The Influence of Stretcher Height on the Mechanical Effectiveness of Rowing

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The aim of the present study was to determine the effect of varying the height of the foot stretcher on the mechanical effectiveness of rowing. Ten male university level rowers rowed maximally for 3 minutes 30 seconds on a modified Concept 2 rowing ergometer. Each participant completed one trial at three foot stretcher heights. Position 1 was the original Concept 2 stretcher position, with Position 2 being located 5 cm and Position 3 being 10 cm above the original position and in the same orientation. Pull force and velocity were measured, and mean power generated by the rowers was calculated for each stroke. It was shown that in all three stretcher positions, mean power per stroke decreased as a function of time during the trial, confirming the fatiguing effects of the task. Although mean power per stroke did not differ significantly between stretcher positions at the start of the trial, $p = 0.082$, a significant difference was observed between the original stretcher position and Positions 2 and 3 at the end of the trial, $p < 0.05$. The lowest decline in mean power occurred in the highest stretcher position. It is suggested that this improvement in effectiveness is due to a reduction in the active downward vertical forces applied to the foot stretchers which does not contribute to forward propulsion, and thus a reduction in energy waste during each stroke. It was hypothesized that further raising the stretchers will continue to lead to an improvement in effectiveness until the optimum stretcher height is reached, above which effectiveness will be reduced.

Key Words: force, moments, power

The aim in rowing is to propel the boat as fast as possible over a race distance typically of 2,000 meters. The rower applies high forces to the foot stretchers during the drive phase of each stroke (Figure 1), which are transferred by the oar to the water in an attempt to maintain a high mean boat velocity.

When looking at the mechanical effectiveness of rowing technique, it is important to consider a number of factors. First, vertical forces applied to the foot stretchers ($F_{foot-V}$, see Figure 1A) should be minimized as they do not contribute to boat propulsion and will result in an ineffective transfer of energy. In the following
analysis we consider the vertical components of force maintaining static equilibrium in a stationary catch position. If the foot stretcher height is below seat level (by the height differential $h_1$, see Figure 1B), as is commonly the case, a vertical component of force ($F_{foot-V}$) applied to the stretcher will arise from the resulting downward inclined line of action of the musculoskeletal force applied at the feet. This reduces the proportion of the rower’s body weight that is applied to the seat. Since the rower’s weight, $W$, must be distributed between the stretcher ($R_{foot-V}$) and seat ($R_{seat-V}$), it follows that

$$W = R_{foot-V} + R_{seat-V} \quad (1)$$

This reduction in body weight applied to the seat is due to the rower bracing against the foot stretchers to apply a body lifting force. It is this lifting force that causes an ineffective use of energy, since it does not contribute to propulsion. Decreasing the foot stretcher height, $h_1$, by raising the stretcher position relative to the seat, can reduce the downward component of stretcher force ($R_{foot-V}$) as shown in Figure 2A, decreasing the body lifting force and reducing energy waste.

When examining the forces the rower applies to the boat, however, a second factor must be considered: that of the distance between the forces applied to the oar handle and the foot stretcher, as determined by the height $h_2$ (Figure 1B). Depending on the magnitude of the forces the rower applies during the drive, this offset of force alignment will have a rotational effect on the rower’s body. When a resisting force is applied by the oar handle, the rower’s body may begin to rise away from

Figure 1 — Forces in rowing. (A) Forces applied to boat by rower during drive phase. Reaction forces also shown. Horizontal seat forces are ignored as they are assumed to be negligible. The handle forces are shown to be horizontal, although in practice a small vertical component of force should be present in on-water and ergometer rowing. (B) Vertical distances between point of application of foot stretcher force and height of both the seat and oar handle.
Figure 2 — Free body diagrams and force polygons for two stretcher conditions. (A) Foot stretcher is located below height of seat such that a downward vertical component of force is applied by the feet. Due to this, the reaction at the seat (R_{seat}) is less than body weight (W), as shown by corresponding force polygon. (B) Forces present when the stretcher is at a height at which there is no vertical component of stretcher force. Thus the reaction force at the stretcher is horizontal and the reaction at the seat is equal to body weight.
the seat if it is not counterbalanced fully by the restraining moment arising from the rower’s weight, again resulting in energy waste.

Summing the moments about the foot stretcher while neglecting horizontal frictional forces at the seat gives,

\[ W_e_1 - R_{\text{seat-V}}e_2 - R_{\text{handle}}h_2 = 0 \] (2)

where \( e_1 \) is the horizontal lever arm distance of the rower’s center of mass from the point of application of stretcher force, and \( e_2 \) is the horizontal lever arm distance of the seat reactive force, \( R_{\text{seat-V}} \), relative to the stretcher. From Equation 2 we can see that as the vertical distance \( h_2 \) approaches zero, the vertical reaction force exerted by the seat tends toward

\[ R_{\text{seat-V}} \rightarrow W e_1 / e_2 \] (3)

From Equation 1, the proportion of the rower’s body weight supported by the seat is therefore maximized, which will result in decreased passive vertical forces at the foot stretcher. There will also be a reduction in the magnitude of the vertical component of the active musculoskeletal forces acting at the foot stretchers. Any active downward stretcher forces would act to lift the rower’s body away from the seat. Therefore, by reducing these forces, more of the energy the rowers put into the system could be used to propel the boat and improve the mechanical effectiveness.

The purpose of this study, therefore, was to examine the influence of foot stretcher height relative to the seat and the oar handle pull height on the mechanical effectiveness of the rowing action by examining the decline in mean power per stroke due to fatigue for different stretcher heights. It was hypothesized that higher stretcher positions would improve the mechanical effectiveness of the rower and thus attenuate the decline in mean power per stroke during each trial as a result of fatigue.

**Methods**

Ten male university level rowers age 20.6 years (±1.6 yrs), with a mean height of 182.6 cm (±6.3 cm) and a mean mass of 80 kg (±8.7 kg) participated in the study. They all gave written informed consent, and ethical approval for the study was granted by the local ethics subcommittee. The participants had 2.3 years (±1.8 yrs) experience in on-water rowing and were accustomed to at least 4 days a week of ergometer rowing training.

A Concept 2 model C rowing ergometer (Concept 2, Morrisville, VT) was used in the study. We used an ergometer since land-based rowing ergometers provide a simple way to replicate the movements made during rowing for controlled testing of mechanical and physiological factors. Also they have been shown to closely simulate on-water rowing (Hagerman, 1984; Lamb, 1989; Nelson & Widule, 1983). The air resistance of the fan that provided a resistance to pull force at the handle was set to 4 for all trials. This setting equated to a drag factor, \( k \), of \( 1.25 \times 10^{-4} \text{ Nms}^2 \), which was calculated by the PM2+ monitor of the ergometer by the equation,

\[ k = I \frac{d(1/\omega)}{dt} \] (4)

where \( I \) is the moment of inertia of the flywheel and \( \omega \) is the angular velocity of the flywheel (Dudhia, 2002).
Force applied to the handle was measured using a 5-kN axial load cell (F256, Novatech Measurements Ltd., St Leonards on Sea, U.K.) which was inserted in series between the handle and the chain of the ergometer. The load cell had a linearity of 0.05% and a hysteresis of 0.05%. Handle velocity was measured using a DC tachometer (263-6005, RS Components, Corby, U.K.). The tachometer enabled measurement of the rotational velocity of the ergometer chain sprocket (pitch diameter = 2.83 cm), from which linear handle velocity was calculated to a resolution of 0.07%. Both analogue signals were sampled at 50 Hz and passed to a 12-bit resolution analogue-to-digital converter (KPCI-3101, Keithley Instruments, Cleveland, OH) before being downloaded to a PC for later analysis.

The foot stretchers of the ergometer were modified so that along with normal foot height, two higher foot positions could be provided (\(d_1 = 5\) cm and \(d_2 = 10\) cm, Figure 3) on the same inclined surface. This meant the stretchers were in effect raised vertically by 3.4 cm between conditions. In each position the foot was held in place using the original Concept 2 foot cradle and strap.

![Figure 3 — Foot stretcher conditions used. (A) Original Concept 2 foot stretcher position relative to the seat. (3B and 3C) The two new positions for the foot stretcher, with \(d_1 = 5\) cm and \(d_2 = 10\) cm.](image)

Each participant was required to attend three testing sessions with the foot stretcher position being shifted up the plate by 5 cm on each visit, approximately a week apart. The participants were instructed not to alter their normal training during this period. At the start of each testing session they performed a 4-min warm-up in which they rowed at 18 strokes per minute. Three 5-sec bursts of higher intensity effort were undertaken during the last minute of the warm-up period. During the next 4 minutes the participants performed static stretching. They were then instructed to row with maximal effort for 3 minutes 30 seconds, at 30 strokes per minute, during which time we collected data on handle force and velocity. Handle force and velocity outputs were sampled continuously throughout each trial, and stroke rate was indicated to participants by the PM2+ display of the ergometer. They were verbally encouraged to maintain both the maximal effort and the requested stroke rate throughout each trial, and all were blind as to the purpose of the study.
Power, $P_{\text{rower}}$, applied by the rowers to the handle was calculated using the formula,

$$P_{\text{rower}} = F_{\text{handle}} \times V_{\text{handle}}$$

(5)

where $F_{\text{handle}}$ is the force applied to the oar handle and $V_{\text{handle}}$ is the velocity of the oar handle. Mean power per stroke was then given as the mean of the power data over the drive phase of each stroke. As power is a function of both force and velocity, any changes in power over the duration of the trial might be caused by changes in both handle force and stroke distance. Stroke distance was calculated by,

$$\text{Stroke Distance} = \int_{t_o}^{t} V_{\text{handle}} \, dt$$

(6)

where $t_o$ and $t$ are times for the start and end of the drive.

The last 100 strokes of each trial were identified for data analysis. This allowed an initial 10-sec period for participants to reach the required stroke rate. Three analysis periods during the 100 strokes identified for each trial were defined (first 10 strokes; middle 10 strokes; last 10 strokes), and the mean power per stroke was calculated for each of the three analysis periods. A $3 \times 3$ (Condition = stretcher height $\times$ Interval = analysis period) two-way analysis of variance for repeated measures was performed to determine whether there was a significant interaction between foot stretcher height and analysis period for mean power per stroke. If a significant interaction was observed between variables, a one-way ANOVA, post hoc Tukey, was carried out to determine where these significant interactions occurred. A 95% confidence level was used throughout.

**Results**

Nine of the 10 participants successfully completed the study, with one withdrawing for medical reasons. The mean stroke rate maintained by all participants throughout the trials was $30.8 \pm 0.3$ strokes·min$^{-1}$, $30.5 \pm 0.3$ strokes·min$^{-1}$, and $30.2$ strokes·min$^{-1}$ for Positions 1, 2, and 3, respectively.

| Table 1 Mean (± SD) Data for All Participants During Each Analysis Period |
|---------------------------------|-----|-----|-----|
| Stretcher Position             | 1   | 2   | 3   |
| Mean power (W)                 |     |     |     |
| First 10 strokes               | 710 ± 11 | 721 ± 13 | 735 ± 18 |
| Middle 10 strokes              | 611 ± 8  | 657 ± 4  | 660 ± 9  |
| Last 10 strokes                | 564 ± 8  | 609 ± 9  | 630 ± 14 |
| Mean force (N)                 |     |     |     |
| First 10 strokes               | 353 ± 5  | 363 ± 6  | 374 ± 8  |
| Middle 10 strokes              | 314 ± 3  | 338 ± 2  | 344 ± 4  |
| Last 10 strokes                | 297 ± 4  | 318 ± 4  | 330 ± 6  |
| Stroke distance (m)            |     |     |     |
| First 10 strokes               | 1.41 ± 0.004 | 1.40 ± 0.005 | 1.36 ± 0.003 |
| Middle 10 strokes              | 1.41 ± 0.002 | 1.40 ± 0.003 | 1.36 ± 0.002 |
| Last 10 strokes                | 1.40 ± 0.005 | 1.38 ± 0.003 | 1.37 ± 0.003 |
Mean (± SD) values for mean power per stroke, mean force per stroke, and stroke distance are shown in Table 1 for the three analysis periods. All 9 participants who completed the study showed a decline in mean power per stroke as a function of time in all three foot stretcher positions (Figure 4). When they rowed with the foot stretchers located in the original ergometer stretcher position, there was a significant decrease in mean power per stroke between the first 10 strokes and the last 10 strokes, \( F(2, 267) = 86.167, p < 0.05 \). A significant decrease in mean power per stroke was observed in the second foot stretcher position, \( F(2, 267) = 52.8, p < 0.05 \), and also in the highest stretcher position the mean power per stroke decreased significantly, \( F(2, 267) = 34.052, p < 0.05 \). The significant decrease in mean power per stroke by the rowers in all 3 foot stretcher positions suggested that they had become fatigued.

There was a significant interaction between foot stretcher position and analysis period for mean power per stroke, \( p < 0.05 \). During the first analysis period the differences between all three positions were not significant, \( F(2, 267) = 2.522, p = 0.082 \). However, by the time the middle analysis period had been reached, a significant difference was observed between the original foot stretcher position and the two higher positions, \( F(2, 267) = 10.719, p < 0.05 \), although the difference between the two new positions (Positions 2 and 3) was not significant, \( p = 0.994 \). This difference in mean power per stroke between the original foot stretcher position and the two new positions continued to be present during the last analysis period, \( F(2, 267) = 13.65, p < 0.05 \). Again, there was no significant difference between Positions 2 and 3, \( p = 0.229 \).
Figure 5 — Mean force per stroke (A) and stroke distance (B) for 100 strokes for all participants at all 3 foot stretcher positions. Mean force decreased with fatigue whereas stroke distance remained constant throughout each trial.
Similar trends were seen in the mean force data (Figure 5A), with mean force per stroke decreasing significantly throughout each trial for Position 1, \(F(2, 267) = 75.413, p < 0.05\); Position 2, \(F(2, 267) = 51.488, p < 0.05\); and Position 3, \(F(2, 267) = 26.543, p < 0.05\). Mean stroke distance for all participants, however, did not change significantly throughout each trial (Figure 5B) in Position 1, \(F(2, 267) = 0.549, p = 0.578\); Position 2, \(F(2, 267) = 1.937, p = 0.146\); or Position 3, \(F(2, 267) = 0.25, p = 0.779\). A significant interaction was observed between stretcher position and analysis period for stroke distance, \(p < 0.05\), with the mean stroke distance for all participants being significantly reduced in the highest stretcher position when compared to the lower two positions for the analysis periods at the start, \(F(2, 267) = 15.749, p < 0.05\); middle, \(F(2, 267) = 17.595, p < 0.05\); and end, \(F(2, 267) = 11.235, p < 0.05\) of each trial.

**Discussion**

The purpose of this study was to examine how changing the foot stretcher height influences the mechanical effectiveness of rowing, and to determine whether increasing the height of the foot stretcher relative to both the seat and oar handle would improve rowing performance, as measured by the mean power generated during each stroke and the rate of decline in mean power per stroke over the duration of the trial.

From the data presented, it was shown that the rowers became less fatigued during trials in which the foot stretchers had been raised, with the smallest decline in mean power per stroke occurring in the highest stretcher position. Thus it would appear that a more mechanically effective position was achieved by increasing the height of the foot stretchers, leading to improved performance, as a result of a decrease in energy waste throughout each stroke cycle. As mean power per stroke is a function of both mean force per stroke and stroke distance, these factors were also examined. The data for all stretcher heights showed that the decrease in mean power with time was due entirely to the decrease in mean force, since stroke distance remained constant throughout each trial. However, stroke distance decreased as stretcher height increased, and it is suggested that the increase in stretcher height might limit the maximum joint rotations possible at the ankle, knee, or hip joints, resulting in this shorter stroke distance.

Although at first a decrease in stroke distance might be deemed detrimental to rowing performance, the data suggested that the increase in mean force per stroke outweighed this detrimental effect, as illustrated by the significantly greater mean power per stroke in the highest stretcher position during the last 10 strokes. By altering the joint posture throughout the stroke, muscle lengths would also be changed which may influence the effectiveness of muscle activity. This would require further study to confirm.

The fixed order of presentation of the stretcher heights could have induced a learning effect on the measured data. However, since the rowers commonly used the lowest stretcher height during training, it would have been unlikely that the time spent using the higher positions would have caused them to surpass their proficiency at the lowest stretcher height. Despite this training advantage at the lowest stretcher height, a greater mechanical effectiveness was still observed at the higher stretcher positions. The differences seen between the two highest stretcher positions, however, could be influenced more by a learning effect during testing due to the rowers being
unaccustomed to these stretcher heights prior to their participation in the study. Since no significant differences in power or force were found between Positions 2 and 3, the rowers did not appear to gain by experiencing a learning effect during Stretcher Position 2 that benefited them during Position 3.

The potential improvement in effectiveness resulting from raising the stretcher relative to the oar handle pull height (to reduce $h_2$), and the improvement resulting from raising the stretcher relative to the seat height (to reduce $h_1$) as discussed earlier, may explain the reduced effects of fatigue observed in the present study. Both sources of improvement in effectiveness contribute to the better performance measured for the raised stretcher in Positions 2 and 3 (Figure 3). However, this does not explain the lack of significant difference in the fatigue effects found between Stretcher Positions 2 and 3.

This may be explained as follows. It is assumed that at some stretcher height above that shown in Figure 2B, the active musculoskeletal force applied to the foot stretchers will be inclined upward, causing the corresponding stretcher reaction force, $R_{\text{foot}}$, to be inclined downward (Figure 6). This condition would result in a downward vertical component of reaction force, $-R_{\text{foot-V}}$, which increases negatively as the stretchers are raised further. As before, we must consider this increasing vertical force to be an increasing ineffective use of energy. Therefore the improvement in effectiveness resulting from raising the stretchers relative to the oar handle pull height (to reduce $h_2$) is counteracted to some extent by the reduction in effectiveness resulting from raising the stretchers relative to the seat. Optimum stretcher height will be achieved at some point above the height at which reactive force $R_{\text{foot-V}}$, due to the active musculoskeletal force, is zero.

**Figure 6** — Free body diagram and force polygon when stretcher is raised above seat, resulting in an upward vertical force at the stretcher. The resultant reaction force at the stretcher is directed downward, causing the reaction force at the seat to increase to above body weight.
This explains why the improvement in effectiveness measured between Stretcher Positions 2 and 3 is not as great as that measured between Positions 1 and 2. That is, the rate of improvement resulting from incrementing the height of the stretchers toward the pull height is slowing down because of the negative impact of the active forces being applied to the stretchers.

Overall, this suggests that if foot stretcher height is increased further above the height of the seat, mechanical effectiveness will only continue to improve if the increase in upward active musculoskeletal forces applied to the foot stretcher through the leg drive of the rower is less than the reduction in passive downward force applied to the stretcher by the rower’s body weight. On a more practical level, however, if the stretcher is raised too far, then when flexed the legs will interfere with the smooth passage of the oar handle from the catch to the finish position. Thus the optimum stretcher height may only be found by experimentation, and may be specific to each rower’s anatomy and musculoskeletal technique.

It must be remembered that the present study used ergometer rowing to simulate on-water rowing in the collection of data. Although the two situations are not identical, the effect of stretcher height on changes in two-dimensional rower posture and the application of force will be substantially the same, and therefore the relationships between stretcher heights determined here should apply equally to on-water rowing.

In summary, the results presented in this study showed that the most effective foot stretcher height tested was the one closest to the level of the seat. Examination of the moments acting about the foot stretchers indicated that the stretchers should be raised to the same height as the oar handle. However, when considering the active vertical forces applied to the stretchers by the rower’s legs, it becomes apparent that the most effective height for the stretchers would be at some height above the seat where the increase in active upward forces at the stretcher were no greater than the gains in passive downward forces at the seat.

The rationale presented above is in agreement with the results shown in the present study. However, the expected decline in mechanical effectiveness which would occur at some point above the horizontal line of musculoskeletal force applied to the stretcher was not observed, suggesting that the stretcher heights tested did not reach optimum levels. It is therefore suggested that a continued improvement in mechanical effectiveness might be observed for a further increase in foot stretcher height above those tested here.

References