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AN ASSESSMENT OF HYDRODYNAMIC AND SIMULATED RACE PERFORMANCE FEATURES OF THREE C-1 HULL DESIGNS

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ABSTRACT

Purpose. Recently engineered Canadian Single (C-1) canoe hull designs have been found to produce less resistive drag than the traditional Delta design in tow tank test conditions. If these laboratory findings were found to be similar to on-water performance tests, then these new hull designs could give canoe sprint athletes a competitive advantage. However, these claims have not been independently confirmed nor has it been shown that these new designs result in improved performance under race conditions. Three C-1 hull designs (traditional Delta and the recently engineered Armageddon and Ergo-Starlight) were compared in order to detect differences in C-1 boat dynamics. **Methods.** The C-1 canoes were propelled by eleven national- and international-class paddlers who performed 350-m all-out trials from a dead start in each of the three crafts. One-way ANOVA compared differences in means for individual 50-meter segment and 350-meter performance times. **Results.** Performance times over the 350-meter race simulations were significantly faster ($p = 0.038$) among international-class paddlers with the Armageddon and Ergo-Starlight designs compared with the Delta. **Conclusions.** International level canoeists should expect improved performance times by choosing the Armageddon and Ergo-Starlight versus the Delta-designed C-1.

Key words: canoe, hull design, paddling, sprint racing, technology

Introduction

In the sport of sprint canoe and kayak racing, performance improvements have been related to technological advancements [1, 2]. Until 1998, the Danish-made Delta design of the Canadian Single canoe (C-1, see Fig. 1, 2, 3) had dominated international sprint canoe competition. At the 1998 Sprint World Championships, the Polish-made Ergo-Starlight (Fig. 1, 2, 3) was introduced and within a year became the preferred C-1 design. In April of 1999, the Danish-made Armageddon (Fig. 1, 2, 3) was introduced to compete with the Ergo-Starlight. Although the Delta has been the preferred sprint race C-1 design for 30 years, it has been replaced by international level paddlers with the newer hull designs albeit little objective research showing improved craft performance.

Over the past decade, there has been an architectural revolution in the field of sprint race canoe design. Tow tanks have been used to test, under various conditions, the factors affecting the motion and velocity of different sprint race canoe designs. These studies have found that the dimensions, shape, and material used in the construction of sprint race canoes can affect the motion and velocity of the craft. One of the most important factors is resistive drag force.

Resistive drag is an opposing force, acting on the desired motions of the system (canoeist and craft). Two determinantal features of resistive drag force as related to any water-sport craft are the dimensions of the craft (e.g. shape) and the amount of surface area interface.

Designers of the Armageddon (Struer Sprintboards, Denmark) and Ergo-Starlight (Plastex Composite, Poland) have made several design modifications to the basic Delta hull design in an effort to reduce resistive drag. The scientists, engineers, and naval architects of Struer and Plastex have attempted to decrease the amount of interface between the hulls of the crafts with the water (wetted surface) to reduce resistive drag force from a hydrodynamic standpoint. For example, one architectural change incorporated by the designers was a decreased surface area in the 'wing' section of the Ergo-Starlight and Armageddon compared with the Delta (Fig. 1). In the Delta design, the large delta (diamond) shape (Fig. 2A, 3A) may add stability to the craft, but it also encompasses a large wetted surface area. However, the delta shape is reduced (less wetted area) in the Ergo-Starlight and Armageddon (Fig. 2A, 3A).

The second important amendment relates to the bow sections of the Ergo-Starlight and Armageddon. When compared with the mid-section of the Delta (Fig. 2B, 3B), the streamlined mid-sections of the Ergo-Starlight and Armageddon allow for placement and tracking of the paddle parallel to the craft. This should allow for a more efficient application of force via the paddle during the propulsion phase of the canoe stroke. Furthermore, a streamlined mid-section may reduce the amount of resistive drag force as a consequence of less bow wave. This hydrodynamic-accommodating feature may be most

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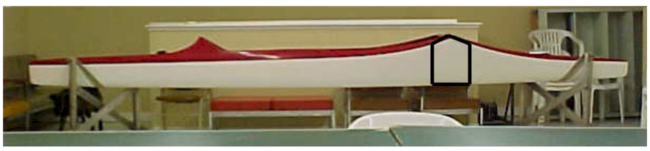
pronounced at higher race velocities. The line of travel of the craft is heavily influenced by the ordination of the placement of the paddle's blade and the direction of travel of the blade through the water during the propulsion phase of the canoe stroke. That is, at entry, if the blade is perpendicular to the water surface and travels in the opposite direction of the moving craft and parallel to the long axis of the craft, vector analysis theory would suggest that the canoeist is managing an efficient application of force. The application of force in a path not parallel to the long axis of the boat would lead to an insufficient expenditure of energy and fatigue, an obvious undesirable physiological consequence where the goal is to optimize performance. From a systems standpoint, the linear and parallel application of force via the blade will optimize the linear forward propulsion of the craft.

Other design considerations include the breadth of the hull of the craft, consisting of the port and starboard wings. These wings are features of the craft designed to enhance stability. As such, the breath is the widest section of the hull and, from a hydrodynamic standpoint, a major factor in boat displacement. Indeed, the larger the displacement of the hull, the greater the interface between the boat surface and water and, consequently, increased resistance drag. In most cases, resistance drag has a negative effect on boat speed. Thus, streamlining the breadth should reduce resistance drag and therefore potentially improve boat speed. Although a wide breadth design may increase the stability of the craft particularly to counter wave action, Figure 4 illustrates that the wider breadth of the Delta requires the canoeist to place and manipulate the blade of the paddle in a direction not parallel to the long axis of the craft or through its center of mass. This generates torque on the system

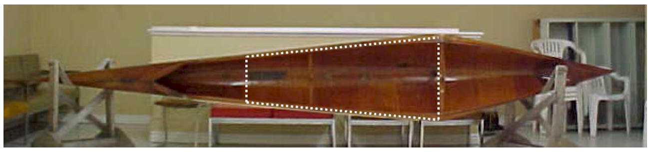
(a) Delta



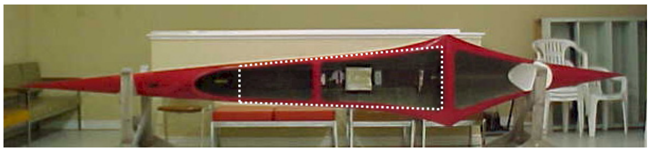
(b) Ergo-Starlight

(c) Armageddon

Figure 1. Port view of the (a) Delta, (b) Ergo-Starlight, and (c) Armageddon; box outlines highlight areas that correspond to wetted surfaces of the port wing section of the hulls; note the larger wetted area of the Delta compared with the Ergo-Starlight and Armageddon



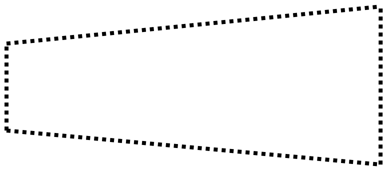
(a) Delta



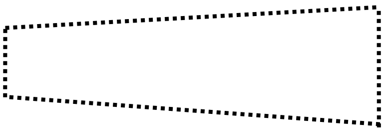
(b) Ergo-Starlight

(c) Armageddon

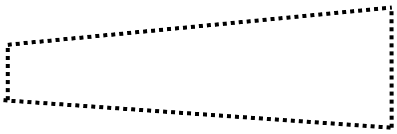
Figure 2A. Top view of the three C-1 designs: (a) Delta, (b) Ergo-Starlight, and (c) Armageddon; dashed outlines highlight the mid-sections of the craft



(a) Delta



(b) Ergo-Starlight



(c) Armageddon

Figure 2B. Comparison of the mid-sections of the (a) Delta, (b) Ergo-Starlight, and (c) Armageddon; note that the Delta is wider compared with the Ergo-Starlight and Armageddon

and creates a yawing moment, in what can be regarded as a hydrodynamically insufficient approach in boat locomotion.

Another important factor is the construction material of the craft. During forceful propulsion, the hull shape of a craft constructed of delicate material can twist and bend, losing its potential hydrodynamic accommodating features. In the case of the Ergo-Starlight, the designers have used a reinforced honeycomb composite, which the manufacturer suggests is able to withstand torsion stress (changes in shape) during maximum race velocity.

To the best knowledge of the authors, only after this evolution of design modifications has tow tank testing

(a) Delta (b) Ergo-Starlight (c) Armageddon

Figure 3A. Rear view of the (a) Delta, (b) Ergo-Starlight and (c) Armageddon; curved lines highlight the breadth of the crafts

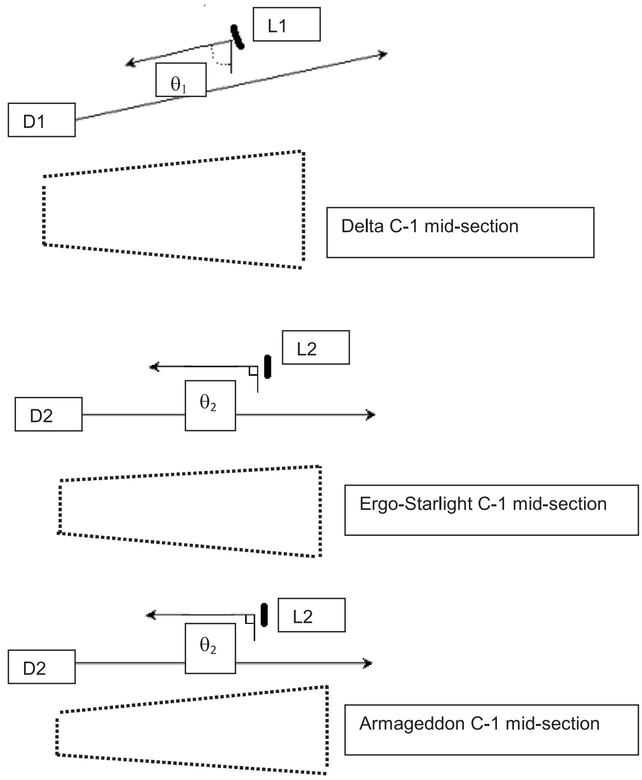
(a) Delta (b) Ergo-Starlight (c) Armageddon

Figure 3B. Comparison of the breadths of the Delta (a), Ergo-Starlight (b) and Armageddon (c)
Note that the Delta (a) has a larger breadth compared to the Ergo-Starlight (b) and Armageddon (c)

been used to compare the traditional Delta and the new Armageddon design. In this form of testing, the Armageddon was found to have 1.7% less surface resistive drag than the Delta at a velocity of 5 m/s [3]. However, these claims have not been independently confirmed, nor has it been shown that this new design will result in improved performance under race conditions. Ultimately, the only measure of technological advancement is reduced performance time.

However, it would appear that paddling the Delta C-1 is not an efficient system in achieving better performance in sprint racing (Fig. 4). At the international level (e.g. Olympic Games, Word Championships), the venue for sprint canoeing is a marked 1000-m race course of nine straight parallel lanes. The goal for the canoeist is to paddle the race distance in the shortest time frame. Except for the 5000-m race, the canoeist is required to remain within their assigned lane and travel from the start to the finish line in one direction. To paddle a 200-m, 500-m, or 1000-m race, the canoeist attempts to travel in the shortest possible distance (straight line) from start to finish as it is the most energy efficient strategy of propelling the craft. Hypothetically, it appears that the energy expenditure of a canoeist racing in a Delta may be higher than that of a canoeist paddling an Armageddon or Ergo-Starlight. For example, a canoeist in the Delta may expend additional energy in manually steering the craft, and perform a greater number of strokes per distance, possibly with a great effort (force) per stroke. However, these interpretations have not been tested.

Therefore, in order to determine if the recent changes in Olympic sprint C-1 canoe design indeed result in improved racing performance, the Ergo-Starlight and Armageddon along with the traditional Delta C-1 were tested and compared in simulated race conditions.



D1 – direction of Delta, L1 – path of the blade of the paddle, θ_1 – direction of force; D2 – direction of Ergo-Starlight or Armageddon, L2 – path of the blade of the paddle, θ_2 – direction of force

Figure 4. Diagrammatic representation of the paths of travel of the Delta, Ergo-Starlight, and Armageddon during propulsion via a canoe stroke

Material and methods

The experiment was based on a counterbalanced design where all participants performed trials in each of the three crafts. The order of trials was randomized to control for learning, fatigue, and environmental effects. The trials were then compared for differences in performance (time, dependent variable) based on treatment (C-1 design, independent variable).

Of the twenty Canadian male national- and international-caliber C-1 paddlers asked to participate, eleven subjects completed the study. Participants' competitive ability ranged from 82–100% of the best world championship performance time. Participants ranged in weight from 67.4 kilograms to 94.8 kilograms (77.53 ± 8.37 kilograms) and were 15 to 27 years of age (20.16 ± 4.87 years).

Prior to taking part in this study, subjects were provided with a letter of information outlining the purpose and procedures of the study. Details of the study were made clear and any questions were addressed. They were then asked to sign a consent form. This study received ethical approval by the School of Health and Human Performance, Dalhousie University.

The experimental procedure consisted of performing three blocks of trials during a 350-m all out race effort in the Delta, Ergo-Starlight and Armageddon crafts.

The distance of 350 m was chosen to minimize fatigue while being long enough to reflect the three stages (start acceleration, traveling speed, and finishing kick) of the 500-m and 1000-m race distances. This distance has been successfully used in previous experimental conditions [4]. Trials were performed individually from a dead start. All trials were performed on an internationally certified course located on a freshwater lake with markers present at 50-m intervals. Trials were randomized to control for the possible effect of fatigue and wind conditions. To minimize learning effects, participants paddled each of the crafts prior to taking part in the study for familiarization purposes. No testing was conducted until an adequate comfort level was established and confirmed by the participant. The weight of the each craft, including the floorboard and kneeling stand, was standardized to 16.4 kg. Each paddler selected a paddle to their liking and did not change paddles at any time in the study.

Performance times were recorded and examined at 50-m intervals as well as the entire 350-m distance. Participants had a minimum of 20 min of rest between trials and were not made aware of the results until all trials were complete. Of the eleven subjects four completed three trial blocks, another four completed two trial blocks, and three completed one trial block. Therefore, all subjects performed at least one trial in each of the canoes. However, seven of the eleven subjects did not complete all three random sequences of trials. Several participants had training and competition obligations and were forced to drop out of the study. This reduced the sample size and therefore limited the statistical power of this study.

Comparative analyses were performed for the performance times collected in the three canoe designs. Mean performance times were measured to determine differences among C-1 designs. A series of one-way analysis of variance (ANOVA) tests were carried out on all participants to compare differences in means for individual 50-m segments and 350-m performance times. Participants were then grouped based on 350-m performance times with the 'best' paddlers (international) finishing below 100 seconds and 'slower' (national) paddlers above 100 seconds. Arranged in this manner, ANOVA measures were again performed on the grouped data. Given that a difference between first and second place in international competition may be as small as 0.01 s, a p value of 0.1 was selected for the purpose of determining statistical significance.

Results and discussion

Mean performance times for the individual 50-m segments and overall 350-m distance are presented in Figure 5 and Figure 6, respectively. It can be seen from Figure 6 that the Ergo-Starlight and Armageddon were faster than the traditional Delta in each 50-m segment, with the greatest difference in the middle 200 m stretch in favor of the Ergo-Starlight. ANOVA of mean performance times found no statistical significance ($p < 0.1$) for the 350-m distance (Tab. 1) or for individual 50-m segments.

Table 1. Statistical significance of ANOVA measures comparing mean 350-m performance times

Grouping	Craft	Degrees of freedom	p value
All subjects	Delta/ Ergo-Starlight/ Armageddon	32	0.376
> 100 s	Delta/ Ergo-Starlight/ Armageddon	17	0.270
< 100 s	Delta/ Ergo-Starlight/ Armageddon	14	0.038*
< 100 s	Delta/Ergo-Starlight	9	0.022*
< 100 s	Delta/Armageddon	9	0.046*
< 100 s	Ergo-Starlight/ Armageddon	9	0.600

* $p < 0.05$

Subjects were then grouped based on 350-m performance times with the 'best' paddlers having a mean performance time below 100 s for all three crafts and the 'slower' paddlers having a time above 100 seconds in one or more of the crafts. Grouped in this manner, ANOVA found statistical significance for the 'best' paddlers in favor of the Ergo-Starlight and Armageddon C-1 designs (Tab. 1).

One-way ANOVA tests used to compare the mean performance time of the 'best' paddlers found significant differences for the third ($p = 0.001$) and the fourth ($p < 0.078$) 50-m segments (Tab. 2). Statistical significance ($p = 0.038$) was found among the 'best' paddlers for the entire 350-m race simulation.

Table 3 presents ANOVA results carried out on the Delta and Ergo-Starlight designs revealing significance in four of the seven 50-m segments as well as the overall 350-m distance. Although differences were found in mean performance times between the Ergo-Starlight and Armageddon designs (Fig. 5, 6; Tab. 1, 2), no statistically significant differences in performance time were found.

However, for the 350-m trials, the Ergo-Starlight had a better mean performance time in most of the 50-m segments with the greatest difference found in the middle 200-m stretch (Fig. 5, 6; Tab. 1, 2). Given the fact that the World Championship sprint races are held over 200-, 500-, and 1000-m distances, it can be surmised that as race distance increases the positive effects of a more accommodating hydrodynamic craft may become more pronounced, resulting in statistically significant decreases in performance time.

Limitations of the study that need to be taken into consideration include psychological bias, subject diversity, and performance variability. Performance variability may be partially explained by the time of the testing [5]. Testing was performed during the post-competitive sea-

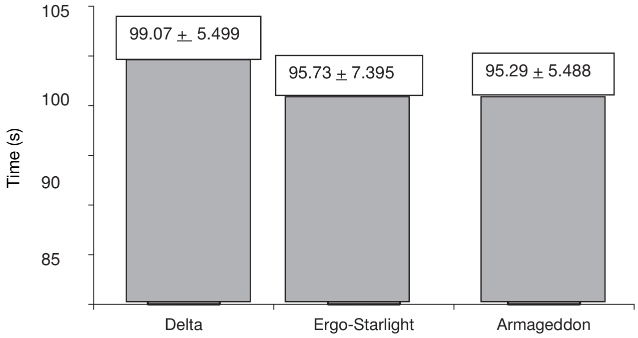


Figure 5. Means and standard deviations of 350-m performance times for all participants

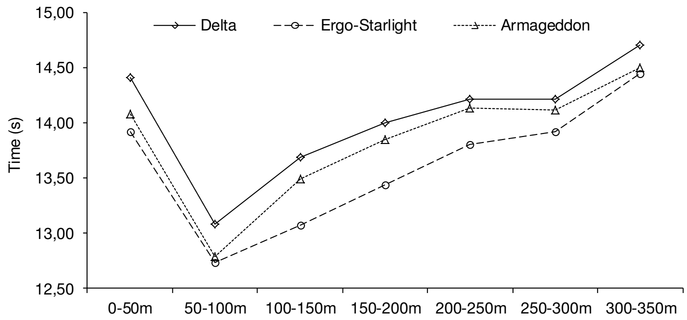


Figure 6. Mean 50-m performance times for all participants

Table 2. ANOVA statistics of mean performance times of the 'best' paddlers for individual 50-m and the overall 350-m segments

Distance	*n*	Delta		Ergo-Starlight		Armageddon		Degrees of freedom	*p* value
		Mean (s)	*SD* (s)	Mean (s)	*SD* (s)	Mean (s)	*SD* (s)		
1st 50 m	15	13.739	0.115	13.127	0.155	12.871	0.980	14	0.148
2nd 50 m	15	12.486	0.186	12.129	1.072	13.343	0.973	14	0.808
3rd 50 m	15	12.913	0.026	12.287	0.061	12.550	0.036	14	0.001***
4th 50 m	15	13.143	0.203	12.547	0.101	12.833	0.116	14	0.078*
5th 50 m	15	13.257	0.112	12.903	0.257	13.077	0.245	14	0.487
6th 50 m	15	13.437	0.101	12.997	0.146	13.017	0.129	14	0.127
7th 50 m	15	13.940	0.078	13.647	0.291	13.583	0.195	14	0.410
0–350 m	15	92.727	2.393	89.290	4.993	90.013	4.007	14	0.038**

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3. ANOVA statistics comparing the Delta and the Ergo-Starlight

Distance	*n*	Delta		Ergo-Starlight		Degrees of freedom	*p* value
		Mean (s)	*SD* (s)	Mean (s)	*SD* (s)		
1st 50 m	15	13.729	0.115	13.127	0.155	9	0.033**
2nd 50 m	15	12.486	0.186	12.129	1.072	9	0.496
3rd 50 m	15	12.913	0.026	12.287	0.061	9	0.001***
4th 50 m	15	13.143	0.203	12.547	0.101	9	0.042**
5th 50 m	15	13.257	0.112	12.903	0.257	9	0.229
6th 50 m	15	13.437	0.101	12.997	0.146	9	0.083*
7th 50 m	15	13.940	0.078	13.647	0.291	9	0.312
0–350 m	15	92.727	2.393	89.290	4.993	9	0.022**

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

son. Participants were in the recovery/transition phase of their seasonal periodization and were not in peak condition for sprint racing. Furthermore, Plagenhoef [6] stated that the best paddlers might not be pressed to commit all-out effort until the three-quarter mark during a race and only then if the race is closely contested. For this reason, this data may represent less than peak performance and must be cautiously interpreted.

Validity of Tow Tank Testing

Is the use of tank testing a valid means to measure craft performance as it relates to competition? In April of 1999, the Danish Marine Institute (DMI) performed tow tank testing to determine the hydrodynamic characteristics of the Delta and Armageddon C-1 designs, where Figure 7 displays the DMI's results for the crafts' skin friction (surface drag) at velocities of 3–5 m/s.

The hydrodynamic measures of kinetic resistance (drag) can be seen to overlay each other at speeds below 4.0 m/s with the Armageddon showing slightly less resistive drag force at speeds above 4.5 m/s. It was predicted by the DMI that at a speed of 5.0 m/s this would result in a 1.7% difference in time [3]. Indeed, more capable subjects performed significantly better in the Armageddon than in the Delta in the present study.

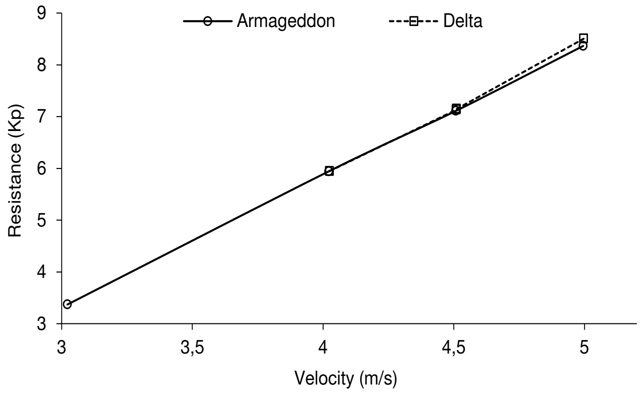


Figure 7. Resistive drag for the Delta and the Armageddon designs from the Danish Marine Institute [3] (Kp – kiloponds)

Our results show a 3.07% difference in mean performance time between the two crafts in favor of the Armageddon. According to the DMI results there should be no significant difference due to resistive drag at speeds less than 5 m/s. However, it is important to note that boat velocity remained constant when drag resistance was measured during the DMI testing. True paddling consists of cyclic periods of accelerations, where peak velocities exceed those represented by the means recorded in this study. With this in mind, it would seem that the peak velocities of the best athletes exceeded the 4.0 m/s threshold, allowing them to take advantage of the craft's more accommodating hydrodynamic characteristics more so than the slower paddlers.

Recommendations for further research

Is the improved performance of the Armageddon and the Ergo-Starlight designs a result of decreased resistive drag or other design factors? The Armageddon is considerably narrower (streamlined) than the Delta and results in a paddle path both parallel and closer to the longitudinal axis of the craft. This and other design effects may be partially responsible for improved performance. A comparative biomechanical analysis of differences in the stroke mechanics of canoeists while racing in the Delta, Armageddon, and Ergo-Starlight would be a worthy investigation. It would be also be desirable to repeat tow tank testing similar to the DMI's on the Armageddon and the Ergo-Starlight to further determine the validity of such measures in predicting craft performance between these newly engineered C-1 hull designs.

On-board accelerometers used by Pelham et al. [4] have been shown to be practical in the analysis of craft performance as related to paddle design. A collection of video, in-board accelerometer, and aerobic capacity data would provide for a more complete evaluation of craft performance. A study merging video and on-board accelerometry data is currently in progress by the senior author. Ultimately, competitive performance is the result of the interaction of the paddler and craft system. For this reason, future examinations of C-1 designs must involve performances at or near athletes' peak condition and utilize international level paddlers over true race distances.

In the future, without changes to the regulations determining craft design, athlete selection per boat will be increasingly based on anthropometric data and relevant climatic conditions of the racecourse. For example, individuals with smaller pelvic girths may be better suited for the number 1 position in the K-2 kayak or the number 1 and 2 positions in the K-4, whereas individuals with larger pelvic girths will be selected for positions closer to the stern of the craft. Similar conclusions may be reached for canoes, although athlete selection per position may differ, such as where smaller individual may be better suited to the limited space of the number 2 position of the C-2.

Conclusions

From a theoretical standpoint, including engineering (tow tank testing) and race simulations, the contemporary designs of the Armageddon and Ergo-Starlight have vastly more accommodating hydrodynamic features and advanced-material construction compared with the Delta. Canoeists racing in the Ergo-Starlight and Armageddon designs should feature improved performance times.

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