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Section: Original Research

Article Title: Backstroke Swimming: Exploring Gender Differences in Passive Drag and Instantaneous Net Drag Force

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Abstract

This study explored and quantified gender differences in passive drag and instantaneous net drag force profile for elite backstroke swimmers (FINA points 938 ± 71). Nine female and ten male backstroke swimmers completed eight maximum speed trials. During the passive drag condition participants were towed at the speed achieved within the maximum effort backstroke swimming trials, whilst holding a supine stationary streamline position. The remaining trials, swimmers performed their natural swimming stroke, whilst attached to an assisted towing device. Male participant’s passive (p < 0.001) and mean net drag force (p < 0.001) were significantly higher compared to female participants. Additionally, there were no significant differences by gender between either the minimum or maximum net drag forces produced during the left and right arm strokes. Instantaneous net drag force profiles demonstrated differences within and between individuals and genders. The swimmers who recorded the fastest speed also recorded the smallest difference in net drag force fluctuations. The instantaneous net drag force profile within elite backstroke swimming provides further insight into stroke technique of this sport.

Key words: swimming technique, biomechanics, stroke technique, kinetics, sport
Introduction

In competitive swimming, backstroke is one of the four swimming strokes and the only stroke that is performed where the swimmer’s forward vision is obstructed, as they are orientated on their back. Despite this unique, and somewhat unnatural configuration, backstroke research to date has focused predominately upon the performance of starts, turns and stroke coordination/timing,\(^1\)-\(^3\) however fundamental to each of these aspects is the biomechanical analysis of stroke technique when moving the arms posteriorly.

The effectiveness of a swimmer’s stroke technique can be explored through forces generated within the stroke phases. The traditional methods that have provided force for swimming have represented net drag force as a mean, with a primary focus on front-crawl swimming technique. The resultant between the propulsive and resistive drag forces is defined as net force.\(^4\)-\(^5\) Methods such as the measurement of active drag system (MAD) and the velocity perturbation method (VPM) were based upon the assumption at a constant speed the propulsive force was equal to the opposing active drag/net drag force.\(^6\)-\(^7\)-\(^8\) Conversely, a key advantage of systems that enable measurement of instantaneous force profiles is the ability to identify intra-stroke force fluctuations both within and between individuals.\(^9\)-\(^10\) This new information may allow coaches and scientists to objectively relate swimming technique to the measurement of net drag force. This knowledge can also determine the effectiveness of any intervention strategies. Although researchers have acknowledged the relationship between speed, passive drag, net drag force and gender in front crawl,\(^9\)-\(^11\)-\(^12\)-\(^13\) the nature of this distinct ‘backward’ relationship in backstroke swimming with forces generated in a weak anatomical position has not been explored. It is currently unknown whether the net drag force fluctuations in backstroke swimming are influenced by maximum swimming speed and/or gender.
The challenge of scientifically understanding the complex biomechanical relationships in the aquatic environment were reflected by the limited published investigations on active drag or net drag force in backstroke. Early research on backstroke used the velocity perturbation method (VPM) to estimate mean active drag in skilled and unskilled swimmers. Formosa et al. conducted a pilot study reporting the mean and instantaneous net drag force during backstroke swimming. This was presented more as a case report. The aim of this study was to quantify the passive drag profile, whilst holding the streamline position and the net drag force profile generated during backstroke free swimming in an elite male and female cohort. It was hypothesized that there would be gender differences in passive and net drag force profile. Furthermore, right and left stroke minimum and maximum net forces will be quantified to help scientists understanding the net drag force profile.

**Methods**

Nine elite female (aged 18.8 ± 3.1 yrs, height 173.6 ± 5.4 cm, mass 58.9 ± 5.2 kg, FINA points 949 ± 82) and ten elite male (aged 21.2 ± 2.9 yrs, height 184.3 ± 9.3 cm, mass 79.4 ± 7.8 kg, FINA points 929 ± 62) backstroke swimmers participated within this study. Written information consent was obtained prior to data collection. The human ethics committees of the University of the Sunshine Coast and the Australian Institute of Sport approved the experimental design.

Each participant completed a standardized warm up. Three maximum speed trials (unaided) were conducted over 10 m and calculated through two time-coded 25 Hz cameras (Samsung model: SCC-C4301P). Unaided simply indicated that the participant was not attached to a towing device. The cameras were positioned at the side from the starting end of a 50 m pool adjacent to 5 m and 15 m marks. Cameras were time-coded and the mean
maximum speed during the 10 m interval calculated. The fastest mean speed from the three trials was used during the passive drag towing trials. Stroke rates (SR) were calculated using video recorded within the 10 m interval. This was based upon the participant’s time to complete four strokes.

A motorized assisted towing device (drum: 220 mm diameter, 290 mm length; 1 m.s\(^{-1}\) equivalent to 89.5 RPM) positioned directly on a calibrated Kistler force platform (Kistler Instruments in Winterthur Switzerland, Dimensions: 900 x 600 m Type Z12697) was used to collect the passive and net drag force data. The force platform was positioned 430 mm above the water and 45 mm from the edge of the pool. The towing device was fitted with an adjustable arm and pulley. During the passive drag towing trials, the adjustable arm and pulley was at water level and during the net drag force trials the arm and pulley was set at a distance of 30 cm below the water. This was to ensure that the tow-line would not interfere with the swimming action. The assisted towing device was fixed to the force platform using rubber pads that were designed to minimize the collection of vibrations from the towing device. This system was used previously to assess net drag forces generated in front crawl.

A reliability and validity study was conducted before the commencement of testing. The results identified within and between days of testing there was an intra-class correlation coefficients (ICCs) of 0.97 (0.93 to 0.99) and 0.99 (0.96 to 1.00) for passive and net drag force measurements, respectively.

Following the completion of several familiarization trials, three passive drag trials (aided) were completed at the participant’s fastest free swimming maximum speed on that day. Aided indicated that the participant was attached to the assisted towing device. Passive drag trials required the swimmer to be in a supine position holding the end of the tow-line around the middle finger of their dominant hand, with the non-dominant hand interlocking to
minimize any additional movement. A passive drag trial was deemed successful if the swimmer maintained a streamline position on the water surface, with no arm strokes or kicking. The body position was monitored with a side-on underwater and above water camera, synchronized with a video mixer. During the five net drag force trials, participants were attached to the assisted towing device using an adjustable towing belt that was secured around the lumbar region. Participants were then required to swim at maximum speed using their typical stroke. To simulate maximum competition swimming for each participant, and to ensure constant tension on the tow-line, participants were towed at 5% faster than their measured maximum free swimming. The assisted towing device was programmed at 5% faster than participants calculated maximum swimming speed. This was considered small enough not to have any major effect on the swimmer’s stroke pattern, whilst still allowing continuous force measurement via the towing apparatus. Monitoring of the swimmer’s stroke rate ensured that participants were swimming with a consistent swimming technique. Feedback was provided to the participants during the assisted towing trials to ensure that the participants were using a standardized stroke rate between the assisted towing and maximum speed conditions.

Each trial was video-recorded using three synchronized regular analogue cameras (50 Hz) positioned under and above water in the sagittal and transverse plane. The sagittal plane camera images were mixed with a video mixer (EDI-V8) and video recording was conducted on a moveable trolley. A synchronized trigger started the video timers and initiated data collection capturing four complete strokes. This allowed the video footage to be synchronized to the force data. The sensitivity of the amplifier was set at 5000 pC (Pico Coulombs) (range in the y direction is 0-1 kN) for the passive and net drag force trials. A 12-bit analogue to digital card, sampled at 500 Hz processed the force data. Data collected were reduced using a Butterworth 5 Hz low pass digital filter. As per previous studies this raw force data were
inputted into the hydrodynamic equation and rearranged to determine the drag coefficient variable. The raw net force data remained positive because there was a constant towing speed above the participant’s maximum swimming speed. Then using the common assumption when estimating active drag 6-8, or net drag force 10, when travelling at a constant speed the mean propulsive force was equal to the opposing net drag force 8-13-14, the net drag force was calculated. 6 When the participant was towed the magnitude of the net drag force decreased as the swimmer generated an effective propulsive swimming action. This measure conversely increased when the participant was not as effective in their swimming. For practical clarity with coaches and swimmers this net force data was simply inverted so that an increased net drag force represented an improved swimming action, rather than reporting the towing force.

\[ F_1 = 0.5C \cdot \rho \cdot A \cdot V_1^2 \]

(Net drag force acting on the swimmer during the maximum swimming trials (unaided)

\[ F_2 = 0.5C \cdot \rho \cdot A \cdot V_2^2 - F_b \]

(Net drag force acting on the swimmer during the assisted towing condition (aided)

Where:

- \( C \) = the drag coefficient
- \( \rho \) = the water density
- \( A \) = the frontal surface area of the swimmer
- \( F_1 \) = net drag force acting on the swimmer within free swimming condition
- \( F_2 \) = the force needed to pull the swimmer at the increased speed and was measured by the force-platform
If it was assumed that equal power output ($P$) was achieved in aided and unaided conditions, the following formula may be used to estimate net drag force.

If $P_1 = P_2$ therefore $F_1 \cdot V_1 = F_2 \cdot V_2$

Then substitution of $F_1$ and $F_2$:

$$0.5C \cdot \rho \cdot A \cdot V_1^3 = 0.5C \cdot \rho \cdot A \cdot V_2^3 - F_b \cdot V_2$$

Re-arrange the formula to find $C$:

$$C = \frac{F_b \cdot V_2}{0.5 \rho \cdot A \cdot (V_2^3 - V_1^3)}$$

Then substitution of $C$:

$$F_1 = \frac{F_b \cdot V_2 \cdot V_1^2}{V_2^3 - V_1^3}$$

$V_1$ = Free swimming unattached maximum speed trial (unaided)

$V_2$ = 5% greater than the swimmer’s free swim maximum speed (aided)

Equation 1: Hydrodynamic Fluid Force Equation

It was assumed that the participants produced the same equal power output within the unaided and aided conditions. This study minimized the potential to violate this assumption by using elite participants only, and by monitoring stroke rate through all testing conditions. For example the use of elite participants, will minimize intra-individual differences in swimming speed between both trial and conditions. Similarly, the use of stroke rate, a variable used commonly to assess stroke technique. 15-16

Time-coded video footage synchronized to instantaneous net drag force was used to analysis each stroke cycle (Figure 1). The stroke cycle was subdivided into six phases. 16-17
Variables identified for analysis were mean stroke rate, passive drag, net drag force, minimum and maximum net drag forces. Mean and confidence interval (95% CI) were expressed for each of the parameters. All statistical analyses were completed using SPSS (Windows v17). A normality of distribution and equality of variance was conducted before performing parametric statistics. ANOVA testing was conducted to determine whether there was a significant difference in mean when comparing by both gender and stroke side (right or left).

**Results**

There were no significant differences (p = 0.964) in mean stroke rates between free swimming (unaided) and net drag force swimming (aided) conditions. There were no significant differences when comparing the minimum (p = 0.251) or maximum (p = 0.319) net forces between the right and left stroking actions (Table 1).

ANOVA testing reported no significant gender differences for mean stroke rate in either the unaided (p = 0.267) or aided (p = 0.582) conditions. There was a significant gender effect (p < 0.001) for mean swimming speed with the male participants demonstrating a faster speed than the female participants (Table 1). There were significant differences between the male and female swimmers for both passive drag (p < 0.001) and net drag force (p < 0.001) (Table 1, Figures 1 & 2). Examining the data by stroke side identified that there was no gender effect for left stroke minimum net drag force (p = 0.101), although there was a significant gender difference (p = 0.004) for the right stroke minimum drag net force. Also, gender effects were found for the maximum net drag forces on both the right (p < 0.001) and left (p = 0.002) stroke sides (Table 1).
No significant differences were found for the male ($p = 0.410$) and female ($p = 0.735$) participants mean stroke rates when comparing free swimming, unaided and aided, testing conditions (Table 1, Figure 1 & 2).

When the male and female data were combined there was a strong positive correlation between speed and mass ($r = 0.764, p = 0.001, n = 19$) measurements but not between speed and height ($r = 0.408, p = 0.117, n = 19$). Male swimmers were significantly faster ($p < 0.001$), taller ($p = 0.017$) and heavier ($p < 0.001$), which was in line with previous research. This variable would explain the speed-mass correlation. There was also a strong positive correlation between mass and passive drag ($r = 0.845, p < 0.001, n = 19$). However, no correlation between height and passive drag ($r = 0.482, p = 0.059, n = 19$) although the relationship approached $p = 0.050$. Similarly, there was no relationship between mass ($r = 0.471, p = 0.066, n = 19$) or height ($r = 0.108, p = 0.691, n = 19$) and net drag force.

**Discussion**

Backstroke swimming follows a similar cyclic swimming action to front-crawl swimming. An assisted towing device allowed quantification of front-crawl free swimming and, unlike other methods the data output were expressed as an instantaneous net drag force profile. A similar protocol was used to quantify the fluctuations within the cyclic backstroke action. The hypothesis was accepted that there would be gender difference in passive and net drag force.

Past criticisms of any assisted towing device have focused upon the possible changes this methodology had on swimming technique. In the present study, these criticisms were addressed by comparing stroke rates of both the unaided and aided conditions. Stroke rate comparisons between the two conditions found no significant differences ($p > 0.05$) in stroke rates between the free swimming (unaided) and net drag force (aided) conditions. Stroke rate
has been used previously as an objective measure of consistency in swimming speed, stroke timing and technique.\(^{15-18,19}\) The stroke rate similarities demonstrated that participants maintained a consistent speed, stroke timing and technique during both the unaided and aided conditions.

Passive drag quantifies the amount of resistance a participant’s stationary body shapes created while being towed at maximum swimming speed and required the swimmer to hold and maintain a streamline position throughout the duration of each trial. Regardless of equipment, passive drag is typically measured with participants holding a prone streamline position. However, within this backstroke protocol, passive drag was assessed with participants in the supine position more closely reflect the actual body position within backstroke swimming.

The measurement of net drag force is dependent upon the swimmer’s ability and technique.\(^{20}\) Therefore, there was an increased likelihood of differences in net drag force within and between studies. Mean net drag force (n = 19) was similar to those reported in a recent study that used a similar protocol,\(^9\) although mean net drag forces were higher when comparing a resisted method.\(^6-12\) The higher net drag force may be a result of several factors including; slower testing speeds (1.47 m.s\(^{-1}\)), ability, skills, anthropometrics and/or technique.\(^{21-22}\) Research has established that speed and drag force/net drag force have an exponential relationship.\(^{13-23}\) Therefore, testing at higher mean maximum speeds was likely to increase net drag force. In addition, the Velocity Perturbation Method was a resisted method, which may have influenced mean net drag force.\(^6\) Comparisons between an assisted and resisted towing method have identified that resisted testing resulted in an altered stroke length, stroke rate/depth, hand speed and range of movement within the stroke cycle. However, the assisted towing method was reported to minimally influence the swimmer’s stroke rate.\(^{24-25-26-27}\)
Furthermore, the stroke rates within this study were not significantly different (p < 0.05) when comparing the free swimming (unaided) and assisted towing conditions (aided).

The influences of anthropometric (mass and height) variables on speed, passive drag and/or net drag force were analyzed. All females reordered lower mass scores than males and males were significantly (p = 0.017) taller than the females, despite five female being taller than males. The relationships between height/mass and speed/passive drag/net drag force were investigated further. The mass of a swimmer was positively correlated with both speed and passive drag. An increase in body surface area could influence an increase in passive drag with an increase in the participants mass. There was no relationship between passive drag and height. Conversely, Benjanuvatra et al. and Chatard et al. identified that there was a significant relationship between passive drag and height. The differences could be due to testing speed and/or participant level of expertise.

A key advantage of this Assisted Towing Device was it enabled one to quantity an instantaneous net drag force. The more precisely one can compare participants capable of the same maximum swimming speeds the more one can identify unique differences within the stroke technique variations between individuals (Figure 1 & 2). Participants with the fastest speeds recorded the smallest differences in intra-stroke fluctuations between the overall minimum and maximum net drag forces, whilst minimizing mean net drag force production. This was demonstrated by the results of males 8 and 10 and females 2 and 5 (Table 1). The instantaneous net drag force profile also showed that, although participants demonstrated the same maximum speeds, their force profiles were considerably different (Figure 1).

Comparably, researchers have identified a similar occurrence when exploring elite male front-crawl swimmers. The females within this backstroke study identified participant 2 recorded the second slowest maximum speed and second lowest mean net drag force (93 N) with large differences between the minimum and maximum net drag forces (152 N) (Figure
1. Conversely, the female swimmer who achieved the fastest maximum speed (participant 3) recorded a mean net drag force of 136 N and differences between the minimum and maximum net drag force production of 114 N (Figure 1). This was repeated for the male participants 8 and 10 (Figure 1). In this case, the two swimmers generated the same mean net drag force (200 N), however participant 8 was still faster than participant 10 (Figure 1). Conversely, differences between the minimum and maximum net drag forces were 78.9 N and 214.2 N, respectively. The exponential relationship between speed and net drag force explained why faster swimmers also generated significantly greater net drag force, however it also seemed that minimising the magnitude of the fluctuations in net drag force was also important in determining proficiency of backstroke swimming.

The ability to represent net drag force as an instantaneous net drag force profile was a clear advantage of this system. The outcome of this study highlighted the practical relevance of explore instantanteous net drag force. A limitation of this study was that the net drag force was measured for the whole body swimming action and masks the effects of the interaction of leg kick rate on the net drag force profile. Future studies should examine a larger cohort to further clarify this matter.

Acknowledgements

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References


Figure 1: The instantaneous net drag force profile for selected swimmers highlighting the variations in force fluctuations between and within individuals.

a) Female participants at the same maximum speed
b) Male participants at the same maximum speed
c) Male participants at the different maximum speed
d) Female participants at the different maximum speed
**Figure 2**: The instantaneous net drag force profiles for a male and female participant highlighting the left and right stroke cycle.
**Table 1:** Speed, passive drag, net drag force and minimum and maximum values expressed as a mean and confidence interval.

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