Identifying Key Performance Indicators in Elite Kayak Paddlers Using the E-kayak System

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Abstract: The aim of this exploratory study was to investigate multiple variables, that may affect sprint kayak performance on a 500 m race distance. 14 male elite paddlers participated in this study. The chosen variables were divided into three categories; on-water, body composition variables, and strength variables. A system called e-kayak, was used to conduct the on-water kayak measurements. This system makes it possible to synchronously measure the kinetics (paddle and leg forces) and kinematics (stroke frequency, displacement, velocity, acceleration and the angular velocity). The body composition of the paddler was evaluated using Dual-Energy X-ray absorptiometry, and the strength was assessed in a private lab. One repetition maximum was identified for four exercises including bench press, bench pull, pull up and a single arm machine. A significant negative correlation was found between the race time and lean body mass (r=-0.60, p=0,03). The results showed that multicollinearity exist between the mean force, peak force, and the two impulses, as all four variables showed significant positive co-correlations. The strength in the single arm machine was correlated with the strength in bench press, bench pull and the pull up exercise. The strongest correlation in relation to the strength variables were found between the SAM and race time (r=-0.27, p=0,38). Based on the findings in this study it can be deduced that the lean body mass of the paddler is a key performance indicator among elite kayak paddlers on a 500 m distance. Furthermore, the results could indicate that a kayak specific exercise such as a SAM would enhance performance on the 500 m distance more than the BP, BPU and PU exercise among elite paddlers.

1 INTRODUCTION

Flatwater kayaking was first introduced as an Olympic discipline in 1936 with 1,000 m and 10,000 m racing distances. In the present day, the sport known as "sprint kayaking" involves competing in races spanning 200m, 500m, and 1,000m, to complete the course in the shortest possible time [1]. Therefore, the total race time is often used as an objective criterion for kayak performance [2]. Flatwater kayaking is a variant of canoeing where the paddler is seated in a kayak within the deck [3]. From a stationary position, the paddler uses a double-bladed paddle with maximal effort for propulsion through the water [2]. To minimize the total race time, it is imperative for the paddler to enhance the velocity of the kayak. This can be achieved through the generation of substantial propulsive power during each stroke, accompanied by the application of substantial force to both the paddle blade and footrest [1, 3, 4]. A kayak stroke consist of two parts; the left and right side. A stroke cycle encompasses the time from a given position to the same position on the opposite paddle side. A stroke cycle is divided into a water phase, which is when the paddle is submerged in the water and a aerial phase, which is considered a recovery phase. Further, the water phase is divided into three subphases; entry, pull and exit [4]. According to Brown et al. [5] performance can be improved by increasing the stroke rate, which can be achieved by extending the relative water phase time and reducing the duration of the aerial phase. The stroke rate is inversely proportional to stroke time (s) and is usually displayed as the number of strokes per minute (spm) [4]. McDonnell et al. [1] states that male elite paddlers keep the paddle blade in the water for up to 63% of the stroke, and 64% for female paddlers in the 200 m distance. When the paddle is submerged into the water during the entry phase it is important to enter the whole blade to achieve maximal grip in the water. The pull phase creates the greatest force when the paddle shaft is perpendicular to the water. The paddler then pulls the paddle with maximal effort to create propulsion. In the exit phase, the paddle must leave the water quickly and rotate the blade out of the water to minimize drag [1]. Drag force acts on the kayak in between strokes when there are no propulsive forces applied from the paddler. Drag forces acts in opposition to the kayak velocity, which causes the kayak to decelerate. The drag force is composed of hydrodynamic (water resistance) and aerodynamic (air resistance) drag. Therefore, the average kayak velocity is defined as the result of the combined effects of the propulsive effort generated by the paddler and the drag forces acting on the kayak, paddler and paddle [1, 2, 4].

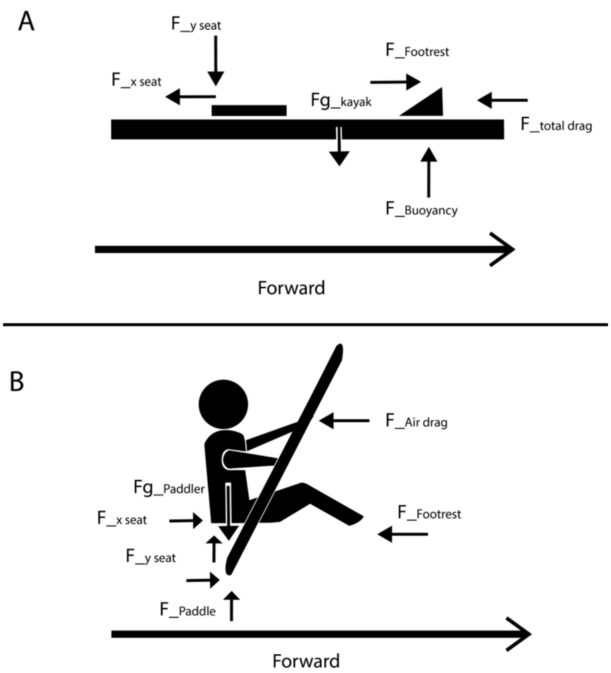

Figure 1: *Free-body diagram of the kayak (A) and paddler (B), illustrating the forces involved in a sprint kayak.*

Figure 1 shows a free-body diagram (FBD) of the kayak (A) and paddler (B), which illustrates that force is produced in the paddle and transferred through the kayak via the footrest, footstrap and seat. One leg pushes on the footrest in order to produce force, while the other leg pulls the footstrap. This means that the force produced by the paddler must travel through the seat and footrest to be translated from force to velocity [3, 6]. These actions allows for a rotation of the trunk and a moment of force is produced. This helps obtain a faster exit of the paddle from the water as the trunk muscles participate in the propulsion of the kayak [4]. To obtain maximal propulsive forces and a faster exit of the paddle from the water, the paddler must maintain the same height of the top hand while the pulling hand must pull the paddle diagonally to the kayak throughout the stroke [4]. To ensure that the paddle blade presents its maximum area to the direction of the pull, the paddle must be maintained at a nearly vertical position for the main part of the stroke [3].

By evaluating the kinetics and kinematics of the kayak, a better understanding of how it affects the kayak velocity is achieved. Aitken & Neal were the first to investigate on-water kinetics by instrumenting the paddle with strain gauges to measure the paddle forces [7]. A study by Gomez et al. created a system called "*Fpaddle*", which measures the forces in the paddle and transfers the data to a data acquisition station [8]. The system consists of strain gauges placed in different planes to provide a detailed view of the forces applied on the paddle shaft [8]. The *Fpaddle* system was utilized to investigate how the changes to water and aerial phases throughout the stroke cycle increased the stroke rates. The results emphasized the importance of reaching a high stroke rate to achieve a high velocity [9]. Nilsson & Rosdahl [10] developed an on-water measurement system, that measures the forces applied on the footrest and seat to achieve a better understanding of the leg forces in kayaking. Furhter, Nilsson & Rosdahl utilized the system in a study, which found a 21% reduction in the average speed when paddling with locked legs compared to paddling with free legs. This emphasizes the importance of the leg forces during sprint kayak performance. However, the leg forces have not been as widely investigated as the paddle forces.

The movement of a kayak can be measured using both GPS system, accelerometer and gyroscope. These systems help assess the position, velocity and acceleration of the kayak. The GPS and accelerometer systems are widely used to quantify the kayak performance and optimize the paddling technique [11]. A gyroscope can be used to measure the angular velocity of the kayak, which is categorized as the roll, pitch and yaw depending on which axis (x, y or z) the kayak rotates. A study by Bonaiuto et al. [12] found that the kayak velocity is mostly affected by the yaw and roll rather than the pitch. However, it is clear that the rotations of the kayak should be as small as possible, but it is difficult to identify a paddling technique that represents the best trade-off between a great paddle force and a limited roll [12]. Bonaiuto et al. suggest that in order to identify the best trade-off, it has to be investigated individually for each paddler.

A paddlers individual characteristics are responsible for the paddlers ability to achieve and sustain a given stroke rate. Elite kayak paddlers are best described as mesomorphs, meaning they have a great upper body girth and narrow hips. van Someren & Howatson [13] found that the chest circumference and humeral breadth were correlated with performance for the

200 m and 500 m distances for male paddlers. van Someren & Palmer [14] investigated anthropometric measures and physiological profiles in relation to performance on the 200 m distance. It was reported that elite male paddlers have a significantly greater circumference of the upper arm, relaxed forearm, tensed forearm and chest. Anthropometric variables are not as investigated for women, thus, correlations have not been found between anthropometric variables and performance [15]. Michael et al. [2] states that the body fat percentage of elite male and female paddlers ranges from 5.4±1.1% to 14.1±2.9%, measured as a sum of eight skinfolds. Large upper body musculature and a lean body mass have shown to be required to produce the power needed to sustain a high stroke rate [1]. It has been found that body fat percentage influence the performance of the 500 m and 1,000 m distances, but for the shorter 200 m distance, the paddler can afford to maintain a certain degree of body fat without hindering performance. Based on these findings it seems that elite paddlers may benefit from reducing body fat within a healthy range for longer distance events, while maintain a high muscle strength particularly in the upper body [1].

To enhance the upper body muscle strength it is necessary to do strength training in a dry-land environment. It is reported, that movements in which the time window to apply force is between 150 ms and 300 ms are increasingly dependent on maximal strength. This underlines the fact that kayak paddlers need to develop a high maximal strength in the upper body [6]. van Someren and Palmer [14] found a moderate negative correlation between 200 m performance and dynamic strength among elite male paddlers[14]. Further, McKean and Burkett [16] found a strong correlation between performance (in 500 m and 1000 m) and strength for both male and female paddlers for 1 repetition maximum (RM) pull-up and bench press. A recent study by Pickett et al. [17] reports that in order to improve the propulsive phase the paddlers usually condition the strength and power of the upper body trough prone bench pulls and bench press. The study found a strong negative correlation between 3RM bench presses, bench rows and chin ups relative to 200 m performances for national elite male paddlers.[17]

Based on the existing literature, it can be deduced that the most objective criterion for kayak performance is the total race time [1, 2, 3]. Existing research state, that multiple parameters may affect kayak performance including paddle and footrest forces, stroke rate, velocity of roll, body composition and strength of the paddler [1, 2, 3, 4, 17, 18]. With the existing technology it has not been possible to clarify key performance indicators in kayaking. This could be explained by the fact that it has been difficult to measure the kinetics and kinematics during an on-water kayak sprint [7, 8, 11]. However, a modern system called e-kayak allows to measure the kinetics (forces acting on the paddle and footrest) and kinematics (stroke frequency, displacement, velocity, acceleration, roll, yaw, and pitch of the kayak) during an on-water sprint [12]. Therefore, this exploratory study aims to investigate variables that may affect the kayak performance and thereby identify key performance indicators in sprint kayaking among elite paddlers.

2 METHODS

2.1 Subjects

14 male elite kayakers were recruited as subjects in this study. The subject characteristics are presented in *Table 1*. All subjects had attained a minimum of national elite status in their respective year group. All subjects received an oral and written information regarding the study, as well as a written consent form prior to the study. The studies were approved by the local ethics committee of the North Denmark Region.

Subject Characteristics

Age (years)	*Body mass (kg)*	*Height (cm)*
23±6	85,04±7,57	181,47±4,51

Table 1: *Subject characteristics of the subjects recruited in this study (N=14).*

2.2 Equipment

The equipment used for the on-water kayak measurements was a system called e-kayak (APlap, Rome Italy, E-kayak) validated in a study by Bonaiuto et al. [12]. The system is used to evaluate kinetics and kinematics of on-water sprint kayaking. The e-kayak system acquires the force signal on both the paddle and footrest, the position and speed of the boat, and the velocity of the yaw, roll and pitch of the kayak. The e-kayak system is presented in *figure 2*. The system consist of a master node, a GPS, an accelerometer and an interial measurement unit (IMU). The paddle and footrest are equipped with a conditioned full bridge of strain gauges, which makes it possible to acquire high accuracy force data from the paddle and footrest. It is possible to integrate up to 8 data sources (4 paddles and 4 footrests) [12].

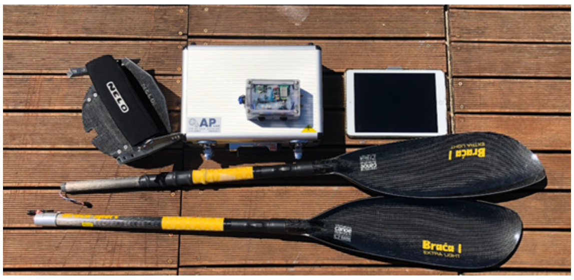

Figure 2: *Shows the e-kayak system consisting of a master node, paddle, footrest and a tablet for data a acquisition (APLab, Rome Italy, E-kayak).*

The master node handles the data stream from the force sensors and the acquisition of the kinematic data from the IMU and GPS. For acquisition, it only acquires a Wi-Fi link to the web page, which allows for immediate monitoring of a restricted number of parameters including the instantaneous stroke rate, boat speed and travel distance. The master node manages the synchronization of the data acquisition, and the system operates with a sample rate of 20Hz. It has over two hours of autonomy as it is equipped with a LiPo battery and 8 GB onboard memory [12].

A Dual-Energy X-ray absorptiometry (DEXA) scanner was used to evaluate the anthropometrics of the subjects, including the body fat percentage and lean body mass [19]. The subject was placed in the DEXA-scanner lying on the back, with arms and legs extended, wearing minimal clothing. This was done to ensure optimal results. The strength test was conducted in a private lab using calibrated weights and a Dansparint single arm machine, which was modified to reasemple the kayak stroke.

2.3 Procedures

The experimental protocol included two test days; a on-water test day and a test day where the body composition and strength of the subject were evaluated. The on-water test day included a warm-up prior to the test, as well as three races; 2x100 m and 1x500 m all out. However, it was only the results from the 500 m race, that were included in this study. The 500 m race time was used as an objective measurement of performance in this study. Furthermore, the system measured the mean and peak paddle and footrest forces and the angular velocity (roll) of the kayak. During the data collection certain data points were compromised or entirely omitted due to the occurrence of heavy rainfall. Therefore the paddle forces will not be processed further in this study, as several data points were compromised.

On the second day the body composition measurements and strength test were completed. First, the body composition were evaluated using a DEXA scanner. The duration of the test was 10-20 minutes depending on the subject's physical size. The aim of the strength test was to identify 1 RM for four exercise, and was performed in a private lab located at Aalborg University Campus. The four exercises were; bench press (BP), bench pull (BPU), weighted pull up (PU) and single arm machine (SAM), which are illustrated in *figure 3*.

Figure 3: *Illustration of the four strength exercises; bench press, bench pull, pull up (without weight) and the single arm machine.*

The exercises were found to be relevant, due to the movement patterns being similar to the kayak movements performed on-water and they improve the strength of the upper body [16, 17, 18]. Prior to the test, a warm-up was conducted, as outlined below:

Strength Test - Warm-Up Protocol
8 reps 40% of 1RM
5 reps 60% of 1RM
3 reps 75% of 1RM
1 reps 85% of 1RM
1 reps 95% of 1RM

The warm-up protocol was used for all exercises, and each exercise were separated by a 5 minute rest period. Several attempts at the 1RM were made, and if successful, additional 2,5-5 kg were added until 1RM was reached. 2-3 minutes rest was allowed between attempts.

2.4 Data analysis

The raw data from the on-water measurements were imported and processed in Matlab version R2021b (Matlab, Massachusetts USA) for each subject. The data were filtered using a fourth order low pass filter with a cutoff frequency of 10 Hz. The variables chosen for analysis were divided into three sections; on-water, body composition, and strength variables. The on-water variables were; the mean and peak footrest forces, stroke rate, impulse for one stroke cycle, the impulse for a 5s time interval, and the velocity of roll. The roll is presented as the mean peak value. The stroke rate and impulses were calculated from the force data acquired with the e-kayak system. The body composition variables were; the body fat percentage and lean body mass, and the strength variables were; 1RM for BP, BPU, PU and SAM. Correlation analyses were performed in SPSS version 28.01.1 (SPSS, Chicago, Il, USA) to investigate the relationship between the kayak performance and the chosen variables. Prior to the analyses, the normality of each variable was tested with a Shapiro-Wilk Test, which showed that not all variables were normally distributed. Therefore, Spearman's correlation analyses were performed. All tests were performed with a significance level of 0.05.

3 RESULTS

The descriptive data are presented in *Table 2* as the mean value across all subjects and the standard deviation. The figure is divided in three sections; on-water variables, body composition variables and strength variables. *Figure 4* presents a correlation matrix with correlation coefficients which include correlations between the race time and the chosen variable which are the stroke rate (SPM), mean force (N), peak force (N), impulse (N*s) over one stroke cycle, impulse (N*s) over 5 s, roll (°/s), body fat (%), lean body mass (kg), bench press (kg), bench pull (kg), pull up (kg) and single arm machine (kg). Furthermore, the matrix presents correlations between the chosen variables in order to identify possible co-correlations. The colouring indicates different levels of correlations, while positive and negative correlations are distinguished by a red and blue color.

A significant negative correlation was found between the race time and lean body mass (r=-0.60, p=0,03). This demonstrates that the lean body mass is related to the race time. In relation, a moderate co-correlation was found between the stroke rate and the pull up exercise (r=-0.47, p=0,13). However, this was not found to be significant. The pull up exercise was also strongly correlated with the PU exercise (r=0.81, p<0,001), suggesting that the level of body fat is negatively related to the strength in the PU exercise. Further the results showed that multicollinearity exist between the mean force, peak force, and the two impulses, as all four variables showed significant positive co-correlations (r=0.90-0.97, p<0,001). The SAM was correlated with the BP exercise (r=0.75, p=0,003), the BPU (r=0.69, p=0,009) and the PU exercise (r=0.67, p=0,013). The strongest correlation in relation to the strength variables was found between the SAM and race time (r=-0.27, p=0,38), however this was not found to be significant. The body fat percentage and stroke rate were moderate correlated (r=0.47, p=0,12) as well as the SAM and roll (r=0.50, p=0,1).

On-water variables	
500 m race time (s)	112,61±1,02
Stroke rate (SPM)	177,65±66,46
Mean paddle force (N)	227,64±25,18
Peak footrest force (N)	510,45±48,53
Impulse (N*s)	450,83±47,76
Impulse (N*s)	1198,23±130,29
Roll (°/s)	516,20±35,06
Body composition variables	
Bodyfat percentage (%)	18,57±1,10
Lean body mass (kg)	66,10±1,60
Strength variables	
Bench press (kg)	113,46±3,43
Bench pull (kg)	104,65±2,29
Pull up (kg)	39,80±2,80
Single arm machine (kg)	63,07±3,63

Table 2: *Descriptive results presented as the mean value ± standard deviation.* ***Note****: The number of subjects (N) vary due to complications during the on-water measurements, thus data has been removed from the data set*

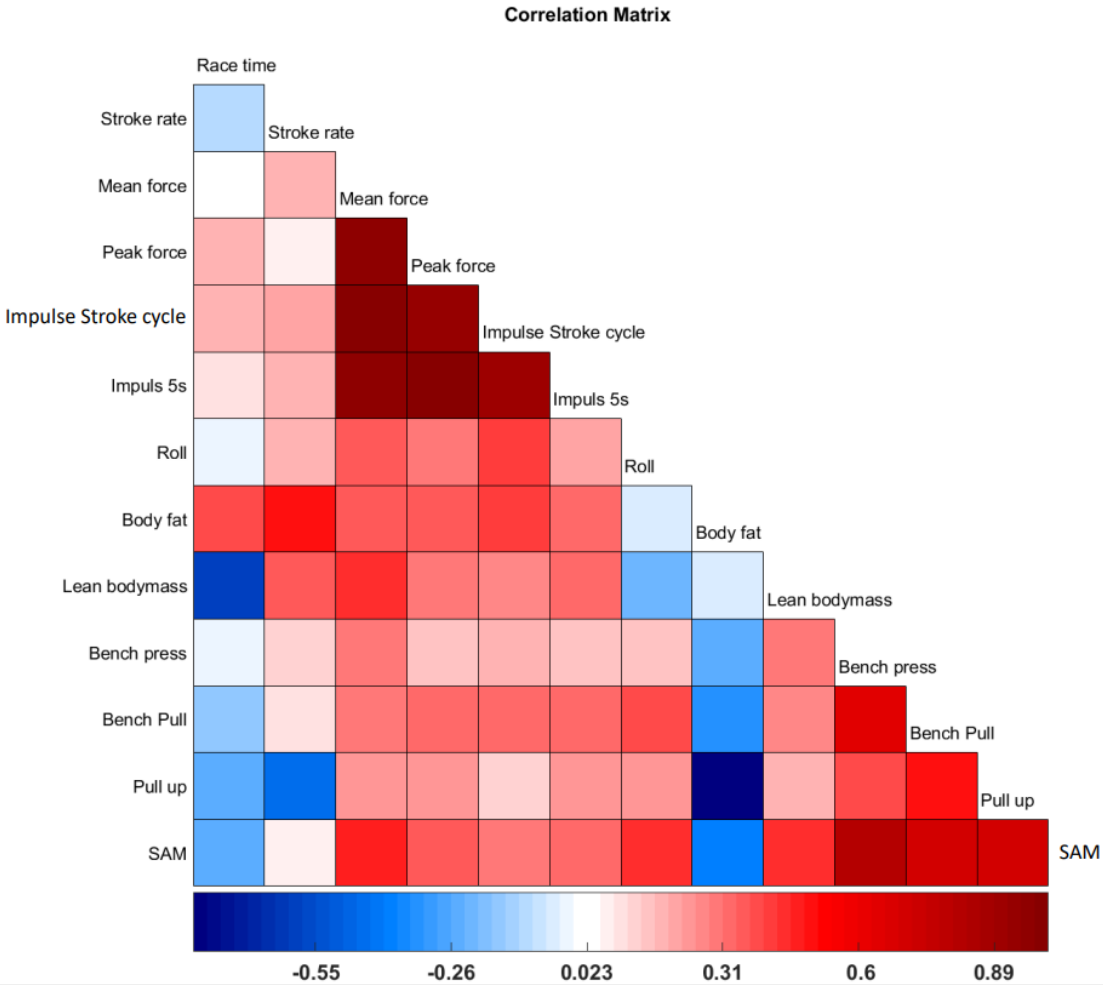

Figure 4: *Correlation matrix with correlation coefficients between the race time and the chosen variables for 14 paddlers (N=14). The colouring indicates different levels of correlations, with dark blue indicating a strong negative correlation, white denotes no correlation, and dark red is a strong positive correlation.*

4 DISCUSSION

4.1 Discussion of results

The aim of this exploratory study was to investigate multiple variables that may affect sprint kayak performance on a 500 m race distance. A significant negative correlation was found between between the race time and lean body mass. Furthermore, the SAM was correlated with the BP, BPU and PU exercise. The strongest correlation in relation to the strength variables was found between the SAM and race time, however this was not found to be significant.

The mean footrest force found in this study was 61,86 N smaller than the mean footrest force found by Klitgaard et al. [20]. However the peak footrest force found in this study was 112,25 N higher than the one measured in Klitgaard et al. The peak footrest force in this study was 44,25 N greater than the one measured by Begon et al. [21]. Begon et al. did the test on a kayak ergometer, which could indicate that differences exist between footrest forces on a kayak ergometer and on-water kayaking [21]. Further, there is a difference in the stroke of 52,65 strokes per minute between this study and the one by Klitgaard et al. This could be explained by the difference in the protocol as the subjects did 20 s paddling with maximal effort in the study by Klitgaard et al., but in this study the subjects dig a 500 m all out on-water. Furthermore, the impulse over one stroke cycle was reported as 554.8±17.4 in the study by Klitgaard et al., but in this study this was found to be 450,83±7,76, which means a difference by 103,97 N*s. The study by Klitgaard et al. also measured the impulse over a 10 s time period, but in this study it was measured over 5 s time interval, meaning it has not been possible to compare the two. Based on the results, Klitgaard et al. suggested that the contribution of footrest forces significantly improves kayakers' paddling performance. A study by Nilsson & Rosdahl [10] investigated the contribution of leg-muscle-generated forces to paddle force and kayak speed during maximal effort flat-water paddling. The results showed that paddling with restricted legs significantly reduced both push and pull footrest forces resulting in a reduction in paddle stroke force and mean kayak speed. Therefore it was also concluded that the contribution of the footrest forces significantly improves kayakers' paddling performance. However, the results of the current study did not show a correlation between the footrest forces and the performance. This could be explained by the fact that the temporal scope of the variables investigated in this study extends beyond the ones examined in both the study conducted by Klitgaard et al. [20] and Nilsson & Rosdahl [10]. Common for all three studies were that all participants were competitors at either national or international elite level, meaning that all samples had a high uniformity.

A significant negative correlation was found between the lean body mass and the race time. This indicates that the higher lean body mass is correlated with a faster race time. This notion finds support in multiple studies highlighting the importance of a high lean body mass, particularly in the upper body, for generating substantial propulsive forces [1, 2, 4, 17]. However, it should be noted that a greater mass of the paddler, leads to a deeper submersion of the boat into the water, consequently resulting in a greater resistance [2]. Ackland et al. [22] assessed 50 male and 20 female sprint canoe/kayakers who competed at the Sydney Olympic Games in 2000 and compared these to paddlers represented at the Montreal Olympics in 1976. According to the findings of Ackland et al., elite paddlers have experienced a morphological evolution over the last 25 years, which shows an upward trend in body mass, but a simultaneous emphasis on achieving a leaner physique. Further, the winning times for both the 500 m and 1000 m distance showed a significant improvement over the last 25 years [22]. The findings of Ackland et al., supports the results found in this, as it states a higher lean body mass is correlated with a faster race time.

In this study, a weak correlation was found between the body fat percentage and the race time, which suggest that the body fat percentage does not influence the performance on the 500 m distance. This notion finds support in a study by McDonnell et al [1] which suggest that paddlers may be able to maintain a certain degree of body fat without it hindering the performance, particularly on the sprint distances [1, 4]. Additionally, Akca & Muniroglu [15] found a strong correlation between the body fat percentage and average kayak velocity on the 500 m distance. This suggest that the body fat percentage enhance the kayak performance. Although the body fat percentage was not correlated with performance, a moderate correlation was identified between the stroke rate and body fat percentage. This suggest that a higher level of body fat is related to a higher stroke rate. Brown et al. [5] states that a high stroke rate would enhance kayak performance, by creating a greater relative water phase time, while reducing the absolute and relative aerial time. However, this study was conducted with elite male paddlers, meaning that all subjects had a relatively low body fat percentage. Therefore, the uniformity of the sample could have affected the results, as the variance of the dataset was low. However, from this specific sample it can deduced that the body fat percentage was not correlated with performance on the 500 m distance. However a moderate co-correlation was identified between stroke rate and body fat percentage.

Andersen & Aaggard [23] states that the time available for propulsive force production in the kayak stroke is strongly related to the maximal strength. Therefore, it would be expected that an increase in maximal strength would allow the paddler to overcome greater resistance encountered as the boat is accelerated [23]. It is stated that general upper-body strength is important in kayaking [16, 17, 18]. Pickett et al. found 3RM bench press and bench pull, reported to be 96 kg. (BP) and 95 kg. (PU), which makes a 17,46 kg. Difference for BP and 9,65 kg. Difference for BPU, when compared to the results of this study. However, in this study 1RM was found, which explains this difference in strength measurements. McKean & Burkett [16] reported 1RM BP as 102,3 kg., whereas the 1RM BP found in this study was 113,46 kg., resulting in a 11,16 kg. Difference. Further Mckean & Burkett reported 1RM PU as 133,8 kg., however this was presented as the sum of body weight plus additional weight, thus the additional weight was 40 kg. The 1RM PU in this study was 39,80 kg., which means a difference of only 0,20 kg. when compared. Romagnoli et al. [18] reported 1RM BP as 135,50 kg. and 1RM BPU as 137,50 kg. This means a difference of 22,04 kg. for the BP and 32,85 kg. for the BPU. This difference is relatively high, this could possibly be explained by the difference in protocol. Romagnoli et al. made a strength test consisting of five session, which were separated by 24 hours between the first three sessions and 48 hours between the last two, meaning the rest period was significantly higher, when compared to this study. In this study all four exercises were tested in one session separated by a 5 minute rest period. It has not been possible to compare the strength measures of the SAM, as similar studies only measures the strength in the BP, BPU and PU exercise. Further, Pickett et al. [17] states replication of the kayak stroke may not be the optimal strength-training strategy. However, in this study the strongest correlation in relation to the strength variables was found between the SAM and race time. Furthermore, co-correlations between the SAM and the other three exercises were identified. This could indicate that specific kayak exercises such as a SAM could actually enhance performance on the 500 m distance.

4.2 Considerations and Assessments of the Measurement Methodologies

A pilot study by Bonaiuto et al [12] investigated the capabilities of the e-kayak system. The results were compared with those available in the literature, which where obtained by a system called *Fpaddle* with similar features [8]. The comparison showed a good correspondence for each stroke and for each cases depicted, in the mean values of the force with respect to the exerted velocity. Further, the values of the other parameters were in a similar range in both studies [12]. Therefore, it was concluded that the e-kayak system provide various data, that can help improve the knowledge of propulsion phases and can support coaches in providing more effective suggestions to improve paddling technique. Additionally, the e-kayak system is a portable system, which is available to the general public to purchase. Recent analyses in inertial sensor technologies provide a new way to perform motion analysis, due to the possibility to apply the inertial measurement units (IMUs) to human body segments [24, 25, 26]. This enables the ability to track human kinematics in real-time during specific activities. Therefore, utilizing inertial motion capture system to record paddlers in their natural ecological conditions can underpin relevant and as-yet unknown aspects of the kayak paddlers' kinematics [6]. The e-kayak system has installed a IMU, which allows for measuring the yaw, pitch and roll of the boat [12]. Furthermore, the e-kayak system has integrated a GPS and a accelerometer. This means that this system allows integration of multiple data sources.

It has not been possible to make a valid comparison of the body fat percentage with the ones found in the literature, due to differences in the measurement method. Michael et al. [2] used a fat caliber to estimate the body fat percentage as a sum of eight skinfolds. Further, Akca & Muniroglu [15] estimated the body fat percentage as a sum of four skinfolds, which resulted a relatively low body fat percentage in both studies. In this study a DEXA-scanner was used to estimate the body fat percentage and lean body mass, which also explains why the body fat percentage is higher in this study. A DEXA scanner usually estimates the body fat percentage higher than a fat caliber, as it gives a regional measurement of the body composition, thus gives a more accurate result [19]. Therefore the body composition measurements in this study should be more precise, when compared to previous studies.

4.3 Limitations

A clear limitation was that the paddle forces were not processed in this study, as certain data points were compromised or entirely omitted due to the occurrence of heavy rainfall during the data collection. Moreover, it should be noted that the data acquisition process relies on a Wi-Fi connection, necessitating its uninterrupted connectivity for successful data acquisition. Any disruption in the Wi-Fi connection would consequently impede data collection by the system. It would have been beneficial to have a larger sample size in this study, in order to increase the reliability of the results. By increasing the sample size, the variance of the dataset would enlarge, thus produce more reliable results. This could also be achieved by diversifying the sample, which can be done by including athletes from different levels. The sample in this study had a high uniformity, as all subjects were national or international elite paddlers, thus a low variance. Therefore the sample size and the uniformity of the sample are a limitation to this study.

5 CONCLUSIONS

This exploratory study aimed to investigate variables that may affect the kayak performance and thereby identify key performance indicators in sprint kayaking among elite paddlers. The on-water measurements were conducted with a system called e-kayak, which is used to evaluate kinetics and kinematics of on-water sprint kayaking. The body composition of the paddler was evaluated with A Dual-Energy X-ray absorptiometry (DEXA) scanner.

The strength test were performed in a private lab, where 1RM of bench press, bench pull, pull up and single arm machine were identified. A significant negative correlation was found between the lean body mass and performance. Further, significant positive co-correlations was found between the SAM and BP, BPU and PU exercises. However, the strongest correlation in relation to the strength variables was found between the SAM and performance. Based on the findings in this study it can be deduced that the lean body mass of the paddler is a key performance indicator among elite kayak paddlers on a 500 m distance. The results could indicate that a kayak specific exercise such as a SAM would enhance performance on the 500 m distance more than the BP, BPU and PU exercise among elite paddlers.

6 PRACTICAL APPLICATIONS

Based on the findings in this study elite paddlers are advised to acquire a high lean body mass, in order to produce substantial propulsive forces during a kayak sprint. The single arm machine showed a higher correlation with performance, than the other strength exercises included in this study. Based on these results, the coaches are advised to implement the single arm machine in dry land strength training among elite kayak athletes. Based on the use of the e-kayak system in this study and the results presented by Bonaiuto et al. [12] the e-kayak system can advantageously be used by coaches as a training tool to monitor various on-water variables. Additionally, the e-kayak system can support the coaches in providing feedback, and thereby improve the paddling technique.

7 PERSPECTIVES

In future studies, it would be beneficial to investigate a larger sample size in order to increase the reliability of the results. Furthermore, it would be relevant to include kayak paddlers from different competition levels, to ensure a higher variance of the data set, which is favorable when performing correlation analyses. Furthermore, the paddling technique was not investigated in this study, therefore it would be interesting to investigate how the technique is related to the sprint kayak performance. Due to technical issues during the data collection, the paddle forces were not included in this study. Therefore, it would be advantageous to investigate the relationship between the paddle forces and performance. Additionally, investigating the effects of different weather conditions on the reliability of the e-kayak system could be of great importance.

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REFERENCES

[1] Lisa K. McDonnell Volker Nolte, & Patria A. Hume. A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. *Sports Biomechanics,*, 12(3), 2013.

[2] Michael Jacob S. Rooney Kieron B. & Smith, Richard. The metabolic demands of kayaking: A review. *Journal of Sports Science and Medicine*, 7(1), 2008.

[3] Michael Jacob S. Rooney Kieron B. & Smith, Richard. Determinants of kayak paddling performance. *Sports Mechanics*, 8(2), 2009.

[4] Lisa K. McDonnell Volker Nolte, & Patria A. Hume. An observational model for biomechanical assessment of sprint kayaking technique. *Sports Biomechanics*, 11(4), 2012.

[5] Brown B.M. Lauder M, & Dyson R. Notational analysis of sprint kayaking: Differentiating between ability levels. *International Journal of Performance Analysis in Sport*, 11(1), 2011.

[6] K.K Kongsøre. kinetics and kinematics of sprint kayaking on-water. *department of health science and technology*, 2021.

[7] Aitken D.A. & Neal R.J. An on-water analysis system for quantifying stroke force characteristics during kayak events. *International journal of sport biomechanics*, 8(2), 1992.

[8] Gomes B.B. Sanders R.H. Vaz M.A. Vilas Boas J.P. Ramos N.V., Conceição F A.V. Paddling force profiles at different stroke rates in elite sprint kayaking. *Journal of applied biomechanics*, 8(4), 2015.

[9] Gomes B.B. Sanders R Vaz M Vilas-Boas J.P. Ramos N.V., Conceição F. Paddling time parameters and paddling efficiency with the increase in stroke rate in kayaking. *Sports biomechanics*, 9(1), 2020.

[10] Nilsson J.E. & Rosdahl H. Contribution of leg muscle forces to paddle force and kayak speed during maximal effort flat-water paddling. *International Journal of Sports Physiology and Performance*, 2016.

[11] Zhang K Li Y Zhang J Cameron W.N. et al. Grenfell R, Deakin R. Gnss for sports ? sailing and rowing perspectives. *Journal of Global Positioning Systems*, 3(1), 2004.

[12] Bonaiuto V Romagnoli C Boatto P Lanotte N Annino G Gatta, G. A pilot study on the e-kayak system: A wireless daq suited for performance analysis in flatwater sprint kayaks. *Sport Engineering Lab*, 2020.

[13] G van Someren, A.K & Howatson. Prediction of flatwater kayaking performance. *Journal of Sports Physiology and Performance*, (3), 2008.

[14] G.S van Someren, A.K & Palmer. Prediction of200-m sprint kayaking performance. *Can. J. Appl. Physiol*, 28(4), 2003.

[15] Akca F & Muniroglu S. Anthropometric-somatotype and strength profiles and on-water performance in turkish elite kayakers. *Int J Appl Sport Sci*, 20(1), 2008.

[16] B McKean, M.R. & Burkett. The relationship between joint range of motion, muscular strength, and race time for sub-elite flat water kayaker. *journal of Science and Medicine in Sport*, 13(1), 2009.

[17] Pickett G.W. Zois J. Blazevich A.J. Nosaka, K. Maximal upper body strength and oxygen uptake are associated with performance in high-level 200-m sprint kayakers. *Journal of Strength and Conditioning Research*, 32(11), 2017.

[18] Romagnoli C Lamouchideli N Bianco A Loddo S Alashram A.R Bonaiuto V Annino G Padua E Gatta, G. Specificity of weightlifting bench exercises in kayaking sprint performance: A perspective for neuromuscular training. *journal Frontiers in Physiology*, 2022.

[19] K.N. Jeejeebhoy. Nutritional assessment. *Encyclopedia of Gastroenterology*, 2004.

[20] Rosdahl H Brund R.B.K Hansen J Mark de Zee Klitgaard, K.K. Characterization of leg push forces and their relationship to velocity in on-water sprint kayaking. *Sensors*, 2021.

[21] Lacouture P Begon M, Colloud F. Measurement of contact forces on a kayak ergometer with a sliding footrest–seat complex. *Sports Eng*, 11(2), 2009.

[22] Kerr D.A Ridge B. Ackland T.R, Ong K.B. Morphological characteristics of olympic sprint canoe and kayak paddlers. *Journal of Science and Medicine in Sport*, 6.

[23] P. Andersen, L.L Aagaard. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology*, 2005.

[24] Chan Y. Fong D. The use of wearable inertial motion sensors in human lower limb biomechanics studies: A systematic review. *Sensors (Basel, Switzerland)*, 12.

[25] Oliveira AS. Svenningsen FP, de Zee M. The effect of shoe and floor characteristics on walking kinematics. *Human Movement Science*, 2019.

[26] Robertson S Hopkins W Ball K. Blair S, Duthie G. Concurrent validation of an inertial measurement system to quantify kicking biomechanics in four football codes. *Journal of Biomechanics*, 17.