Kinetics and Kinematics of Sprint Kayaking On-Water

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BY
KENT KONGSØRE KLITGAARD

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AALBORG UNIVERSITY
DENMARK

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by

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AALBORG UNIVERSITY
DENMARK

DISSERTATION SUBMITTED TO DEPARTMENT OF HEALTH SCIENCE AND TECHNOLOGY AT AALBORG UNIVERSITY

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CV

Kent Kongsøre Klitgaard (KK) earned his bachelor's degree in sports science in 2015 and his master's degree in sports technology in 2017, both at Aalborg University. During his master's degree education, Kent was an intern for the Danish Elite sport federation- Team Danmark in Copenhagen for one semester. Kent wrote his master's thesis during the spring semester in 2017, and the project became a starting point for this PhD.

With a grant from the Danish cultural department research foundation, KK worked as a research assistant and enrolled as a PhD student at the doctoral school of the Faculty of Medicine at Aalborg University. During the first year, the project was co-financed by the Team Danmark research foundation and Aalborg University. The funding was established for a three-year PhD program.

During his PhD studies, KK has given oral presentations at the 9th Annual Meeting of the Danish Society of Biomechanics (Århus, Denmark; 2017) and the VIIth International Congress of Coaches of Sprint Canoeing (Catoira, Pontevedra, Spain; 2018). Additionally, KK presented posters at the 10th Annual Meeting of the Danish Society of Biomechanics (Copenhagen, Denmark; 2018), the 11th Annual Meeting of the Danish Society of Biomechanics (Odense, Denmark; 2019), and the European College of Sport Science (Prague, Czech Republic; 2019). KK is a reviewer for the *European Journal of Sport Science*.

ENGLISH SUMMARY

Sprint kayak is a competitive sport in which the ability to generate propulsion through efficient kayaking locomotion, which involves technique and power, is essential for performance. The technique predominantly utilizes upper-body muscles in the dynamic movement. However, studies have illustrated that cyclic leg movement is crucial as well. Several studies have investigated the kinetics of the paddle, while few studies have examined kinetics in the footrest and seat. These forces are essential as well, as forces produced by the paddlers must travel through the seat and footrest to be translated from force to velocity.

Several studies have investigated kayak kinetics and kinematics through on-ergometer testing, while only a few have investigated these factors in the ecological conditions on the water. Studies have determined that the physiological responses with on-ergometer testing accurately simulate the physiological response of on-water kayaking. However, a few studies have suggested that the biomechanical response may differ between the two conditions.

This PhD project's overall aim was initiated to investigate the kinematics and kinetics of on-water sprint kayaking. Study I investigated the kinematics of on-water and on-ergometer kayaking and differences in stroke rate. Study II developed a force-sensitive footrest and seat that could be utilized on the water. Finally, Study III investigated leg force in relation to performance in on-water kayaking in a team of elite kayakers.

In summary, Study I demonstrates that on-water and on-ergometer kayaking differs in the elbow, shoulder, and knee kinematics. Concurrently, a significantly higher stroke rate was observed during a 2-min all-out effort on the ergometer than on the water. Study II developed, designed, and tested a device that measures forces applied to the footrest during on-water kayaking. The developed seat presents unacceptable values of hysteresis and system weight. Therefore, it must be redesigned if it is to be utilized further in research and testing. The developed seat was not included in the Study II. Study III has demonstrated that sprint kayakers exhibit a positive relationship between leg forces and velocity.
The present thesis provides the first kinematic comparison of on-water and on-ergometer kayaking. Furthermore, it the first to provide on-water leg force data from a team of elite kayakers.

DANSK RESUME

I sprintkajak er evnen til at genererere fremdrift gennem effektiv kajakteknik afgørende for performance. I kajakteknikken anvendes hovedsageligt muskler i overkroppen i den dynamiske bevægelse. Dog har studier illustreret, at cyklisk benbevægelse også er afgørende for performance. Flere studier har desuden undersøgt pagajens kinetik, mens kun få studier har undersøgt kinetik i fodsparket og sædet. Disse kræfter er også vigtige, da kræfter produceret af pagajen skal gennem sædet og fodsparket for at blive translateret til hastighed. Flere studier har undersøgt kajakkinetik og kinematik på kajakergometer, mens kun få har undersøgt kinetik og kinematik under de økologiske forhold på vandet. Studier har fastslået, at det fysiologiske respons på kajakergometer simulerer det fysiologiske respons ved padling på vandet. Imidlertid har nogle få studier antydet, at det biomekaniske respons kan variere mellem de to betingelser.

Formålet med dette Ph.d.-projekt var at undersøge kinematik og kinetik ved sprintkajak på vandet. Studie I undersøgte kinematikken i kajakroning på vand og på ergometer samt forskelle i stroke rate. I Studie II blev der udviklet et fodspark og sæde, som kunne måle kræfter, der kunne bruges på vandet. Endelig undersøgte Studie III benkræfter i forhold til kajakhastighed på vandet.

Sammenfattende viser studie I, at kajakroning på vand og på ergometer adskiller sig kinematisk i albue, skulder og knæ. Samtidig blev der observeret en signifikant højere stroke rate under en 2-minutters all out test på ergometeret end på vandet. I Studie II blev der udviklet, designet og testet en enhed, der måler kræfter, der påføres fodsparket under padling på vandet. Det færdigudviklede sædedesign viste dog uacceptabel hysterese og systemvægt. Derfor skal dette sæde redesignes, hvis det skal bruges yderligere til forskning og testning. Sædet blev af samme grund ikke inkluderet i studie II. Studie III viste, at sprintkajakroere udviser et positivt forhold mellem benkræfter og hastighed.

Denne afhandling tilvejebringer den første kinematiske sammenligning af kajakroning på vand og på ergometer. Desuden omfatter afhandlingen det første studie, der undersøger benkræfter i relation til kajakhastighed i et team af elitekajakroere.

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I would like to thank and recognize my co-authors, who have provided unsurpassed assistance and sparring throughout the process. Associate Professor Anderson de Souza Castelo Oliveira and M.Sc. Frederik Vandvig Heinen, you guided me through my first challenging reviewing process in academia. Professor Hans Rosdahl, thank you for sharing your extensive knowledge and experience while additionally being a great partner for discussion.

I wish to thank Team Danmark, especially M.Sc. Andreas Top Adler, for believing in me and helping me through various challenges in the process. Further, I would like to thank former Team Danmark employee M.Sc. Jarl Venneberg Jakobsen for many hours of nerdy kayak talks, being a great idol, and shaping the way for my PhD. For that, I am truly grateful. Additionally, thanks to the Danish Kayak Federation for supporting my PhD. Special thanks go to Kayak Coach Finn Pape for endless talks about various aspects of sprint kayak.

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I wish to acknowledge the great love and support of my family and friends. To my girlfriend, Sanne Kjeldsteen, thank you for your endless love, support, and amazing ability to look at life with a smile no matter the odds. My life would not have been the same without you and Storm. Finally, I would like to thank Erik Hansen, Børge Petersen, and Ole Tikjøb for shaping the Danish canoe sport and being great role models for my generation. *–Kent, March 2021, Aalborg*

PREFACE

The present studies were conducted between 2017 and 2020 at the Sport Sciences-Performance and Technology, Department of Health Science and Technology, Aalborg University, Denmark.
The thesis is based on three studies with entirely different methodologies that have been tied together through the investigation of kinetics and kinematics in on-water kayaking. The studies are presented numerically throughout Chapters 2-4. Chapter 5 reflects upon the findings in a wider practical context. Chapter 6 shows the thesis at a glance.

The thesis is based on the following three articles. In the text, these are referred to as Study (I), Study (II), and Study (III).

Study I:
Klitgaard, K, Hauge, C., Oliveira, A., Heinen, F. "A kinematic comparison of on-ergometer and on-water kayaking." *European Journal of Sport Science,* 2020 October 1, 1-25.

Study II:

Klitgaard, K., Hansen, J., de Zee, M. "A new device for measuring forces in the footrest during on-water kayaking." *(Manuscript is currently in revision.)*

Study III:

Klitgaard, K., Rosdahl, H., Hansen J., Korsgaard R., de Zee M. "Investigation of change in peak and mean forces in the footrest during different intensities in sprint kayaking." *(Manuscript is currently in revision.)*

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CHAPTER 1. INTRODUCTION

1.1. THE HISTORY OF KAYAKING

Kayaks originate from Greenland, where they were utilized as hunting vessels for seals as well as fishing. However, canoe or kayak vessels can be found worldwide and can be dated back to 6000 B.C. Recreational usage started in the 18th century and developed as a sport at the beginning of the 19th century. Since then, the sport has increased in popularity, especially in Europe, but in recent times, kayaking has become popular in the rest of the world as well. The International Canoe Federation (ICF) was founded in 1924 by four nations (Sweden, Germany, Austria, and Denmark) and was called the International Community of Canoeing Representatives. In 1946, it changed its name to ICF and now includes 160 nations from five continents [1]. Figure 1 presents photos of the Danish Olympian Erik Hansen (1939-2014), who competed from 1958 to 1972.

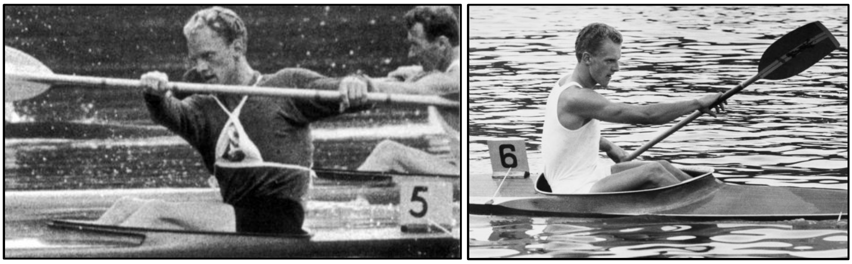

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Figure 1: Erik Hansen from Denmark; Erik shaped modern kayak technique by utilizing his top hand actively in the stroke.

Kayaking can be differentiated into two categories: recreational kayaking and competitive kayaking. Competitive kayaking can either be flatwater sprint kayaking or white water kayaking, which includes slalom kayak where paddlers paddle through portages on white water. [2]. This thesis focuses on flatwater sprint kayaking.

The first European championship was held in Prague in 1933, and the first world championship was organized in 1938 in Waxholm, Sweden. Kayaking became an Olympic sport in 1936. Initially, athletes raced for 500m and 1,000 m. In 2012, the 200m race also became part of the Olympic program. Different boat classes are utilized: K1 (one person), K2 (two-person kayak), and K4 (four-person kayak). A two-bladed paddle is utilized to propel the kayak forward in a cyclic movement that shifts from left to right and back again [1,3,4].

The sport has evolved from utilizing a wide wooden kayak to a narrow kayak, which is currently made of carbon. It has been suggested by Robinson et al. (2002) that the historical improvement of performance times in the kayak does not relate to training but mainly to the improvement of kayak design [4,5].

The kayak's V-shaped hull appeared for the first time at the Olympics in 1952. Before that, the bottom of the kayak was primarily flat. In 1960, the kayak design changed to a more edgy, diamond-like design. These two improvements resulted in a 25 s and 19 s reduction, respectively, on the 1,000m distance performance times. In the early 1970s, the delta-style kayak was introduced, which had a significantly narrower front of the kayak. The 1980s witnessed the introduction of the eagle design, which resulted in a 10 s reduction in performance times. Through the 1990s, a modified eagle design led to an additional 10 s reduction in performance times [1].

Until November 2000, there was a width restriction of 50 cm on the kayaks [1]. At November 2000, ICF has allowed kayaks below 40 cm in width, thereby removing the previous width rule. Since then, only Nelo (Nelo, Vila do Conde, Portugal) has made significant changes to the kayak hull’s design, as the company has styled a kayak with an inverted bow [4,5].

Significant changes have been made to the Olympic kayak program throughout the years. K1 and K2 200m races appeared in the Olympic program for the first time at the London Olympics in 2012. Additionally, K2 and K4 500m races for men will be in the Olympic program in Tokyo 2021. The 200m have changed the competitive K1 race top speeds, which may reach 24 km/h for men and approximately 20 km/h for women in the K1. These higher speeds may influence kayak design further, but it remains to be seen how manufacturers will design future kayaks [1].

The paddle utilized in sprint kayaking started as a traditional, flat-bladed paddle (Figure 2). In 1986, the wing blade was developed, which revolutionized the stroke. It is asymmetrical and has a foil-like blade, which allows the paddler to utilize and maximize different force components that act on the blade (Figure 2). The drag and lift forces act perpendicularly to the blade. Therefore, the applied force contributes significantly to the horizontal propulsion, as opposed to the flat blade in which only drag forces are utilized.

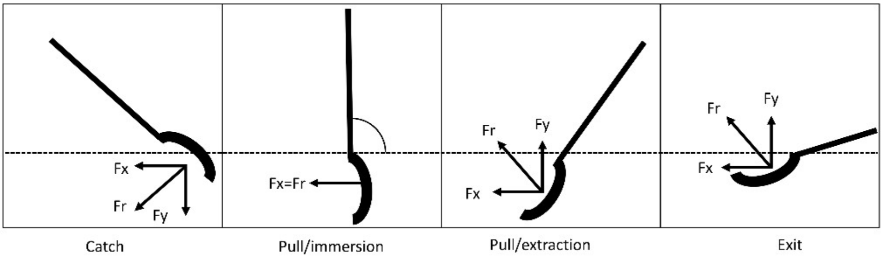

Figure 2: A view of the kayak paddle throughout the stroke cycle. The dotted line indicates the waterline. The paddle forces can be divided into three components: F_X = force in X-direction, F_Y = force in Y-direction, and F_r = resultant force direction [4].

The wing blade soon became widely accepted and quickly proved to be superior in performance by changing the paddling technique and improving paddling times. All sprint paddlers now use the wing blade. This change required researchers to reinvestigate the kayak stroke [3,5-7].

During winter season, paddlers can use a kayak ergometer. This is an indoor training device that simulates the kayaking movement and has been proven to replicate the physiological demand [21]. A cord is fastened to each end of a paddle, and the cords pull an air-braked fan. Each cord is tied to an elastic band that pulls the cord on the non-stroke side. There are several commercially available air-braked kayak ergometers. However, the Dansprint Aps ergometer (Dansprint, Hvidovre, Denmark) and the Australian K1 ERGO (Australian Sports Commission, Australia) have predominantly been utilized in the scientific literature. Several studies have illustrated that ergometer training provides a simulation of on-water kayaking's physiological demands [21,61], whereas the biomechanical demands have recently been questioned [61-63].

1.2. RESEARCH IN KAYAKING

The research field within the kayaking sport has followed Olympic development. The research mainly revolves around the Olympic discipline's sprint distances (< 1,000 m) and performance-relevant factors during sprint kayaking [3,8].

1.2.1. PHYSIOLOGY

In sprint kayaking, the upper-body and trunk musculature are the primary muscles involved. The sport imposes extraordinary demands on the athlete's upper-body musculature, aerobic and anaerobic capacity, and muscular strength. In sprint kayaking, the anaerobic and aerobic demands shift from primarily anaerobic in the

200m distance toward primarily aerobic in the 1,000m distance. The individual disciplines' aerobic contributions can be expressed as a fraction of VO_2max, in which the aerobic contribution is as follows: 38.1±1.7% for the 200 m, 68.8±3.4% for the 500 m, and 84.8±1.9% for the 1,000m [1]. Several physiological and anthropometric parameters impact performance and differ depending on the sprint kayaking discipline [9].

Anthropometry

Elite male kayakers have the same body morphology and physical size. Compared to the public, elite male kayakers feature a greater upper-body girth and narrow hips. When comparing international elite male paddlers with national elite male paddlers, international elite male paddlers have greater circumference measurements of the upper and lower arm and chest compared to national-level paddlers [9,10]. Historically, elite paddlers' body morphology and physical size were small compared to modern paddlers, who are heavier and leaner [9]. To illustrate this, the male paddlers increased their body mass on average by 5 kg in the years between the Olympics in Montreal (1976) and Sydney (2000) [9]. The female paddlers presented a similar development [11]. Several studies have reported that the body fat percentages of female and male flatwater elite kayakers range from 5.4±1.1% to 14.1±2.9% across different studies [10,12,13]. It should be noted that the paddlers' body compositions may differ throughout the year due to competitions and off-season measurements.

Physical size and lean body mass is an important factor for performance. In ergometer kayaking, larger paddlers may have better performance than smaller paddlers at the same resistance levels. The larger paddlers may have a larger absolute peak VO_2, which may be easier for them to obtain on the ergometer, as there is no balance demand, meaning that less skill is required [9]. On the water, the increased size of the paddlers results in increased drag on the kayak and may compromise performance [14]. However, Fry and Morton [15] report that the best national male paddlers were taller, heavier, and leaner than national male paddlers who had lower performance levels.

Several studies have attempted to investigate which anthropometric variables predict performance in kayaking. For male paddlers, it has been demonstrated that chest circumference and humeral breadth were moderately correlated with performance in 200m and 500m distances. No anthropometric variables have been observed to correlate with 1,000m performance [12]. van Someren and Palmer [16] have investigated 200m performances in relation to anthropometric measures and physiological profiles. They have found that international paddlers had a significantly greater circumference of the upper arm, relaxed forearm, tensed forearm, and chest as well as a significantly greater humeral breadth compared to national-level paddlers. Further, they have observed a significantly higher degree of mesomorphy on the international-level paddler. The humeral breadth in particular explained 54% of the variation in performance times, indicating that 200m performance is sensitive to anthropometric parameters. However, body fat percentage did not explain the variance in 200m performances. This indicates that body fat percentage is not related to performance on the 200m distance, nevertheless, body fat percentage has been proven to influence the performance at 500m and 1,000m distances [7]. It should be noted that mixed findings are present for the 500m and 1,000m distances; a negative correlation between body fat and kayak performance has been observed in the study by Acka and Muniroglu [10] and Fry and Morton [15], but no significant correlation has been observed in other studies, such as that of van Someren et al. [12]. Anthropometric variables for female paddlers are less investigated; as only one study by Bishop [11] has reported no correlation between performance at a 500m distance and any anthropometric variables.

Altogether, it seems likely that elite paddlers may benefit from reducing body fat within a healthy range for longer distance events. However, paddlers can afford to maintain a certain degree of body fat on short sprint distances without hindering performance [7,16].

Cardiorespiratory fitness (VO_2-max*)*

Elite kayakers possess high values for maximal aerobic and anaerobic capacities [9,15,17]. It has been suggested that kayakers are the most adapted athletes to upper-body exercise due to the many hours of kayak training and the nature of kayaking [18].

Well-trained female and male paddlers have relative VO_2-max values of approximately 53-59 ml/kg^{-1}/min^{-1} and 70 ml/kg^{-1}/min^{-1}, respectively, measured during on-ergometer or on-water kayaking [1]. This corresponds to an absolute VO_2-maximum of 2.8-3.8 l/min^{-1} and 5.78 l/min^{-1} for females and males, respectively [9]. International and national elite paddlers possess an equal VO_2-max relative to body mass [9,15]. However, the international paddlers are heavier, more muscular, and concurrently have a higher absolute VO_2-max than national elite paddlers, who have lower VO_2-max and body mass.

Therefore, the absolute VO_2-max seems to be a more critical parameter for performance in distances in which the aerobic contribution is high and less critical during 200m distances [11,15]. However, van Someren and Howatson [12] have revealed that VO_2-max (L/min) measured during a discontinuous incremental test is not associated with performance at 200m, 500 m, or 1,000 m. One reason why absolute VO_2-max may not be a suitable determinant for performance in sprint kayaking is the small amount of muscle mass involved in kayaking. Bunc and Heller [19] demonstrate that elite female paddlers reached a greater VO_2-max during a grade exercise test on a cycle ergometer than a kayak ergometer. The heart's ability to deliver oxygenated blood to the active muscles during paddling is greater than the muscles' ability to utilize the oxygen. Therefore, the cardiac output does not seem to be a limiting factor for delivering oxygenated blood to the active muscles and therefore does not affect performance. Consequently, it seems plausible that peripheral factors, such as oxygen utilization in the active muscles, are a more critical parameter for performance. Recently, it has been indicated by Paquette et al. [20] that muscle oxygenation may be a better predictor of performance in kayaking than VO_2-max. Therefore, it may be more relevant to locally examine the muscle oxygenation capacity in the working muscles. Further research is required to clarify this.

The maximal aerobic power (MAP) is defined as the absolute power output reached during a graded exercise test. van Someren and Howatson [12] illustrate that MAP was moderately correlated with 200m and 500m performance (r = -0.59 and r = -0.66, respectively). Kayakers of international and club levels have achieved a MAP of 242.7±33.8 watts during a graded exercise test. MAP is likely better correlated with performance than VO_2-max because both aerobic and anaerobic metabolism is active and contributes to power development.

Anaerobic capacity and lactate threshold

The demanding metabolic requirement of kayaking necessitates elite kayakers to have a high anaerobic capacity, especially in the upper body. On the 500m and 1,000m distances, paddlers present blood lactate levels of 12-14 mmol × L-1 due to the high anaerobic output. On the 200m distance, paddlers reach 6.7 mmol × L-1 [16]. van Someren and Phillips [21] have investigated the efficacy of ergometry-determined heart rates for flatwater kayak training. They have found the mean lactate threshold of paddlers to be a blood lactate concentration of 2.7 mmol × L-1, 89.6% of the maximum heart rate, and 82.4% of the VO_2-peak during a maximal incremental exercise test on an air-braked kayak ergometer. This underscores that there is a considerable anaerobic component in kayaking, which is crucial for performance.
However, van Someren and Howatson [12] have not found a correlation between lactate threshold and male paddler performance for international- and club-level athletes. Instead, they have found a correlation between the level of exercise that can not be sustained called lactate turn-point and MAP on the 1,000m performance, which means that there is a relationship between the power produced at the lactate threshold and the performance. On the 200m and 500m distances, the power produced at the lactate threshold was also correlated with the performance [12]. In women, Bishop [11] has been unable to find a correlation between the 500m performance and lactate variables (peak blood lactate and lactate threshold). However, the study reveals correlations between the 500m performance and the power produced at the lactate threshold. Additionally, power at the VO_2-peak and the VO_2-max had a significant correlation to the 500m performance. The study's take-home message is that the 500m performance for women is considerably dependent on both aerobic and anaerobic systems.

Anaerobic power has additionally been demonstrated to be crucial for performance. van Someren and Howatson [12] have conducted three anaerobic power tests in their efforts to predict flatwater kayaking performance across the three distances (200 m, 500 m, and 1,000 m). They reveal that all three tests of anaerobic power correlated with performance across the three distances. However, fewer tests correlated with performance on the 1,000m distance compared to the 200m and 500m distances. This indicates that the paddlers on 200m and 500m distances must address aspects of power and anaerobic capacity to improve performance. This makes sense, as the energetic demands are 63% anaerobic and 37% aerobic for the 200m and 38% anaerobic and 62% aerobic for the 500 m. The energetic demands for the 1,000m are estimated at 82% aerobic and 18% anaerobic [22]. Although the anaerobic energy demand is lower for the 1,000m distance, several studies indicate that the 1,000m paddlers must include both aerobic and anaerobic training to improve 1,000m performance [9,12,23].

Strength demands

Strength training is a fundamental part of kayak paddlers' training to improve their power output and keep them safe from injuries. In the literature, paddlers have exhibited superior upper-body strength feats. Table 1 presents the different findings related to the strength feats of kayak paddlers. Ackland et al. [13] suggest that elite paddlers' morphology has altered during the past 25 years toward a heavier, leaner, and stronger paddler; this is especially observed in the female paddlers. With the addition of the 200m sprint distance and the K4 500m distance, strength may be significantly more deterministic in the future. The ability to develop a rapid rate of force is crucial on these distances due to the high stroke rate. It has been well-established that muscular power is related to maximal strength [24-27]. Furthermore, several studies have found a positive correlation between maximal muscle strength and sprint performance in maximal jumping ability [28,29] and 100m running sprint times [30], indicating that maximal strength in kayak-specific movements may be beneficial for performance.

Table 1: Different strength findings across sprint kayak literature.

Study	Sex	Strength variables
Pickett et al. 2019	Males	Deadlift 1 repetition maximum (RM; kg): 126.80±17.80
Pickett et al. 2017	Males	Bench press 3 RM (kg): 96±19. Range: 60–130 Bench row 3 RM (kg): 95±20. Range: 60–137 Chin-up 3 RM (kg): 119±19. Range: 84–162 Deadlift 3 RM (kg) 121±16. Range: 90–160
Uali et al. 2012	Males and females mixed	Bench row 1 RM (kg): 77.0±27.4 Right-arm row 1 RM (kg): 54.0±11.01 Left-arm row 1 RM (kg): 53.5±11.32

McKean and Burkett 2009	Males and females	Males: Bench press 1 RM (kg): 102.3±13.5 Pull-up 1 RM (kg): 133.8±15.8 Females: Bench press 1 RM (kg): 59.2±5.9 Pull-up 1 RM (kg): 77.6±9.7
Acka and Moniroglu 2008	Males	Bench press 1 RM (kg): 85.45±8.20 Bench pull 1 RM (kg): 88.63±10.5 Bench press 1 min maximum repetitions (kg): 48.54±5.08 Bench pull 1 min maximum repetitions (kg): 59.36±6.03
Liow and Hopkins 2003	Males and females mixed	Bench press 1 RM (kg): 58±17 Dumbbell press 1 RM (kg): 59±19

During the short distances, paddlers reach a stroke rate of 170 strokes/min, which is almost three strokes/s with a water phase time of 0.200 s [31]. In this short amount of time, the paddler must apply enough force to the paddle to maintain the desired velocity. It has been suggested by Andersen and Aagaard [24] that explosive muscle strength is increasingly dependent on maximal strength as the time from the onset of the contraction increases. Therefore, quick movements with a contraction time of less than 150 ms, such as throwing, are less dependent on maximal strength. In contrast, movements such as jumping or sprinting, in which the time window to apply force is between 150 ms and 300 ms, are increasingly dependent on maximal strength [32]. Thus, a paddler needs to develop a high maximal strength in the upper body's specific kayaking muscles.

Some studies have investigated the influence of maximal strength on sprint kayak performance. van Someren et al. [33] have investigated the relationship between 200m performance time and dynamic strength in elite male 200m paddlers. This was performed utilizing a modified dynamometer, which replicated a paddle stroke. A moderate negative correlation has been found (r = -0.57; p = 0.013). Acka and Muniroglu [10] have found a non-significant moderate negative relationship between a 1 RM bench press and a 200m sprint performance (r = -0.51) in national elite male paddlers. McKean and Burkett [34] have found strong correlations between 500m and 1,000m performances and strength in national elite male and female paddlers. The correlations were found in the following exercises: 1 RM pull-up, 1 RM bench press, 8 RM external shoulder rotation, 8 RM bent-over trapezius raise, 8 RM dumbbell, and 8 RM shoulder press for both men and women. Bench pulls at maximum power (85% of 1 RM) and bench pulls at maximum repetitions (40 kg for male paddlers and 25 kg for female paddlers) correlated significantly to kayak performance for women. These findings are supported by Uali et al. [35], who have found a correlation between 1 RM bench pulls and sprint performances over 8m starting from a still position in young male and female international-level paddlers. These findings suggest that a high 1 RM bench pull translates to a better solid start performance in the kayak. In line with the previous studies, Pickett et al. [36] demonstrate a strong negative Pearson correlation between 3 RM bench presses (r = -0.8), bench rows (r = -0.76), and chin-ups (r = -0.73) relative to 200m sprint performances in national elite male 200m paddlers. Recently, Pickett et al. [37] have been unable to correlate mid-thigh pulls to 200m performances in a national-level male senior group. The findings suggest that the lower body's isometric strength may not translate to sprint performance in the kayak. However, the authors would like to further investigate lower body strength in relation to kayak performance.

It should be mentioned that all the studies utilized correlation analysis. However, correlation does not imply that there is a causation relationship between the variables [38]. The current literature, therefore, lacks large-scale strength training interventions. Intervention studies can clarify the strength qualities in relation to sprint kayak performance.

1.2.2. HYDRODYNAMICS IN KAYAKING

Hydrodynamics is an engineering discipline that describes the forces acting on a solid body in a fluid. *Drag* is the term utilized to quantify these forces. The drag forces can be divided into three types: (1) friction drag, which is the friction of the water on the kayak, (2) form or pressure drag, the force required to move water to form a path for the kayak, and (3) wave drag, the resistive force associated with the production of waves by the kayak [39]. Furthermore, these types of drag can be classified into passive drag, which is the resistance on an object that is not moving, and active drag, the resistance on an object which is moving [40].
Studies have investigated hydrodynamics in relation to sprint kayaking. A modern sprint kayak design is complex, yet the most important design feature is the hull. An effective hull design minimizes the total passive drag (kayak plus the drag created by the kayaker's mass). This is highly dependent on the frontal and wetted surface areas [4]. Gomes et al. [39] have investigated which of the drag forces acting on the kayak are the most dominant and reveal that friction drag is the most dominant, and developers should, therefore, seek to reduce it.

Gomes et al. [41] have additionally investigated the interaction between the paddler's weight and kayak in relation to passive drag, which is defined as the hull resistance. This was tested with a special towing device utilizing a force transducer to measure the kayak's combined resistance. A single male paddler tested the setup at different speeds with different weights and different kayak sizes (Nelo Quarto K1 kayak in sizes M, ML, and L). The investigation indicates that target velocity and body mass are the main factors that influence passive drag, although the manufacturer states that the paddlers should choose their kayaks according to body mass only. Mantha et al. [42] similarly confirm that race pace should be the deterministic factor when choosing a kayak. Additionally, they have observed a significant reduction in drag acting on the first Nelo Vanquis generation of kayaks versus the third generation model, which is mainly due to design improvements that led to the optimization of hydrodynamic geometric parameters for efficiency at higher velocities. Drag reduction for newer Nelo generations is yet to be investigated.

1.2.3. BIOMECHANICS

Kinetics and kinematics of the kayak

The paddler's main objective is to overcome the drag acting on the kayak through efficient kayaking locomotion, which involves technique and power. Consequently, the kayak continuously accelerates and decelerates. Hence, towing a kayak through the water (passive drag) is not representative of real locomotion, and it does not represent the drag (active drag). Passive drag is, on the one hand, easy to measure; active drag, on the other hand, has only been inferred from metabolic measures [9,41,43-47].

The movement of the kayak can be measured with a global positioning system (GPS) based accelerometer unit to correlate the movement of the kayak with performance. These devices have made their way into water sports recently [48], and they are widely utilized throughout the kayak community to quantify performance and optimize technique. Jansen and Sachlikidi [49] have assessed the validity and reliability of a GPS-based accelerometer unit compared to the video-derived measurements related to the kayak's velocity and acceleration. They have found a slight underestimation of velocity and acceleration with the GPS-based accelerometer units and small fluctuations during the day in measurements. They conclude that GPS-based accelerometers can be utilized for intra-stroke measurements. However, devices should be substantiated by validity and reliability studies, as accuracy is essential because the margin of error is small in elite kayaking.

In a review by Michaels et al. [4], kayaks are compared to rowing boats in relation to vessel movement and performance. It has been found that rowing boats in motion are influenced more by yaw and roll rather than pitch, which may apply to kayaks as well [50-52]. However, as the kayak is shorter than the rowing boat (5m versus 8 m), the pitch may influence the kayak more due to its shorter length. However, the rowing studies suggest that the boat's movements influence the rowing boat's hydrodynamic drag due to the increased wetted surface area of the boat. From the rowing studies, it can be deduced that the key object for the paddler is to maintain the kayak steadily during each stroke. This affects the hydrodynamic drag the least, enabling the paddler to maintain or even increase kayak velocity with a minimum of locomotion power lost to drag and kinetic power. Michaels et al. [4] emphasize yaw, pitch, and roll, and their effects on performance have been largely undescribed in the literature.

A recent study by Pickett et al. [53] has investigated pacing and stroke kinematics during a 200m race between elite and sub-elite paddlers. An accelerometer GPS was utilized to investigate pacing and stroke kinematics. The results illustrate that the ability to accelerate quickly during the first 25% of the race was associated with faster racing times. Furthermore, reducing the stroke rate decline and maintaining stroke length in the final part of the race was associated with better performance. The study indicates that a high stroke rate is vital for sprint performance and the ability to accelerate quickly.

Similarly, Vein Goreham et al. [54] have investigated pacing strategies in international elite paddlers for 200m, 500m, and 1,000m distances utilizing principal component analysis. Velocity data was measured by a GPS unit on each participant's kayak during the 2016 Olympic Games, the 2016 World Cups 1, 2, and 3, and the 2017 World Championships. It has been found that 1,000m distance paddlers utilize a seahorse-shaped pacing strategy, meaning a fast start, a slower middle pace, and a strong finish. No significant pacing pattern was observed on the 200m and 500m distances, indicating that pacing strategy on shorter races is less critical due to the competition's nature, whereas peak velocity and rapid acceleration are strongly associated with high performance.

Kinematics and kinetics of the paddler

The flatwater kayaking technique has often been analyzed through video recordings. Several studies have utilized video analysis to investigate the sprint kayak kinematics. The first to utilize video analysis were Plagenhof in 1997 [55] and Mann and Kearney [56]. Both studies analyze the basic sprint kayak technique. A study by Sanders and Kendal [6] describes the kayak technique regarding stroke length, angles of the blade during the water phase, and the path of the hands during the stroke. Baker et al. [57] made the first analysis utilizing markers in 1999, in which Baker and colleagues made a video-calibrated area of 6m in which the paddlers could complete two stroke cycles. However, no clear conclusions could be made regarding the kinematics of the kayaker, as the study was preliminary. The study nevertheless demonstrates that it is possible to perform kinematic analysis with markers.

The kayak stroke can be divided into two parts: a stroke on the left side and a stroke on the right side. Each side stroke can then be further divided into a water phase and an aerial phase. The water phase can be further divided into three sub-phases: entry, pull, and exit [7]. The phases can be seen in **Error! Reference source not found.**.

In the entry phase, the blade is submerged in the water. It is of great importance to submerge the whole blade to achieve the maximal grip in the water. In the pull phase, the blade is locked in the water, and the paddler can then pull the kayak forward with maximal force. Here, the greatest force is produced [8]. In the exit, the blade must leave the water quickly. The blade is rotated out of the water to minimize drag [3,7].

The aerial phase is the preparation for the following stroke on the opposite side. It has been found that elite male kayakers have the blade in the water of up to 63% of the stroke, and females achieve 64% on the 200m distance [3]. Brown et al. [58] have suggested that absolute water phase times and longer relative water phase time are associated with better performance.

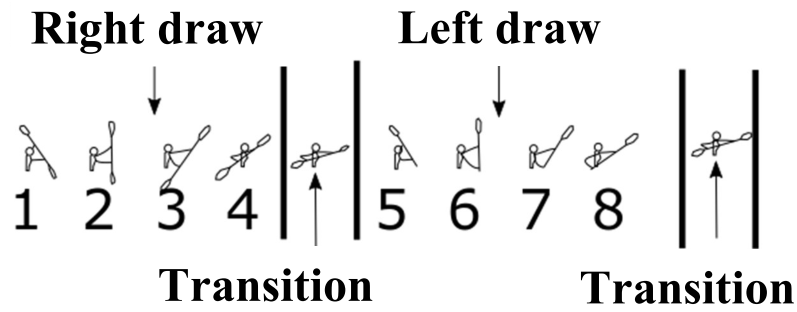

Figure 3: An overview of the phases of a stroke cycle from right to left, including phases and sub-phases.

An efficient technique is vital to utilize the wing blade paddle fully. The top hand must maintain the same height throughout the stroke, and the pulling hand must pull the paddle diagonally to the kayak while maintaining the paddle at a nearly vertical position for the main part of the stroke. This technique also involves prominent usage of the legs and rotation of the trunk. The athlete must push down with one foot on the footrest, and the contralateral leg pulls the foot strap. This push-and-pull action allows for a rotation of the pelvis, and thereby, a moment of force is produced. The force allows the trunk muscles to participate in the propulsion of the kayak. The paddle is rotated out of the water, and thereby, a faster exit phase is obtained [7,59,60].

A few studies have investigated the kinetics of paddlers on kayak ergometers. Tornberg et al. [64] have investigated the leg forces produced by paddlers on a kayak ergometer with a specially developed load sensor embedded in the ergometer's footrest. They have found peak leg forces of 650N for an international elite paddler. A study by Begon et al. [65] has measured forces on the seat and the footrest on a sliding ergometer with a sliding footrest-seat complex. The have found that the seat predominantly experienced pushing forces, with peak pushing forces of 351N±100N during the draw phase of a stroke cycle. Another study by Begon et al. [66] utilized a similar setup and has found peak leg forces of 895N applied on the footrest. Finally, a study by Michael et al. [67] has investigated paddle force, paddle angle, mechanical efficiency, and stroke timing on a rowing ergometer that was modified to simulate kayaking. They have found significant differences in mechanical efficiency between the paddlers on the left and right stroke. The subjects were international-level paddlers. Trevithick et al. [61] have elucidated the shoulder muscle recruitment patterns throughout a kayak ergometer stroke cycle. They recorded EMG (electromyography) for eight shoulder muscles in the dominant arm. The following five muscles have been found to be dominant: upper trapezius, supraspinatus, latissimus dorsi, serratus anterior, and rhomboid major. Begon et al. [66] utilized computer simulation to estimate the lower limbs' contribution to performance. They have found that the cyclic leg movement in kayaking increased the velocity by 6% and reduced the internal work by 4%. A study by Brown et al. [68] has recorded EMG for the trunk and lower limbs together with stroke force during repeated sprints. They have found an apparent activation of the major muscle groups in the legs during a stroke cycle. They suggest in the study that the legs provide a stable base for power transmission. Additionally, Fleming et al. [63] have recorded stroke force, 2D kinematics, and EMG during ergometer and on-water kayaking. They have found that the time required to achieve vertical shaft position was significantly less on an ergometer. Furthermore, they have found increased activity in the anterior deltoid muscle in on-ergometer kayaking. However, no significant differences were detected in the recorded force variables between on-water and on-ergometer kayaking. The results of Fleming et al.'s study [63] reveal that the ergometer does not replicate the on-water kinematics and kinetics entirely. Fleming et al. have investigated the ergometer's different elastic tension effect on EMG, stroke force, and 3D kinematics. They have found that the built-in loading mechanism appears to be responsible for the considerable activity in the anterior deltoid muscle in on-ergometer kayaking. The elastic tension increased, and the mean anterior deltoid activity during this phase progressively increased as well [62]. A specific result of the study is the quantification of the different segments involved in the stroke cycle. The overhead arm movements accounted for 39±16% of the cycle. Elbow angle at stroke cycle onset was 144±10°; maximal elbow angle (151±7°) occurred at 78±10% into the cycle.

In a review study by McDonnell et al. [3], kinematic variables during sprint distances in kayaking were analyzed. The findings summarize the current knowledge about factors affecting performance during sprint kayaking at distances up to 1,000 m. The study determines that an increased stroke rate via decreased absolute water phase time and increased relative water phase time elicited better performance. Absolute water time refers to the time the paddle blade is in the water in seconds. Relative water phase time refers to a percentage of the stroke cycle. No significant positive relationship was observed between stroke displacement and velocity. Nevertheless, it indicates that a significant decrease in stroke displacement may negatively influence performance.

As previously mentioned, van Someren and Howatson [12] have not found a positive correlation between kayak performance and arm span. Therefore, it may not be beneficial for paddlers to fully extend the elbow joint when the blade enters the water (catch phase) if it is at the expense of a high stroke rate. One could theorize that paddlers with longer arm spans would achieve a greater forward reach and thereby increase the stroke displacement. However, no studies have currently observed this.

The review study by McDonnell et al. [3] concludes that propulsion and water resistance have an immediate impact on the performance during sprint kayaking.

To date, it has been challenging to measure kinematics during on-water sprint kayaking. Recent advances in inertial sensor technologies provide a new way to perform motion analysis. The inertial measurement units (IMUs) can now be applied to human body segments, enabling the ability to track human kinematics in real-time during specific activities [69-71]. Therefore, IMU technology has made its way into biomechanics, and several studies have utilized the Xsens system to investigate kinematics [69-79]. Therefore, utilizing inertial motion capture systems to record athletes in their natural ecological conditions can underpin relevant and as-yet-unknown aspects of the kayak paddlers' kinematics (Study I).

Measuring forces in the paddle on the water

The kayak can be seen as a free-body diagram, as presented in Figure 4. The force is produced in the paddle and transferred through the kayak via the footrest, seat, and foot strap. One leg pushes on the footrest to produce a forward force, while the other leg pulls in the foot strap, which produces a backward force. These push-and-pull forces on the footrest create reaction forces in the seat [4,80]. An overview of the forces involved in sprint kayaking can be seen in Figure 4; one presents the kayak, and one presents the paddler. The paddler's force must travel through the seat and footrest to be translated from force to velocity.

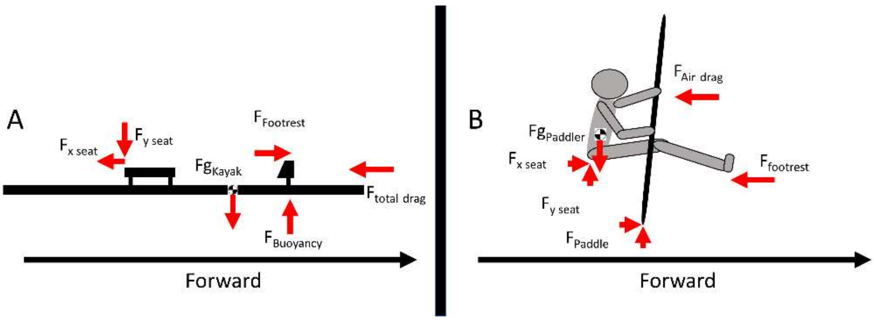

Figure 4: Free-body diagrams of the kayak (A) and paddler (B), illustrating the forces involved in sprint kayaking.

Aitken and Neal [81] were the first to instrument a paddle with strain gauges, providing the first view of on-water kayaking paddle forces in scientific literature. Since then, others have followed. Sperlich and Baker [82] developed a paddle with force transducers mounted in the paddle that were hard-wired to a collection system in the kayak. A study by Sturm [2] developed a kayak performance monitoring system called *The Kayak XL System*. The system had a wireless connection to a smartphone, and the paddler could therefore see live data of the stroke force while paddling. Gomes et al. [8] developed a measuring system called *The Fpaddle system* that can measure the forces in the paddle and transfer data wirelessly to an investigator station. Gomes et al. [8] placed strain gauges in different planes, and this provides a detailed view of the forces applied on the paddle shaft and during the exit phase of the stroke. In the same line, Gomes et al. [83] utilized the previously developed Fpaddle system to investigate force profiles in four cadences, finding that the profile became rectangular at higher cadences. The system allows, among other things, comparison of different paddle techniques. Gomes et al. [84] further utilized the Fpaddle system to investigate how paddlers' changes to water and aerial phases throughout the stroke cycle increased stroke rates. The results indicate that it is important to reach a high stroke rate to achieve a high kayak velocity. It has been suggested that paddlers must remove the ineffective parts of the stroke if the stroke rate is to be increased. This should be done by reducing the water phase—primarily the end of the water phase—as this has been found to be associated with negative acceleration.

Likewise, Nilsson and Rosdahl [59] also utilized an instrumented paddle to examine restricted versus unrestricted legs. However, the paper provides little knowledge of the instrumented paddle other than their usage of two moveable strain-gauge-based sensors that could record forces in one plane

Recently, Niu et al. [85] utilized optical fiber technology to measure water paddling performance. The setup enabled measurement of the handgrip's loading characteristics and various paddle blade regions during kayaking. However, the study had limitations: the setup was not wireless, as it required a 50m optical fiber cable connected to the system. Additionally, the system was sensitive to temperature changes in the environment. For example, there was a temperature shift between water and air. Nonetheless, the system is an excellent example of new technology being utilized to investigate sprint kayaking.

Kong et al. [86] utilized instrumented commercially available paddles from One Giant Leap in Nelson, New Zealand, to investigate the kinetic profiles of K2 crew members at different self-paced intensities. This was conducted with 74 paddlers who were divided into three groups: national, recreational, and school teams. The results indicate that the front and back paddlers' paddle force characteristics were similar during maximal effort. Additionally, they reveal that the better paddlers produced greater kinetic outputs than the lower-level paddlers. Bifarettia et al. [87] created a wireless data acquisition (DAQ) system that could be utilized for real-time performance analysis. Forces in the paddle and footrest were measured with velocity from a high frequency (10 Hz) GPS receiver. Additionally, they included tri-axial accelerometer and gyroscope measurements. The system demonstrates that it is possible to measure several data inputs and provide real-time feedback to the athlete.

Measuring forces in the footrest and seat on the water

To better understand the leg forces in kayaking, Nilsson and Rosdahl [86] have developed an on-water system that measures through individually integrated load cells the forces that are applied by the paddler on the footrest and seat. Nilsson and Rosdahl [59] have examined the importance of the leg forces during sprint kayaking in international elite paddlers. Two tests were performed: one with locked legs and one with free legs. The results present a decrease of 21% in the average speed when paddling with locked legs. This emphasizes the importance of the leg forces during sprint kayak performance. The previously developed seat was not utilized in the study. To the author's knowledge, no one has previously studied forces acting on the seat during ecological conditions in flatwater sprint kayaking.

1.2.4. UNEXPLORED AREAS

The majority of the studies in the literature have focused on kayak ergometers. Studies suggest that the upper-limb mechanics of on-ergometer and on-water kayaking are not entirely comparable, as differences do exist despite the similar metabolic demand [21,61-63]. Regardless of the desirable environmental standardization, ergometer testing may not be ideal for understanding on-water performance since the kinematics may not be similar. However, investigating movement patterns during on-water kayaking is challenging since kinematic analyses based on marker tracking that utilizes optical systems can be difficult. These systems require a steady base to ensure the correct position of a marker in space with respect to a reference frame. To date, it remains unclear how similar on-water and ergometer kayaking kinematics are.

The main focus of the kinetics studies has been procedures and methods [2,64-66,85,87-89]. The studies of Gomes et al. [83] and Kong et al. [86] have investigated paddle force with different performance parameters; however, only the study from Nilsson and Rosdahl [59] has investigated leg forces in relation to performance. Therefore, the extent to which on-water kinetics in the kayak affect performance is unknown.

1.3. AIM

The work of this PhD was initiated to investigate kinematics and kinetics of on-water sprint kayaking. This was accomplished by investigating kinematics of on-water and on-ergometer kayaking, developing a force-sensitive footrest and seat, and investigating leg force in on-water kayaking.
The specific aims of the project were as follows:

- To compare sprint kayak paddlers' kinematic profiles while they perform maximal on-ergometer and on-water kayaking utilizing their competition equipment. (Study I)

- To develop and validate a device that measures forces transferred to the footrest during on-water kayaking that concurrently does not hinder the kayak athletes' performance. (Study II)

- To develop and validate a device that measures forces transferred to the seat during on-water kayaking that concurrently does not hinder the kayak athletes' performance. This project was independent of the other projects.

- To characterize leg forces and their relationship to velocity in on-water sprint kayaking using the footrest developed in study II. (Study III)

CHAPTER 2. METHODS

2.1. SUBJECTS

A total of 40 kayaking subjects participated in the three studies that comprise this dissertation. Baseline characteristics are presented in Table 2 for each of the studies and the pilot seat test. All subjects had attained a minimum of national elite athlete status in their respective year group.

Table 2: Baseline characteristics of the subjects recruited for the three studies.

Study	(I)	(II)	Seat test	(III)
Number of subjects	11	1	1	28
Age (years)	16.8±1.2	18	30	17.6±2.3
Height (cm)	167.0±6.2	184	180	175.6±8.9
Body mass (kg)	64.1±8.1	70.5	100	69.9±10.3
Competition level	Nat/int	Int	Nat	Nat/int

All subjects received oral and written information regarding the study. Afterward, they provided written informed consent prior to the study in which they participated. The studies were approved by the local ethics committee of the North Denmark Region.

2.2. DEVELOPMENT PHILOSOPHY

The footrest development was inspired by a need for objective technical feedback of the forces within the kayak as well as how the cyclic leg movement works; additionally, it fills the literature's knowledge gap. A feedback loop system was utilized in the development [2,91,92] and can be seen in Figure 5. The stages are design, development, testing and evaluation. The development of the seat followed the same philosophy even though it was an independent project.

Thus, every phase of the design was developed, and every significant design step was discussed extensively with supervisors, the coach of the youth kayak national team, active elite paddlers, and Team Danmark's experts.

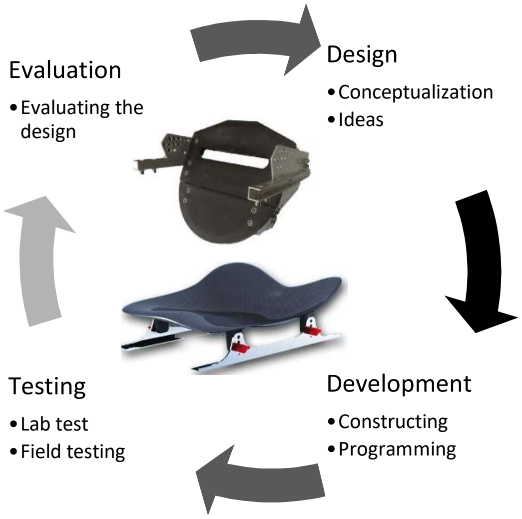

Figure 5: The design feedback loop for the development of the footrest and seat.

2.3. KINEMATIC COMPARISON OF ON-WATER AND ON-ERGOMETER KAYAKING (STUDY I)

Study (I) was performed during the autumn, at the same stretch of water for all paddlers. The testing was performed over two days. The two conditions (on-water and on-ergometer) were in randomized order and split between the two days. The subjects performed a standardized warm-up, followed by 2 min of all-out effort to simulate a 500m distance. The subjects were allowed to utilize their kayak and paddle, as changes to the equipment have hindered performances previously [90]. The ergometer test was performed on the same air-braked drag-adjustable kayak ergometer from Dansprint for all subjects. The ergometer resistance was set to 3 if the athlete's body mass was below 75 kg, and it was set to 5 if body mass was above 75 kg [62,63]. The elastic tension of the cords was adjusted according to the participant's preferences. The subjects were instructed to utilize the same paddle grip distance and footrest-seat distance for on-ergometer kayaking as they had utilized for the on-water test (Study I). The test setup and Xsens 3D representation can be seen in Figure 6.

Figure 6: View of the on-water test, the on-ergometer test (B), and the Xsens 3D representation of an ergometer test.

An inertial motion capture system (Xsens MVN Link, Xsens Technologies BV, Enschede, The Netherlands) was utilized to record full-body kinematics at a sampling rate of 240 Hz, which has previously been utilized in biomechanics [69-71]. The inertial system had 17 IMU. The IMUs were mounted on a tight-fitting Lycra suit that had predefined sensor placement locations. For data analysis, the Xsens MVN Studio was utilized (Xsens MVN Studio version 4.2.4). The IMUs were placed bilaterally on the following areas: shoulder, arm, forearm, hand, thigh, shank, foot, head, chest, and sacrum. The manufacturer's sensor calibration procedure was followed by asking participants to assume an N-pose (quiet standing with arms alongside the body. (Study I).

2.4. DEVELOPMENT OF FORCE-SENSITIVE FOOTREST (STUDY II)

A custom-made force-measuring footrest was developed for Study II and is portrayed in Figure 7. The footrest, via its two load cells, measured the force that was perpendicular to the surface of the footrest; its design is a metal "sandwich" with the load cells in between the plates on each side, and its shape is similar to a Nelo Cinco footrest (Nelo, Vila do Conde, Portugal). The aluminum spacers and load cell can be seen on the right-hand part of the footrest. The final footrest is displayed from a frontal view and an above view in Figure 8. It is mounted on a Nelo footrest frame.

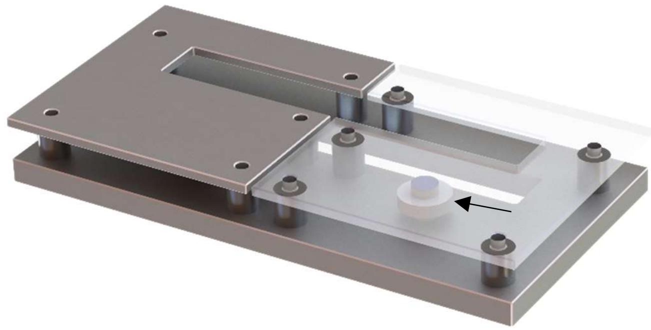

Figure 7: Illustration of the footrest design. The right part of the footrest is portrayed transparently for visual clarification. The black arrow marks the load cell.

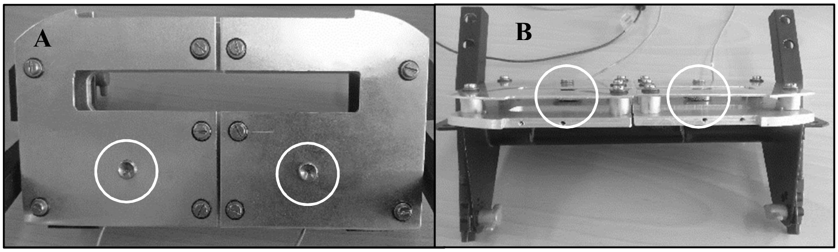

Figure 8: The footrest in A) frontal view and B) view from above. Load cells are highlighted with white circles. Adapted from Study II.

The footrest device was mounted in a Nelo Cinco kayak (see Figure 9). The wires were strapped to the steering cords of the kayak with cable connectors to avoid possible damage. The footrest added 0.6 kg to the kayak (Study II).

Figure 9: The footrest mounted in a kayak. Adapted from Study II.

A portable custom-built data acquisition system was built. A Latte Panda Windows 10 Mini PC (DFRobot, Shanghai, China) with MATLAB 2018a (Mathworks, Natick, MA, USA) was installed, which provided the platform for the data acquisition system. A USB 6003 data acquisition board (National Instruments, Austin, Texas) was utilized for the data acquisition, and a force amplifier (Biovision, Wehrheim, Germany; http://www.biovision.eu/biovision2_en.htm) augmented the signals from the load cells. The system was powered by a PowerCore 20100 power bank (Anker, Shenzhen, Guangdong, China). The system offered a gain of 10,000 and was set to a differential recording. The load cell output was sampled at a rate of 1,000 Hz. An overview of the setup can be seen in Figure 10 as a flow diagram. The system was mounted in a custom-made waterproof box, which can be seen in Figure 11.

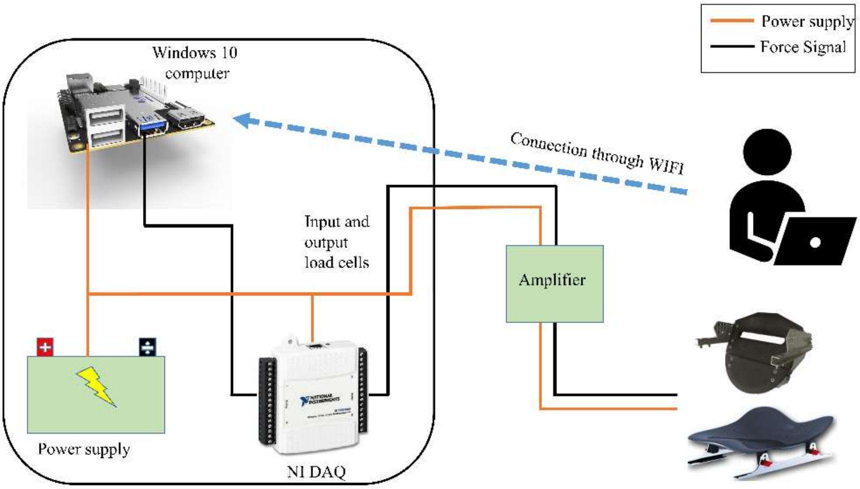

Figure 10: Overview of the custom-built data acquisition system seen as a flow diagram. The computer, power supply, and NI DAQ are in a custom 3D-printed box. Wires from the amplifiers and load cells are connected to the data acquisition system via binder connectors. A laptop could connect to the acquisition system via TeamViewer (TeamViewer 14, TeamViewer AG, Germany) to see live data.

Figure 11: Portable custom-built data acquisition system in the waterproof casing. Note the four input binder connectors in the bottom left portion of the photograph.

The data acquisition system was placed behind the kayak seat, and the cables from the footrest were connected to the data acquisition system. The data collection system added 1.2 kg to the kayak (Study II).

2.4.1. FOOTREST TESTING AND EVALUATION PROTOCOL

The following testing and evaluation protocol was utilized in Study (II). A deadweight setup was utilized to calibrate the footrest device. The following loads were utilized: 49 N, 98 N, 196 N, 294 N, 441 N, and 588 N. They were placed perpendicularly on the footrest (Study II).

A sequence of tests was performed to estimate the validity and reliability of the developed devices in the following order:

Hysteresis tests examined the relative difference in the signal before and after the applied force.

Drift tests measured the relative difference in the signal every 10 minutes to quantify the drift.

Tests and retests determined the difference between values of the same applied weights over time.

One elite male paddler was recruited to test the setup on the water. The setup was mounted in a K1 Cinco XXL (Nelo, Vila do Conde, Portugal) that was set to the paddler's preferences. The participant then went on the water and was performed 5 min of self-chosen warm-up. The participant was then asked to paddle with three different velocities: 12 km/h for 60 s, 15 km/h for 30 s, and a maximal effort for 20 s. A GPS watch (Feniks 5, Garmin, Olathe, Kansas, USA) was mounted on the kayak so the paddler could maintain velocity (Study II).

2.5. DEVELOPMENT OF THE FORCE-SENSITIVE SEAT

The seat was not a part of the manuscript of Study II. Therefore, the seat device is described here in more detail.

A custom-made seat was developed for the PhD project, utilizing the forward feedback loop. Several prototypes were discarded because they failed laboratory tests. However, each failing prototype was evaluated and thus contributed to the final seat design. The final seat prototype measures force in the longitudinal axis with a single load cell, meaning that forward and backward forces in the seat are measured. The load cells are identical LCM200 miniature tension and compression single-point load cells with a measurement range of 1,112 N, a tolerance of overload of 500 N, linearity of±0.5%, and hysteresis of±0.5% (Futek, Irvine, CA, USA) Study (II). The seat was fixed on a linear ball-bearing system (T rail TW-01 Drylin, Igus ApS, Cologne, Germany), which can be seen in Figure 12.

Figure 12: Linear ball-bearing system mounted at the bottom of the kayak.

A metal plate was attached to the linear ball-bearing system to form a platform where the seat could be attached (Figure 13). The seat was attached to the plate with eight bolts connecting the plate to the seat. The seat utilized the portable custom-built data acquisition system developed in Study II.

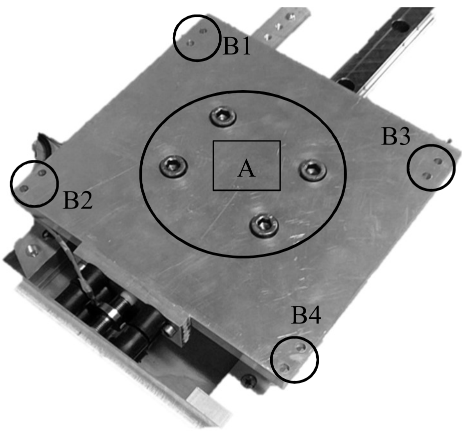

Figure 13: Platform placed on top of the linear ball-bearing system. *A* is where the platform is attached to the linear ball-bearing system, and *B1-4* are the holes to attach the custom-made seat.

A single load cell was attached to the sliding seat at one end, and a fixed metal bar was attached at the other end. Springs on either side were attached to the seat and connected to the metal bar. This enabled the load cell's pre-tensioning, allowing it to measure both tension and compression (push and pull). With this configuration, the distance between the seat and the footplate could be individualized. The seat can be seen in Figure 14 in a laboratory setup. The modified seat featured the same height as the original seat: 40 mm from rail to seat.

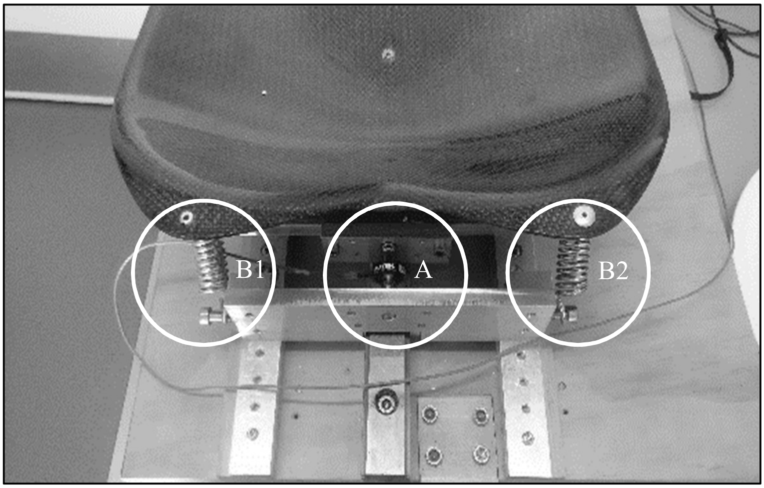

Figure 14: Laboratory view of the seat setup. The linear ball-bearing system is mounted to a fixed wooden plate. Note the single load cell attached to the metal beam (A). Furthermore, note the springs mounted to the metal beam on each side of the seat (B1 and B2).

The linear ball-bearing system was mounted with bolts at the bottom of the kayak to the kayak's weight system rails. The seat was then mounted to the linear ball-bearing system, as seen in Figure 15. The seat system added 6.6 kg to the kayak.

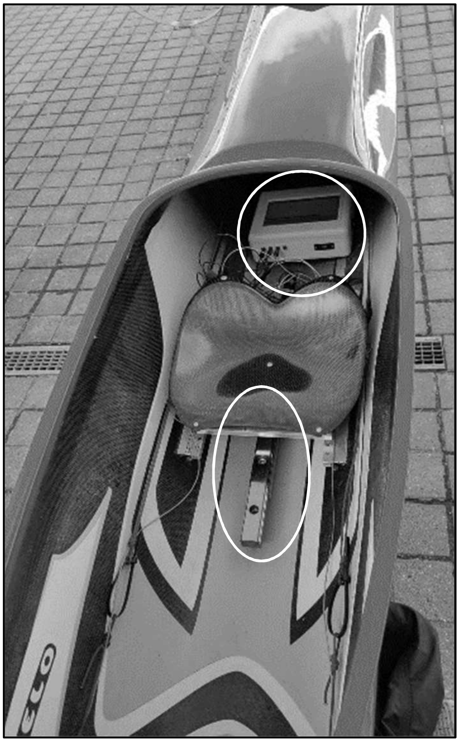

Figure 15: The seat mounted in a kayak (foreground, marked by a white oval). The data acquisition system was placed behind the seat in the kayak (marked by a white circle).

2.5.1. SEAT TESTING AND EVALUATION PROTOCOL

The seat's calibration followed two conditions: one placed 55 kg on top of the seat, and one placed 80 kg on top of the seat. This simulated the weight of the paddler. The following loads, 49 N, 98 N, 196 N, 294 N, 441 N, and 588 N, were utilized to calibrate the seat in a pulling setup, so the seat could then be flipped 180° to calibrate in both directions. It should be noted that the forward (pulling) direction of the seat was not loaded with 588 N, as this would cause the springs to elongate. The loads were each held for 5 s. Otherwise, the seat's evaluation followed the protocol utilized in Study II concerning hysteresis, drift, and test-retest differences.

One elite male kayak paddler was recruited to test the setup on the water. The setup was mounted in a K1 Cinco XXL (Nelo, Vila do Conde, Portugal) that was set to the paddler's preferences. The subject was asked to maintain a still position in the kayak for 20 s with his feet under the foot strap. This measurement was utilized to correct for an offset of the data from the footrest and the seat. Further, a GPS-based accelerometer (Minimax, Catapult Innovations, Victoria, Australia) was mounted on the kayak to record forward acceleration and velocity (Study II). The subject was asked to paddle three all-out bouts of 20 s each, with 6 min of rest between each session.

2.6. CHARACTERIZATION OF LEG FORCES (STUDY III)

Study (III) was performed during the summer, at the same water stretch for all paddlers. The testing was performed over three days. The custom-made footrest device was mounted with the portable custom-built data acquisition system in each participant's kayak prior to each test. Data from the footrest was collected continuously at a sampling rate of 1,000 Hz. The distance between the seat and footrest was secured to be the same as the participants' own setup. The participants then went on the water and performed 5 min of self-chosen warm-up exercises. Participants were then asked to paddle at three velocities: 12 km/h for 60 s, 15 km/h for 30 s, and a maximal effort for 20 s. The research team followed closely in a motorboat to monitor and encourage the participants. A photo from the data collection can be seen in Figure 16.

Figure 16: Photo from the data collection in Study III.

2.7. DATA ANALYSIS

MATLAB was the primary data analysis software utilized in the three studies.

The kinematic data from Study (I) was filtered and fragmented in Xsens MVN Studio before being exported to MATLAB. Xsens MVN Studio utilizes an extended Kalman filter to fuse accelerometer, gyroscope, and magnetometer signals to acquire joint angles and angular velocities. The first 10 s of recordings were eliminated from the analysis due to high variability in movement initiation and acceleration; therefore, the following 100 strokes (50 stroke cycles) were utilized for analysis. To account for the impact of fatigue on the kinematic results, trials that deviated more than 25% from the median were excluded. This left 39±4 stroke cycles to be analyzed, on average, for on-water testing and 45±2 stroke cycles for on-ergometer testing (Study I).

Study (I) focused on data from elbow flexion/extension angle and angular velocity, shoulder flexion/extension angle and angular velocity, and knee flexion/extension angle and angular velocity as well as thoracolumbar anterior-posterior movement (flexion/extension) and medial-lateral movement (lateral bending) in the comparison between on-ergometer and on-water kayaking.

In Study (II), the seat investigation, and Study (III), data from the footrest, seat, and GPS-based accelerometer were filtered with a fourth-order low-pass filter with a cutoff frequency of 10 Hz. Data from the footrest and seat were averaged across 12 stroke cycles for the maximal bout and 15 stroke cycles for the submaximal bout to display the forces throughout a stroke cycle. One stroke cycle was defined as the time from a force peak on the left side through a force peak on the right side until the force peak returned to the left side. The footrest and seat were time normalized to the maximum force peak on the left side. Consequently, one stroke cycle was defined as one left-force peak until the next left-force peak. The impulse was calculated with a trapezoidal numerical integration for leg forces on the left and right sides. The two sides were summed to determine the total impulse (Study II).

2.7.1. STATISTICS

Study (I) utilized the novel statistical methods of statistical parametric mapping (SPM), which was initially developed to analyze cerebral blood flow in neuroimaging. However, it was recently introduced to biomechanics and other areas [93-96]. SPM allows smooth, bounded data to be processed without reducing the data to a simple minimum or maximum point. However, it should be noted that data must be filtered smoothly before the SPM analysis is performed. Data is preserved in the same time domain during the statistical analysis, which allows complex cyclic data to be presented in a non-abstract way [93]. SPM utilizes random field theory to calculate the statistical *p*-values for the supra-threshold clusters [93], which are the areas that exceed the critical value and were chosen in the analysis. MATLAB was utilized for the SPM analysis (Study I).

Study II utilized descriptive statistics to test the footrest. The coefficient of variation (CV) was calculated from the hysteresis. MATLAB was utilized in investigation as well. The evaluation of the seat utilized the same descriptive statistics as the testing of the footrest.

Statistical analyses in Study III were performed in the most updated R-studio version (Stata Corp LP, College Station, TX), except for the bootstrapping, which was conducted in version 15. To investigate leg forces relative to velocity, two multiple linear regressions analysis were performed: one algorithm predicted maximal paddling velocity, and the second investigated the effect of paddling speed on the different leg forces with an explanatory model (Study III).

CHAPTER 3. RESULTS

3.1. DIFFERENCE IN JOINT KINEMATICS BETWEEN ON-ERGOMETER AND ON-WATER KAYAKING (STUDY I)

The results of the paired student *t*-test revealed a significantly greater stroke rate for the on-ergometer kayaking (122.1±6.8 strokes/min) compared with on-water kayaking (107.1±4.6 strokes/min, $p < 0.05$; Study I).

The SPM model results are displayed in a 2 x 2 subplot for each joint that was studied (Figure 17). Two subplots contain joint data and two subplots contain the associated SPM model. The thick lines on the graphs represent average elbow angles and angular velocities, and shaded areas represent standard deviations. An approximation of the phases in the stroke cycle is presented as A (contralateral transition), B (ipsilateral draw), C (ipsilateral transition), and D (contralateral draw). The vertical gray lines indicate the phases. In Graph P2 (upper right corner of Figure 17), statistical results from the SPM analysis throughout the stroke cycle are presented for the elbow angle; the elbow angular velocity is illustrated in Graph P4. The gray area in Graph P4 marks a significant difference between on-water and on-ergometer testing (Study I).

The SPM model results revealed a significant kinematic difference between on-water and on-ergometer kayaking in all variables except knee flexion/extension angle (Study I).

The elbow joint flexion/extension angle presented a similar pattern between the two conditions. However, a significantly greater elbow joint angle was observed in the on-water ipsilateral draw phase compared to on-ergometer kayaking (see Figure 17; $p < 0.05$, Phase B). Furthermore, a significantly greater elbow flexion/extension angular velocity was observed in the on-water ipsilateral and contralateral transition phases compared to on-ergometer kayaking ($p1 < 0.001$, $p2 < 0.001$, Phases B and C). Furthermore, the maximal flexion occurred later in on-ergometer testing compared to on-water testing (Study I).

The shoulder flexion/extension exhibited a similar pattern throughout the stroke cycle between the two conditions (on-water and on-ergometer testing). Significantly greater and earlier flexion of the shoulder was observed in on-water testing than in on-ergometer testing in the ipsilateral draw phase and contralateral transition phase ($p1 < 0.001$ and $p2 < 0.001$, Phases B and C). A significantly greater and earlier shoulder angular velocity was observed in on-water testing compared to on-ergometer testing in the ipsilateral draw phase and contralateral transition ($p < 0.001$, Phases B and C; see Figure 18; Study I).

No significant differences in the knee flexion/extension angle were observed between conditions. Nevertheless, significantly greater angular velocity was observed in on-ergometer testing compared to on-water testing in the ipsilateral transition phase ($p < 0.001$, Phase A; see Figure 19; Study I).

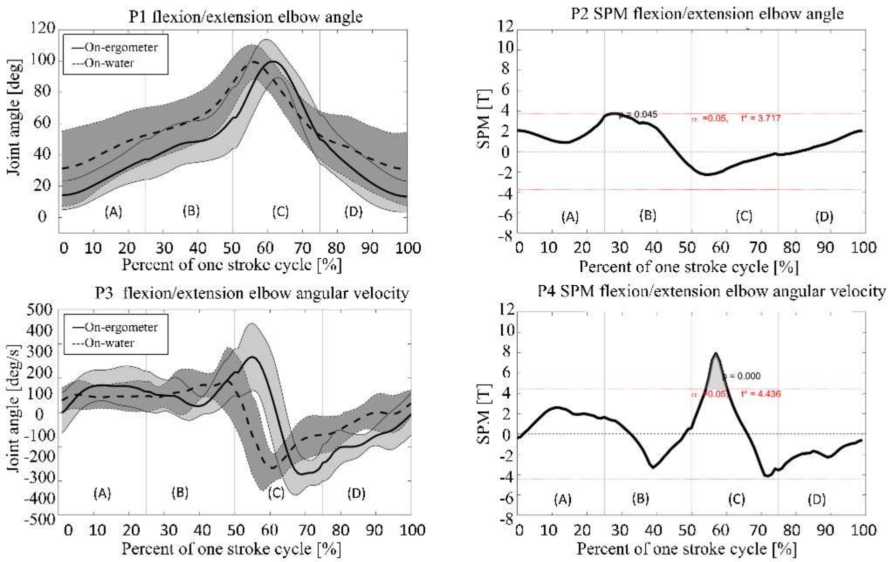

Figure 17: Elbow flexion/extension angle (P1) and elbow flexion/extension angular velocity (P3) during on-ergometer (solid line) and on-water kayaking (dotted line) normalized to the stroke cycle duration. Adapted from Study I.

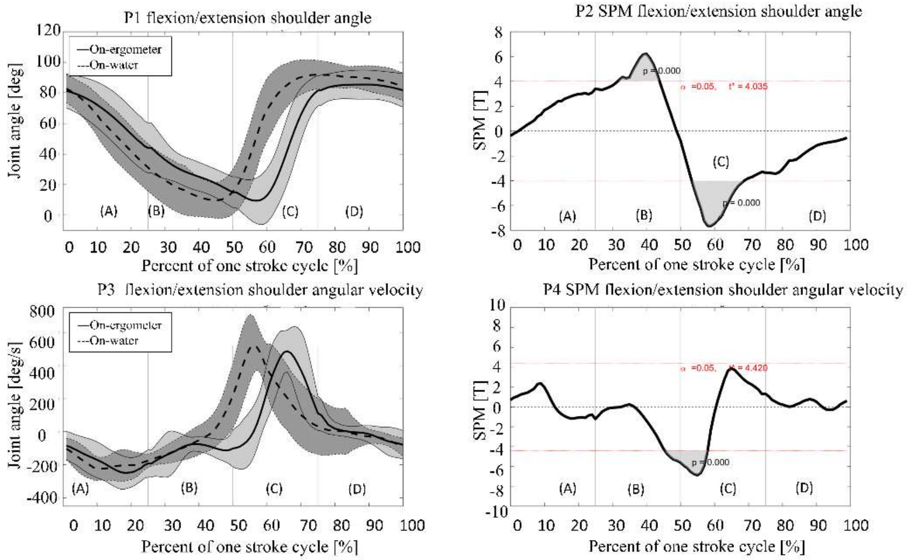

Figure 18: Shoulder flexion/extension angle (P1) and shoulder flexion/extension angular velocity (P3) during on-ergometer (solid line) and on-water kayaking (dotted line) normalized to the stroke cycle duration. Adapted from Study I.

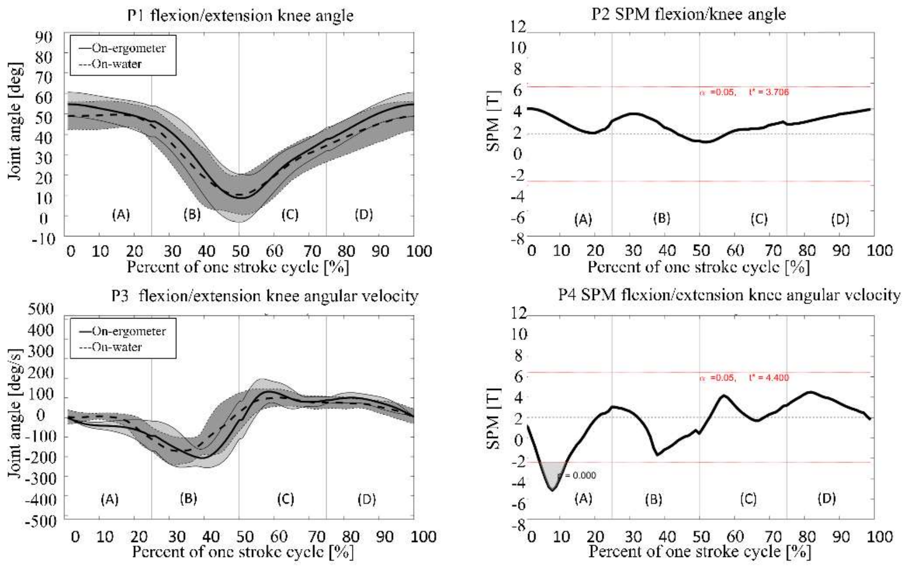

Figure 19: Knee flexion/extension angle (P1) and knee flexion/extension angular velocity (P3) during on-ergometer (solid line) and on-water kayaking (dotted line) normalized to the stroke cycle duration. Adapted from Study I.

3.2. EVALUATION OF FOOTREST DESIGN (STUDY II)

The aim of Study II was to develop and validate a force-sensitive footrest for a Nelo kayak. The footrest elicited a significant linear response to loading (left: 0.9987 and right: 0.9903). The results of the validation tests regarding the footrest are listed in Table 3. Overall, acceptable values were obtained. However, it should be noted that the footrest displayed a small amount of hysteresis: 1.8±2.0% on the right side and 0.8±1.3% on the left (Study II).

The on-water test demonstrated that leg forces display a distinctive loading and unloading pattern. Furthermore, some subtle differences were observed in peak leg forces between the right and left sides. The time-normalized, leg force on-water data is presented in Figure 20. Additionally, there were observable differences over the three bouts.

Table 3: Validity and reliability measurements of the footrest device. Adapted from Study II.

	Footrest right	**Footrest left**
Drift (%)	< 1	< 1
Hysteresis (%)	1.8±2.0	0.8±1.3
Δ Test-retest deviation (N)	1.8±1.3	0.8±5.1
CV (%)	0.72	0.16

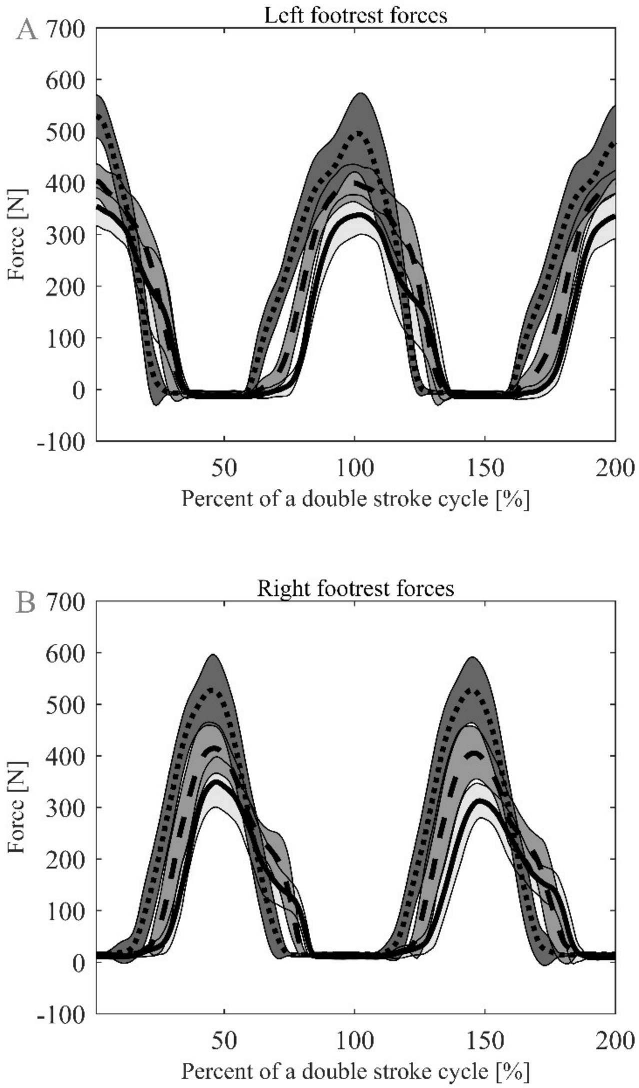

Figure 20: Mean force of two stroke cycles. The data in the top is from the left side, and the bottom is the sight side. The three bouts can be seen: 3.3 m/s (light gray solid line), 4.1 m/s (gray dashed line), and 6.2 m/s (dark gray dotted line). Data was normalized to the left side utilizing the force on the left footrest. The start of the stroke cycle (at 0%) is when the force on the left footrest peaks. The end of the second stroke (at 200%) is when the force on the left footrest peaks for the third time. Adapted from Study II.

3.3. EVALUATION OF SEAT DESIGN

This investigation aimed to develop and validate a force-sensitive seat for a Nelo kayak. The seat demonstrated an average linear response of 0.9536 in the backward direction and 0.9457 in the forward direction. The results of the validation tests for the seat are listed in Table 4. The seat displayed a problematic hysteresis of 4.7±5.4% in the forward direction and 6.3±3.9% in the backward direction. The hysteresis issue is also portrayed in Figure 21. Furthermore, a considerable variation was observed in the test-retest process.

Table 4: Reliability measures of the seat device.

Variables	Seat forward force	Seat backward force
Drift (%) with 55 kg	< 1	< 1
Drift (%) with 80 kg	< 1	< 1
Hysteresis (%) with 55 kg	3.7±4.7	6.1±3.2
Hysteresis (%) with 80 kg	4.7±5.4	6.3±3.9
Δ Test-retest deviation (N) with 55 kg	8.9±13.2	0.4±15.8
Δ Test-retest deviation (N) with 80 kg	8.5±15.4	0.2±15.5
CV (%) with 55 kg	1.81	0.01
CV (%) with 80 kg	0.67	0.03

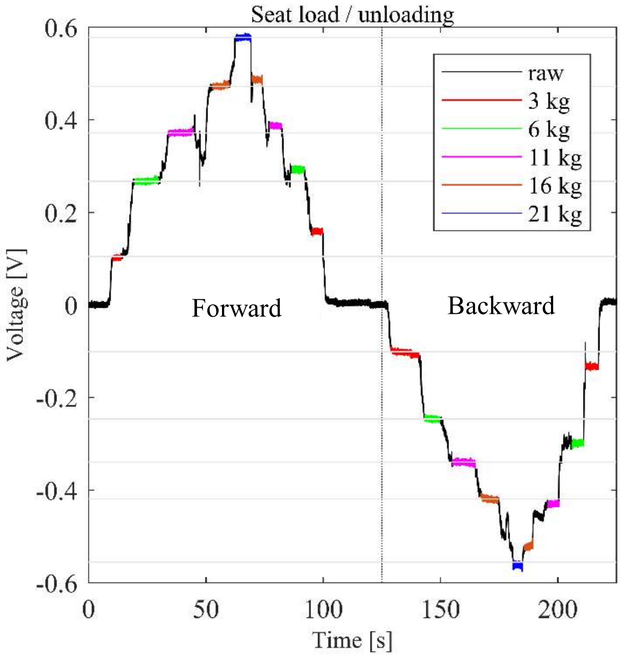

Figure 21: Stepwise loading and unloading of the seat system following the loading protocol: 3 kg, 6 kg, 11 kg, 16 kg, and 21 kg, first in the pull direction and then in the push direction. The values of the *y*-axis are presented in voltage. The raw signal is the solid black line. Red markings indicate a 3 kg load and unload; green markings indicate a 6 kg load and unload; magenta markings indicate an 11 kg load and unload; orange markings indicate a 16 kg load and unload; and blue markings indicate a 21 kg load and unload. The gray horizontal lines indicate the start of each load.

The on-water measurements indicate that the peak seat forces in the forward direction occurred together with peak force in the footrest. The seat forces seem to follow a distinguished pattern: a force peak whenever there is a leg push, followed by a force peak in the backward direction before the next leg push. Overall, the seat forces were small compared to the leg pushing forces (see Figure 22). An overview of the collected variables can be seen in see Table 5.

The solo paddler reported that the kayak felt heavier than usual. This was due to the weight of the seat system, which added 6.6 kg to the kayak.

Table 5: Investigated variables during the test of the footrest and seat.

Variables	
Speed (m/s)	5.2
Stroke cycles analyzed	12
Stroke rate	135
Heart rate at the end (Bpm)	175
% of maximum heart rate	92.1
Forward peak seat force (N)	73.2±69
Backward peak seat force (N)	94±48

Note: The stroke rate was measured in strokes/min.

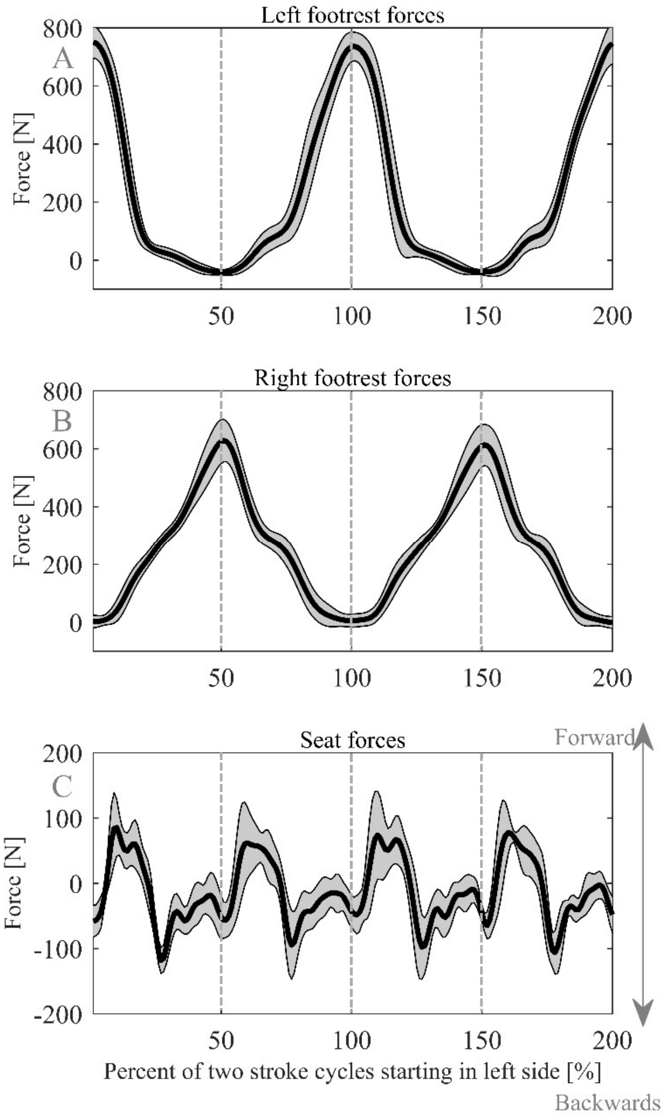

Figure 22: On-water data for leg force and seat data: Force data from three channels was recorded. The graphs illustrate the mean force of two stroke cycles. The top plot is the left leg forces (A), middle is the right leg forces (B), and the bottom the the seat forces (C) during a maximal trial. The arrow on the right-hand side indicates force direction in the seat. It should be noted that the *y*-axis on Graph C has been scaled to display the maximum and minimum values. Gray dotted lines were added to the figure at each force peak in the footrest.

3.4. DESCRIPTION OF LEG FORCES AND THEIR RELATIONSHIP TO VELOCITY (STUDY III)

In Study (III), leg forces were collected from 25 subjects who utilized the custom-developed footrest at three velocities. The results revealed that the leg force elicits a sinus-like pattern, increasing and decreasing throughout the stroke cycle. Descriptive results demonstrated that leg force characteristics increased at each velocity, as did the stroke rate. However, impulses over 10 s showed a different pattern between the bouts. Only maximal effort displayed a greater impulse than at 12 km/ h and 15 km/h (See Table 6: Mean and standard deviation of the collected variables for the three bouts (12 km/h, 15 km/h, and maximal effort).Table 6); Study III).

The explanatory model was manually adjusted for paddler level to allow elaboration on different potential associations between paddler levels. The results demonstrated a significant positive relationship between leg forces and increased velocity ($p < 0.05$). The R^2 values range from 0.14 to 0.34, indicating that leg forces are only part of the mechanism leading to higher paddling speeds (Study III).

Table 6: Mean and standard deviation of the collected variables for the three bouts (12 km/h, 15 km/h, and maximal effort).

Variables	**12 km/h**	**15 km/h**	**Maximal effort**
Velocity (km/h)	12.3±0.5	15.1±0.3	19.7±2
Mean stroke rate	74.6±10.6	93.2±11.7	125±12
Peak force (N)	328±108.7	347.3±91.6	398.2±106.2
Mean force (N)	201.3±67.7	217.7±78	289.5±82.7
Impulse (N/s) over one stroke cycle	39,720±16,566.9	46,738±15,656.8	55,486.3±17,359
Impulse (N/s) over 10 s	1,812,195.4±727,41 5.3	1,756,809.3±698,13 3.2	2,383,635±869,99 5

Notes: Two subjects withdrew from the test for personal reasons, and data from one subject was lost due to a systematic error, leaving a total of 25 subjects. The stroke rate was measured in strokes/min. Adapted from Study III.

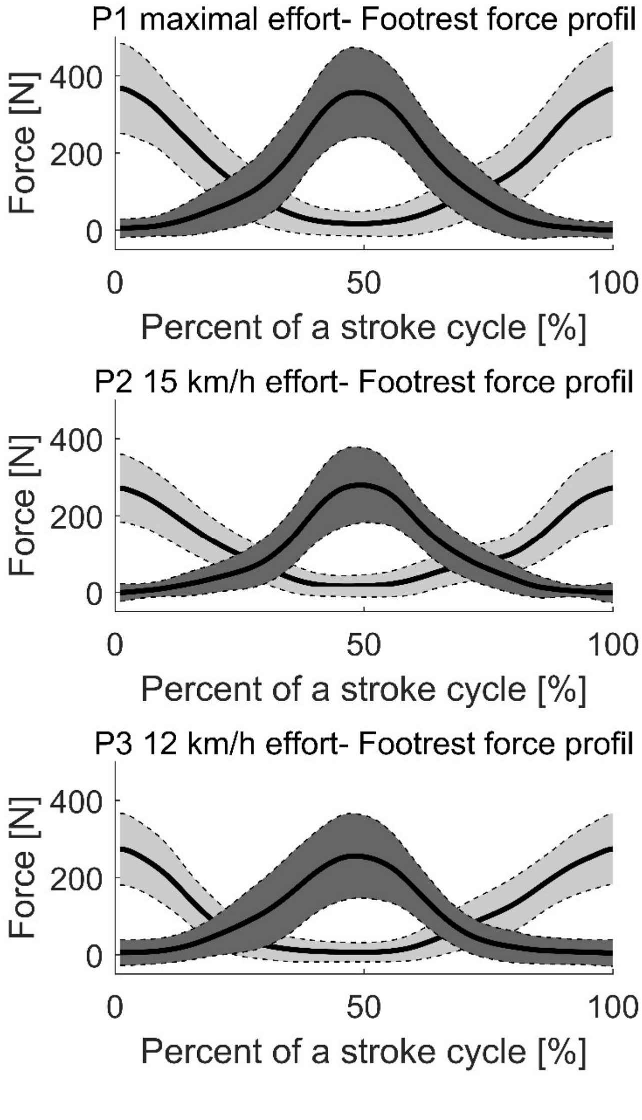

Figure 23: The figure portrays the mean force of a stroke cycle for each intensity with a standard deviation; light gray represents the left side of the footrest, and dark gray represents the right side. P1 is maximal effort, P2 is 15 km/h, and P3 is 12 km/h. The *x*-axis presents a stroke cycle, starting from the left side, continuing to the right side, and returning to the left side, and the *y*-axis presents force in Newtons. Data was normalized to the left side, utilizing the force on the left footrest. The start of the stroke cycle (at 0%) is when the force on the left footrest peaks. The end of the second stroke (at 100%) is when the force on the left footrest peaks for the second time. Adapted from Study III.

The following performance prediction equation was generated from the linear mixed-model regression analysis (Study III):

$$(1)\quad V_{\max} = (0.0045 \cdot F_{\text{peak}}) + (0.000017 \cdot J_{10\text{ seconds}}) + (0.05 \cdot SR) + 7.62$$

$$(F(3, 21) = 37.41;\ p\text{-value} < 0.001),\ \text{adjusted } R^2 = 0.8$$

where $V_{\max}$ is maximal velocity, F_{peak} is the peak force, $J_{10\text{ seconds}}$ is the impulse over 10 s, and SR is the stroke rate. All predictors displayed a slope that was significantly different from zero (see Equation 1). The model correctly predicted 68% of the paddlers' velocities within 1 km/h (Study III).

The predictive model proves that it is possible to predict maximal kayak velocity utilizing leg force characteristics and stroke rates.

3.5. SUMMARY OF MAIN RESULTS

An overview of the main results of Studies I-III and the findings regarding the developed seat can be seen in Figure 24. A kinematic difference was found between on-water and on-ergometer kayaking in Study I. The developed footrest in Study II was valid and applicable. Therefore, it was utilized in Study III. However, the developed seat demonstrated unacceptable values of hysteresis and weight. The seat was, therefore, not included in Study III. In Study III, leg forces revealed a positive relationship with velocity.

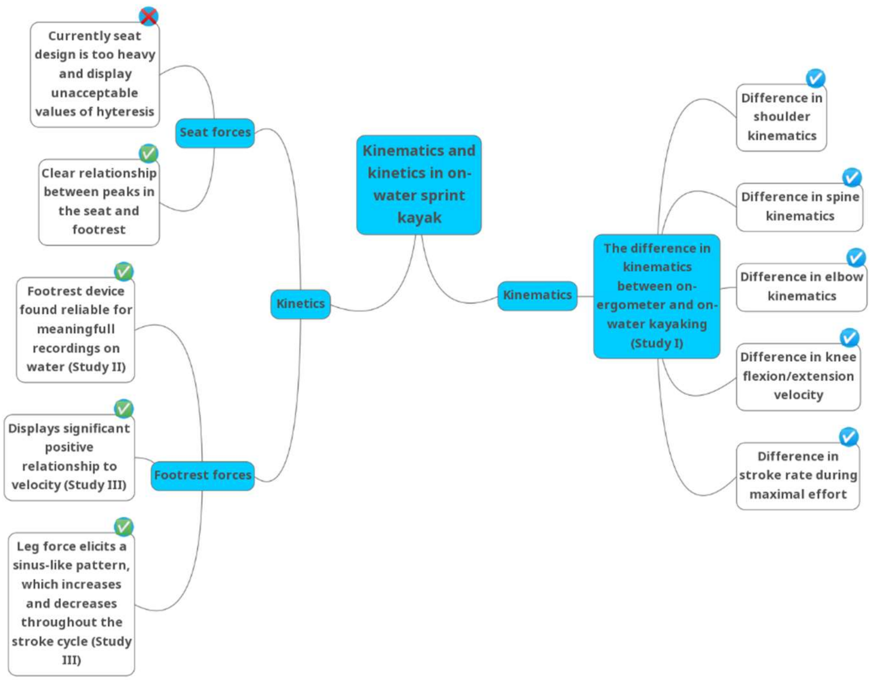

Figure 24: An overview of the main findings of the PhD study. Ticks mark the positive findings of the PhD, and an *x* marks the negative finding.

CHAPTER 4. DISCUSSION

This thesis investigated the kinematics and kinetics of on-water sprint kayaking. Three studies were conducted. The studies' main findings are as follows. Study (I): Kinematic differences were observed between on-ergometer and on-water kayaking in young elite female kayak athletes. They exhibited differences in elbow, shoulder, and knee kinematics. Moreover, the results demonstrate a higher stroke rate during on-ergometer kayaking when compared to on-water kayaking. Study (II): A custom-made footrest was developed to measure the cyclic leg forces upon the footrest. The footrest reveals acceptable reliability and validity. Additionally, a seat was developed to measure the paddlers' forward and backward forces in the seat. This design was not described as a part of Study II. The developed seat presented a significant amount of hysteresis. Therefore, only the footrest was utilized as a part of the second and third studies. Study (III): The results demonstrate that the stroke rate and leg force characteristics increased with velocity. This was, however, not the case for impulses over 10 s, where only maximal effort testing displayed a greater impulse than 12 km/h and 15 km/h. Furthermore, the explanatory model results display a significant positive relationship between leg forces and increased velocity. The R^2 values ranged from 0.14 to 0.34, indicating that leg forces are only part of the mechanism leading to higher paddling speeds. Most notably, the mean force increased by 14.13N for a 1 km/h increase in velocity (Study III).

The following sections elaborate upon and discuss the results as well as specific strengths and limitations.

4.1. DIFFERENCE IN KINEMATICS BETWEEN ON-WATER AND ON-ERGOMETER KAYAKING

In Study (I), kinematic differences between on-water and on-ergometer kayaking were investigated. The study confirms the results by Fleming et al. [63], which state that the kayak ergometer may not perfectly replicate the biomechanical demands of sprint kayaking. They have found a significantly greater anterior deltoid activation throughout the contralateral transition phase in on-ergometer testing. This aligns with the results of Study I, which reveal a greater and earlier flexion of the shoulder during the contralateral transition phase in on-water testing than in on-ergometer testing. The elbow angular velocity reported in Study (I) supports this, as a significant difference was observed in the ipsilateral draw phase and contralateral transition, which presented a greater and earlier shoulder angular velocity. The recoil forces created by the cords on the ergometer may be responsible for the difference in timing of the shoulder flexion, supporting the results by Fleming et al. [63]. They suggest that the recoil forces on the ergometer pull the shoulder in a downward trajectory (Study I).

It should be noted that Study (I) does not find a significant difference in knee kinematics between the two conditions. This implies that the kayak paddler's technique of specific cyclic leg movement can be trained on a kayak ergometer.

Additionally, Study (I) finds that the stroke rate differs in the maximal efforts between on-water and on-ergometer kayaking. This may be related to the shorter ergometer paddle length (173cm) compared to the kayak paddle (210.5±1.9cm). The subjects were asked to maintain the same hand positioning in both conditions. However, this means that the distance between the hand and the applied force may have differed between the two conditions. The ergometer's paddle has the shortest length, and holding the paddle with the same hand position may result in a higher stroke rate. The question related to stroke rate should be investigated further with strain gauges on the paddle in each condition (Study I). Furthermore, the difference in stroke rate between on-water versus on-ergometer testing could explain some of the kinematic differences that have been found in the study. Therefore, future studies should investigate paddler kinematics while maintaining constant stroke rates throughout each condition to clarify the findings. Furthermore, the subjects of Study I were young females (16.8±1.2years). It could be interesting to see if the same results apply to other kayaking groups.

Study I utilized inertial sensor technologies to perform on-water motion analysis, although the accuracy of detailed kinematic data is still not fully proven [97]. This could be an issue regarding the complex shoulder joint. However, it is important to recognize that IMU technology has excellent reliability and validity for flexion/extension kinematics [73,77,97] (Study I). Especially regarding knee flexion, IMU technology is superior because the knee joint is hidden within the kayak. Video analysis can, therefore, not be utilized to analyze the knee movement.

Future studies should utilize the latest inertial sensor technology to ensure satisfactory data from complex joints such as the shoulder.

4.2. VALIDATION AND RELIABILITY OF FOOTREST DEVICE

The following section discusses the validity and reliability of the developed footrest. Moreover, a comparison is made to other developed footrest devices from the literature.

The developed footrest revealed a relatively low amount of hysteresis (see Table 3), which translates to an acceptable validity. The values are similar to the footrest developed by Nilsson and Rosdahl [89], which features hysteresis below 1N. The footrest in the present study expressed CV values of 0.72 and 0.16 for the right and left sides, respectively, in terms of reliability. Nilsson and Rosdahl's footrest [89] has a CV that ranges from 0.07% to 1.13%. The two footrests have similar validity and reliability. Therefore, the footrest developed for this study is considered reliable and valid for meaningful recordings in the field during on-water kayaking (Study II).

4.2.1. ON-WATER TEST OF FOOTREST DEVICE

The on-water leg force data presented results that are comparable with the results obtained by Nilsson and Rosdahl [89]. Looking at the measured leg forces, it is possible to distinguish between different paddling intensities (see Figure 20). The leg forces were considerably higher in the maximal bout at 552±47N (see Figure 20). However, Nilsson and Rosdahl [59] have found lower peak forces in the footrest of 400N in on-water testing. Begon et al. [66] reveal peak forces of 815N in one of their subjects who was on a sliding ergometer, which is considerably higher than the current study. Tornberg et al. [64] present peak leg forces of 650N for an international elite paddler. However, this was on a Dansprint ergometer with no sliding seat or footrest. These findings could indicate that leg forces are generally higher in on-ergometer testing than in on-water testing. Future studies investigating on-water and on-ergometer kinematics and kinetics should, therefore, include a force-sensitive footrest to measure the leg forces.

The stroke cycle analysis demonstrated that the left footrest peak force was obtained at 0%, 102%, and 200%, and the right footrest peak force was obtained at 50% and 152% of the stroke cycle (see Figure 22). It is difficult to pinpoint the phase in the kayak technique to which this corresponds. Mann and Kearney [56] suggest that the kayak's peak horizontal acceleration occurs when the paddle is in a vertical position, meaning that the leg pushing force is maximal when the paddle is in a vertical position. This is supported by Plangenhoef et al. [55] and Kendell and Sanders [98]. Both studies have found peak forces on the paddle when at a vertical position in the water.

4.3. VALIDATION AND RELIABILITY OF THE DEVELOPED SEAT DEVICE

The following section discusses the validity and reliability of the developed seat. Moreover, the findings are compared to other developed seat devices described in the literature.

The seat displayed a significant amount of hysteresis, revealing a 5% higher hysteresis than the seat developed in the study by Nilsson and Rosdahl [89] (see Table 1). The results of the test and retest of the seat presented a variation of 8.7% on average. This could be explained by a considerable amount of hysteresis, which is portrayed in Figure 21. The signal did not return to the same value. Nilsson and Rosdahl [89] observed a low test-retest difference in which their developed seat demonstrated a test-retest difference of up to 8% with a standard deviation of almost 16%. The developed seat only had one load cell attached to measure both push-and-pull forces in the seat. This was conducted with a pretension of the load cell. However, the tension of the involved springs may drift and lose tension over time. Additionally, small movements of the system may change the tension of the springs. This may cause the zero values to drift, causing an offset at the start of a new recording. The calibration of the seat in the present study was not influenced by the different loads placed on top of the seat (see Table 1). This indicates that the friction of the linear ball-bearing system was not sensitive to the load on top of the seat.

Another point of issue is the seat system's mass of 6.6 kg, which is an increase of 55% of the kayak’s total weight that will affect performance. This is prohibitively high to be utilized during racing. Therefore, the seat must be redesigned to reduce the weight of the system if the intention is to utilize it during racing. A future setup should contain a minimum of two load cells to measure force in each direction. This would allow for a setup without pretension springs. Additionally, a setup with a force plate below the seat could be developed to allow for the measurement of the moment on the seat, which could elucidate how the paddler's forces transfer through the seat. Furthermore, if the center of pressure could be calculated from the seat forces, then this could provide a measure for each paddler's specific kayak balance.

4.3.1. ON-WATER TEST OF SEAT DEVICE

The on-water test results demonstrate that the seat has a small peak in the backward direction every time there is a force peak in the footrest (see Figure 22) and a small peak in the forward direction every time the two footrests’ force lines cross. The backward peak could be explained by the cyclic leg movement that causes the pelvic girdle to rotate above the seat [98]. The leg causes the foot to pushes on the footrest, and consequently, the pelvic bone of the same side pushes the seat on that side. On the opposite side, the leg is pulling, and the pelvic bone applies force in the forward direction [89]. This cyclic leg movement creates backward forces on the seat due to the pelvis' backward motion.

The seat data is not included in any of the publications due to the current limitations of the design. Therefore, reviewers suggest removing the seat from the publications. The seat data is challenging to interpret, as the design presented unacceptable hysteresis values. Therefore, the absolute values cannot be trusted. Nevertheless, the seat's force data displayed an interesting pattern that seems to be connected to the leg force. Further investigation is, therefore, needed to clarify the role of the forces on the seat in kayak performance.

4.4. CHARACTERIZATION OF LEG FORCES

Study III is the first study to quantify leg forces on a large group of different paddlers (see Table 6). The leg force profile presents a resemblance in pattern to the leg force profile found in Nilsson and Rosdahl [59] and Begon et al. [66]. A sinus-like curve rises along the stroke cycle and drops, which makes logical sense according to the cyclic leg movement of paddlers (Study III).

The mean and peak leg forces are similar to the findings of Nilsson and Rosdahl [59]. However, there are subtle differences in absolute values, although there seems to be a greater difference between the peak leg forces in on-ergometer testing, as reported by Begon et al. [66]. The explanation for this could be the unstable environment of the on-water kayak, which simply means that more force is lost to balance demands. This may affect the force transferred from paddle to kayak, contrary to the ergometer's fixed nature in the sideways direction. Begon et al. [66] utilized an ergometer with a sliding footrest-seat complex, which should, in theory, mimic the kayak's moving action. Another explanation could be the difference between the utilized subjects. The subjects in Begon et al. [66] were, on average, eight years older than the subject in Study III. Furthermore, all subjects were senior paddlers in Begon et al.'s study [66]. It could be assumed that senior paddlers are stronger due to greater muscle mass and better kayak techniques (Study III).

4.5. LEG FORCES AND THEIR RELATIONSHIP TO VELOCITY

Study III finds a positive relationship between leg pushing forces and maximal velocity, which had previously been established on the water by Nilsson and Rosdahl [59]. The relationship had also been present on the ergometer [66]. This positive relationship can be related to the kayak technique in which the cyclic leg movement creates a push-and-pull action on the footrest, which includes and activates the trunk muscles in the kayak stroke [59]. This could explain the significant positive relationship between leg pushing forces and maximal velocity. Additionally, it has been established that leg and trunk actions are essential for elite sprint kayak performance [58]. The predictive model, which consists of leg force variables, only predicts 68% of the paddlers' velocity within 1 km/h. The residual 32% could be explained when pull forces are built into the predictive model. The seat forces could improve the predictive model as well as transfer force. However, the push forces on the footrest are applied in the forward direction. Concurrently, the pull forces on the footrest are applied in the opposite direction. As previously mentioned, the cyclic leg movement increases forward reach and allows additional muscle mass to be recruited in the stroke. These technical benefits may compensate for the pull forces opposite of the moving direction (Study III).

Study (III) did not explore leg pull, seat, or paddle forces. Therefore, the study could not investigate and fully understand the kinetics of the paddler within the kayak. Consequently, it is crucial to understand that the leg force profiles viewed in Study

(III) only display a part of the total kinetic forces that the paddler applies on the kayak. Future studies should include leg push and pull, seat, and paddle forces to provide a detailed picture of the on-water kinetics and clarify how forces are transferred from paddler to kayak.

4.6. GENERAL CONCLUSIONS

This PhD thesis has successfully investigated kinematics and kinetics in on-water sprint kayaking. The thesis provides the first kinematic comparison of on-water and on-ergometer kayaking. Study I is the first to utilize the state-of-the-art inertial sensor technologies to perform on-water motion analysis. Furthermore, the thesis is the first to provide on-water leg force data from a team of elite kayakers. These findings contribute to the kayak community and the scientific field of kayaking.

Study I demonstrates that on-water and on-ergometer kayaking differ in elbow, shoulder, knee, and spinal joint kinematics. Furthermore, a significantly higher stroke rate during a 2-min all-out effort was observed in on-ergometer than in on-water testing. The findings illustrate that although the movement patterns are alike, paddlers should be aware of the significant kinematic differences (Study I).

Study II developed, designed, and tested a device that measures forces applied to the footrest during on-water kayaking. It proves that it is possible to measure forces acting on the footrest within functional limits during kayaking on the water (Study II).

The present thesis provides the first on-water seat force data. However, the seat must be redesigned due to its high mass and unacceptable hysteresis values if it is to be utilized further in research and testing. However, the seat force data displayed an interesting pattern that seems to be connected to the leg force.

Study III investigated leg forces and their relationship to velocity. The results reveal that sprint kayakers exhibit a positive relationship with leg forces and velocity. Furthermore, the current study results indicate the same pattern of leg forces observed on the paddle (Study III).

CHAPTER 5. PRACTICAL APPLICATIONS

The results from this thesis provide new insights into the scientific field of kayaking. Paddlers should be aware of potential unwanted kayak technical transfer from the ergometer to the water that could deteriorate their performance on-water. However, the athletes should consider the ergometer as a highly valuable training tool during the off-season, when the weather can be cold and bad. It is an excellent tool for training specific physiological adaptations. Furthermore, when the water is cold, it can be challenging to obtain high velocities and stroke rates on the water. The ergometer can provide high-velocity training during the winter months.

The results of Study I can be utilized by manufacturers to improve kayaks' current ergometer design by rethinking the elastic cord system, which may contribute to a difference in joint kinematics.

The measured leg force could be utilized either as an intensity monitor or an efficiency monitor coupled with velocity. This could provide helpful knowledge for the paddlers, as the current velocity measurements are from a GPS unit, which is vulnerable to wind and current. Therefore, the velocity does not reflect the actual intensity. Training tools that combine GPS velocity and leg forces may better reflect the intensity than the two variables individually. Study III finds that impulses over 10 s are considerably correlated with velocity. A moving average of leg impulses could be utilized in the training tool. However, the impulses can be difficult for a paddler or coach to understand. Therefore, dissemination of the term *impulse* is of great importance if it is to be utilized.

The devices developed for this study could be utilized in the selection and training of crew boats if a successful measurement of seat forces can be achieved. Reliable seat force measurements would help crew selection by reflecting how each paddler sits in the kayak. Currently, no objective measures exist regarding how paddlers sit in crew boats. Paddlers may say that they are sitting poorly, but this can be difficult for coaches to manage, as they may be unable to see the issue. Objective seat measures could resolve this problem both for paddlers and coaches.

Another interesting topic is the leg timing within the crew boats. Paddlers often refer to the timing between the cyclic leg movements within the kayak. The currently developed footrest could be utilized to monitor the timing. Crew boat training is challenging for coaches. Therefore, force measurements inside the kayak would help them in training crew boats.

Furthermore, paddlers with similar leg force profiles may fit better together. It is currently unknown how leg force relates to performance in crew boats. An investigation of leg forces in crew boats could illuminate a relatively untouched area in the literature, as few studies have investigated crew boats in sprint kayaking.

The footrest and seat forces presented in this thesis may be a starting point for future studies on quantification and understanding of the forces within the kayak. This thesis does not explore leg pull forces and paddle forces, and these should be investigated to understand the complete kinetics of the paddler within the kayak. A future study could seek to elucidate the full force chain of transfer, from paddle to footrest and seat, and be utilized to establish an efficiency index. Furthermore, the current system could be redesigned for usage in other water sports, such as rowing.

CHAPTER 6. THESIS AT A GLANCE

Title of study	Primary aim	Method	Main findings
Study I			
A kinematic comparison of on-ergometer and on-water kayaking	Study I compares the kinematic profiles of high-level athletes while they perform maximal on-ergometer and on-water kayaking, utilizing their personal competition equipment on the water.	Kinematic recordings during on-water and on-ergometer kayaking	Elite female kayak athletes exhibit differences in elbow, shoulder, and knee kinematics when comparing on-ergometer to on-water performance. Moreover, the results demonstrate a higher stroke rate during on-ergometer than on-water kayaking.
Study II			
A new device for measuring forces in the footrest during on-water kayaking	This study aims to design, develop, and test a device that can measure forces applied to the footrest during on-water kayaking that does not hinder the kayak athletes' performance.	Development of a force-sensitive footrest for on-water kayaking	It is possible to measure forces acting on the footrest within functional limits during on-water kayaking.
Seat device			
A new device for measuring forces on the seat during on-water kayaking	This study aims to design, develop, and test a device that can measure forces applied to the seat during on-water kayaking that does not hinder the kayak athletes' performance.	Development of a force-sensitive seat for on-water kayaking	The seat design is excessively heavy and displays unacceptable values of hysteresis. However, the forces in the seat reveal a clear relationship with the leg pushing forces.
Study III			
Characterization of leg forces and their relationship to velocity in on-water sprint kayaking	Study III aims to describe leg pushing force characteristics in sprint kayak paddlers and investigate the relationship between leg pushing force characteristics and velocity.	Measurement of forces acting on the footrest during on-water kayaking and exploration of their relationship with velocity through mixed statistical models	Leg force emits a sinus-like pattern, which increases and decreases throughout the stroke cycle. Sprint kayak paddlers present a strong positive relationship between leg pushing forces and velocity.

REFERENCES

1. McKenzie D(C, Berglund B. Canoeing. Hoboken, New Jersey ;: International Canoe Federation; 2019.

2. Dennis Sturm. Wireless multi-sensor feedback systems for sports performance monitoring: Design and development. Stockholm; 2012.

3. McDonnell LK, Hume PA, Nolte V. A deterministic model based on evidence for the associations between kinematic variables and sprint kayak performance. Sports Biomechanics 2013;12(3):205-220.

4. Michael JS, Smith R, Rooney KB. Determinants of kayak paddling performance. Sports Biomechanics 2009 Jun 1,;8(2):167-179.

5. Robinson MG, Holt LE, Pelham TW. The technology of sprint racing canoe and kayak hull and paddle design. International Sports Journal 2002;6(2):68-85.

6. Sanders R, H., Kendal S, J. A description of Olympic flatwater kayak stroke technique. Aust J Sci Med Sport 1992;24(1):25-30.

7. McDonnell LK, Hume PA, Nolte V. An observational model for biomechanical assessment of sprint kayaking technique. Sports Biomechanics 2012;11(4):507-523.

8. Gomes Beatriz, Viriato Nuno. Analysis of the on-water paddling force profile of an elite kayaker. Biomechanics in Sports 2011(11):259:262.

9. Michael JS, Rooney KB, Smith R. The metabolic demands of kayaking: a review. Journal of sports science & medicine 2008 Mar 1,;7(1):1-7.

10. Akca F, Muniroglu S. Anthropometric-somatotype and strength profiles and on-water performance in Turkish elite kayakers. Int J Appl Sport Sci. 2008;20(1):22-34.

11. Bishop D. Physiological predictors of flat-water kayak performance in women. Eur J Appl Physiol 2000 May;82(1):91-97.

12. van Someren KA, Howatson G. Prediction of flatwater kayaking performance. International journal of sports physiology and performance 2008;3(2):207-218.

13. Ackland TR, Ong KB, Kerr DA, Ridge B. Morphological characteristics of Olympic sprint canoe and kayak paddlers. Journal of Science and Medicine in Sport 2003;6(3):285-294.

14. Jackson PS. Performance prediction for Olympic kayaks. Journal of Sports Sciences 1995 Jun 1,;13(3):239-245.

15. Fry RW, Morton AR. Physiological and kinanthropometric attributes of elite flatwater kayakists. Medicine and science in sports and exercise 1991 Nov;23(11):1297-1301.

16. Someren KV, Palmer GS. Prediction of 200-m sprint kayaking performance. Canadian journal of applied physiology 2003 Aug 1,;28(4):505-517.

17. Tesch PA, Lindeberg S. Blood lactate accumulation during arm exercise in world class kayak paddlers and strength trained athletes. European journal of applied physiology and occupational physiology 1984;52(4):441-445.

18. Lutoslawska G, Sendecki W. Plasma biochemical variables in response to 42-km kayak and canoe races. Journal of sports medicine and physical fitness 1990 Dec;30(4):406.

19. Bunc V, Heller J. Ventilatory threshold and work efficiency during exercise on cycle and paddling ergometers in young female kayakists. European journal of applied physiology and occupational physiology 1994;68(1):25-29.

20. Paquette M, Bieuzen F, Billaut F. Muscle oxygenation rather than VO2 max as a strong predictor of performance in sprint canoe-kayak. International journal of sports physiology and performance 2018 Nov 19,:1.

21. van Someren KA, Phillips GRW, Palmer GS. Comparison of physiological responses to open water kayaking and kayak ergometry. Int J Sports Med 2000;21(3):200-204.

22. Byrnes WC, Kearney JT. Aerobic and anaerobic contributions during simulated canoe/kayak sprint events 1256. Medicine and science in sports and exercise 1997 May;29(Supplement):220.

23. Michael JS, Smith R, Rooney K. Physiological responses to kayaking with a swivel seat. Int J Sports Med 2010;31(8):555-560.

24. Andersen LL, Aagaard P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. Eur J Appl Physiol 2005 Oct 26,;96(1):46-52.

25. Bell GJ, Petersen SR, Quinney HA, Wenger HA. The effect of velocity-specific strength training on peak torque and anaerobic rowing power. Journal of sports sciences 1989 Dec 1,;7(3):205-214.

26. Jensen RL, Freedson PS, Hamill J. The prediction of power and efficiency during near-maximal rowing. European journal of applied physiology and occupational physiology 1996;73(1-2):98-104.

27. Stone MH, Sanborn K, O'Bryant HS, Hartman M, Stone ME, Proulx C, et al. Maximum strength-power-performance relationships in collegiate throwers. Journal of strength and conditioning research 2003 Nov;17(4):739-745.

28. Birch K, Sinnerton S, Reilly T, Less A. The relation between isometric lifting strength and muscular fitness measures. Ergonomics 1994 Jan 1,;37(1):87-93.

29. Pääsuke M, Ereline J, Gapeyeva H. Knee extension strength and vertical jumping performance in nordic combined athletes. Journal of sports medicine and physical fitness 2001 Sep;41(3):354-361.

30. Meckel Y, Atterbom H, Grodjinovsky A, Ben-Sira D, Rotstein A. Physiological characteristics of female 100 metre sprinters of different performance levels. Journal of sports medicine and physical fitness 1995 Sep;35(3):169-175.

31. Isorna Manuel. Training sprint canoe. 2nd ed. Spain: Real Federación Española de Piragüismo; 2015.

32. Schmidtbleicher D. Training for power events. The Encyclopeadia of Sports Medicine 1992;Vol 3: Strength and Power in sport:169-179.

33. Palmer GS, Someren KV. Prediction of 200-m sprint kayaking performance. Canadian Journal of Applied Physiology 2003 Aug 1,;28(4):505-517.

34. McKean M, Burkett BJ. The relationship between joint range of motion, muscular strength, and race time for sub-elite flat water kayakers. 2010.

35. Ualí I, Herrero A, Garatachea N, Marín P, Alvear-Ordenes I, García-López D. Maximal strength on different resistance training rowing exercises predicts start phase performance in elite kayakers. Journal of strength and conditioning research 2012 Apr;26(4):941-946.

36. Pickett C, Nosaka K, Zois J, Hopkins W, J A, Blazevich. Maximal upper body strength and oxygen uptake are associated with performance in high-level 200-m sprint kayakers. Journal of Strength and Conditioning Research 2017 Dec 27,;32(11):3186-3192.

37. Pickett C, Nosaka K, Zois J, Blazevich A. Relationships between midthigh pull force development and 200-m race performance in highly trained kayakers. Journal of strength and conditioning research 2019 Jun 19,;Publish Ahead of Print.

38. Stigler SM. Correlation and Causation: A Comment. Perspectives in biology and medicine 2005;48(1):88-S94.

39. Gomes BB, Machado L, Ramos NV, Conceição FAV, Sanders RH, Vaz MAP, et al. Effect of wetted surface area on friction, pressure, wave and total drag of a kayak. Sports Biomechanics 2018 Oct 2,;17(4):453-461.

40. Zamparo P, Gatta G, Pendergast D, Capelli C. Active and passive drag: the role of trunk incline. Eur J Appl Physiol 2009 May;106(2):195-205.

41. Gomes BB, Gomes BB, Conceição FAV, Conceição FAV, Pendergast DR, Sanders RH, et al. Is passive drag dependent on the interaction of kayak design and paddler weight in flat-water kayaking? Sports Biomechanics 2015 Oct 2,;14(4):394-403.

42. Mantha VR, Silva AJ, Marinho DA, Rouboa AI. Numerical simulation of two-phase flow around flatwater competition kayak design-evolution models. Journal of applied biomechanics 2013 Jun;29(3):270-278.

43. Pendergast DR. Cardiovascular, respiratory, and metabolic responses to upper body exercise. Medicine and science in sports and exercise 1989 Oct;21(5 Suppl):S121.

44. Pendergast DR, Bushnell D, Wilson DW, Cerretelli P. Energetics of kayaking. European journal of applied physiology and occupational physiology 1989;59(5):342-350.

45. Gray GL, Matheson GO, McKenzie DC. The metabolic cost of two kayaking techniques. International Journal of Sports Medicine 1995;16(4):250-254.

46. Millward A. A study of the forces exerted by an oarsman and the effect on boat speed. Journal of sports sciences 1987;5(2):93-103.

47. Zamparo P, Gatta G, Pendergast D, Capelli C. Active and passive drag: the role of trunk incline. Eur J Appl Physiol 2009;106(2):195-205.

48. Zhang K, Deakin R, Grenfell R, Li Y, Zhang J, Cameron WN, et al. GNSS for sports ? sailing and rowing perspectives. Journal of Global Positioning Systems 2004 Dec 31,;3(1&2):280-289.

49. Robinson GM, Pelham WT, Furneaux K. Accelerometry measurements of sprint kayaks: The coaches' new tool. International Journal of Coaching Science 2011 January;5(1).

50. Smith RM, Loschner C. Biomechanics feedback for rowing. Journal of sports sciences 2002;20(10):783-791.

51. Intra-stroke boat orientation during single sculling. 18 International Symposium on Biomechanics in Sports: Hong, Y., Johns, DP, and Sanders, R; 2000.

52. Wagner J, Bartmus U, Marées Hd. Three-axes gyro system quantifying the specific balance of rowing. International Journal of Sports Medicine 1993 Sep;14(S 1):S35-S38.

53. Pickett CW, Abbiss C, Zois J, Blazevich AJ. Pacing and stroke kinematics in 200-m kayak racing. Journal of sports sciences 2020 December 15,;ahead-of-print(ahead-of-print):1-9.

54. Goreham JA, Landry SC, Kozey JW, Smith B, Ladouceur M. Using principal component analysis to investigate pacing strategies in elite international canoe kayak sprint races. Sports biomechanics 2020 August 26,;ahead-of-print(ahead-of-print):1-16.

55. Plagenhoef S. Biomechanical analysis of olympic flatwater kayaking and canoeing. Research Quarterly. American Alliance for Health, Physical Education, Recreation and Dance 1979 Oct 1,;50(3):443-459.

56. Mann RV, Kearney JT. A biomechanical analysis of the Olympic-style flatwater kayak stroke. Medicine and science in sports and exercise 1980;12(3):183-188.

57. Baker J, Rath D, Sanders R, Kelly B. A three-dimensional analysis of male and female elite sprint kayak paddlers. ; 1999.

58. Brown BM, Lauder M, Dyson R. Notational analysis of sprint kayaking: Differentiating between ability levels. International Journal of Performance Analysis in Sport 2011 Apr 1,;11(1):171-183.

59. Nilsson JE, 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 2016:22-27.

60. Logan SM, Holt LE. The flatwater kayak stroke. National Strength & Conditioning Association Journal 1985;7(5):4-9.

61. Trevithick BA, Ginn KA, Halaki M, Balnave R. Shoulder muscle recruitment patterns during a kayak stroke performed on a paddling ergometer. Journal of Electromyography and Kinesiology 2007;17(1):74-79.

62. Fleming N, Donne B, Fletcher D. Effect of kayak ergometer elastic tension on upper limb EMG activity and 3D kinematics. Journal of sports science & medicine 2012 "B";11(3):430-437.

63. Fleming N, Donne B, Fletcher D, Mahony N. A biomechanical assessment of ergometer task specificity in elite flatwater kayakers. Journal of sports science & medicine 2012 B;11(1):16-25.

64. Tornberg ÅB, Håkansson P, Svensson I, Wollmer P. Forces applied at the footrest during ergometer kayaking among female athletes at different

competing levels - a pilot study. BMC sports science, medicine & rehabilitation 2019;11(1):1-6.

65. Begon M, Begon M, Colloud F, Colloud F, Lacouture P, Lacouture P. Measurement of contact forces on a kayak ergometer with a sliding footrest–seat complex. Sports Eng 2009 Feb;11(2):67-73.

66. Begon M, Colloud F, Sardain P. Lower limb contribution in kayak performance: modelling, simulation and analysis. Multibody Syst Dyn 2010 Apr;23(4):387-400.

67. Michael JS, Rooney KB, Smith RM. The dynamics of elite paddling on a kayak simulator. Journal of sports sciences 2012 Apr 1,;30(7):661-668.

68. Brown M., Lauder M., Dyson R. Activation and contribution of trunk and leg musculature to force production during on-water sprint kayak performance . Paper presented at the proceedings of the XXVIII International Conference on Biomechanics in Sports 2010:22-27.

69. Fong D, Chan Y. The use of wearable inertial motion sensors in human lower limb biomechanics studies: A systematic review. Sensors (Basel, Switzerland) 2010 Dec 16,;10(12):11556-11565.

70. Svenningsen FP, de Zee M, Oliveira AS. The effect of shoe and floor characteristics on walking kinematics. Human Movement Science 2019 Aug;66:63-72.

71. Blair S, Duthie G, Robertson S, Hopkins W, Ball K. Concurrent validation of an inertial measurement system to quantify kicking biomechanics in four football codes. Journal of Biomechanics 2018 May 17,;73:24-32.

72. Carson HJ, Collins D, Richards J. "To hit, or not to hit?" Examining the similarity between practice and real swings in golf. International journal of golf science 2014 Dec;3(2):103-118.

73. Fleron MK, Ubbesen NCH, Battistella F, Dejtiar DL, Oliveira AS. Accuracy between optical and inertial motion capture systems for assessing trunk speed during preferred gait and transition periods. Sports biomechanics 2019 Jul 4,;18(4):366-377.

74. Hamacher D, Krebs T, Meyer G, Zech A. Does local dynamic stability of kayak paddling technique affect the sports performance? A pilot study. European journal of sport science 2018;18(4):491-496.

75. Lee Y, Ho C, Shih Y, Chang S, Róbert FJ, Shiang T. Assessment of walking, running, and jumping movement features by using the inertial measurement unit. Gait & Posture 2015;41(4):877-881.

76. Li Q, Zhang J. Post-trial anatomical frame alignment procedure for comparison of 3D joint angle measurement from magnetic/inertial measurement units and camera-based systems. Physiological measurement 2014 Nov;35(11):2255-2268.

77. Magalhaes FAD, Vannozzi G, Gatta G, Fantozzi S. Wearable inertial sensors in swimming motion analysis: a systematic review. J Sports Sci 2014;33(7):1-14.

78. Saber-Sheikh K, Bryant EC, Glazzard C, Hamel A, Lee RYW. Feasibility of using inertial sensors to assess human movement. Man Ther 2010;15(1):122-125.

79. Schepers M, Giuberti M, Bellusci G. Xsens MVN: Consistent tracking of human motion using inertial sensing. 2018.

80. Michael JS, Rooney KB, Smith RM. The dynamics of elite paddling on a kayak simulator. J Sports Sci 2012;30(7):661-668.

81. Aitken DA, Neal RJ. An on-water analysis system for quantifying stroke force characteristics during kayak events. International journal of sport biomechanics 1992 May;8(2):165-173.

82. Biomechanical testing in elite canoeing. Extremadura Spain: In JE Gianikellis (Ed.); 2002.

83. Gomes BB, Ramos NV, Conceição F AV, Sanders RH, Vaz MA, Vilas-Boas JP. Paddling force profiles at different stroke rates in elite sprint kayaking. Journal of applied biomechanics 2015 Aug;31(4):258-263.

84. Gomes BB, Ramos NV, Conceição F, Sanders R, Vaz M, Vilas-Boas JP. Paddling time parameters and paddling efficiency with the increase in stroke rate in kayaking. Sports biomechanics 2020 July 29,;ahead-of-print(ahead-of-print):1-9.

85. Niu L, Kong PW, Tay CS, Lin Y, Wu B, Ding Z, et al. Evaluating on-water kayak paddling performance using optical fiber technology. JSEN 2019;19(24):11918-11925.

86. Kong PW, Tay CS, Pan JW. Application of Instrumented Paddles in Measuring On-Water Kinetics of Front and Back Paddlers in K2 Sprint Kayaking Crews of Various Ability Levels. Sensors (Basel, Switzerland) 2020 Nov 5,;20(21):6317.

87. Bifaretti S, Bonaiuto V, Federici L, Gabrieli M, Lanotte N. E-kayak: A Wireless DAQ System for Real Time Performance Analysis. Procedia engineering 2016;147:776-780.

88. Bjerkefors A, Tarassova O, Rosén JS, Zakaria P, Arndt A. Three-dimensional kinematic analysis and power output of elite flat- water kayakers. Sports Biomechanics 2017:1-14.

89. Nilsson JE, Rosdahl HG. New devices for measuring forces on the kayak foot bar and on the seat during flat-water kayak paddling: A technical report. International journal of sports physiology and performance 2014 Mar;9(2):365-370.

90. Ong K, Elliott B, Ackland T, Lyttle A. Performance tolerance and boat set-up in elite sprint Kayaking. Sports Biomechanics 2006 Jan 1,;5(1):77-94.

91. Aston WJ. Product design and development. Biosens Bioelectron 1992;7(2):85-89.

92. Cole RE. From continuous improvement to continuous innovation. Total quality management 2002 Dec 1,;13(8):1051-1056.

93. Pataky TC. One-dimensional statistical parametric mapping in Python. Computer Methods in Biomechanics and Biomedical Engineering 2012 Mar 1,;15(3):295-301.

94. Simonsen MB, Yurtsever A, Næsborg-Andersen K, Leutscher PDC, Hørslev-Petersen K, Andersen MS, et al. Tibialis posterior muscle pain effects on hip, knee and ankle gait mechanics. Human movement science 2019;66:98-108.

95. Fleron MK, Ubbesen NCH, Battistella F, Dejtiar DL, Oliveira AS. Accuracy between optical and inertial motion capture systems for assessing trunk speed during preferred gait and transition periods. Sports Biomechanics 2018:1-12.

96. De Ridder R, Willems T, Vanrenterghem J, Robinson M, Roosen P. Lower limb landing biomechanics in subjects with chronic ankle instability. Medicine and science in sports and exercise 2015 Jun;47(6):1225-1231.

97. Zhang J, Novak AC, Brouwer B, Li Q. Concurrent validation of xsens mvn measurement of lower limb joint angular kinematics. Concurrent validation of Xsens MVN measurement of lower limb joint angular kinematics 2013;34(8):63-69.

98. Kendal SJ, Sanders RH. The technique of elite flatwater kayak paddlers using the wing paddle. International Journal of Sport Biomechanics 1992 Aug;8(3):233-250.

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