Development of a device for measuring force and timing in a K2 kayak during flatwater paddling

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Abstract

The aim of the study was to develop a device which could measure leg kicking forces and timing between paddlers in a flatwater sprint K2 kayak. The two footrests of a K2 were each fitted with two load cells mounted on an aluminum plate which was attached to each footrest. A Shimmer3 bridge amplifier was used as an analog amplifier and as a data acquisition system. Three pilot tests with different set-ups were conducted with two national elite male paddlers. The devices were calibrated by loading each footrest with a series of weights placed on the middle of the footrest. Further, the footrest measuring devices were tested for validity by placing a fixed load on different points of the footrest. A strong linearity of both footrests measuring devices was found (r2 = 0.99948 and 0.99684) when force was applied on the middle of the footrest. However, the validity test showed that the force output had a large percentage of deviation from the fixed load dependent on the position of the load. Thus, the measured force might deviate from the actual force. The tests did, however, show that the footrest measuring devices were able to record data without drifting in time, thereby enabling analysis of timing. Wireless data was not obtained due to a short range of the Bluetooth connection. A training tool prototype which enables measurement of the timing in the leg kick both in K1 and crew boats (K2 and K4) has been developed based on the findings of the study.
Key Words: Biomechanics, Kayak foot-bar, Flaterwater kayak, Load Cells, Kayak Leg Kick

Introduction

Flatwater kayaking places high demands on the upper body and trunk musculature [Tesh, & Lindberg, 2011]. High peak forces in the paddle are produced in order to maintain the velocity in the kayak[Mononen et al., 1994], which calls for the high physiological demands of the upper body.

A wing paddle is used to propel the kayak forward. However, an efficient technique is vital to fully utilize the wing paddle. This technique involves a prominent use of the legs and rotation of the trunk. The athlete must push down with one foot on the footrest, in a knee extension, the contralateral leg pulls in the footbar in a knee flexion. This push/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 [Nilsson, Rosdahl, 2016].

The overall kayak technique can be divided into four phases: A catch, a drive, an exit, and a recovery phase. The catch starts when the tip of the blade touches the water. The catch is important for the rest of the stroke as it sets the conditions for the force production. If a bad set up of the paddle is achieved in the catch, the paddler will not be able to generate force to the full potential. The drive is the phase where the majority of the force is produced. The paddler pulls the paddle in a "j shaped movement" until it exits the water. The first part of the drive is achieved in a straight line.

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However, in the second part of the drive, the paddler rotates the trunk and thereby the blade away from the boat. The opposite arm fully extends in a pushing motion across the kayak. The exit is the finish of the stroke, the paddle is pulled out of the water. During this phase, the pulling hand of the paddler must not be further forward than the hip seen from a horizontal point of view. Therefore, the rotation of the trunk during the stroke is a crucial element, as it prolongs the time that the pulling hand is behind the hip. The recovery is where the blade exits the water, and up until the opposite blade is in the water. The paddler tries to utilize the time by preparing for a new stroke, keeping the trunk rotated and getting the optimal set-up for the catch [Logan, & Holt, 1985; Sturm et al., 2010; McDonnell et al., 2012].

A study by Brown et al. [2010] investigated the activation of the major muscles in the legs during a stroke cycle on eight international level paddlers (six men and two women). Findings of the study showed a clear activation of the major muscle groups in the trunk and legs during the stroke cycle. It is suggested in the study that the lower limbs provide a stable base for force production. Lee, Nam [2012] fond that the legs contribute with 6% of the total force production. Another study related the angle of the knees to how efficient the stroke cycle was [Begon et al., 2010]. Nilsson, Rosdahl [2014] investigated the contribution of leg muscles generation of force during maximal effort. The study found a drop in maximal speed of 16 % if the legs were restricted, compared to unrestricted. This underlines that the leg kick is an important part of the kayak stroke. The study used a set-up from [Nilsson, Rosdahl, 2014] where force transducers were mounted in the footrest and seat of a K1.

In conclusion to the above studies, the assistant head coach of the Danish national kayak team Finn Pape has said:

"Using the legs is an important part of the crew boat technique, as the leg kicking contributes to the rhythm of the K2 and helps to make the kayak stable in the water. As not to say it's importance for the individual technique."

No study to the author's knowledge has investigated paddling kinematics in crew boats in sprint kayak. However, it is known from technique analyses that the leg kick enables a further rotation of the trunk and that the legs provide a stable base for force production. One must presume that these findings also are evident in crew boats.

It is commonly known in the kayak community that when paddling crew boats the paddlers must paddle in sync, as this provides a more stable kayak, thereby, obtaining a higher velocity. A study by [Wing, & Woodburn, 1995] has investigated timing in rowing and found a positive correlation between timing of strokes and velocity. It could be presumed that the same correlation is evident in K2 and K4 in flatwater kayaking. The initiation of a leg kick marks the beginning of a new stroke [Logan, & Holt, 1985]. Therefore, one would assume that the timing between paddlers' leg kick is essential for the kayaks performance. Finn Pape underlines the importance of the leg kick in the previous statement.

A study by [Sturm et al., 2010] states that *"A coach outside the laboratory has very little data to use in order to assess the athlete's performance."* Therefore, tools that can assist the coach on the water could improve training and act as motivation for the athlete and coach.

With respect to previous studies and the lack of training tools in flatwater sprint kayak, the aim of this study was to develop a training tool that was able to live record and quantify the forces produced by the major muscles in the legs during a stroke cycle in a K2 during maximal effort. Further, the timing of the leg kicking between the front paddler and the rearmost paddler was investigated.

Methods

Considerations of the design

The development of the footrest measuring device is inspired by a need described by the assistant coach of the Danish national sprint kayak team. Therefore, the set up must be user-friendly, in order to be used on a daily basis by the national Danish kayak sprint team.

In the product design of this study, a feedback loop was used to guide the design, meaning that when developing a prototype, users are in direct involvement of the development. Thus, every phase of the design was developed with the end-user in mind, and every step was discussed with the assistant coach of the national team, active elite paddlers, and Team Danmark's experts.

A list of requirements for the design was listed based on the current literature, regarding leg kick in flat water kayak.

1. Measure forces in the footrest in range 0-600 newton. As the results of Nilsson, Rosdahl [2016] showed forces of 500 newtons.

2. Determine timing between forces in the front footrest and the rearmost footrest, in up to 180 strokes per minute.

3. The system must not inhibit the paddlers in their technique. The footrest must not hinder the paddler's leg kick.

4. A K2 must weigh at least 18 kg in competitions. However, paddlers seek to have a kayak that weighs around the limit, therefore is must be a relatively lightweight system. A K2 will often from the manufacturer weigh 1.5 - 2 kg below the limit.

5. Live stream the data to a PC or tablet and thereby enabling live performance feedback for the coach.

Design of footrest measuring device

The final footrest measuring device can be seen on figure 2(c.d.e.f). A complete set of Nelo k2 footrests was used to make the footrest measuring device. Each footrest was fitted with two load cells (YZC-908). An aluminum plate was added to the footrest, and the two load cells were placed in sockets on the aluminum. The wooden plate from the original footrest was placed over the aluminum plate. Metal disks were added to the backside of the wooden plate, thereby avoiding abrasion on the wood when the load cells were in contact with the wood. Hard rubber spacers were placed between the aluminum plate and the wooden plate in order to avoid movement and tilting of the wooden plate of the footrest. The two footrests were equally distorted, as the distance between the plates was measured with a vernier caliper. Further, the footrest had an equal distance all the way around the plate. Figure 2.a shows the two final aluminum plates with sockets for the load cells.

A custom-built data acquisition system was made to fit behind the footrest. The two load cells mounted on the footrest was connected to the custom-built data-acquisition system. This system was a Wheatstone bridge soldered to a circuit board, where a Shimmer3 bridge amplifier collected the data. The bridge consisted of 2 x 61.9 Ω resistors, 2 x 1017 Ω resistors and 2 x Potentiometers. The bridge was connected to a four pole jack plug.

The Shimmer3 Bridge Amplifier(Shimmer3, Shimmer, Dublin, Ireland) was used as an analog amplifier of the bridge voltage outputs and as a data acquisition system with a sample rate of 1014 Hz. Consensys Pro v1.1(Shimmer, Dublin, Ireland) was used to set-up the shimmers. When writing data to the SD card under tests, Consensys Pro v1.1 was used to import and export data to MATLAB. A Bluetooth connection from the Shimmer3 to a computer was established, when collection real-time data a. A MATLAB app (MATLAB 2016a MathWorks Inc, Massachusetts, USA) was made in order to collect and analyze data in real time.

A box was 3D printed in order to mount and protect the circuit board. The box had the outer measures: Length 108 mm, width 42 mm, height 37 mm and a wall thickness of 4 mm. The lid had the same bottom measures and was printed with an edge, which helped to seal the box. The box can be seen on figure 2.g and 2.h. The box was designed in SolidWorks (DS SolidWorks Corp. Klarabergsviadukten 90 111 64Stockholm Sweden). And printed by an Ulitimaker 3 (Ultimaker B.V. Watermolenweg 2, 4191 PN Geldermalsen, The Netherlands) and was printed in "standard" quality. The box was attached to the footrest with double adhesive tape on the back of the footrest.

Calibration

A calibration of the two footrests was done as a validity assessment. The voltage output was amplified with the Shimmer3 Bridge Amplifier. A deadweight set-up was used. The footrests were in a horizontal position, with blocks as supporting points, approved precis weights of 5 kg, 10 kg, 15 kg, 20 kg, 25 kg, 30 kg and 50.1 kg were used. The weights were put on the middle of the footrests, with a small wooden block under the weights [Libii, 2006; Nilsson, Rosdahl, 2016].

The Shimmer3 was set to "write to SD card". Each step would last five seconds with 10 seconds in between where the footrest was unloaded. After the test, the data were imported to MATLAB with Consensys and plotted with the corresponding weights. A quadratic line was fitted to the front footrest, and a cubic to the rearmost footrest:

Front footrest:

y = - 6.3244*x^2 + 44.764*x - 12.52

Rearmost footrest:

y = 313.73*x^3 - 1209*x^2 + 1566.4*x - 652.83

The test was repeated in order to test for reliability. The data sets from the two tests were then tested for correlation with a linear regression model with the function "fitlm"in MATLAB. Further, an additionally validity test was made in order to test for right and left difference in the footrest measuring devices. 15 kg was placed 6 positions on the front footrest and 7 positions on the rearmost footrest. The force-application positions can be seen on figure 1.

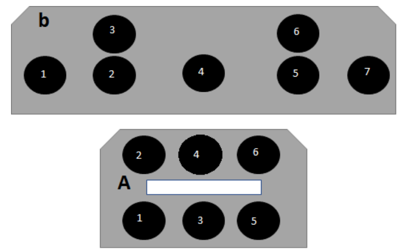

Figure 1: *The force-application positions on the footrest. A) being the front footrest and B) being the rearmost footrest. The black dots indicates force-application positions*

Test procedure

Two national elite male kayaking paddlers were recruited for the study. Both subjects had trained at least ten times a week for the past three years, competed at international level and were former national team paddlers.

The two footrest measuring devices were mounted in a Nelo Vanquish 2 K2. (Nelo- Vila DO Conde - Portugal). The two footrests were shaken in the shimmers x,y and z-direction before they were mounted in the kayak, creating a simultaneous artefact on the accelerometer signal. The same procedure was done after the test was completed. Thereby, the signal could be tested for drift.

The two participants did 15 minutes warm up, consisting of their regular competition warm-up. Then the actual test would begin, which was 3-5 bouts with a duration of 20-30 seconds. The intensity of the bouts would be 85 % of the maximal effort. Force data from the footrest and acceleration of kayak in vertical, lateral and longitude direction were recorded during these trails with a sampling frequency of 1024 Hz. The test was repeated three times, and the design was changed if necessary.

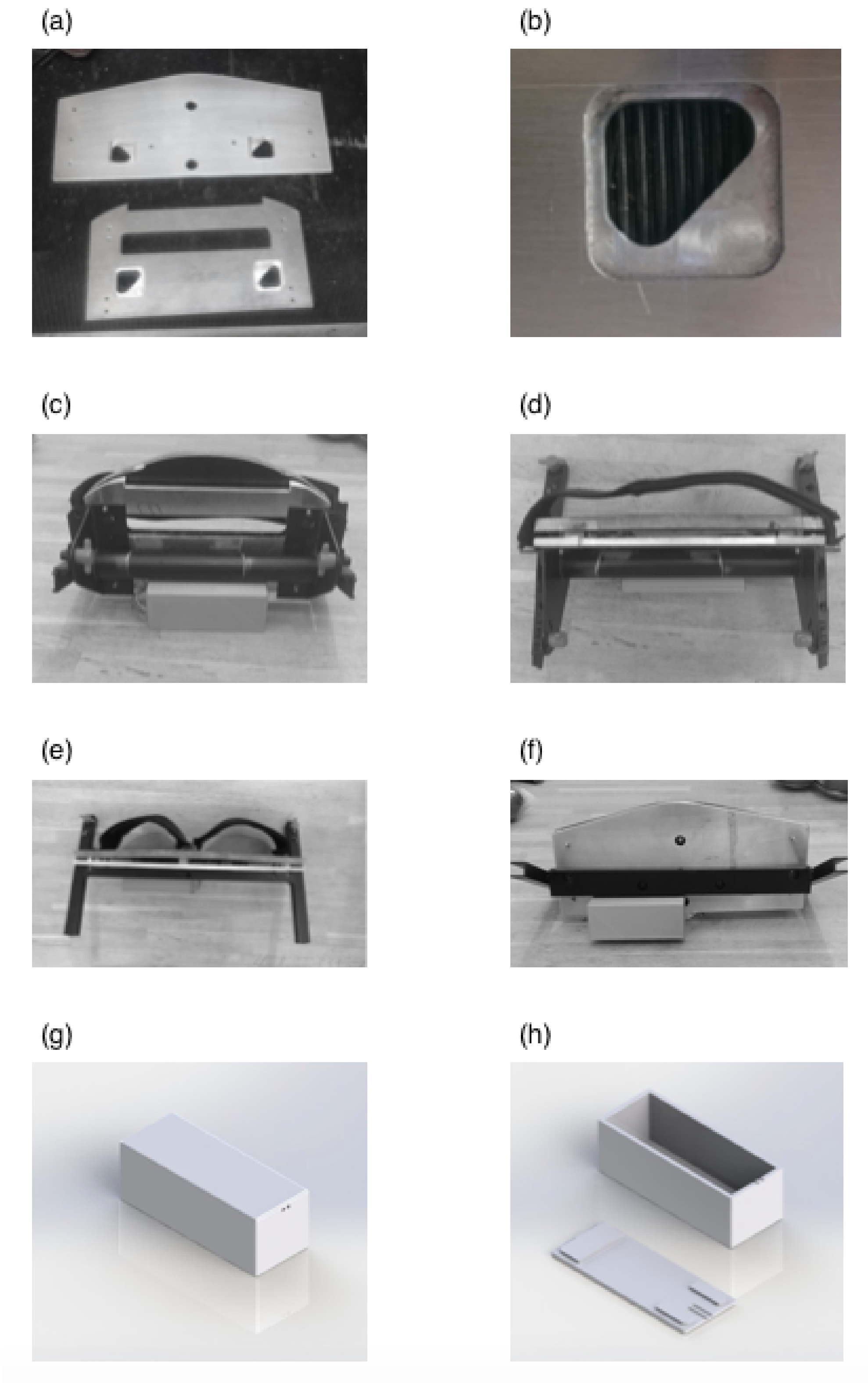

Figure 2: - *(a) Aluminum plates made for the footrests. (b) socket in the aluminum plate for load cell. (c) Back view of the front footrest. (d) Top view of the front footrest. (e) Top view of the rearmost footrest. (f) Back view of the rearmost footrest. (g and h) 3D printed box for circuit board.*

Data processing

All data from the footrest measuring devices were exported to MATLAB for further analysis (MATLAB 2017a MathWorks Inc, Massachusetts, USA). As previously elaborated, a best fit line for a load test for each footrest was found. Each line was inspected for the best fit line. Each equation was used to calculate force in the test performed on water. For the test performed on water, force data were plotted with the internal Shimmer time, which were synchronized with the computer time. Therefore, it allowed the data to be aligned, enabling synchronized data from both footrests measuring devices.

The voltage output of the validity tests was converted to kilograms with the equations described in the calibration. The percentage deviation of each pressure point compared to the actual weight (15 kg) was then calculated.

Results

Table 1 shows the percentage deviation of different force-application positions on the two footrests with 15 kg. Positive values mean that the specific point results in a lower output, and a negative value results in a higher output.

Pressure Points	1	2	3	4	5	6	7
Front footrest [%]	37.45	64.55	1.89	-9.33	55.17	40.04	-
Rearmost footrest[%]	- 55.37	14.49	2.52	3.11	-16.34	-5.42	-31.9

Table 1: *Shows the percentage deviation from 15 kg placed on different positions of the footrests. The pressure points can be seen on figure 1.*

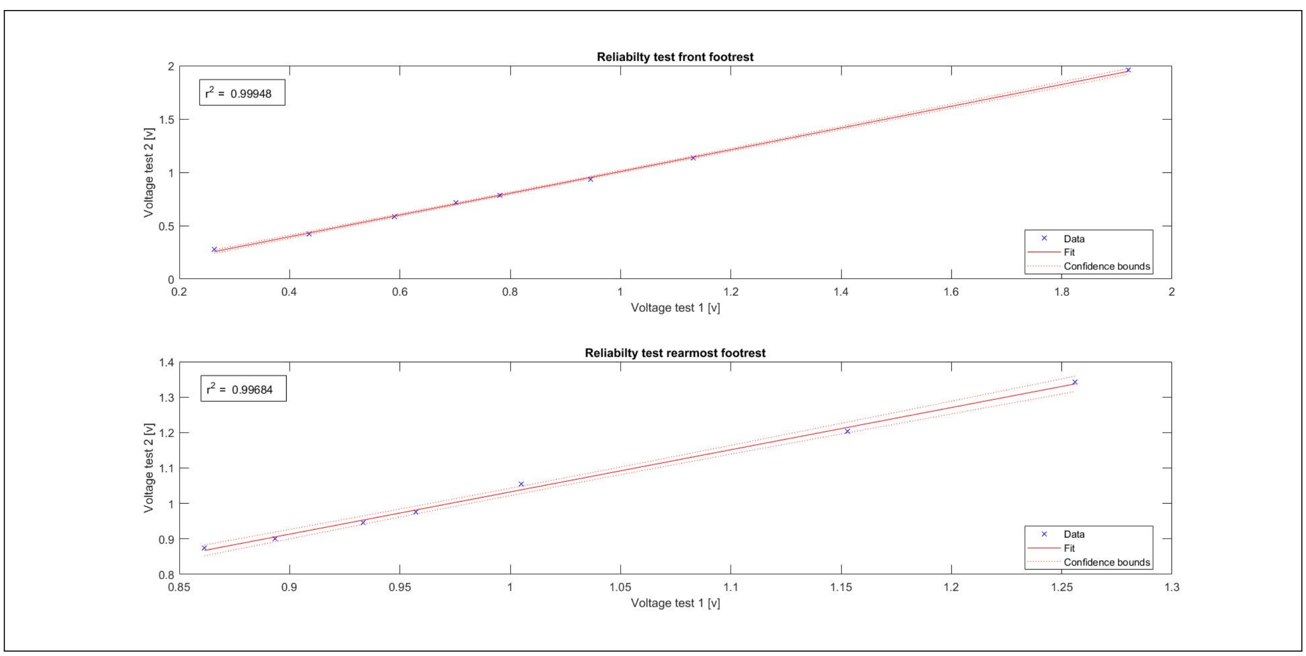

Figure 3: *Reliability test of the footrest measuring device which shows a clear linear correlation between two loading tests of the footrests.*

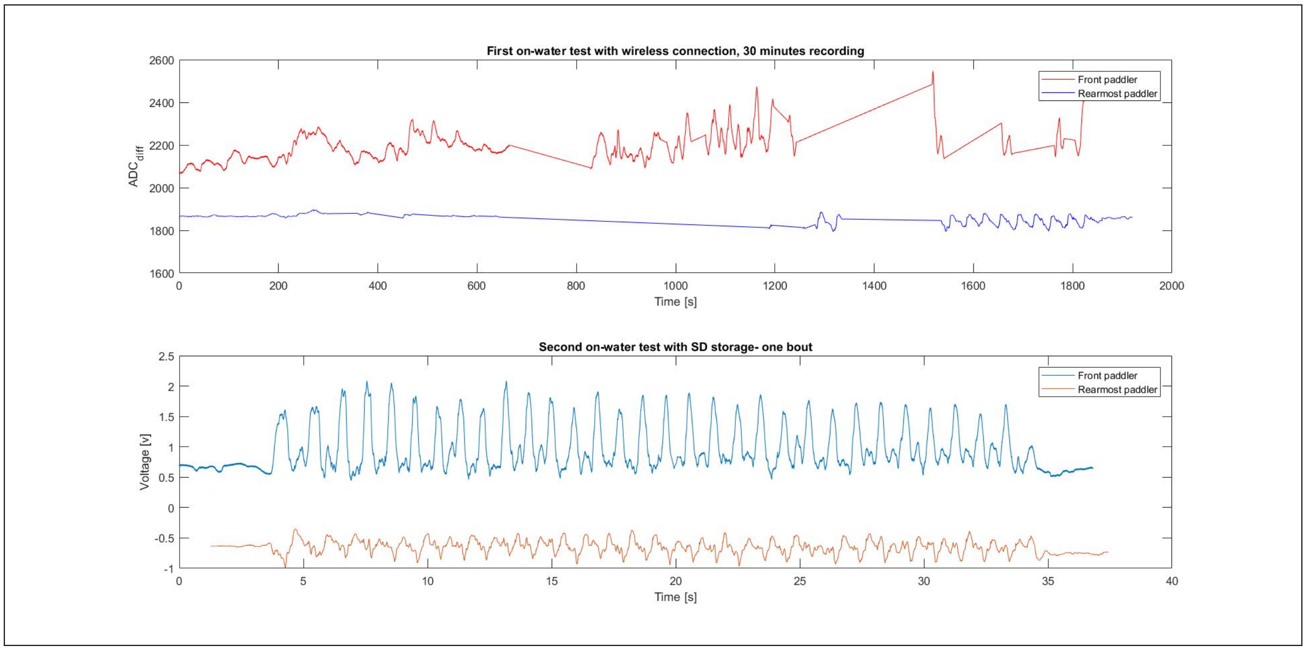

Figure 4: *Shows wireless data from the footrests in the first pilot test, and force data from the footrests in the third pilot test with storage to internal SD card.*

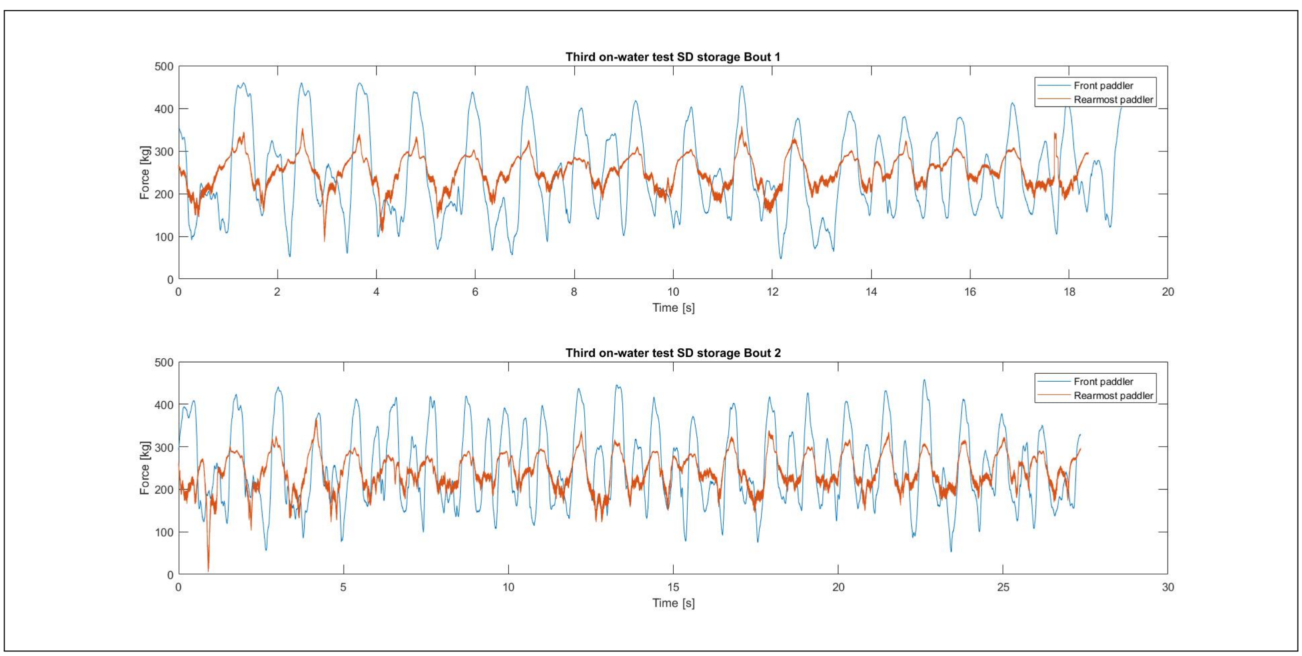

Figure 5: *Force data from the two footrests in the third pilot test with storage to a SD card. Two bouts are presented; bout one at the top, and bout 2 in the bottom.*

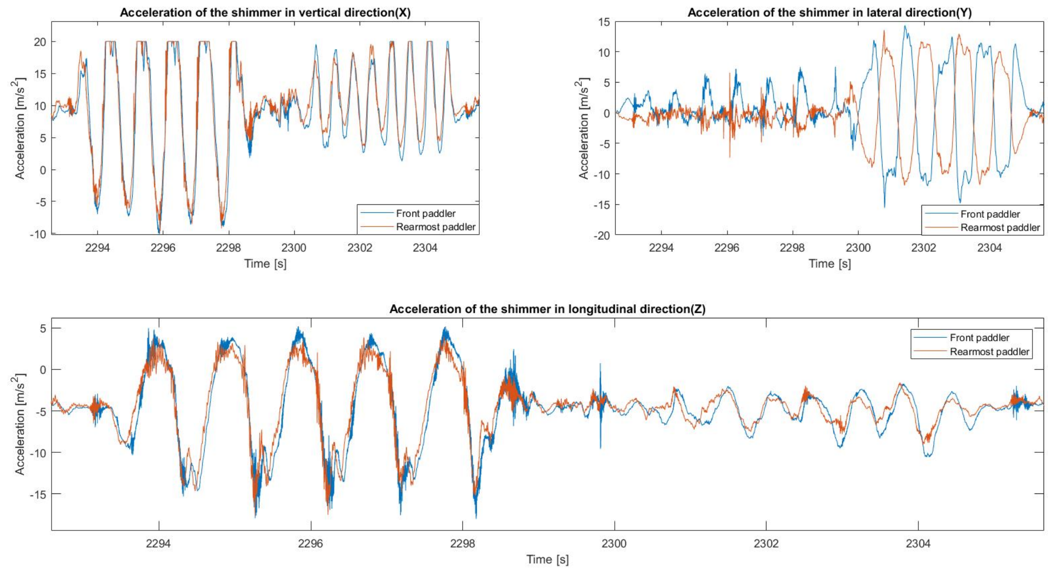

Figure 6: *Acceleration data of the shimmer in the vertical, lateral, and longitudinal direction. The data is from the second pilot test. Artefacts were made in the end of the test to test if the data had drifted.*

Figure 3 shows the reliability test of the footrest. There was a good correlation between two tests on two different days with a R squared value of 0.99948 and 0.99684 and a P value less than $p < 0.001$ and less than $p < 0.001$ The test was done with a loading range: 5 kg, 10 kg, 15 kg, 20 kg, 25 kg, 30 kg and 50.1 kg and placed on the middle of the footrests, point 3 (front footrest) and point 4 (rearmost footrest) as seen on figure 1.

Figure 4 shows data from the footrest measuring devices of the first pilot test which were wireless, and data from the footrest measuring devices of the second pilot test. It was not possible to calculate the force from the data as the calibration was done on the final design of the footrests. Therefore, the data from both tests are in ADC_{diff} for the wireless tests and voltage for the SD card tests as they are the raw outputs.

Figure 5 shows force data from the third pilot test. Two bouts are presented; one on 19 seconds and one on 29 seconds. The bouts were cut out from the original file by identifying the first and the last peak of the bout.

Figure 6 shows artefacts made in the end of the test after 2294 seconds of the second pilot test. The data showed that there was no displacement in time. Artefacts were made in the start and in the end of the recording. .

Discussion

Reliability of the footrest measuring device

Data were collected from eight loadings of both footrest devices with 5 kg, 10 kg, 15 kg, 20 kg, 25 kg, 30 kg and 50.1 kg. The loading was done twice on each footrest.

Figure 3 shows that there is a strong correlation between the two loading trails of the front footrest. Although it can only investigate the pushing force on the footrest, this makes the footrest measuring devices reliable enough to investigate the timing of leg kick in on-water kayaking. However, a comparison between forces in the leg kick is not yet possible. As the footrest is only reliable in repeated loadings on the middle of the footrest. An extensive reliability analysis must be done on the footrest measuring devices in order to know the reliability of the whole footrest. Figure 1 shows pressure points on the footrests. A reliability test must be done for all these points to know the total reliability for the footrests. The current reliability test is too simple to state anything about the forces of the leg kick.

Validity of footrest measuring device

A loading test was performed on each footrest measuring device on different force application positions with 15 kg. Table 1 shows the force values of different spots. The data show that the footrest measuring devices are not able to produce the same output when loaded on different points. This excludes the device for measuring the absolute force of the leg kick. A possible explanation for this could be the mechanical or electronic design of the footrest measuring device and must, therefore, be considered a design error. However, measure point 3 on the front footrest and point 4 on the rearmost footrest seem to have less percentage deviation than the other pressure point. This supports the findings of the reliability test, as these points were the same points which the reliability test was conducted on. The reliability test showed that the footrest measuring device is consistent when loaded on the same point.

The mechanical issue could possibly be the distortion of the footrests as applied force would make the wooden footrest tilt, and thereby pressuring the load cells differently. Regarding that, the placing of the load cells could have been wrong as they may have been placed too low. However, it raises another design issue. The footrest measuring device must be able to record different types of leg kicks. Some paddlers might have their feet high on the footrest, and some have their feet low on the plate. Further, the pulling motion of the contrary leg pull might unload the load cell if the distortion of the footrest has not been sufficient.

The electronic issue might be the layout of the Wheatstone bridge. It is currently configured as a half-bridge, and thereby only one force output comes from the bridge. If each load cell had their own bridge, it would be possible to see how much each loading cell was loaded. A series of equations could then be lined up, one equation for each specific loading point. The equations could be utilized to make a model taking specific loading points into account.

Pilot test 1

Recording of live data was not successful as seen on figure 4. The straight lines on the two graphs indicates loss of data packages.The recorded data were of a very poor quality, and thus no analysis could be made due to package loss in the Bluetooth connection. The lab test did show an acceptable range of the Shimmers' Bluetooth connection. However, the range of the Bluetooth connection was very bad when the footrest measuring devices were in the K2 with the crew and on the water. Another wireless technology might be a better solution

The design was changed after pilot test 1. The Shimmer3 bridge amplifier was set to store date on the internal SD card instead of using wireless Bluetooth connection. After Pilot Test 1, the design was changed, the rearmost footrest was distorted a little bit, as the paddler complained about that the footrest was moving some millimeters when pressured.

Pilot test 2

Figure 4.b a 30 seconds test at 85% can be seen. Data was successfully recorded and stored on the SD cards on the Shimmer3. The front footrest did only record 32 peaks which are not consistent with the stroke rate of the K2. When paddling at 85% the K2 stroke rate would be around 120-130 strokes per minute and thereby 60-70 strokes per 30 seconds. The 32 peaks could indicate that the front paddler has a large difference between his left and right kick as there are small peaks between the large peaks on figure 4.b. However, as the subject is a former national team paddler, we must assume that he has an efficient technique and thereby eliminating the large left - right difference. This could indicate that the footrest

measuring device is not able to distinguish between left and right kicks. An explanation for this could be that the pulling motion of the contrary leg is hindering the load cells in measuring the applied force. The pull counteracts the direct pushing force, and the load cells are only able to measure a downward going force on the load cell.

This may account for the study of Nilsson, Rosdahl [2016] choosing a set-up which could measure both push and pull forces in the footrest. The current study's set-up could be upgraded with two additional load cells; one extra on each side of the footrest which measures the contrary direction enabling the device to measure the pulling force in the footrest.

The rearmost footrest recorded 32 small peaks in pilot test 2 as seen on figure 4.b. The peaks were significantly smaller than the peaks from the front footrest. However, it is probably not because of the paddler as the rearmost paddler, too, is a former national team paddler. Compared to the front footrest, the rearmost footrest has a signal that seems to be in double peaks. However, the signal changes are too small to make a clear distinction of the double peak.

The explanation for the small peaks could be that the rearmost footrest tilted a bit. Therefore, extra spacers were put between the wood and the aluminum plate. The spacers were nuts, and they may have reduced the voltage output of the load cells.

Figure 6 shows the acceleration during artefacts made in the end of the second pilot test. It shows that the devices are able to record artefacts simultaneously. The test lasted 50 minutes. Artefacts were made at the start and the end of the session. Figure 6 shows no drift in the data after 39 minutes of recording. This is mainly because of the shimmer3's ability to synchronize with a computer clock when undocking the shimmer, and the fact that each data point has a timestamp. Even though data packages are lost, the timestamp will still have the correct time of the data. The shimmer3's high range accelerometers are an addition to the leg kick analysis. These could be used to investigate the leg kick influence on the kayak and other factors influencing the kayak movement in the water.

Figure 4.b do show that both footrest measuring devices are able to measure a pattern which is evident at the time of the bouts. Peaks on both graphs seem to occur simultaneously, thereby enabling an analysis of timing, A there is a positive correlation between timing of strokes and velocity [Wing, & Woodburn, 1995], at least in rowing. However, it is impossible to know where in the stroke cycle the peaks are, as the peaks in the graph do not indicate whether it is the right or left leg kick. Further, the peaks of the rearmost footrest device are small and difficult to separate.

After pilot test 2, spacers were put between the wooden plate and aluminum plate on the rearmost footrest. The spacers would avoid tilting of the wooden plate.

Pilot test 3

In pilot test 3 as seen on figure 5, data were successfully recorded, two bouts are presented. The peak forces seem to be 450 N for the front footrest and 350 for the rearmost footrest. However, as previously discussed the footrest is only reliable on the middle point of the footrest. Meaning that the measured force can not be compared to the findings of [Nilsson, Rosdahl, 2016].

There are some irregularities on the rearmost footrest as the peak seems to vary in the plot. Further, the two footrests have not recorded the same amount of peaks. On the second bout, the front footrest (blue) has recorded around 40 peaks, and the rearmost footrest has recorded around 23 peaks. The subjects did 40 strokes. It fits with the peaks of the front footrest, however, it does not fit with the peaks of the rearmost footrest. An explanation for this could be that the footrests are not able to measure the individual leg kicks because the footrest is loaded with the weight of the feet all the time. It is clear that there is some synchronized activity on figure 5, as there was in pilot test 2, seen on figure 4.b. However, the two graph seem to resemble each other on figure 5, compared to figure 4.b. This may have an effect of the extra spacers put in the rearmost footrest, between the wooden plate and aluminum plate. This makes an analysis of the peaks easier, compared to the data obtained in pilot test 2. However, as explained, it is impossible to see where in the stroke cycle the peaks occur. A further pilot test with additional equipment must be done in order to distinguish the peaks. To obtain this, cameras could be mounted on the kayak, which should be synchronized with the footrest. Thereby, it would be clear where in the stroke cycles the peaks occur. If a clear distinction of the leg kicks could be made, the set-up would be able to measure timing as it would be the difference between the peaks. Combining the data with video analysis could be useful for the coaches as this will provide the coach with the opportunity to see precisely where in the stroke cycle the leg kick begins and ends. A GoPro camera could be mounted on the front end of the kayak with a good view of the paddler. The video and data from footrests should be imported to MATLAB in a MATLAB app. The video could be displayed alongside a force plot from the footrest, allowing the user to scroll in the data alongside the video. This would enable the user to see precisely were in the stroke peak forces are generated.

In conclusion, when evaluating the footrest measuring devices in the present study, the devices were not able to record live data, and the footrests were highly sensitive to the position of the load on the footrest. However, the set-up was successful in devolving a design which could measure the timing of the paddlers in a K2 without hindering the paddlers' technique. The set-up had a combined weight of 1.437 kg and could therefore be used in competition without compromising the weight of the kayak, as K2 often ways around 16 kg. Further, the reliability test showed a strong linear correlation between the applied force and the voltage output of the load cell when applied to the middle section of the footrests. However, it was not possible to measure the force in the leg kick as the results of the validity test showed a high percentage of deviation in the position of the loads. No clear distinction of timing between paddlers were made in the study, however, video analysis could enable this.

Limitations and system improvements

Although the footrest measuring devices were able to collect data without hindering the paddlers' technique, some further refinements could be made. Using another wireless technology with a stronger range would solve the wireless problem. Changing the set-up of load cells would solve the reliability issues regarding the pressure points applied to the footrests. And lastly, cameras will be used together with the footrest measuring devices to relate the force curves to the stroke cycle.

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The aim of the study was to develop a device which could measure leg kicking forces and timing between paddlers in a flatwater sprint K2 kayak. The two footrests of a K2 was each fitted with two load cells. A Shimmer3 bridge amplifier was used as an analog amplifier and as a data acquisition system. Three pilot tests with different set-ups were conducted with two national elite male paddlers. The devices were calibrated by loading each footrest with a series of weights placed on the middle of the footrest. Further, the footrest measuring devices were tested for validity by placing a fixed load on different points of the footrest. A strong linearity of both footrests measuring devices was found (r2 = 0.99948 and 0.99684). However, the validity test showed that the force output had a large percentage of deviation from the fixed load dependent on the position of the load. Thus, the measured force might deviate from the actual force. Wireless data was not obtained due to a short range of the Bluetooth connection. A training tool prototype which enables measurement of the timing in the leg kick both in K1 and crew boats has been developed based on the findings of the study.

Contents

1 Introduction

Flatwater kayak is a competitive sport where the athlete is seated in a kayak, a two-bladed paddle is used for propulsion. The race is on a straight course on flat water, the competitive race distances are 200, 500, and 1000 m. It is done in K1, K2 or K4 (one man, two men or four men) [McDonnell et al., 2012; Nilsson, Rosdahl, 2016].

To maintain a high velocity in the kayak, high peak forces in the paddle are produced [Mononen et al., 1994] which places high demands on the upper body and trunk musculature [Tesh, & Lindberg, 2011]. The high forces are necessary to overcome the hydrodynamic drag of the kayak as well as the aerodynamic drag of the kayak and athlete [Nilsson, Rosdahl, 2014]. A wing paddle is used to propel the kayak forward. However, an efficient technique is important to fully utilize the wing paddle. This technique involves a prominent use of the legs and rotation of the trunk. The paddler must push down with one foot on the footrest in a knee extension while the contralateral leg pulls in the footbar in a knee flexion. This push/pull action allows for a rotation of the pelvis and thereby a moment of force is produced. This allows the trunk muscles to participate in the propulsion of the kayak. The paddle is also rotated out of the water and thereby a faster exit phase is obtained [Nilsson, Rosdahl, 2016].

A study by Brown et al. [2010] investigated the activation of the major muscles in the legs during a stroke cycle on eight international elite level paddlers (six men and two women). Findings of the study showed a clear activation of the major muscle groups during the stroke cycle. It is suggested in the study that the lower limbs provide a stable base for force production. Lee, Nam [2012] found that the legs contribute with 6% of the total force production. Another study related the angle of the knees to how efficient the stroke cycle was [Begon et al., 2010]. Nilsson, Rosdahl [2014] investigated the contribution of leg muscles' generation of force during maximal effort. The study found a drop in maximal velocity of 16 % if the legs were restricted, compared to unrestricted. This underlines that the leg kick is an important part of the kayak stroke. The study used a set-up from [Nilsson, Rosdahl, 2014] where force transducers were mounted in the footrest and the seat of a K1.

In conclusion to the above studies, the assistant head coach of the Danish national kayak team, Finn Pape, has said:

"Using the legs is an important part of the crew boat technique, the leg kicking contributes to the rhythm of the K2 and helps to make the kayak stable in the water. As not to say it's importance for the individual technique."

No study to the author's knowledge has investigated paddling kinematics and technique in crew boats in flatwater sprint kayak. However, it is known from technique analysis that the leg kick enables a further rotation of the trunk and that the legs provide a stable base for force production. Furthermore, one must presume that these findings are evident in crew boats as well.

It is commonly known in the kayak community that when paddling crew boats the paddlers must paddle in sync as this provides a more stable kayak, and therefore a higher velocity can be obtained. It is known from rowing that there is a positive correlation between timing of strokes and velocity [Wing, & Woodburn, 1995]. The initiation of a leg kick marks the beginning of a new stroke, therefore one would assume that the timing between paddlers' leg kick is essential as well for the kayak's performance.

In rowing, leg forces have been studied, however, only few commercial set-ups are available. In a study by [Buckeridge et al., 2013], a set-up to test foot force production and asymmetries in the rowing leg kick has been developed. They used a strain gauge set-up with two additional beams mounted on the footplate. The two beams were reverse of each other. Shear forces and normal reaction forces were measured corresponding to vertical and horizontal forces.

As stressed in the previous statement, Finn Pape underlines the importance of the leg kick. A study by [Sturm et al., 2010] states that *"A coach outside the laboratory has very little data to use in order to assess the athlete's performance."* Therefore, training tools that can assist the coach on the water could improve training and act as motivation for the athlete and coach.

With respect to previous studies and the lack of training tools in sprint kayak, the aim of this study was to develop a training tool that was able to live record and quantify the forces produced by the major muscles in the legs during a stroke cycle in a K2 during maximal effort. Further, the timing of the leg kicking between the front paddler and the rearmost paddler was investigated.

Methods 2

The following chapter outlines the methodological design used to attain the aim of the study. This includes experimental design, subjects, technical development of force sensitive equipment and the test protocol.

2.1 Considerations of the design

The development of the footrest measuring device is inspired by a need described by the assistant coach of the Danish national sprint kayak team. Therefore, the set up must be user-friendly in order to be used on a daily basis by the Danish national kayak sprint team.

In the product design of this study, a feedback loop was used to guide the design. Meaning that when developing a prototype, it was a user involvement development. Thus, every phase of the design was developed with the end-user in mind, and every step was discussed with the assistant coach of the national team, active elite paddlers, and Team Danmark's experts. Figure 2.1 illustrates this design process. The first picture shows the loop of a user involvement development, and the next shows the engineering stages of the design phase.

Figure 2.1: *Design phases of the set up [Sturm et al., 2010]*

The three stages of conceptualization: Design, build and test were implemented in the project. This fits well with the problem-based learning structure at Aalborg University where projects seek to solve an existing problems. Therefore, the user involvement is an important aspect of the project as the users will be using the final device.

2.1.1 Understanding the kayak stroke

In order to design a user-friendly force sensitive footrest measuring device, the following section will elaborate an understanding of the kayak technique. The kayak stroke can be characterized as a cyclic movement with the paddle where there is a left and right side. According to the literature, the stroke can be divided into four phases: *catch*, *drive*, *exit* and *air* phase, all phases can be for the right or left side [Sturm et al., 2010].

1. **The catch** starts when the tip of the blade touches the water. The catch is important for the rest of the stroke as it sets the conditions for the force production. If a bad set up of the paddle is achieved in the catch, the paddler will not be able to generate force to the full potential. Therefore, the paddler must ensure that the blade is perpendicular to the water along the kayak so the full potential of the wing blade can be utilized. And thereby give the optimal conditions for the generation of power and achieve a higher velocity. The opposite arm extends in order to maintain the pivot of the paddle. The first extension of the leg starts in this phase which gives the stable base for force production. Overall, this movement activates these muscles: Arms (Biceps, brachioradialis, triceps brachii, wrist extensors anterior deltoid the opposite arm activates triceps brachii), trunk (Trapezius, latisimus dorsi, teres major, teres minor, right erector soinea group, left external obliquea and Pectoralis-major in the opposite side) and legs (Quadriceps femoris and Gastrocnemius) [Logan, & Holt, 1985; Sturm et al., 2010; Brown et al., 2010]. It can be seen on figure 2.2.

Figure 2.2: Catch [TopSport, 2010]

2. **The drive** is the phase where the majority of the force is produced. The paddler pulls the paddle in a ”j shaped movement” till it exits the water. The first part of the drive is achieved in a straight line. However, in the second part of the drive, the paddler rotates

the trunk and thereby the blade away from the kayak. The opposite arm fully extends in a pushing motion a cross the kayak as seen on figure 2.3. Overall, this movement activates these muscles: Arms (Deltoid, Biceps, brachioradialis, triceps brachii, wrist extensors and wrist flexors opposie arm), trunk (Trapezius, latisimus dorsi, pectoralis major opposite side and serratus anterior) and legs (Quadriceps femoris and Gastrocnemius)[Logan, & Holt, 1985; Sturm et al., 2010; McDonnell et al., 2012]. It is important to underline that the blade does not go through the water, it stands firmly in the water and the paddler uses it as a "pole" in the water. However, the blade will not stand 100 % firm in the water. The efficiency of the blade will depend on the type of blade and the paddler's technique which can be seen on figure 2.3 [McDonnell et al., 2012].

Figure 2.3: Drive [TopSport, 2010]

3. **The exit** is the finish of the stroke where the paddle is pulled out of the water. During this phase, the pulling hand of the paddler may not be further than the hip seen from a horizontal point of view. Therefore, the rotation of the trunk during the stroke is a crucial element as it prolongs the time that the pulling hand is behind the hip. The rotation of the trunk also rotates the opposite shoulder forward which enables a prolonged stroke on the opposite side. The rotation is made from the contraction of the biceps and latissimus dorsi, and the blade exit of the water is caused by the contraction in deltoid and trapezius. Overall, this movement activates the following muscles: Arms (Biceps, brachioradialis, Deltoid (anterior and medial), triceps brachii and wrist extensors, the opposite arm activates Biceps brachii, brachialis and pronator teres) trunk(Trapezius and pectoralis major) [Logan, & Holt, 1985; Sturm et al., 2010; McDonnell et al., 2012]. It can be seen on figure 2.4.

Figure 2.4: Exit [TopSport, 2010]

4. **The recovery** is from the blade exit of the water to the point where the opposite blade is in the water. No force is generated during the air phase as there is no contact between the water and the blade. The paddler tries to utilize the time on preparing a new stroke by keeping the trunk rotated, and thus obtain the optimal set-up for the catch [Sturm et al., 2010]. McDonnell et al. [2012] found that good paddlers have a short air phase, compared to their water phase. The movement activates the following muscles: Arms (Biceps, brachioradialis, Deltoid (anterior and Medial), triceps brachii and wrist extensors) trunk (Trapezius, latisimus dorsi, teres major and left external oblique) [Logan, & Holt, 1985; Sturm et al., 2010; McDonnell et al., 2012]. It can be seen on figure 2.5

Figure 2.5: Recovery or air phase [TopSport, 2010]

As the paddlers vary in size: arm length, height, weight, trunk height etc [McDonnell et al., 2012], it can be complicated to outline an optimal kayak technique. Likewise, the actual movement is complex as energy must be transferred through multiple segments of the body and down in the kayak. This involves arms, shoulders, trunk, and legs in combination [Sturm et al., 2010].

If the current literature is taken into account, a list can be summed up of factors that influence the design of the footrest measuring device:

- Good paddlers have a short air phase, compared to their water phase. McDonnell et al. [2012].

- The average water phase time is (0.24 ± 0.03 s) for international male paddlers [McDonnell et al., 2012].
- The stroke rate(strokes per minute) is important for the velocity, and can reach 141 spm in a K1 200m (It is likely higher in K2 and K4)McDonnell et al. [2012].
- The legs contribute with 6% of the total force production [Lee, Nam, 2012].
- The angle of the knees must be around 120 degrees for highest stroke efficiency [Begon et al., 2010].

Taking the above mentioned factors into account, the footrest measuring device must be able to measure the characteristics of the stroke. One stroke takes (0.24 ± 0.03 s) at the maximal velocity and may be even shorter in a K2 as higher stroke rates are observed. The footrest must not prevent the paddlers from having a knee flexion of 120 degrees. Further, the software must be easy to use as the assistant coach of the national team will use it in the daily training.

2.1.2 Footrest measuring device requirements

The footrest measuring device must be able to:

1. Measure forces in the footrest in range 0-600 newton. As the results of Nilsson, Rosdahl [2016] showed forces of 500 newton.
2. Determine timing between forces in the front footrest and the rearmost footrest in up to 180 strokes pr minute.
3. The system must not inhibit the paddlers in their technique. The footrest must not hinder the paddlers' leg kick.
4. A K2 must weigh at least 18 kg in competitions. However, paddlers seek to have a kayak that weighs around the limit, therefore it must be a relatively lightweight system. A K2 will often from the manufacturer weigh 1.5 - 2 kg below the limit.
5. Live stream the data to a PC or tablet and thereby enabling live performance feedback for the coach.

2.1.3 Design of footrest measuring device

The following components were used in order to design the two footrests:

- A complete set of Nelo K2 footrests(400 gram and 300 gram)

- 4 x Bodyweight scale strain gauges YZC-908
- 4 x 61.9 Ω resistors
- 4 x 1017 Ω resistors
- 4 x Potentiometers
- 2 x Shimmer3 bridge amplifiers
- 2 x Aluminum plates
- 4 x Metal disks
- 2 x Solder plates
- 2 x Four pole jack plug

Footrests

Two Nelo footrests were fitted with two load cells. An aluminum plate was added to the footrest, and the two strain gauges were placed in sockets on the aluminum plate that were fitted to the strain gauges. The wooden plate from the original footrest was placed over the aluminum plate. Metal disks were added to the backside of the wooden plate, thereby avoiding abrasion on the wood when the strain gauges were in contact with the wood. Hard rubber spacers was put between the aluminum plate and the wooden plate in order to avoid movement and tilting of the wooden plate on the footrest. The two footrests were equally distorted as the distance between the plates was measured with vernier calliper. Further, the footrest had an equal distance all the way around the plate. On figure 2.6 and 2.7 the final aluminum plates can be see. Figure 2.6 shows the two final aluminum plates.

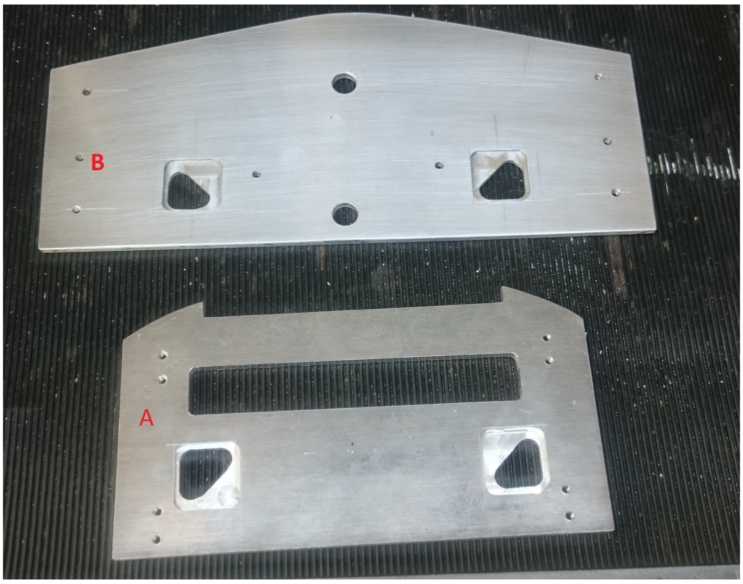


Figure 2.6: *The two aluminum plates made for the footrests, A is for the front footrest and B is for the rearmost footrest*

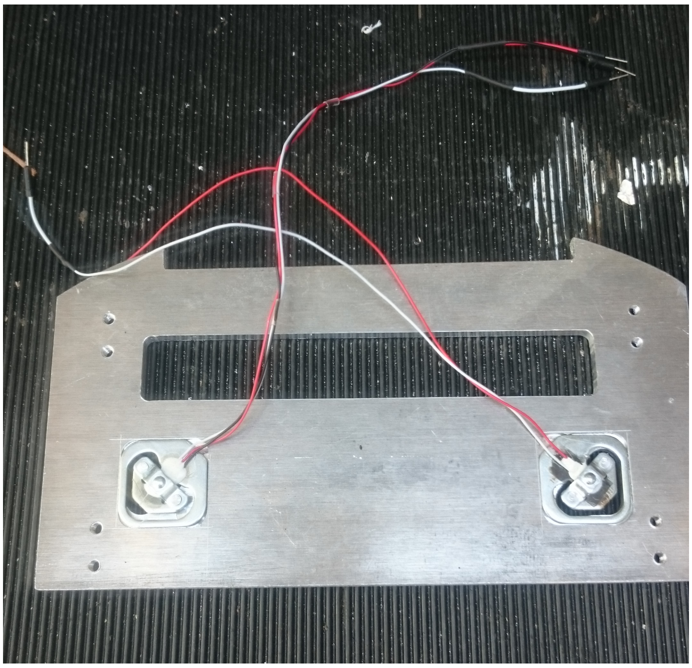


Figure 2.7: *The two strain gauges in the socket of the front paddler's aluminum plate.*

Strain gauges

The two strain gauges mounted on the footrest were configured as a half Wheatstone bridge with two 61.9 Ω resistors, two 1017 Ω resistors and two 10 k Ω potentiometers to adjust the bridge. See- appendix A.1

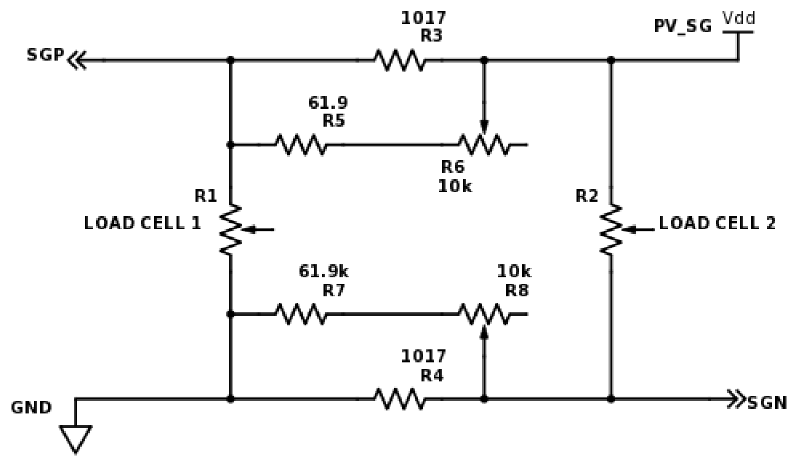


Figure 2.8: *The Wheatstone bridge which was used in the set-up*

The bridge can be seen on figure 2.8. The circuit has a signal negative(SGN), a signal positive(SGP), a ground (GND) and a power(PW_SG). A equation for parallel resistors was used to balance the bridge:

$R_{total} = R_1 + R_2 + R_3...$

The load cells had two outputs, a high and a low output. In order to zero phase the strain gauges, two potentiometers were added to each bridge. Wires were connected to a four pole jack which could be connected to the shimmer3 bridge amplifier.

The Wheatstone bridge was soldered to a circuit board where the Shimmer3 bridge amplifier was placed with a rubber band. The circuit board with the bridge amplifier was then placed in a 3D printed box which made the set-up water-repellent.

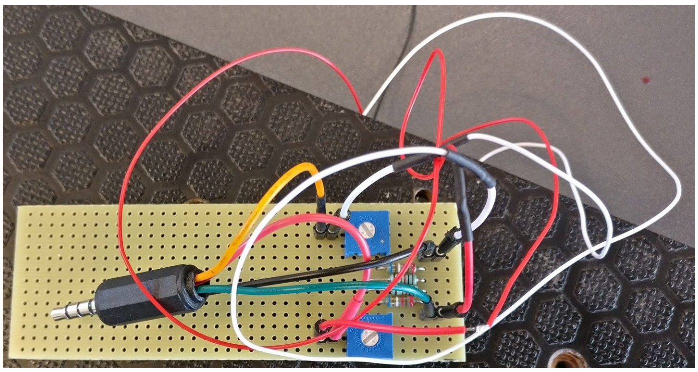


Figure 2.9: *The circuit board with solded resistance, potentiometers, wires and a jack cable*

Bridge Amplifier

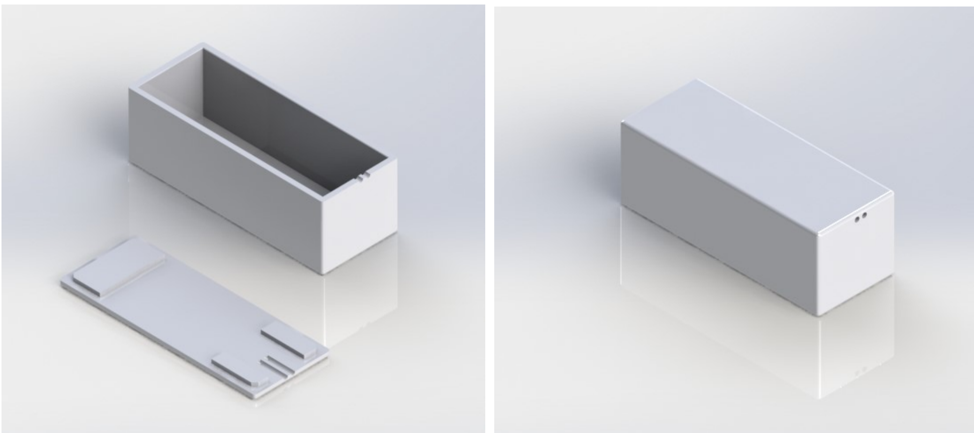
A Shimmer3 Bridge Amplifier(Shimmer3, Shimmer, Dublin, Ireland) was used as an analog amplifier of the bridge voltage outputs and as a data acquisition system with a sample rate 1014 Hz See - appendix A.2 for more detailed information. Consensys Pro v1.1(Shimmer, Dublin, Ireland) was used to set up the shimmers. When writing data to the SD card under tests, Consensys Pro v1.1 was sued to import and export data to MATLAB. A Bluetooth connection from the Shimmer3 to a computer was used when collecting real time data. A MATLAB app (MATLAB 2016a MathWorks Inc, Massachusetts, USA) was made in order to collect and analyze data real time.

Protection box

A box was 3D printed in order to mount and protect the circuit board. The box had the outer measures: Length 108 mm, width 42 mm, hight 37 mm and a wall thickness of 4 mm. The lid had the same bottom measures, and was printed with edge which helped to seal the box.

It can be seen on figure 2.10a and figure 2.10b that the box was designed in SolidWorks (DS SolidWorks Corp. Klarabergsviadukten 90 111 64Stockholm Sweden). And printed by an Ulitimaker 3 (Ultimaker B.V. Watermolenweg 2, 4191 PN Geldermalsen, The Netherlands) and was printed in ”standard” quality.

The box was attached to the footrest with double adhesive tape on the back of the footrest. It can be seen on figure 2.11



(a) *Box without top on* (b) *Box with top on*

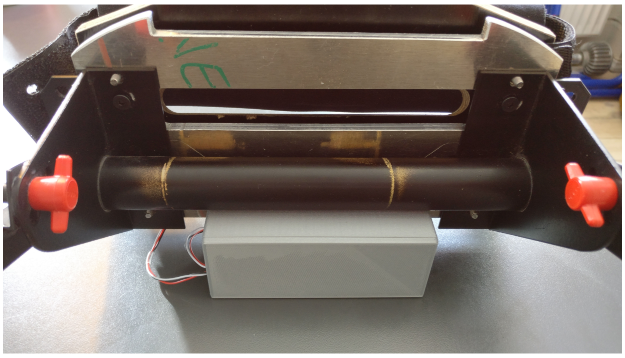


Figure 2.11: *A back view of the footrest with the box attached in the bottom*

The two footrest measuring devices had a combined weight of 1.437 kg. When mounted in the K2, the weight of the K2 was 17.893 kg. Thereby, the extra weights of the footrests did not make the kayak go above the 18 kg limit.

2.1.4 Software interface

In order for live data recording, a GUI was made in MATLAB which was capable of:

- Control the Shimmer3 bridge amplifiers
- Start/stop function
- Process data and plot data
- Provide visual feedback which indicates the level of sync between the paddler's leg kicks
- A save function which saves data and plots

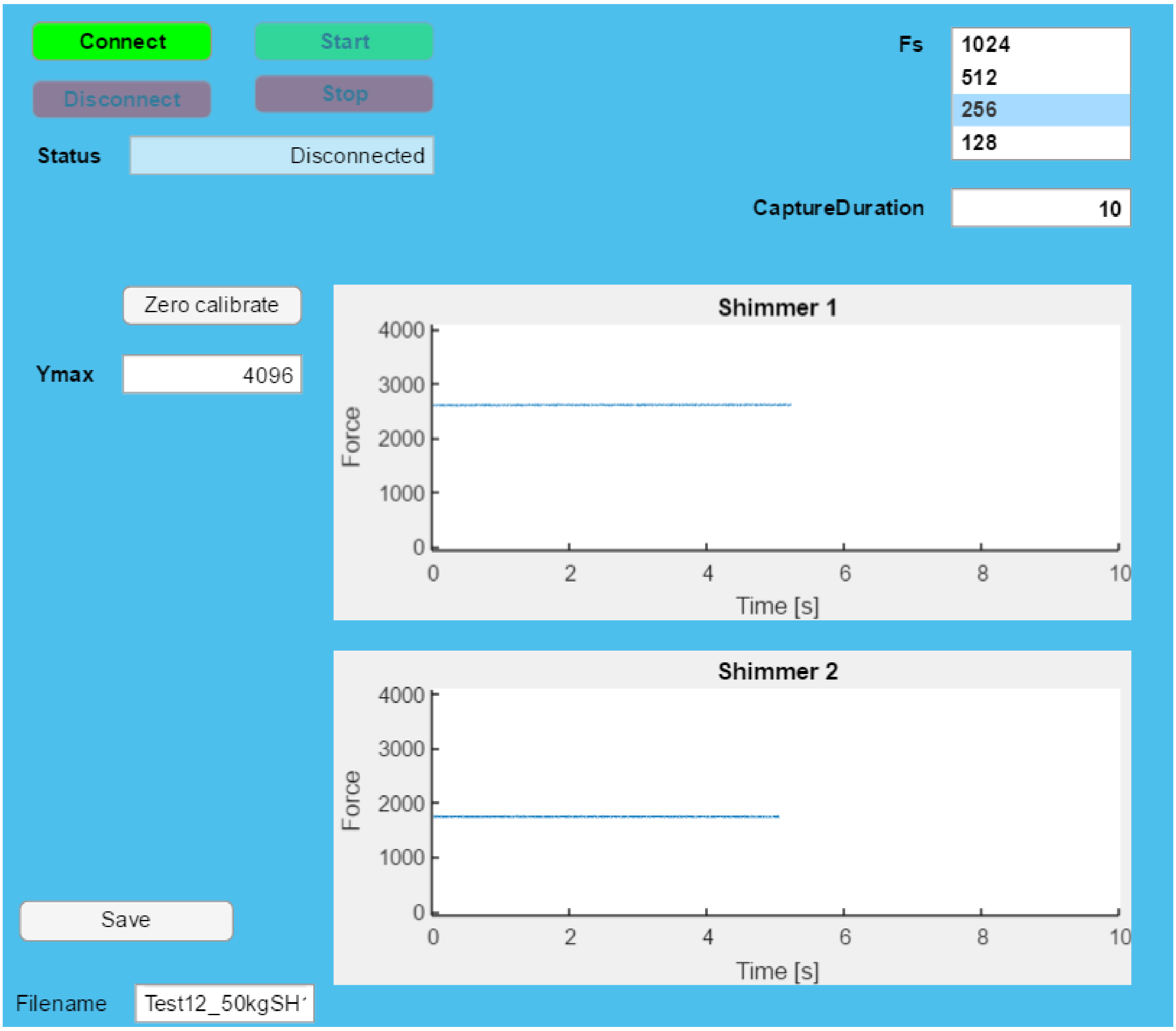


Figure 2.12: *The GUI made in MATLAB*

On figure 2.12 the GUI can be seen. It has multiple features such as a connect and disconnect button and a start and stop button. If not relevant for the given situation, buttons are grayed out. For instance when the shimmers are disconnected, the start button is grayed out so no recording can start if the shimmers are disconnected. From the GUI, sample rate and capture duration can be set. Two plots make it possible to see the data live. A Zero calibrates button was added to the GUI, so off-set's could be withdrawn from the data. Lastly, when the recording is stopped it is possible to save the data to the default MATLAB folder.

The GUI was set to communicate with the Shimmer3's over Bluetooth. The connection length was tested at the university lab where the connection was good up till 30 m. The test showed that even though the connection was lost, the shimmer was still able to send the lost packages when the connection was re-established. It means that there is a handshake between the computer and the Shimmer3. Therefore, the shimmer is able to store data when no handshake is obtained. The data is stored on a buffer in the Shimmer, however, the Shimmer is not able to do this in a longer period.

The Shimmer was also put in a refrigerator to test the connection in a shielded environment, the device was still able to send and receive data with no package loss in the refrigerator. Moreover, the Shimmer was put in a K2 on land to see how far the connection range was, the connection was down to 4-5 meters. Lastly, the connection range was tested on water with paddler in the K2 by a bridge. The connection range was down to 2-3 meters on-water. This indicated how close the backup boat should be on the kayak in the actual test.

2.2 Calibration

A calibration of the two footrest was done as a validity assessment. The voltage output was amplified with the Shimmer3 Bridge Amplifier. A deadweight set-up [Stefanescu, 2011] was used. The footrests were placed in a horizontal position with blocks as supporting points. Precisely approved weights of 5 kg, 10 kg, 15 kg, 20 kg, 25 kg, 30 kg and 50.1 kg was used. The weights were put on the middle of the footrests with a small wooden block under the weights.

The Shimmer3 was set to "write to SD card". Each step would last five seconds with 10 seconds in between where the footrest was unloaded. After the test, the data were imported to MATLAB with Consensys. The output from the sensors were plotted against the weights. On table 2.1 the calibration data can be seen. Studies by Libii [2006] and [Nilsson, Rosdahl, 2016] provided the calibration protocol.

A quadratic line was fitted to front footrest, and a cubic to the rearmost footrest:

Front footrest y = - 6.3244*x^2 + 44.764*x - 12.52

Rearmost footrest y = 313.73*xx^3 - 1209*xx^2 + 1566.4*x - 652.83

Mass [kg]	0	5	10	15	20	25	30	50.1
Footrest 1 Voltage [v]	0.2632	0.4347	0.5902	0.7019	0.7817	0.9452	1.1326	1.9210
Footrest 2 Voltage [v]	0.8614	0.8933	0.9332	0.9571	1.005	1.153	1.256	1.653

Table 2.1: *Shows the calibration data from the calibration of the footrests*

The test was repeated in order to test the level of reliability. The data sets from the two tests were then tested for correlation with a linear regression model. The function ”fitlm” was used in MATLAB to calculate this.

Further, an additionally validity test was made in order to test for right and left difference in the footrest measuring devices. It consisted of loads of 15 kg placed 5 places on the front footrest and 6 places on the rearmost footrest. The force-application positions can be seen on figure 2.13. All calibrations were done after the third pilot test because change of the design or the distortion could change the output of the load cells.

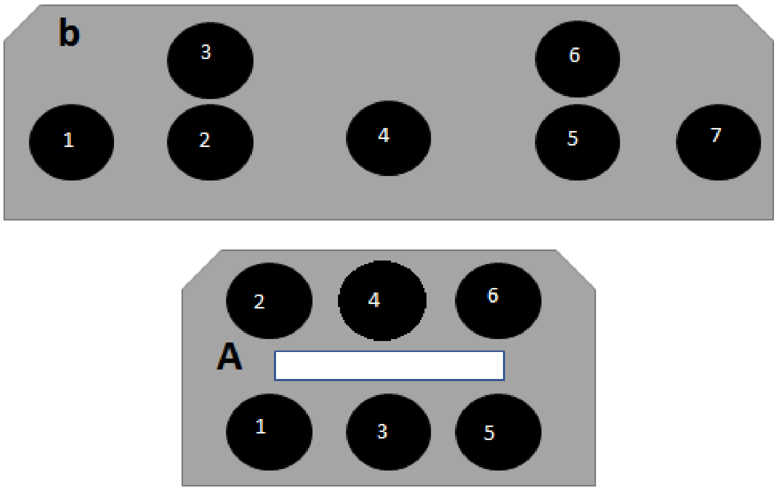


Figure 2.13: *The force-application positions on the footrest. A being the front footrest and B being the rearmost footrest. The black dots indicates force-application positions*

2.3 Test

The following section will elaborate the subjects, test procedure and data processing. All calculation, data analysis and plots were done in Matlab 2017a.

2.3.1 Subjects

Two national elite male kayaking paddlers (n=2)(age 26 years ± 2.8, weight 89 kg ± 9.9 kg and height 179 cm ± 1.4 cm were recruited for the study. Both subjects had trained at least ten times a week for the past three years and competed at international level as former national team paddlers. In addition, the two subjects have competed as a team in the same K2 for several years. Meaning that they are an experienced K2 crew and thereby able to minimize balance and ”rhythm” problems in the test.

Criteria for participation

To compare data with the finding of [Nilsson, Rosdahl, 2016], the subjects had to be male kayak athletes. Furthermore, they were required to have international competitive experience while training at 'Kajakklubben Limfjorden' on a daily basis.

The subjects were excluded from the study if they have had a recent injury, were sick up to the test or unable to complete the test. Moreover, subjects were excluded if they in any way were feeling pain or injury during the initial protocol.

2.3.2 Declaration of consent

Prior to the first test, both subjects were informed (orally and in writing) of the purpose, test procedures, possible benefits and risks involved in the study. All subjects signed the declaration of consent and verbally agreed to participate in the study - see appendix C.0.1.

2.3.3 Test procedure

The two footrests were mounted in a Nelo Vanquish 2 K2. (Nelo- Vila DO Conde - Portugal). The two footrests were shaken in the shimmers x,y and z direction before they were mounted in the kayak. Thereby, creating simultaneous artefacts on the accelerometer signal. The same procedure was done after the test was completed. Thereby, the signal could be tested for drift or small difference in sample frequency.

The K2 used in the test can be seen on figure:

Figure 2.14: *Nelo Vanquish 2 K2 side view*

The two participants did 15 minutes warm up consisting of their regular competition warm-up - See appendix B.1. Then the actual test would begin which would be 3-5 bouts with a duration of 20-30 seconds. The intensity of the bouts would be 85 % of the maximal effort. Force data from the footrest and acceleration of the kayak in vertical, lateral and longitude direction was recorded during these trails with a sample frequency of 1024 Hz. The test was repeated three times, and the design was changed if necessary.

2.4 Data processing

All data from the footrest measuring devices was exported to MATLAB for further analysis (MATLAB 2017a MathWorks Inc, Massachusetts, USA).

As section 2.2 elaborates, there was found a best fit line for a load test for each footrest. Each line was inspected for the best fit line. The front footrest has a best fit with a quadratic line, and the rearmost footrest had a best fit with a cubic line. Each equation was used to calculate weight in the on-water test. For the on-water test, data was exported to MATLAB from Consensys, and force data was plotted with the Shimmer clocks which were synchronized with the computer time. Therefore, it allowed the data to be aligned, enabling synchronized data from both footrest measuring devices.

2.5 Statistics

A linear regression model, made in MATLAB using the function ”fitlm”, was used to test for correlation between the two loading tests. The function ”fitlm” makes a linear regression model for two variables.

The voltage output of the validity tests was converted to kilograms with the equations described in section 2.2. The percentage deviation of each pressure point compared to the actual weight (15 kg) was then calculated.

Results 3

The following chapter will present data from the calibration of the footrests where a test for validity and a test for reliability have been done. Lastly, the main results from the on-water test will be presented showing data from the three pilot tests.

3.1 Data from calibration tests of footrest measuring devices

The following section displays the data from the validity test and the reliability test. The validity test is displayed in table 3.1 and the results from the reliability test is displayed in figure 3.3.

Table 3.1 shows the percentage deviation of different force-application positions on the two

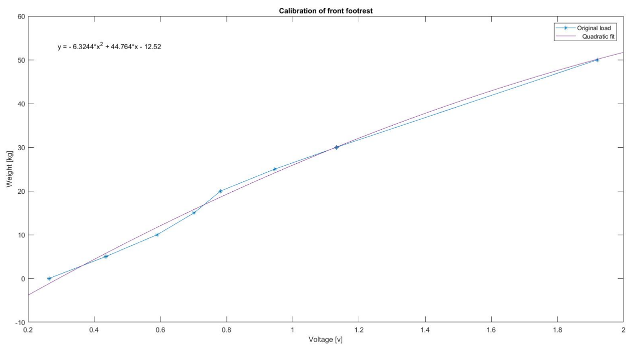


Figure 3.1: *Loading calibration of the front footrest measuring device*

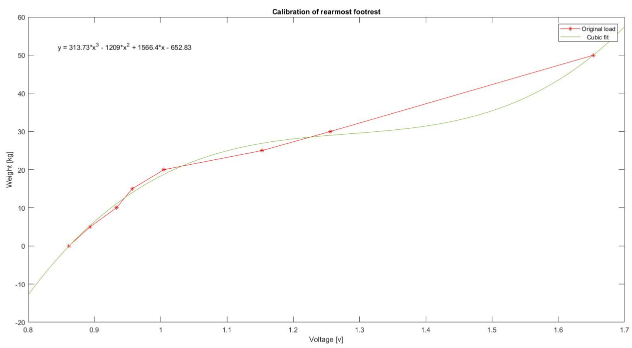


Figure 3.2: *Loading calibration of the rearmost footrest measuring device*

footrests with 15 kg. Positive values mean that the specific point results in a lower output, and a negative value results in a higher output.

Pressure Points	1	2	3	4	5	6	7
Front footrest [%]	37.45	64.55	1.89	-9.33	55.17	40.04	-
Rearmost footrest[%]	- 55.37	14.49	2.52	3.11	-16.34	-5.42	-31.9

Table 3.1: *Shows the percentage deviation from 15 kg in the validity test*

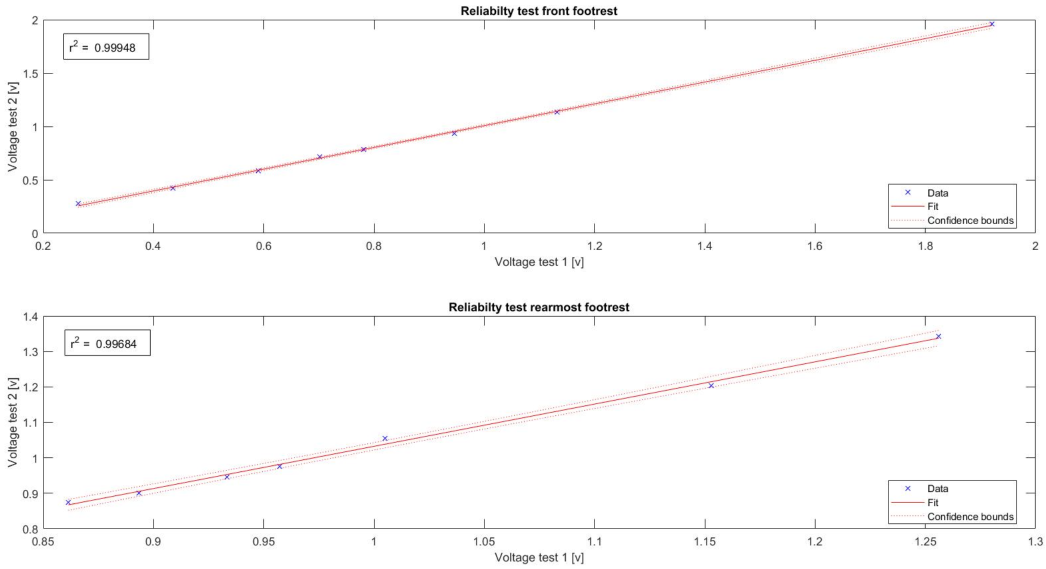


Figure 3.3: Reliability test of the the two footrests

Figure 3.3 shows the reliability test of the two footrest measuring devices. There was a good correlation between two tests on two different days with a R squared value of 0.99948 and 0.99684 and a P value less than $p < 0,001$ and less than $p < 0,001$ The test was done with a loading range: 5 kg, 10 kg, 15 kg, 20 kg, 25 kg, 30 kg and 50.1 kg and placed on the middle of the footrests, point 3 (front footrest) and point 4 (rearmost footrest) as seen on figure 2.13.

3.2 Data from on-water test

The following section displays data from the three pilot tests in a chronological order. First, the force data from pilot test 1 on figure 3.4. Second, force and acceleration data from pilot test 2 on figure 3.5, and 3.7, lastly force data from two bouts of the last pilot test in figure 3.8.

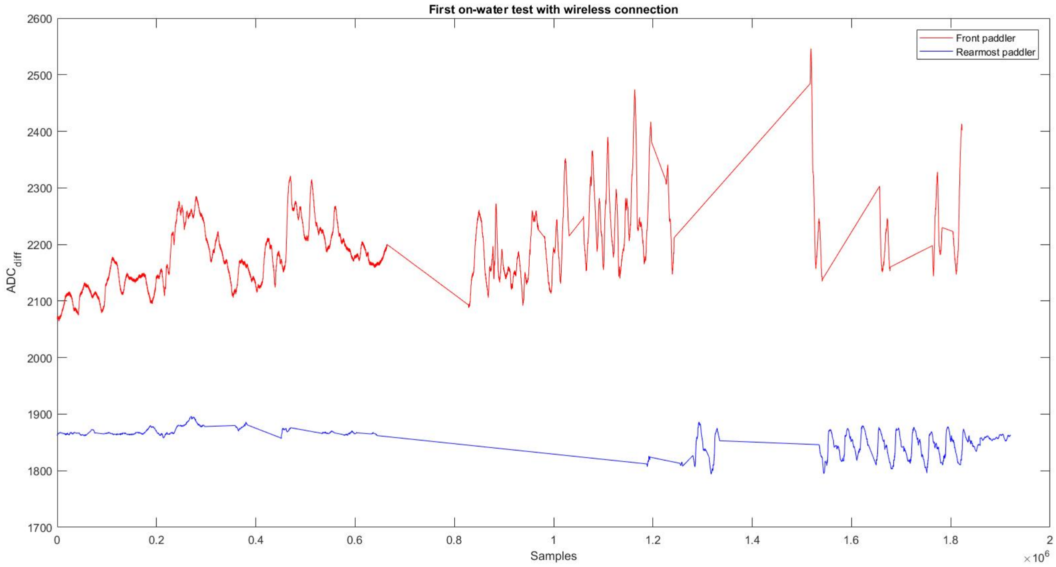


Figure 3.4: Force data from the footrests from first pilot test with wireless connection

Figure 3.4 shows the data from pilot test 1. The line clearly indicates loss of data packages under the test. And data from the rearmost paddler did not record anything of great importance. It should have recorded 30 seconds of 85 % of maximal velocity in the K2.

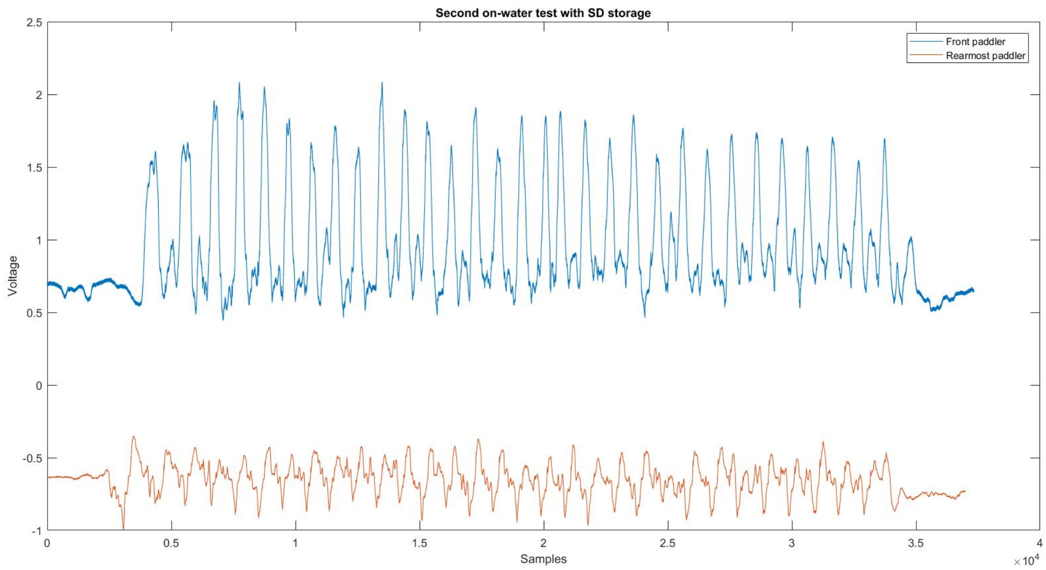


Figure 3.5: Force data from the footrests from the second pilot test with storage to SD card connection

On figure 3.5 the data from the second pilot test can be seen. The plots show data from a bout of 30 seconds. With data from the front and rearmost paddler, the data clearly shows peaks of applied pressure to the footrests.

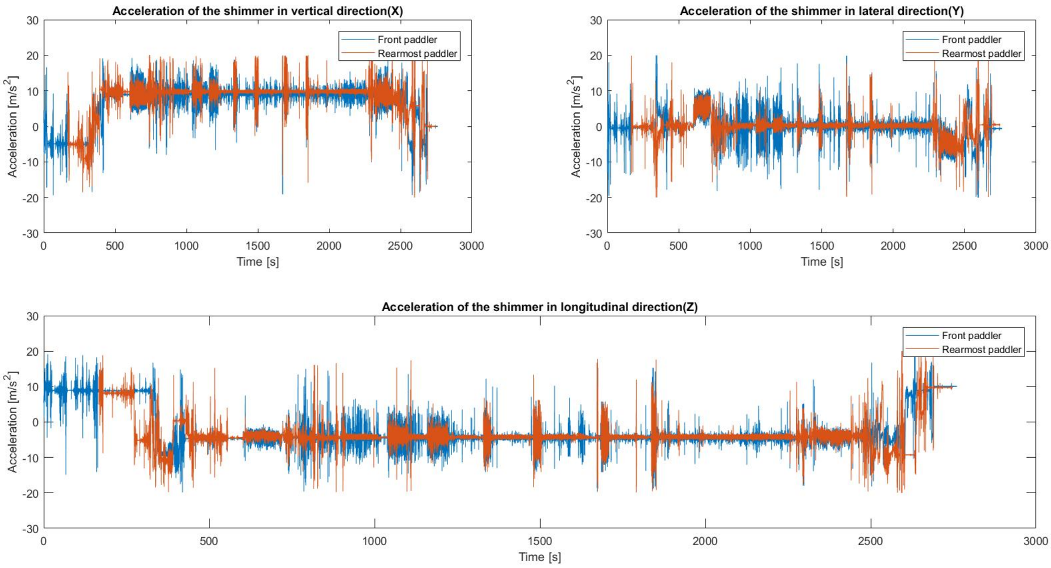


Figure 3.6: Acceleration data from the footrests from the second pilot test with storage to SD card connection. The data has not been calibrated for offset of the accelerometers.

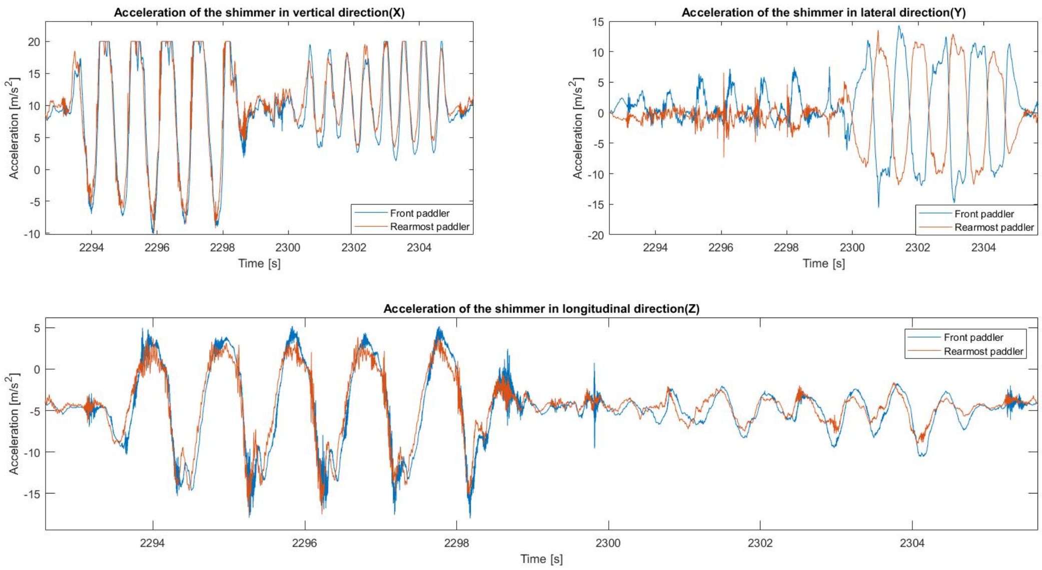


Figure 3.7: Acceleration data of the shimmer in the vertical, lateral, and longitudinal direction. The data is from the second pilot test. Artefacts were made in the end of the test, in order to see if the data had drifted.

On figure 3.6 acceleration data can be seen from the second pilot test. The data was recorded, and artefacts were made in the start and end of the recording. Figure 3.7 shows artefacts made in the end of the test after 2294 seconds. No drift in data has occurred.

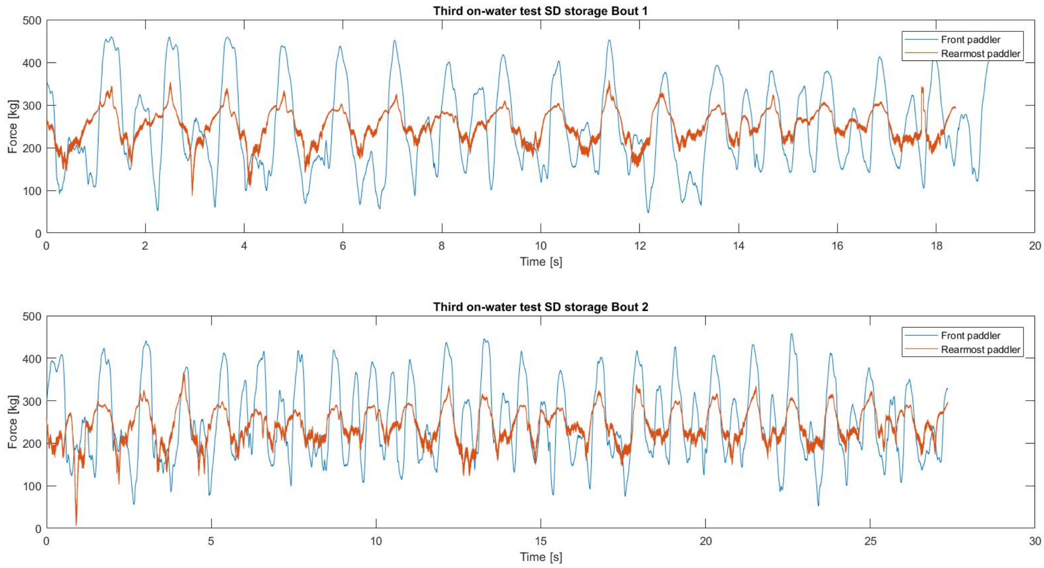


Figure 3.8: Force data from the footrests from the third pilot test with storage to SD card connection

On figure 3.8 force data from the third pilot test can be seen. Two bouts are presented; one on 19 seconds and one on 29 seconds. The bouts were cut out from the original file by identifying the first and the last peak of the bout.

Discussion 4

The following section will discuss and reflect on the design of the footrest measuring device by discussing the subjects, the design, the validity and the reliability. Subsequently, a discussion of the main findings, which aims to explain the outcomes of the results, will be presented.

With respect to previous studies and the lack of training tools in the sprint kayak, the aim of this study was to develop a training tool that was able to live record and quantify the forces produced by the major muscles in the legs during a stroke cycle in a K2 during maximal effort. Further, the timing of the leg kicking between the front paddler and the rearmost paddler was investigated.

4.1 Discussion of subjects

The subjects in the study both had at least ten years of sprint kayak experience. Further, they had both been training ten times per week the last three years. In addition, they were used to paddle K2 together as they are former K2 buddies. This makes them ideal for testing crew boat kinematics as an unexperienced crew could have difficulties paddling together and thereby difficulties using the legs. The high level of the paddlers ensures that they are used to using their legs and have, most likely, a minimum left to right variance.

4.2 Discussion of the footrest measuring device

The footrest measuring devices was tested for reliability and validity in order to clarify error margins and determine the scientific strength of the experimental design.

4.2.1 Reliability of the footrest measuring device

Data was collected from eight loadings of both footrest devices with 5 kg, 10 kg, 15 kg, 20 kg, 25 kg, 30 kg and 50.1 kg. The loading was done twice on each footrest. The relationship between loading and voltage output can be seen on figure 3.1 and 3.2.

Figure 3.3 shows that there is a strong correlation between the two loading trails of the front footrest. Although it can only investigate the pushing force on the footrest, this makes the footrest measuring devices reliable enough to investigate timing of leg kick in on-water kayaking. However, a comparison between forces in the leg kick is not yet possible. As the footrest only is reliable in repeated loadings on the middle of the footrest. An extensive reliability analysis must be done on the footrest measuring devices, in order to know the reliability of the whole footrest. Figure 2.13 shows pressure points on the footrests. A reliability test must be done for all these points, to know the total reliability for the footrests. The current reliability test is to simple to state anything about the forces of the leg kick.

4.2.2 Validity of footrest measuring device

A loading test was performed on each footrest measuring device on different force application positions with 15 kg. Table 3.1 shows the force values of different spots. The data shows that the footrest measuring devices are not able to produce the same output when loaded on different points. Thereby, excluding the device for measuring absolute force of the leg kick. A possible explanation for this could be the mechanical or electronic design of the footrest measuring device and must therefore be considered a design error. However, measure point 3 on the front footrest and point 4 on the rearmost footrest seem to have minor percentage deviation than the other pressure point. This supports the findings of the reliability test, as these points were the same points which the reliability test were conducted on. The reliability test showed that the footrest measuring device is consistent when loaded on the same point.

The mechanical issue could possibly be the distortion of the footrest as applied force would make the wooden footrests tilt, and thereby pressuring the load cells differently. Regarding to that, the placing of the load cells could have been wrong as they may have been placed too low. However, it raises another design issue. The footrest measuring device must be able to record different types of leg kicks. Some paddlers might have their feet high on the footrests, and some have their feet low on the footrest. Further, the pulling motion of the contrary leg pull might unload the load cell if the distortion of the footrest has not been sufficient.

The electronic issue might be the layout of the Wheatstone bridge. It is currently configured as a half-bridge, and thereby only one force output comes from the bridge. If each load cell had their own bridge it would be possible to see how much each loading cell was loaded. A series of equations could then be lined up, one equation for each specific loading point. The equations could be utilized to make a model taking specific loading points into account.

4.3 Discussion of on-water tests

The developed footrest measuring device was partly successful in measuring the leg kick in K2 under maximal intensity. A series of three pilot tests were done. The design of the footrest measuring devices was change after each pilot test, in relation to the design method elaborated in chapter 2.1.

4.3.1 Pilot test 1

Recording of live data was not successful as seen on figure 3.4. The recorded data was of a very poor quality, and thus no analysis could be made due to package loss in the Bluetooth connection. The lab test did show an acceptable range of the Shimmers' Bluetooth connection. However, the range of the Bluetooth connection was very bad when the footrest measuring devices were in the K2 with the crew and on the water.

A solution to this could be to mount a jack pole extensor on the circuit board of the footrest measuring device. Thereby, mounting the Shimmer3 on the top of the kayak's outer hull and having a wire going down to the circuit board. This could be a solution to solve the range issue. However, another wireless technology might be a better solution such as: Wifi, cellular data service, mobile satellite communications or wireless sensor networks. A wifi solution could write data instantly to the "sky" and thereby enabling a collaboration with an online training app such as: Strava, Endomondo or Garmin Connect.

The design was changed after pilot test 1. The Shimmer3 bridge amplifier was set to store date on the internal SD card instead of using wireless Bluetooth connection. After Pilot test 1, was changed to Further, the rearmost footrest was distorted a little bit, as the paddler complained about that the footrest was moving some millimeters when pressured.

4.3.2 Pilot test 2

On figure 3.5 a 30 seconds test at 85% can be seen. Data was successfully recorded and stored on the SD cards on the Shimmer3. The front footrest did only record 32 peaks which is not consistent with the stroke rate of the K2. When paddling at 85% the K2 stroke rate would be around 120-130 stroke per minute and thereby 60-70 strokes per 30 seconds. The 32 peaks could indicate that the front paddler has a large difference between his left and right kick as there are small peaks between the large peaks on figure 3.5. However, as the subject is a former national team paddler, we must assume that he has an efficient technique and thereby eliminating the large left - right difference. This could indicate that the footrest measuring device is not able to distinguish between left and right kicks. An explanation for this could be that the pulling motion of the contrary leg is hindering the load cells in measuring the applied force. The pull counteracts the direct pushing force, and the load cells are only able to measure a downward going force on the load cell.

This may account for the study of Nilsson, Rosdahl [2016] choosing a set-up which could measure both push and pull forces in the footrest. The current study's set-up could be upgraded with two additional load cells; one extra on each side of the footrest which measures the contrary direction enabling the device to measure the pulling force in the footrest.

The rearmost footrest recorded 32 small peaks in pilot test 2 as seen on figure 3.5. The peaks were significantly smaller than the peaks from the front footrest. However, it is probably not because of the paddler as the rearmost paddler is as well a former national team paddler. Compared to the front footrest, the rearmost footrest has a signal that seems to be in double peaks. However, the signal changes are too small to make a clear distinction of the doublet peak.

The explanation for the small peaks could be that the rearmost footrest tilted a bit. Therefore, extra spacers were put between the wood and the aluminum plate. The spacers were nuts, and they may therefore have reduced the voltage output of the load cells.

Figure 3.7 shows the acceleration during artefact's made in the end of the second pilot test. It shows that the devices are able to record artefact's simultaneously. The test lasted 50 minutes. Artefact's were made at the start and the end of the session. Figure 3.7 shows that the data has not drifted after 39 minutes of recording. This mainly because of the shimmers3 ability to syncronize with a computer clock when undocking the shimmer, and the fact the each data point has a timestamp. Thereby, even though data packages are lost, the timestamp will still have the correct time of the data. The shimmer3 high range accelerometers are an addition to the leg kick analysis. These could be used to investigate the leg kick influence on the kayak, and other factors influencing the kayak movement in the water. Figure 3.6 shows the acceleration of the shimmer during the entire 50 minute test. It is clear that accelerations can be seen during the four bouts.

Four bouts were made, and they are visible in the middle of the plot as four high acceleration periods. The shimmer3 high range accelerometer is an addition to the leg kick analysis as the shimmer3 has 3 accelerometers. These could be used to investigate the leg kick influence on the kayak. Further, different types of paddlers could be tested to see who has the least amount of influence on the tilting of the kayak. Other factors of kayaks movement in vertical, horizontal and lateral direction could be investigated.

Figure 3.5 do show that booth footrest measuring devices are able to measure a pattern which in evident in the time of the bouts. Peaks on both graphs seems to occur simultaneous, thereby, enabling an analysis of timing. However, it is impossible to know where in the stroke cycle the peaks are, as the peaks in the graph do not indicate whether it is the right or left leg kick. Further, are the peaks of the rearmost footrest device small and difficult to separate-

After pilot test 2, spacers were put between the wooden plate and aluminum plate on the rearmost footrest. The spacers would avoid tilting of the wooden plate.

4.3.3 Pilot test 3

In pilot test 3 as seen on figure 3.8, data were successfully recorded, two bouts are presented. The peak forces seem to be 450 N for the front footrest and 350 for the rearmost footrest. However, as previously discussed the footrest is only reliable on the middle point of the footrest. Meaning that the measured force can not be compared to the findings of [Nilsson, Rosdahl, 2016].

There are some irregularities on the rearmost footrest as the peak seems to vary in the plot. Further, the two footrests have not recorded the same amount of peaks. On the second bout, the front footrest (blue) has recorded around 40 peaks, and the rearmost footrest has recorded around 23 peaks. The subjects did 40 strokes. It fits with the peaks of the front footrest, however, it does not fit with the peaks of the rearmost footrest. An explanation for this could be that the footrests are not able to measure the individual leg kicks because the footrest is loaded with the weight of the feet all the time. It is clear that there is some synchronized activity on figure 3.8, as there was in pilot test 2, seen on figure 3.5. However, the two graph seems to resemble each other on figure 3.8, compared to figure 3.5. This may an effect of the extra spacers put in the rearmost footrest, between the wooden plate and aluminum plate. This makes an analysis of the peaks easier, compared to the data obtained in pilot test 2. However, as explained in section 4.3.2, it is impossible to see where in the stroke cycle the peaks occur. A further pilot test with additional equipment most be done in order to distinguish the peaks. to obtain this cammeras could be mounted on the kayak, which should be syncronized with the footrest. Thereby, it would be clear where in the stroke cycles the peaks occur. If the clear distinction of the leg kicks could be made, the set-up would be able to measure timing as it would be the difference between the peaks. This could be added to GUI without further complications.

5 Conclusion

The initial aim of the study was to develop a training tool that was able to live record and quantify the forces produced by the major muscles in the legs during a stroke cycle in a K2 during maximal effort. Further, the timing of the leg kicking between the front paddler and the rearmost paddler was investigated.

When evaluating the footrest measuring devices in the present study, the devices were not able to record live data, and the footrests were highly sensitive to the position of the load on the footrest. However, the set-up was successful in devolving a design which could measure the timing of the paddlers in a K2 without hindering the paddlers' technique. The set-up was relatively light weighted and could therefore be used in competition without compromising the weight of the kayak. Further, the reliability test showed a strong linear correlation between the applied force and the voltage output of the load cell when applied to the middle section of the footrests. However, it was not possible to measure the force in the leg kick as the results of the validity test showed a high percentage of deviation in the position of the loads. No clear distinction of timing between paddlers were made in the study, however, video analysis could enable this.

The following will evaluate whether or not the design requirements of the footrest measuring device were obtained in the final design.

Measure forces in the footrest in range 0-600 newton: The footrest measuring devices were able to measure force in the given range. However, as the reliability of the footrest measuring devices was low, it was not possible to obtain accurate force data.

Determination of timing between the footrest measuring devices in stroke rates up to 180 strokes pr minute: A determination of timing was achieved, but the paddlers did not paddle at maximal intensity. Therefore, further testing must be done at higher intensities.

The system must not inhibit the paddlers in their technique: The final design did not hinder the paddlers in using their legs or their technique. Changes were made during the test period in order to fit the footrest measuring devices to the paddlers' needs.

Must be relative lightweight system: The paddlers seek to have a K2 which weigh around 18.00 kg. The end system resulted in a total kayak weight of 17.893 kg, thereby keeping the kayak weight below 18.00 kg.

Live stream of the data: A live stream of the data was not obtained as the connection from the Bluetooth was too short.

5.1 Limitations and system improvements

In conclusion, the following section will discuss the future aspects of the project and how the footrest measuring device can be improved.

Wireless connection: Improving the wireless system would be crucial as this allows real time feedback. The improvement could be done by adding a radio transmitter on the footrest measuring device. As it has a higher range and a better signal strength than the Bluetooth connection. Another option could be Wifi, cellular data service, mobile satellite communications or wireless sensor networks in the footrest measuring device.

If the wireless system was improved, live data would be possible. The GUI would then be relevant as it would allow coaches to monitor the leg kick in the K2. Feedback "lamps" could be an addition to the GUI. Three lamps in red, yellow and green could be made. The lamps would represent the synchronization in the leg kick between the paddlers in the K2. An example of sync phases could be: Red 0-75 % or less in sync, yellow 75-90 % and green 90-100 % in sync. This would be an user-friendly method to make the synchronization visible.

Mechanical problems: The mechanical problems must be solved. [Nilsson, Rosdahl, 2014] chose to have a footrest with two footrests for optimal force measurement. However, the two footrests might have hindered the stirring of the kayak as it leaves little space for the steering pin. A kayak bouncing the water would be difficult to steer with this small space for the steering pin. The current study attempted to make a footrest measuring device which did not hinder the steering abilities of the kayak. Even though the complete leg kick was not measured, the footrest measuring device of this study could be a better way to measure the leg kick. The footrest measuring device could be improved by adding two additional load cells which measure the contrary direction. Thereby, a more detailed view of the leg kick would be evident as it could give additional information about the pulling motion of the contrary leg in the leg kick. Further, each load cell could have it's own voltage output, as they in the current set-up are summarised. Thereby, leg kicks on either side might be separated from each other.

Video analysis: Connecting the data with video analysis could be useful for the coaches as this will provide the coach the opportunity to see precisely where in the stroke cycle the leg kick begins and ends. A GoPro camera could be mounted on the front end of the kayak with a good view of the paddler. The video and data from the footrests should be imported to MATLAB in a MATLAB app. The video could be displayed alongside a force plot from the footrest. Allowing the user to scroll in the data alongside the video. Enabling the user to see precisely were in the stroke peak forces are generated.

Seat forces: A further development could also be to measure the forces in the kayak seat. The set-up of Nilsson, Rosdahl [2014] could here be implemented. This will result in a force transducer being placed under the kayak seat which allows for horizontal forces to be measured. However, a different set-up could be used as well where load cells are placed under each supporting point of the seat. This will give a more detailed view on how the forces in the seat behave, and the four load cells will probably be lighter than a steel beam.

To sum up, the above mentioned improvements must be solved before implementing the footrest measuring device on the Danish national kayak team.

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A Appendix-Theory

A.1 Strain gauge

If force is applied to a material a deformation of material occurs. This type of deformation is called mechanical strain. A strain gauge can measure this deformation. The strain gauge can measure the change of resistance, resulting in an unbalance in voltage that is proportional to the force applied. in the material. The strain gauge i small and is glued to the material, and thereby, it bends with the material [Winter, 2009,pp.117].

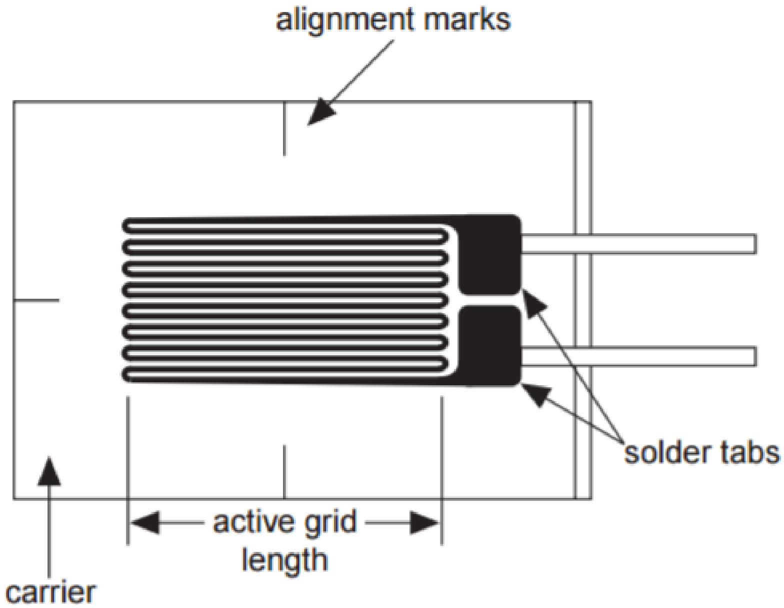

Figure A.1: *A metallic bonded strain gauge*

On figure A.1 a metallic bonded strain gauge can be seen. It consists of a metallic foil folded in a certain pattern called the grid. The grid is mounted to a plat called the carrier. The carrier is glued to the test element. So strain is transfered directly to the grid.

The strain gauge is placed in a bridge circuit, bridge circuits are used in a wide variety of fields from measurement, switching, oscillator and transducer circuits. The bridge circuit is called a

Wheatstone bridge after the man who invented it Sir Charles Wheatstone.

Generally there are three types of bridge circuits.

Quarter bridge Consist of one strain gauge and three resistors. A change in the strain gauge resistance will produce a voltage output due to unbalance in the bridge. However due to only one strain gauge the setup will be temperature sensitive.

Half bridge Consist of two strain gauges and two resistors. In a half bridge circuit the second strain gauge can be used as a dummy gauge by placing it transverse to the strain, so the strain has minimal effect on the dummy gauge. The dummy can therefore be used to correct for temperature changes as the temperature changes is the same on both gauges. Meaning that the ratio resistance between the two do not change.

A half bridge setup can ex. also be used to measure bending and compression of a beam. Be placing one gauge in the bending direction and one i the compression direction.

Full Bridge Consist of four strain gauges. Where two gauges is mounted in bending and two in compression.

The strain gauges that were used in the setup had capacity of 40-50 kg. A comprehensive Error of 0.05 mv/v. They had a Input Resistance of 1000$\pm$20 Ω and an output resistance of 1000$\pm$20 Ω. The limit excitation voltage V $\leq$10. However, 5 V was used.

The strain gauge consists of a rectangular with a beam in the middle with two strain gauges mounted to measure flexion as seen on figure A.2.

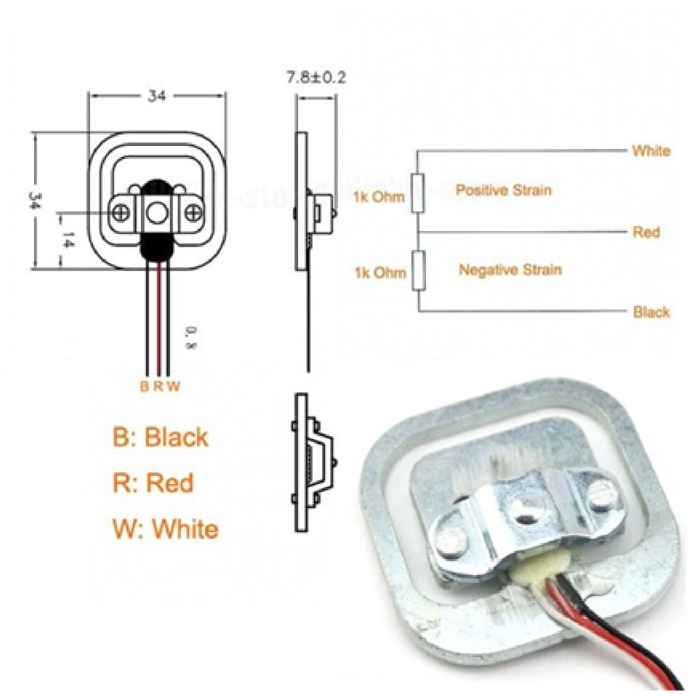

Figure A.2: *The type of strain gauge used in the study. The dimensions is in mm.*

If measurements were between red and black, negative strain would be measured, and if between white and red positive strain would be measured.

A.2 Shimmer3 Bridge Amplifier

The Shimmer3 Bridge Amplifier can gather load cell data from force and resistance measurements. The Shimmer consists of a bridge amplifier, excitation source, two 3.5mm jack connectors and a resistance divider amplifier which permits resistance measurements [Shimmer, 2017 (accessed April 3, 2017]. The shimmer3 can be seen on figure A.3.

Specifications of the Shimmer3 Bridge Amplifier: Gain: 183.7 ± 1 % (Normal Channel), 551 (3x Normal) ± 1 % (High Gain Channel) Frequency Range1: DC..1kHz (Normal Channel), DC..100Hz (High Gain Channel) Input Signal Range: ±7mV, ±2.5mV/V (Normal Channel), 0-4mV, ±1.43mV/V (High Gain Channel) Excitation Voltage: 2.8V ± 5 % Compact Dimensions: 65X32X12mm [Shimmer, 2017 (accessed April 3, 2017].

Figure A.3: *The Shimmer3 bridge amplifier*

A bridge amplifier is an electronic amplifier which is able to increase the power of a signal. An amplifier can have a gain, the gain is the ration between the input signal and output signal. The ratio is output divided with input. If the input is 1 volt and the output is 10 volt, then the gain is 10, as the signal has been increased by a factor 10.

Appendix-Physiology B

B.1 Warm-up

A warm up before exercise helps prevent injuries and prepares the muscles and joints for exercise which is performance-enhancing. A good warm-up simulates the anticipated movement [McArdle et al., 2010].

Five physiologic mechanisms are improved due to warm up:

1. The contraction speed of warmed muscles
2. The economy of movement in the warmed muscles because of a lower viscous resistance
3. The release of oxygen molecules from hemoglobin which facilitates the oxygen utilization
4. The nerve transmission and muscle metabolism
5. The blood flow through active muscle tissue through dilation of the vascular beds which increases temperature

[McArdle et al., 2010, pp. 523-524]

Appendix-Declaration C

C.0.1 Declaration of Consent

Standard Requirements

Prior to the tests, each subject signed a declaration of consent. The declaration was written in danish, as the kayak paddlers were danish.

Aalborg Universitet

kklitg11@student.aau.dk

Deltageinformation og samtykkeerklæring:

I dette dokument vil du finde beskrivelser af de tests som du kommer til at udføre. Formålet med dette dokument er, at sikre at du som testperson føler dig velinformeret og parat til deltagelse i testningen. Endvidere skal du efterfølgende kunne underskrive en samtykkeerklæring, som du vil blive bedt om, at underskrive før testens påbegyndelse. De anvendte tests tager udgangspunkt i videnskabeligt baserede testprotokoller, som er udarbejdet og evalueret af Projektgruppen samt nært tilknyttede forskere. Afklarende spørgsmål vedrørende disse skal rettes til projektgruppen. Forud for testningen vil vi bede dig om, at nærlæse procedurerne på de tests du skal deltage i.

1. Information til testpersonen I forhold til din deltagelse i testning af maksimal fysisk kapacitet, bedes du være opmmærksom på følgende. Hvis du:

- Er skadet,
- Har været skadet for nylig,
- Er syg,
- Har andre forbehold vi som testpersonel bør være opmærksomme på,

bedes du venligst gøre den testansvarlige opmærksom på dette, da der i disse tilfælde kan få medførede sundhedsmæssige konsekvenser, hvis der ikke tages forbehold for dette under testningen. Projektgruppen forbeholder sig retten til, at nægte testning af personer, hvor vi vurderer, at der foreligger markant risiko for hellbredsmæssige risiko, som følge af testning. Vi anbefaler på det kraftigste, at du ikke får foretaget testene hvis du lider af helbredsproblemer såsom forhøjet blodtryk, hjerteproblemer eller lignende.

Op til testene ønsker vi, at:

- Du er veludhvilket.
- Du ikke har trænet til udmattelse på dagen eller dagen før testen påbegyndes.
- Du ikke har indtaget alkohol, eller euforiserende stoffer indenfor de sidste 24 timer op til testens påbegyndelse.
- At du har fastet minimum to timer op til testen.

Hvis du ikke overholder ovenstående vil det medføre, at testresultaterne påvirkes og at de derfor ikke vil være relevante for projektgruppen.

Herudover bedes du udføre testen med følgende udstyr:

- Rotøj
- Pagaj
- Overtræk
- Have en tætsiddende strømpe/sok på

2. Vedrørende ansvar og ulykke

Projektgruppens medlemmer, som varetager testningen, er ikke ansvarlige for skader opstået under testforløbet, medmindre de er sket ved uforsvarlig behandling af dig som testdeltager og uforsvarlig håndtering af testudstyr og/eller mangelfuld overholdelse af sikkerhedsprocedurer undervejs. Ved at underskrive denne samtykkeerklæring accepterer du, at såfremt du har tegnet din egen ansvars- og ulykkesforsikring skal denne dække skader du eventuelt måtte påføre dig selv eller testudstyet forsætligt eller uagtsomt under testen, hvis skaderne sker som følge af:

- Uheld i kajakken på vandet

Test dag: 3-4 x 20-30 skekunder i 90% i toerkajak Under testen vil kræfter i fodsparket bliver opsamlet. Testens forløb er som følger:

1. Introduktion til testforløbet
2. 15 minutters opvarmning

3. Selve at ro testen vil være 3-4 x 20-30 skekunder, mens det formodes at tage 50 min med opvarmning og nedkøling.