THE EFFECT OF STROKE RATE ON FORCE ASYMMETRY IN ROWING

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ABSTRACT

Eliminating imbalances is crucial in rowing, as asymmetry can impact performance or cause injury. This study examines the effect of stroke rate on force asymmetry. A subject rowed on an ergometer at increasing stroke rates, incorporating rotation at the compressed position of the stroke. The angular velocity of the rower's torso and forces on the left and right side of the footplate and seat were measured. Results showed that higher stroke rates increased force asymmetry on the footplate, with a positive linear correlation, corresponding to a 5% increase in asymmetry per stroke rate increase. No correlation was found between stroke rate and force asymmetry on the seat, though a difference of 103.5 ± 4.5 N existed between sides. These findings suggest that while stroke rate affects footplate asymmetry, the rower's body may attenuate it. Coaches and athletes should target asymmetry reduction to improve performance and minimize injury risk.

Keywords: rowing, stroke rate, force, ergometer, asymmetry

INTRODUCTION

In competitive rowing, achieving balance and symmetry in the boat is crucial, as races often come down to fractions of second over the two-kilometer race distance. Depending on the boat class, these races will include around 220 strokes, so even minor imbalances can affect the speed and efficiency of the boat and add up to significant results [1]. Understanding and correcting force imbalances can therefore provide a competitive edge and reduce injury risk by allowing athletes to optimize their stroke. By analyzing the forces involved with the rowing stroke, we aim to identify influential factors to force asymmetry in the stroke, particularly in relation to stroke rate, and contemplate the body's response to these asymmetries.

The rowing stroke consists of a segmented process. From a compressed position with the oar in the water, the athlete will drive his or her legs, then swing the body, then finish by bringing in the arms and taking the oar out of the water. The process then reverses in the recovery sequence, in which the athlete approaches the stern, or front, of the boat where the oar is placed in the water once again. By varying the rate at which an athlete rows on a rowing machine and introducing torso rotation to accurately simulate on the water rowing, we investigate the effects on force asymmetries in the seat and the footplate to determine possible imbalances.

An experienced rower rowed on a dynamic ergometer at varying stroke rates: 20, 24, 28, and 32 strokes per minute. The rower will also be asked to include the element of rotation, as they would in a boat, to create a realistic force distribution. The force on the left and right side of the seat and footplate will be observed. The rower will also be wearing a 3-axis IMU to measure the angular velocity of the torso during the varying stroke rates. With this data, we can determine the effect of varying stroke rate on asymmetry in the boat and help coach more optimal technique and reduce injury risk.

EXAMINING THE ROWING STROKE

THE STROKE SEQUENCE

It is first important to understand the proper sequencing of the rowing stroke. Rowing can be done on the water in a boat, or on land on a rowing machine. The basic mechanics of the stroke remain the same for either case. Each stroke can be divided into different sections as demonstrated in Figure 1.

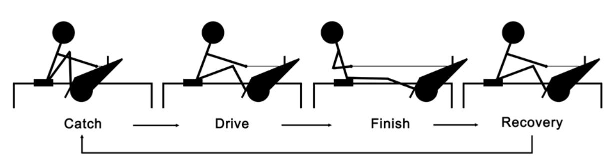

Figure 1: The progression of the rowing stroke. The sequence starts at the catch and continues to the drive, finish, recovery, and back to the catch to repeat the cycle.

Each stroke in the boat or on the ergometer follows the same progression. The rower begins at the catch, in which the legs are compressed, and the body is leaning forward. The rower then starts the drive, where the power of the stroke comes from. The drive is completed by pushing with the legs, swinging the back, and bringing in the arms. Once the drive is done, the rower reaches the finish. The recovery begins from there, when the process is reversed to reach the catch once again. The speed at which one rows is measured in stroke rate, with units of strokes per minute. An easier row is completed at 18-20 strokes per minute, while maximum effort rowing can reach 40 strokes per minute [3] at the highest levels. One should note that on the ergometer, there is typically no rotation of the body at the catch position. The entire motion is done along a single axis back and forth. In actual sweep rowing, in which an athlete holds one oar and the most common amongst collegiate and national rowers, there is significant rotation at the catch in order to achieve a longer stroke and higher watt output [6].

Figure 2: MIT's varsity 8+ at the catch position during a race. [9]

In Figure 2, one can see the rotation to one side of the boat. Throughout the stroke sequence, this position is typically the most unstable [3] due to the divergence from the center axis of the boat. Along with using an oar rather than a handle, this rotation is the main difference between on the water rowing and rowing on the ergometer. Moreover, the rotation to the outboard side of the boat only occurs in sweep rowing.

FORCE ANALYSIS ON AN ERGOMETER

Our experimentation focused on the forces involved between the rower and ergometer; therefore, we should understand the underlying forces between these two systems. Figure 3 demonstrates a free body analysis on the forces applied to the rowing machine. There are three contact points between the rower and the ergometer. The handle, the seat, and the footplate (or foot stretcher). The rower pushes against the footplate to produce power and acts as a mechanical link to the force in the handle. The normal force (F_{seat}) allows the rower to slide up and down the tracks. Our machine will be instrumented to observe F_{seat} and F_{foot}; however, rather than observing the overall force, the force on the left and right side of each will be measured. This methodology differs from much contemporary research, which commonly examines the overall force at each of the three contact points. Due to the angle of F_{foot}, there is a vertical component of force when the rower engages the drive sequence. Performing a force balance, one can observe that pushing on the footplate will involve a decrease in the normal force F_{seat}. The horizontal component of F_{foot} is balanced by F_{handle}.

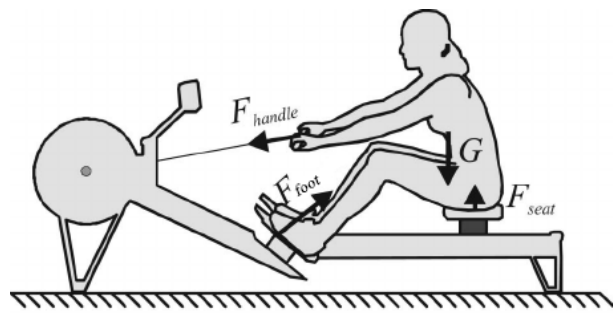

Figure 3: Free body diagram of the ergometer and rower systems displaying the external forces between the rower and the rowing machine. The rower here is shown in the drive position [7].

PREVIOUS STUDIES ON FORCE ASYMMETRY IN ROWING

Several studies have been previously conducted which examine the forces involved with the rowing stroke. Buckeridge et al. explored foot force production in experienced rowers. This study highlighted the importance of symmetrical loading of the footplate for both performance and injury prevention purposes [5]. It was also found that there was asymmetry present in the stroke at all rates, with as high as a 28.9% difference in the left and right side at peak force; however, the asymmetry in forces was not sensitive to the stroke rate [5]. Nasruddin et al. similarly highlighted that symmetrical force loading of the footplate is important for peak performance [3]. This study also found, conversely, that asymmetry decreased from 7.1% to 1.7% from lower to higher rates. The study demonstrated that peak power increased 23.9% from the lowest to highest stroke rate [3]. In a separate study, Buckeridge et al. investigated the body kinematics of the stroke and forces on the seat and footplate. The study ascertained that bilateral asymmetries of the lumbar-pelvic region can be useful predictors for back injury development in rowers [10]. Moreover, symmetrical loading of the spine can assist in lower back injury prevention [10]. In all of these studies, the forces were measured on a static ergometer, in which only the seat slides back and forth. Moreover, there was also no element of rotation at the catch position involved, which differentiates our study from contemporary research.

EXPERIMENTAL DESIGN

DYNAMIC ERGOMETER CONFIGURATION

To analyze the forces applied on the seat and footplate by a rower, a dynamic ergometer (RP3 Model T) was instrumented. On both the seat and footplate, two Interlink Force Sensitive Resistors (IL-406) with a maximum output of 1 kN were placed on the right and left side to measure the force output on the respective sides. Each FSR was calibrated with a Vernier Force Plate (FP) with range 0 to 800 N and resolution 0.3 N. A 3-axis Vernier Gyroscope (GDX-ACC) with range ±34.9 rad/s was mounted on the rower's chest to measure the angular velocity about the Y-axis throughout the stroke. One should note that with a dynamic ergometer, the one used in this experiment, both the seat and body of the ergometer are free to slide along the track to which they are attached. This feature is implemented to create a more realistic feeling of rowing on the water.

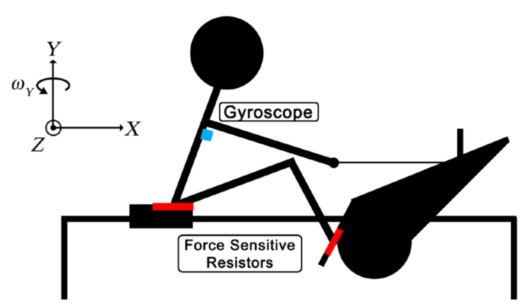

Figure 4: The experimental setup with the rower at the drive portion of the stroke sequence. Both the seat and body of the ergometer are free to slide along a track. The Gyroscope (GDX-ACC) and force sensitive resistors (IL-406) are connected to a LabQuest Mini and LabQuest 3 to collect measurements.

EXECUTION OF THE STROKE

To best simulate the rowing stroke as on the water, an athlete rowed on the dynamic ergometer with the element of rotation at the catch position introduced. The sequencing followed the same cycle as described above, with the added element of rotating the torso in the negative direction about the Y-axis. For each trial, 20 seconds of rowing was recorded at 100 Hz through the instrumentation. 5 trials were conducted at the varying stroke rates of 20, 24, 28, and 32 strokes per minute each.

RESULTS AND DISCUSSION

FORCE CURVES AND ANGULAR VELOCITY

To better understand the force asymmetry across different stroke rates, raw force and angular velocity data were collected. Figure 5 demonstrates the force curve for the left foot for a single stroke. The catch and finish times are indicated to better understand the curve. Applied force increases during the drive phase and decreases to near zero once the stroke is completed after the finish and during the recovery.

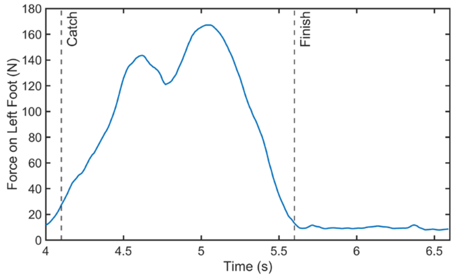

Figure 5: Example force profile of the left foot for a single stroke measured over 4 seconds to 6.6 seconds from the first trial at a rate 20. The force increases during the drive phase after the catch. The applied force settles to zero after the finish when the drive is complete and the recovery sequence begins.

A full trial consisted of several strokes within the 20 second period. Figure 6 shows the full force profile for a single trial at a rate of 20 strokes per minute for both the left and right sides of the footplate. The graph demonstrates periodic increases in force of varying amplitudes which correspond with each stroke. The peak difference in force for a single stroke is annotated. We will use this definition to make overall conclusions about stroke rate and force asymmetry. Moreover, the left foot consistently generated higher peak forces than the right foot on the footplate, indicating either a significant muscle imbalance, or highlighting the asymmetry associated with rotation at the catch. Given that the subject rotated to the right side in all trials, it is expected to see the left side show higher forces at the catch position.

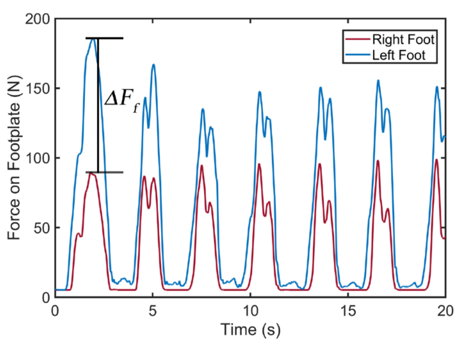

Figure 6: Force applied by the left and right foot on the footplate of the dynamic ergometer at 20 strokes per minute. The force profiles for each foot demonstrate periodic peaks in force corresponding with each stroke, with alternating magnitude in peak force. The annotated ΔF_f defines the peak difference in force for a single stroke. This trial and all subsequent trails were recorded with rotation to the right side.

We continue observing the raw force data in Figure 7, which examines the same trial at a rate of 20 strokes per minute; however, now observing the forces applied to the left and right side of the seat of the dynamic ergometer. Similarly, the graph demonstrates periodic troughs correlated with each stroke in the trial. The fluctuations in force are overall less conclusive and pronounced that the footplate data. The difference suggests that the force on the seat is not as consistently or directly influenced by mechanics of the stroke like rotation. On average, however, the left side shows higher forces applied.

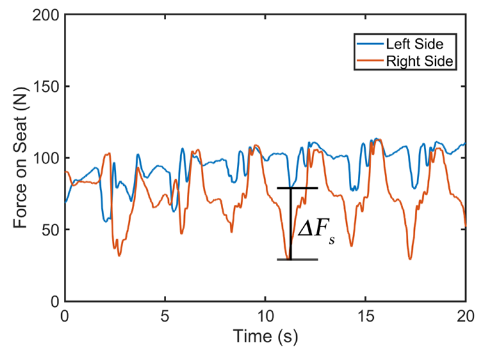

Figure 7: Force distribution on the left and right side of the seat of the dynamic ergometer at 20 strokes per minute. The force profile demonstrates periodic troughs in force on the seat corresponding with each stroke, with alternating magnitudes. The annotated ΔF_s defines the peak difference in force for a single stroke.

Throughout the trials, we also observed the angular velocity of the rower's torso across the difference stroke rates. Figure 8 demonstrates the recorded data from a trial performed at a rate of 20 strokes per minute. Similarly, the velocity follows a periodic cycle that corresponds to the stroke. On average, the angular velocity increases as the rower rotates into the catch position, then sharply drops as the rower reverses the motion and engages in the drive sequence. The angular velocity remains at zero as the rower undergoes the remainder of the stroke. The process begins once again when the catch is approached. The specific periods of this increase in angular velocity corresponding to the catch rotation are highlighted. Comparing the angular velocity and force data, one can see that the period of maximum angular velocity commonly correlates with the peaks or troughs of force asymmetry demonstrated in Figures 6 and 7.

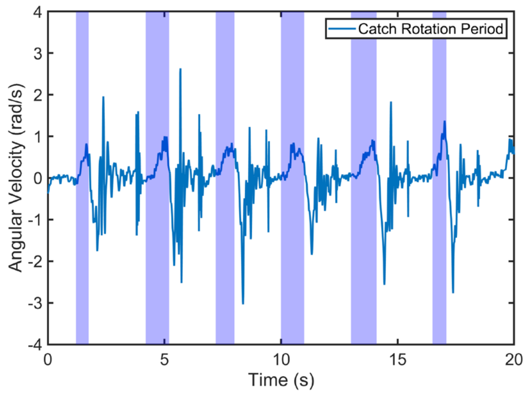

Figure 8: Angular velocity of a rower's torso at 20 strokes per minute. The plot shows periodic patterns in torso rotation speed corresponding with each stroke. The highlighted region demonstrates the rotation period which occurs into the catch position, the point of maximum rotation.

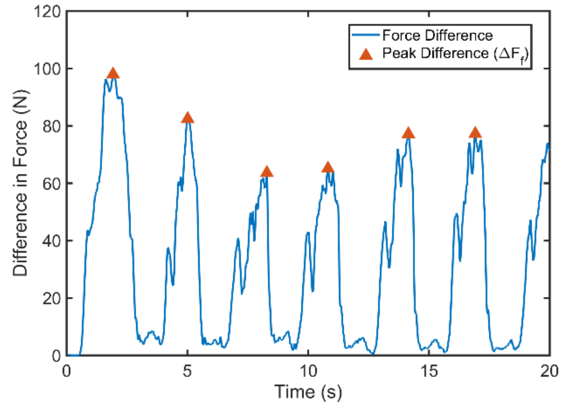

Figure 9: Difference in force between the left and right foot during a trial at 20 strokes per minute. The line represents the continuous force differential over time. The peak difference for each stroke is marked which corresponds to ΔF_f.

DETERMINING FORCE ASYMMETRY

Extracting the peak force differential per stroke was an essential aspect of analyzing the effect of stroke rate on force asymmetry. A MATLAB script was used to exact these large differences in force. To quantify this value, the difference in force between the left and right sides for the whole trial was calculated. The local maxima were then determined and recorded. Figure 9 demonstrates this process for the footplate for a single trial at a rate of 20 strokes per minute. The plot follows a similar periodic cycle as the raw force data, with each peak corresponding to a single stroke in the trial. The calculated maximum is marked and gives us the value of ΔF_f. By identifying ΔF_f for each stroke, we have a basic metric for understanding the asymmetry involved throughout the stroke. Further analysis of ΔF_f across all trials will allow us to determine the relationship between stroke rate and force asymmetry. This process is repeated for the seat to determine ΔF_s for every stroke across all trials.

COMPARISON OF ASYMMETRY

After obtaining the ΔF for each stroke for all trials for both the seat and footplate, the values were plotted against the different strokes rates to determine a possible relationship between the force asymmetry and stroke rate. Moreover, we wanted to determine how the asymmetry may differ between the forces applied to the footplate and the forces applied to the seat of the dynamic ergometer. Figure 10 presents a scatter plot for the ΔF_f across all strokes rates and trials for the footplate. A linear fit of the form $y = ax + b$ was first applied to the data. A positive linear relationship was established, indicating that increasing rate amplified the asymmetry in force in the footplate.

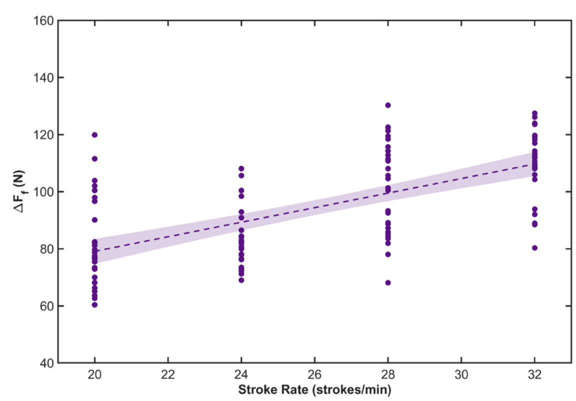

Figure 10: Scatter plot of all ΔF_f for the footplate from each stroke from all trials at stroke rates 20, 24, 28, and 32 strokes per minute. A linear fit of the form $y = ax + b$ was applied with parameters a = 2.55 ± 0.58 and b = 28 ± 15 $\frac{rad \cdot min}{strokes \cdot s}$.

Figure 11 demonstrates the same scatter plot, comparing ΔF_S to stroke rate for each stroke across all trials for the seat. Conversely, no correlation between stroke rate and force asymmetry was observed for the seat. The average force differential, however, was measured and plotted to demonstrate that asymmetry is still present in the seat, but it is not influenced by stroke rate.

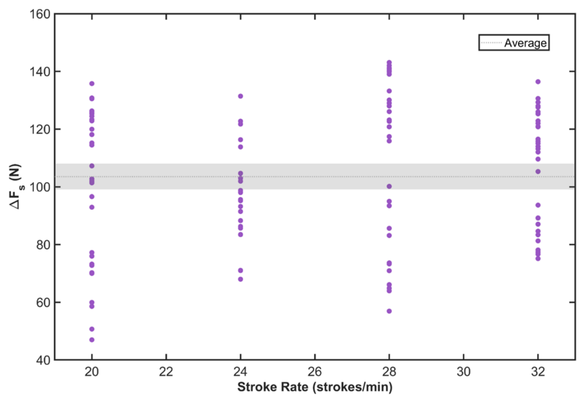

Figure 11: Scatter plot of all ΔF_S for the seat from each stroke from all trials at stroke rates 20, 24, 28, and 32 strokes per minute. No correlation is observed between stroke rate and ΔF_S on the ergometer seat. The average ΔF_S across all trials is indicated with a value of 103.5 ± 4.5 N.

The contrast between results for the footplate and seat indicates that force asymmetry is amplified at higher rates in the footplate but not the seat. This conclusion implies that while asymmetry is present in both measured locations, the body may act as a filter to attenuate the asymmetry as it increases in the footplate with rate. The mechanical chain between the footplate and seat or other supporting muscle groups could filter the force difference between the left and right side of the seat. This increase in asymmetry could also be highlighted in the forces applied to the handle of the ergometer, which were not measured for this experiment. Further experimentation in future studies with instrumentation on the ergometer handle and muscle EMG could provide insight into the discrepancy between results for the asymmetry in the footplate and seat.

COMPARISON TO CONTEMPORARY DATA

The results from this experiment differ from previous research into similar subject matter. One study found that asymmetry in the footplate was not influenced by stroke rate [5], while another found that asymmetry in the footplate decreased with increasing stroke rate [3]. The difference in results could be due to the experience level of rowers in the trials. Moreover, these experiments involved multiple subjects with different weights, peak power, and gender. More experimentation with different subjects is required to verify the comparison to contemporary research.

CONCLUSIONS

This study explored the effect of stroke rate on force asymmetry in rowing and revealed significant differences between the forces on the foot plate and seat of the ergometer. The findings demonstrate a positive linear correlation between stroke rate and asymmetry on the footplate. The linear fit determined a slope of 2.55 ± 0.58 $\frac{rad\cdot min}{strokes\cdot s}$ and an intercept of b = 28 ± 15 $\frac{rad\cdot min}{strokes\cdot s}$. This correlation equates to a 5% increase in force differential between the left and right sides of the footplate with each increase in stroke rate. In contrast, the force asymmetry on the seat demonstrated no significant correlation with stroke rate but revealed an average force differential of 103.5 ± 4.5 N between the left and right sides of the seat. This discrepancy implies that while footplate forces increase in asymmetry with stroke rate, the body may filter out these increased differences in force.

These findings highlight the increased potential for imbalance at high-rate and high-intensity rowing, which could impact both performance and injury risk. Further studies examining muscle activation and output in athletes could provide insight and determine if the body dampens the asymmetry. Coaches and athletes could use this information to focus on reducing imbalance at higher rates and in general to potentially improve performance and decrease risk of injury. Future iterations of the research could expand the measurement apparatus to observe handle forces to provide a complete picture of the rower and ergometer interaction. Additionally, studies of a wider range of rowers with different experience, weight, peak power could add to the application of these findings.

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