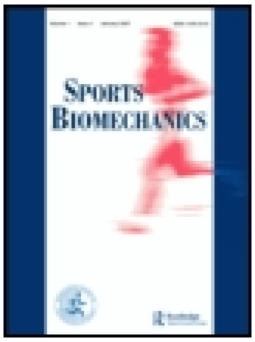

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Effect of wetted surface area on friction, pressure, wave and total drag of a kayak

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Effect of wetted surface area on friction, pressure, wave and total drag of a kayak

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ABSTRACT

Using theoretical principles, the components of drag (friction D_F, pressure D_{PR} and wave D_W) of a single-seat kayak were analysed. The purpose was to examine the effect of changes in wetted surface area due to changes in kayaker's weight and the relative contribution of D_F, D_{PR} and D_W to the total passive drag as function of velocity. The total passive drag values were based on experimental data collected in a single-seat kayak. Three different kayaker simulated weights were tested – 65, 75 and 85 kg. D_F was the drag component that contributed the greatest percentage (between 60 and 68% at 5.56 m/s the top velocity tested) to the total passive drag for all the velocities tested and simulated weights. D_W was the most affected by the increase in kayaker's simulated weight, mainly when comparing 65/75 to 85 kg. Results support the importance of a kayak design selection that minimises the kayak's drag for the individual weight of the kayaker. Also, the results suggest that the path for better hydrodynamic kayak performance should seek changes that can reduce D_F, D_{PR} and D_W with D_F offering the most potential to reduce passive drag.

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Hydrodynamics; passive drag; drag decomposition

Introduction

Choosing the correct boat design could be as important as choosing the best conditioning program or paddle design to optimise performance. As we progress through the age of technology, sports engineering has become as important to athletic performances as physical and psychological conditioning (Robinson, Holt, & Pelham, 2002). Investigators suggest that the improvements in kayaking performance times have been related to advances in boat design (Michael, Smith, & Rooney, 2009).

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To move the kayak at high speed, paddling effort has to increase drastically, due to sharp increase in drag at higher velocities. Because drag is a major factor in the energetics of kayaking, small decreases in kayaking drag can significantly affect performance. The kayaks' hydrodynamic performance is mainly dependent on hull geometrical shape (Mantha, Silva, Marinho, & Rouboa, 2013), type of hull surface and weight of the kayaker sitting in the boat. These factors affect the water displaced and change the wetted surface area of the hull and hydrodynamic resistance.

The design of a kayak is a complex process that has multiple constrains, one of these are the rules governing sprint competition. For example, kayak maximum length and minimum weight are restricted (https://www.canoeicf.com/icf/AboutICF/Rules-and-Statutes.html). In addition, there are other constraints imposed on kayak performance by stroke mechanics (stroke frequency and the distance the kayak travels per stroke [Pendergast et al., 2005]), as well as movement of the trunk and legs that are also involved in the paddling motion (Mantha et al., 2013). Taking into account the hydrodynamic factors together with the task constraints, kayak designs have evolved to a narrowed hull shape that has a decreased frontal and wetted surface areas (Michael et al., 2009). The change in hull shape may have led to a decrease in hull resistance. The total passive drag (kayak plus the drag created by the kayaker's weight) is highly dependent on the wetted area of the kayak (Pendergast et al., 2005). The wetted surface area is, in part, determined by the depth of the kayak in the water, which in-turn is partially determined by the body weight of the kayaker (Pendergast, Bushnell, Wilson, & Cerretelly, 1989). The buoyant force resulting from the volume of the kayak reduces the wetted surface area (Pendergast et al., 1989). Changes in kayak hull design can minimise drag by changing the depth that the hull sinks in the water and consequently the wetted surface area (Pendergast et al., 2005). Depending on the hull design the velocity of the kayak also influences the frontal and wetted surface area.

The total drag force is the sum of forces due to the friction of the water on the boat (friction drag – D_F), the force required to move water to form a path for the kayak (form or pressure drag – D_{PR}) and the resistive force associated with the production of waves by the kayak (wave drag – D_W). These types of drag are individually determined by the shape of the hull, its wetted surface area, and the velocity of progression (Pendergast et al., 2005). Due to different hull shapes, the contribution of the three types of hydrodynamic drag (friction, pressure and wave) at different velocities to the total drag has to be considered. For kayaking, the wetted surface is critical, as it determines D_F (Pendergast et al., 2005) and, along with hull shape the D_{PR} and D_W.

The development of improved kayak designs requires knowledge of the relative contribution of each of the three types of hydrodynamic drag to the total drag. To understand the effect of hull design, per se, on drag, it has to be determined without the kayaker paddling, i.e., passive. The purpose of this study was to examine the effect of changes in wetted surface area on the relative contribution of D_F, D_{PR} and D_W (using theoretical models) to the passive drag (D_P) as a function of velocity. It was hypothesised that increased simulated kayaker's weight (from 65 to 75, and 85 kg), and consequent increase in wetted surface, would significantly increase total hydrodynamic drag due to relative contribution of the hydrodynamic drag components most affected by the increase in wetted surface, namely D_F and D_W.

Methods

One male kayaker weighing 65 kg was towed in a M size single-seat kayak (K_1) (Gomes et al., 2015) to determine D_P over the range of velocities (2.78–5.56 m/s) that are typical in the four distances raced in international kayak sprint competition (https://www.canoeicf.com/icf/Aboutoursports/Canoe-Spring/Results-Records.html) and training. The kayaker was towed three times, once with only him, and twice with added weight in the kayak totalling 75 and 85 kg.

Kayak geometric model

One of the latest models of the M size K_1 (Quattro, Nelo®, M.A.R. Kayaks Lda., Portugal) with 5.2 m length was used in the present study. The manufacturer of this kayak recommends this model for a kayaker weighing up to 70 kg. The 3D surface geometry model of the kayak was acquired by optical measuring techniques (GOM, Braunschweig, Germany). The 3D surface geometry data of the scan were generated in Solidworks CAD software (SolidWorks Premium® 2013, Waltham, Massachusetts, USA) and is shown in Figure 1.

The hydrodynamic geometric dimensions of the kayak (Table 1) were extracted during the generation of the geometry in Solidworks. The location of the waterline was determined by in-field measurements with the kayak (12 kg in weight) in a stationary position on-water with the same kayaker. Three different kayaker weights (65, 75 and 85 kg), by placing appropriate weights under the kayak seat of the 65 kg kayaker were simulated.

Measured towing drag

Passive drag measurements were determined by towing the kayak with a kayaker in a competitive kayak sprint course with a specially designed field-towing system. Detailed information about the design of the field-towing system and passive drag data collection can be found in Gomes et al. (2015). Briefly, the field-towing system included a sliding platform with an electro-mechanical device attached. The device was composed of a drum of 559 mm diameter driven by a 750 W electric motor (Direct Drive, Madrid, Spain). The electric motor had a variable power source controllable by a hand accelerator allowing changes in

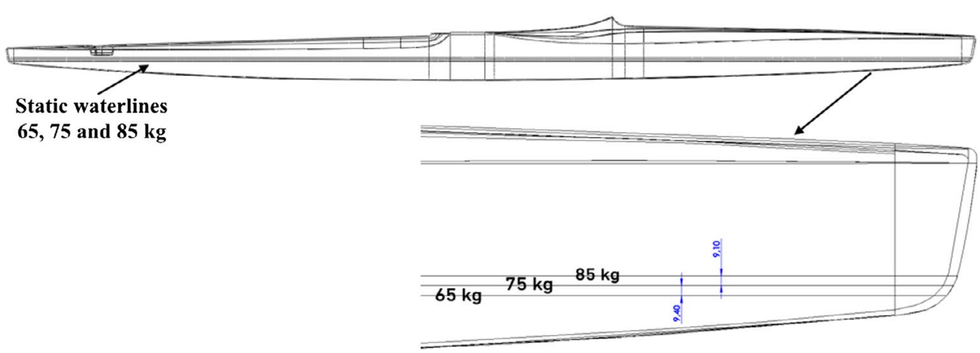

Figure 1. 3D surface geometry model of the kayak.
Notes: Representation of the static waterline for 65, 75 and 85 kg. Bow in detail showing the distance (mm) between the static waterlines of the different weights tested.

Table 1. The hydrodynamic geometric dimensions of the kayak full-scale model (K_1 Quattro M) with three simulated weights (65, 75 and 85 kg).

Total simulated weight			
Paddler	Kayak	Total wetted surface area (cm^2)	Frontal submerged surface area (cm^2)
65 kg	12 kg	15,244.5	253.4
75 kg	12 kg	16,271.4	284.1
85 kg	12 kg	17,254.6	314.7

the angular velocity of the drum. Both sides of the centre of the drum were attached to a load cell (iLoad Pro, Loadstar, Fremont, USA) by a steel cable. The load cell, in turn, was attached to a fixed point behind the device at the same height as the centre of the drum. The kayak was pulled by an inelastic fluorocarbon cable (Caperlan, Villeneuve, France) 300 m in length, 0.8 mm in diameter and 180 g total weight attached to the kayaks' cockpit and bow tip. The testing conditions were not affected by current or wind. The participant was passive thus minimising, or eliminating, kayak accelerations or decelerations, or changes in yaw or pitch. For the decomposition of the total D_P it was assumed that the aerodynamic drag (air on the kayaker and non-submerged portion of the kayak) was approximately 10% of the total drag as previously reported by Jackson (1995). Although the aerodynamic drag could be affected by kayak velocity and wind speed, the effect of the former would be small (Jackson, 1995) as the testing was performed with negligible wind. Thus, 10% of the measured data for D_P at all velocities and simulated kayaker's weights were subtracted to determine the D_P due to the water effects alone.

Passive drag decomposition

There are several potential approaches to analyse the drag of ships, fish, swimmers and kayaks. Models of Naval Architecture for ships or streamlined bodies have been used for specific vessels (Day, Campbell, Clelland, Doctors, & Cichowicz, 2011; Pendergast, Mollendorf, Cuviello, & Termin, 2006; Yang, Huang, & Noblesse, 2013). A kayak has less volume displacement than other types of vessels that have been analysed using the Naval Architecture approach. In addition, although the kayak is pointed at its bow, it has a blunt section to accommodate the kayaker, and narrows past this point. The kayak's length and width are closer to swimmers than ships. Although the competitive velocities of the kayak are greater than the swimmer, they are much lower than that of the boats and ships. Based on these characteristics we considered that a kayak can be analysed based on swimming models of drag decomposition. Previous studies of swimmers have used a blunt body approach to decompose total drag (Mollendorf, Termin, Oppenhein, & Pendergast, 2004; Pendergast et al., 2005, 2006). Similar to the swimmer, it was assumed that the pointed bow of the kayak contributed little to the drag, and the seat portion of the kayak was assumed to be the leading edge. Thus, total passive drag was decomposed into its individual components as described by Mollendorf et al. (2004), Pendergast et al. (2005, 2006) for swimmers. The D_F was calculated for a flat plate, considering that it can be modelled to a good approximation as flows over flat plates (Mollendorf et al., 2004; Pendergast et al., 2006):

$$D_F = q\,A_S\left[\frac{0.074}{\mathrm{Re}_L^{1/5}} - \frac{1,740}{\mathrm{Re}_L}\right] \tag{1}$$

where q is the dynamic pressure calculated as $q = {}^1/_2\rho V^2$ (ρ is the fluid density, V the kayak velocity); A_S the wetted surface area; and $\mathrm{Re}_L = {}^L/_\nu$ where L *is* the kayak length and ν the fluid kinematic viscosity. The D_{PR} was formulated to be proportional to the second power of the velocity and directly proportional to the frontal surface area (A_f). The D_W was formulated to be proportional to the fourth power of the velocity. Drag (D) decomposition consisted of summing the drag components and then determining the proportionality constants using a standard multiple, non-linear regression package (Curve Fitting Toolbox, MatLab R2010a, The MathWorks Inc., Natick, USA) with the expression:

$$D = K_1 D_F + K_2 A_f V^2 + K_3 V^4 \tag{2}$$

where D_F is given by Equation (1), A_f the frontal area of the kayak, V is the kayak velocity and K_1, K_2 and K_3 are regression coefficients.

Although the frontal area of the kayak underwater (A_f) should vary with the change in kayak angle due to changes in kayak velocity, it was assumed that the kayak aligned in a horizontal position and stationary in the present study.

Results

The mean D_P for the M size K_1 ranged from 22.39 ± 0.45 N at 2.78 m/s to 88.89 ± 10.02 N at 5.56 m/s. Figure 2 shows that the increase in kayaker's weight (from 65 to 75 and 85 kg) resulted in an increase in the total kayak D_P. The increments in weight-associated increases in D_P were higher at the higher velocities.

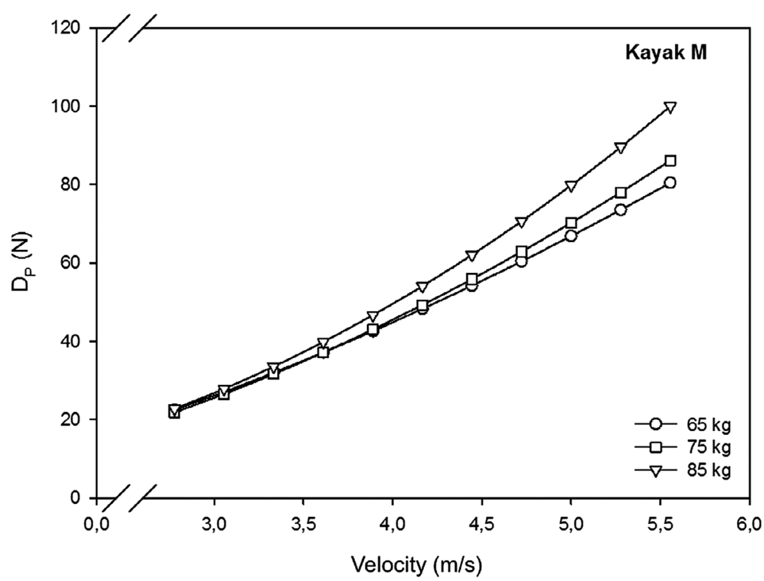

Figure 2. Kayak passive drag (D_P expressed in *N*) plotted against kayak velocity for each of the added weights (65, 75 and 85 kg) for the M size kayak.

Decomposing the total D_P yielded estimated values for D_F, D_{PR} and D_W (Figure 3). The three components of drag increased with velocity, being higher at each of the velocities as a function of the kayaker's weight (weight of the kayaker plus added weights).

D_F increased as function of velocity and contributed the greatest percentage to the total D_P. At the maximum velocity tested it represented 66.37, 66.90 and 59.36% of the total D_P, for 65, 75 and 85 kg, respectively. Differences between simulated weights, for each of the velocities tested, was less than 10%, with D_P for 75 and 85 kg weights very similar to each other. The D_{PR} increased as function of V^2 and at the maximum velocity tested contributed 24.62, 22.37 and 21.05% of the total D_P, for 65, 75 and 85 kg weight in the kayak, respectively. However, it was not significantly affected by increases in simulated kayakers weight. D_W increased as a function of V^4 and was significantly affected by the increased simulated kayaker weights. At the maximum velocity tested, compared to the 65 kg weight (7.05 N), the 75 kg weight (9.52 N) increased D_W by 35% and with the 85 kg weight by 182% (19.90 N). The increased D_W as a function of simulated kayaker weight resulted in an increase in the per cent contribution to the total D_P from 9.00% to 10.73% to 19.60%, respectively, at the maximal velocity studied.

Discussion and implications

The results of this study supported the hypothesis that the increase in the wetted surface, due to the increase in the simulated kayakers' weight, increased the total passive hydrodynamic drag. The increased D_P was due primarily to changes in D_F and D_W, that are the two hydrodynamic drag components most affected by the increase in wetted surface.

For the three simulated kayak weights tested the D_F had the highest contribution to the total D_P at all velocities tested. The data from the present study are in agreement with a

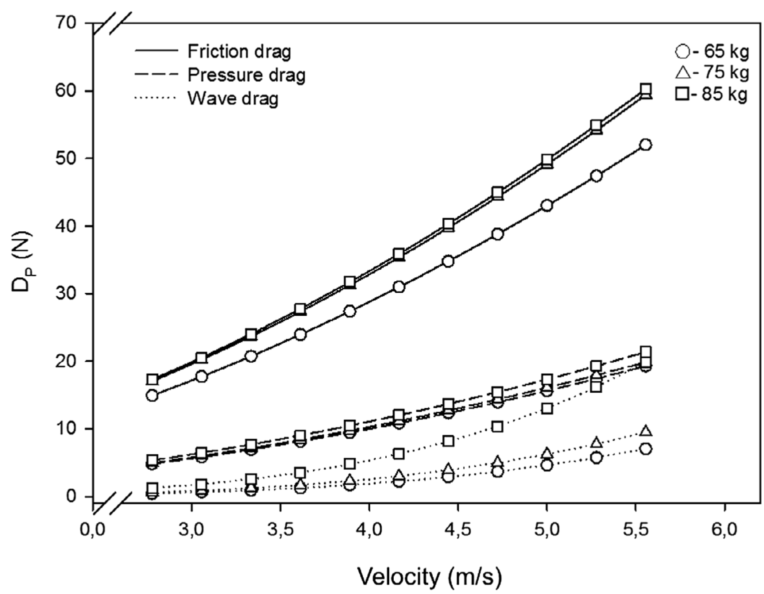

Figure 3. The data for the D_F, D_{PR} and D_W are shown for each of the simulated kayaker weight (65, 75 and 85 kg) in the K_1 size M, as a function of velocity.

previous study (Mantha et al., 2013) who used computational fluid dynamics simulation of a single kayak. Michael et al. (2009) suggested that D_F is the main component of the hydrodynamic drag that acts negatively on the kayaks' movement. This suggestion is supported by the data from this study.

One method of reducing D_F, which accounted for approximately 64% of the D_P, can be accomplished by reducing the friction coefficient (Jackson, 1995). However, ICF rules (https://www.canoeicf.com/icf/AboutICF/Rules-and-Statutes.html) are very restrictive in respect to the hull surface material. Pendergast et al. (2006) suggested D_F could be reduced by smoothing the hull surface, adding substances to the hull (for example, silicone lubricant), or using riblets or turbulators on the hull. However, these changes in the hull are against ICF rules. Another method of reducing D_F is to reduce the wetted surface area (Mantha et al., 2013) by changing the hull design as a function of velocity.

The D_{PR}, which accounted for approximately 23% of the total drag, can be reduced by decreasing the frontal submerged surface area by making the kayak more narrow (Mantha et al., 2013). However, this effort is limited by the size of the cockpit due to the pelvic girdle diameter (since the kayaker goes sit-in the boat). In addition, making the kayak more narrow would probably results in loss of stability.

D_W increased as a function of velocity for all simulated kayaker weights. This increase is likely due to the generation of shorter waves at low velocity while as velocity increases the waves become longer (Mantha et al., 2013). The longer the waves become the higher the levels of energy dissipated, implying greater D_W values (Mantha et al., 2013). D_W had the lowest contribution to the total D_P for all measured velocities. As can be observed in Figure 3, D_W was the drag component that was most influenced by the increase in simulated kayaker's weight. The effect of the weight in the kayak is most likely due to the greater immersed volume of the kayak. As D_W increases as the fourth power of velocity, D_F by V and D_{PR} by the second power, the relatively low contribution of D_W to total D_P in the present study is likely due to the velocities used. This relative low contribution of D_W to the total D_P in the kayak is similar to previously reported data for swimming at slower velocities. It would be expected that at velocities greater than used in the present study the D_W would contribute more to D_P. As the velocities used in the present study represented competitive velocities, studying faster velocities would not be relevant to competitive kayaking.

As observed in Figure 3 the weight of the kayaker is an important contributor to total D_P. D_P was influenced not only by the D_W, but by the increased wetted surface area's affect on D_F and the frontal submerged surface area's affect on D_{PR}. It was however, as previously hypothesised, the differences due to the increase in the simulated kayaker's weight had the greatest effect on D_F and D_W.

The kayak's hull displacement is a balance of the kayak's buoyancy due to its volume, the weight in the kayak and the lift to the kayak resulting from the forward velocity. It can be hypothesised that, since the kayak is narrow it sinks deeper with a heavier paddler (85 kg). The deeper depth would result in less upward hydrodynamic lift, causing a significant increase in D_W at high velocities compared with the lighter paddler weights tested (65 and 75 kg).

The goal of the different kayak manufacturers' is to produce a hull shape (according to the ICF rules) with better hydrodynamic performance. D_F is the drag component that account for the large percentage of the total D_P. Thus, changes that minimise D_F could have greater influence in reducing drag. Mantha et al. (2013) tested a L size, as opposed to the

M size used in this study, of three evolution models of a K_1 (Nelo®, Vanquish, Models I, II and III). They observed improvements in design from Model I to II due to reduction of D_F. However, as hull designs evolve further, possible hull changes to reduce drag diminish. The reduced room for improvement of hull design increase the demands for accuracy of both the experimental and computational approaches to minimise drag (Day et al., 2011).

In contrast to the drag determined by a passive kayaker (D_P), during actually paddling the movements of yaw and roll (Michael et al., 2009) have a large effect on the wetted surface and consequently on D_F and total active drag (D_A). The yaw and roll are due to the asymmetry of the power application resulting from de alternate force application on the left and right side of the kayak (Day et al., 2011). In addition, when the kayaker is actually paddling his/her skill level would affect drag (D_A) (Gray, Matheson, & McKenzie, 1995; Pendergast et al., 2003; Ong, Elliott, Ackland, & Lyttle, 2006). It could be expected that the likely increase in the D_F caused by paddling would be added to the D_P. In spite of this affect, the analysis of the effects of weight would also be relevant to D_A, as well as to D_P as shown in this study. Also, the design of the kayak rudder can probably change not only the drag itself, but assist in compensating for unwanted rotations of the kayak, particularly yaw.

There are several limitations to this study. The kayak drag was determined during passive towing, as opposed to when the kayaker is paddling. The strength of this was to emphasise the drag of the kayak per se, and to eliminate changes in the wetted surface area that would occur if there were accelerations and decelerations from the intermittent application of propulsion during actual paddling. Another limitation of the present study was that the frontal submerged surface area was not varied with kayak velocity for the calculation of the pressure drag. Although, the kayak longitudinal angle (pitch) could change as the kayak was towed at constant velocity, over the narrow range of velocities analysed in this study this affect was judged to be small. Although the analysis of boats and ships with higher speeds requires a different approach, the normal range of kayak velocities is slower. Therefore, we selected the present approach, for theoretical drag decomposition, as previously published by Mollendorf et al. (2004) and Pendergast et al. (2006) for swimmers. Similarly, we did not vary the contribution of aerodynamic drag with velocity as the velocities are relatively low and the range of velocities studied small.

Conclusion

The results of the present study suggest that the D_F is the component of drag that contributes the most to the total D_P, at velocities typical in international kayak sprint competitions and training. Also, present results support the importance of a kayak design selection that minimises the kayak's drag for the individual weight of the kayaker, as it was previously reported by Gomes et al. (2015). In addition, this study contributes to increase knowledge and experimental accuracy of not only total drag, but importantly is components of friction, pressure and wave drag. These data can be applied to design approaches to guide kayak manufacturers to improve hull designs. The goal of new designs is to minimise D_F, D_{PR} and D_W and consequently the total drag. Changes in hull design should take into consideration the effect of the kayaker's weight to minimise the combined sum of D_F, D_{PR} and D_W. This study has shown that the wetted surface area is an important consideration when designing hulls to reduce D_F and D_W.

Disclosure statement

The authors of the present document have none financial conflict or benefit arising from the application of the research.

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