Measurements

Added mass

The computation of added mass was based on a harmonic oscillating system. The natural frequency of a damped spring system is ω_0, and the oscillation period (T) is given by:

$$T = \frac{2\pi}{\omega_0} \qquad \text{(Equation 3)}$$

In a system were the added mass is near the mass of the object, the relative damping is small (<10%) as indicates by Øgrim (1990). By neglecting the relative damping and since:

$$\omega_0 = \sqrt{\frac{k}{M + M_A}} \qquad \text{(Equation 5)}$$

added mass can be found as:

$$M_a = \left(\frac{T^2 k}{4\pi^2} \right) - M \qquad \text{(Equation 4)}$$

where M_a is the added mass, k is the spring constant and M is the mass of the swimmer and the bar with springs. The computation was based on a half oscillation period between a crest and trough of the Force-time curve. The oscillating bar were attached to a force cell, and four (460g) or six (690g) springs with a spring constant k=212N/m and k=318N/m, respectively. By oscillating the spring system vertically, the subjects' oscillating period was recorded. The sampling frequency was set to 200Hz with a low pass-filter (20Hz). A routine was made in Matlab 2007a (The MathWorks, Inc, Natick, USA) to estimate added mass from force data. Given the known masses of the bar and swimmer, made it possible to find the added mass of the system.

Accounting for shape and body size parameters

Body shape and body size parameters were measured from a photo (Camera Nixon D50, Nikon Corp, Japan) taken from above of the subject together with a known measure standard. The subjects were digitized in Adobe Acrobat 7.0 Professional. A calibration factor was estimated from the known measure standard and made it possible to find the swimmers actual shoulder width and projected frontal area.

Statistical analyses

Independent t-tests and ANOVA was used to account for significant differences between groups, and linear regression analyses to find relevant parameters to estimate added mass from shape and body size parameters. A $P < 0.05$ value was considered significant. Data are means ± SE.

Results

Added mass for the three groups were 13.3±2.1kg, 15.1±1.3kg and 21.1±2.5kg for boys, women and men, respectively. This corresponds to a relative added mass of 26.8±2.9%, 23.6±1.6% and 26.8±2.3% of the subject's body mass, respectively. Furthermore, the added mass coefficient was estimated to C_a=0.255 for boys and 0.257 for men. This was estimated by using the buoyancy data from Kjendlie et al. (2004) of similar subjects. Furthermore, significantly lower added mass (p=0.001) and relative added mass (p=0.002) for women compared to men were found. There where significantly lower added mass (p=0.001) for boys compared to men, but not for relative added mass (p=0.996).

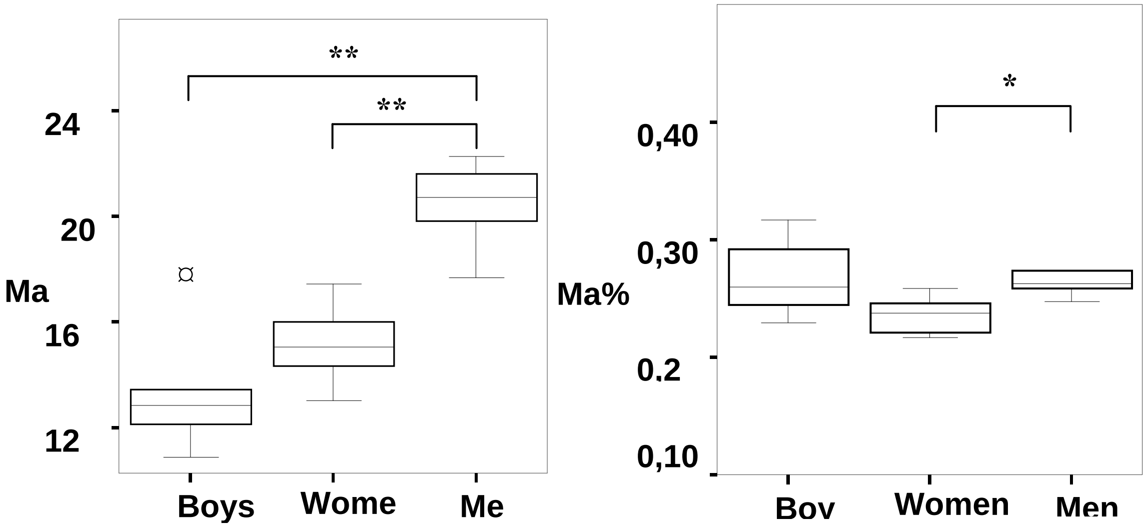

Figure 2: *Added mass (left) and relative added mass (right) for boys, women and men (n=30). ¤ is outlier, * is p<0.05 and ** is p<0.01.*

Correlation analyses for women and men indicated that body mass, frontal area and reaching height were all significantly associated with added mass. Frontal area and reaching height (RH) had r values of 0.747 and 0.709, respectively. A regression equation combining all three variables ($AM=16.042+0.235\cdot BW+21.996\cdot FA-0.049\cdot RH$) showed r^2=0.857, but only a significant coherence

($p<0.03$) with body mass and added mass. Regression analyses show that fineness ratio ($r^2=0.801$) and body mass parameters ($r^2=0.857$) gave the highest r^2 values for added mass for women and men.

Correlation analyses for boys and men indicated that body mass was significantly ($p<0.001$) associated with added mass. Frontal area and reaching height had r values of 0.781 and 0.786, respectively. A regression equation combining all three body size parameters ($AM=0.034+0.234 \cdot BW+15.763 \cdot FA-0.001 \cdot RH$) showed $r^2=0.888$, and only a significant coherence ($p<0.05$) with body mass and added mass.

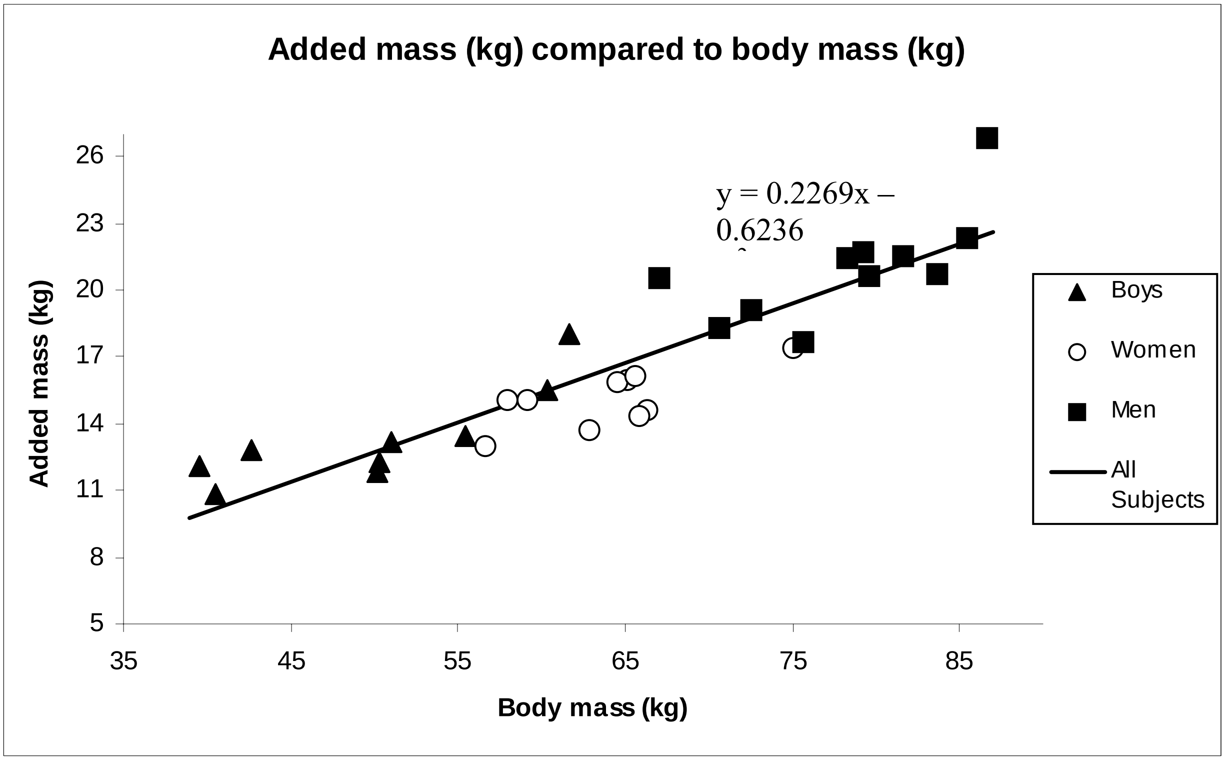

Figure 3: *Added mass versus body mass for boys (▲) women (○) and men (■).*

Discussion

Size effect on added mass

Boys and men had both a relative added mass of 27%, indicating that added mass in some way is dependent on body size. Regression analyses for body size parameters showed that body mass (89%), frontal area (78%) and reaching height (77%) separately influenced variations in added mass. This study found only a significant correlation ($p<0.004$) between body mass and added mass. This was in agreement with the results that indicated no significant difference ($p=0.996$) between boys and men for relative added mass (27%). Boys had significantly (0.149±0.008) lower fineness ratio than men (0.169±0.014), and it is thus assumed that boys are less streamlined and with elevated drag coefficient compared to men. This was not in agreement with the results of the relative added mass.

A regression equation combining all three body size parameters showed a higher r^2 (0.86) than for body mass alone ($r^2=0.84$), which explained more of the variation in added mass than reaching height and frontal area between genders. Women had significantly ($p<0.001$) lower body mass than men, which indicated smaller body size and probably reduced total drag. This could also be applied for added mass.

There are disagreements in the literature on how body size influences active drag (Huijing, 1988; Clarys, 1978, 1979; Zamparo, 2009). Clarys (1978, 1979) found that body shape and composition did not affect active drag. On the contrary, Huijing (1988) found high correlation for height and maximal cross-section area (in the direction of motion) ($r=0.87$) with active drag. Kolmogorov et al. (1997) found no difference in drag coefficient for active drag when children ($C_D=0.25$) was compared with elite swimmers ($C_D=0.30$). However, Kjendlie & Stallman (2008) found significantly lower ($p<0.001$) drag coefficient for boys ($C_D=0.66$) than men ($C_D=0.84$). A previous study investigated children's growth in a 2 years period (Toussaint et al., 1990). They found that increase in height, body mass and frontal area did not change total drag ($C_D=0.64$ vs. 0.66). This was consistent with the anthropometric changes that gave the swimmer a more streamlined body, increased height, reduced wave drag and increased body size gave larger frontal drag. These results should be evaluated in the light that the children swam on the MAD system with their legs fixed to a pull buoy, which can lead to variations in trunk incline.

Gender effects on added mass

The difference between genders in this study was significantly higher added mass for men compared to women. Not surprisingly, men had also higher values on all anthropometrical measurements. However, when scaled for size, looking at the relative added mass, men still had significantly higher added mass (AM%) than women. This can be due to differences in body shape.

The literature reports lower drag coefficients for females than males (Toussaint et al., 1988; Zamparo et al., 2009). Lower added mass for women could mean that other effects such as drag coefficient or body composition influence them differently compared to men. Body composition is an important difference between men and women that affect buoyancy and thus the total drag (Vogel, 1996). It is general knowledge that women have higher share of fatty tissue and different distribution compared to men, which can give women higher net buoyancy (Zamparo et al., 1996). Drag coefficient depends on fineness ratio and body shape and gives an idea on how streamlined a body is. There were no significant differences ($p=0.129$) for fineness ratio between men and women, which did not directly explain the variation between genders in body shape observed in the present study. Thus, it might be speculated that the fineness ratio did not cover all aspects of body shape, and that future studies should look at other parameters of body shape when explaining the difference in relative added mass between males and females. This could indicate that other measurements like hip width should be taken into consideration in addition to fineness ratio. The variations in added mass were explained more by body size parameters (86%) than fineness ratio (80%), using linear regression calculations.

The main finding of this study was that added mass seems to be lower and within a smaller range than previously estimated. The added mass coefficient was estimated to $C_a=0.255$ and 0.257 for boys and men, respectively. Eik et al., (2008) reported a lower added mass coefficient (0.1-0.47) than Klauck (1999) ($C_a=0.47\text{-}1.1$). The reason for this discrepancy could be different use of methods and subjects. Body size (length, depth and width), the swimmer's position during oscillation and experience could lead to different values of added mass.

Methodological considerations

Before the oscillation test the subjects was instructed to be as streamlined as possible at the bar. This was controlled with underwater video during testing. The subjects, who did not have an optimal position at the bar, were excluded. The hands are tied next to each other, which do not represent an ideal swimming position, however it was the most optimal solution to hold still at the bar. Three boys did not adapt to the cold water, which lead to a tense position and unnecessary shivering on the bar. This could explain the large range in relative added mass for boys. Two springs were additionally supplied to the spring system for heavier subjects to carry out more oscillations. In addition, a small number of subjects induce to a type II error that could be a contributing cause why we did not find a significant difference for relative added mass between boys and men. One should be careful to interpret if the difference in effect of gender or effect of size is representative for all swimmers.

Conclusion

This study indicated that about 1/4 of a swimmer's body mass would come in addition to regular mass when a swimmer accelerates in the water. Boys had significantly lower added mass than men, but there were no significant differences in relative added mass, indicating that body size is an important determining factor of added mass. Furthermore, women were found to have significantly lower added mass and relative added mass than men. This indicated that also body shape probably was an important factor determining added mass between genders.

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