Strapping rowers to their sliding seat improves performance during the start of single-scull rowing

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ABSTRACT

In this study, the effect of strapping rowers to their sliding seat on performance during 75 m on-water starting trials was investigated. Well-trained rowers performed 75 m maximum-effort starts using an instrumented single scull equipped with a redesigned sliding seat system, both under normal conditions and while strapped to the sliding seat. Strapping rowers to their sliding seat resulted in a 0.45 s lead after 75 m, corresponding to an increase in average boat velocity of about 2.5%. Corresponding effect sizes were large. No significant changes were observed in general stroke cycle characteristics. No indications of additional boat heaving and pitching under strapped conditions were found. The increase in boat velocity is estimated to correspond to an increase in average mechanical power output during the start of on-water rowing between 5% and 10%, which is substantial but smaller than the 12% increase found in a previous study on ergometer starting. We conclude that, after a very short period of adaptation to the strapped condition, single-scull starting performance is substantially improved when the rower is strapped to the sliding seat.

Introduction

Performance in many sporting activities such as running, cycling, speedskating and rowing depends critically on forces exerted by the athlete directly or indirectly propel the athlete forwards (e.g., van Ingen Schenau & Cavanagh, 1990). In a previous paper (van Soest & Hofmijster, 2009), it was noted that slip or loss of contact between a body part and the mechanical environment is undesirable in many cases. For example, a sprint runner does not want his foot to slip relative to the surface, and a cyclist does not want contact between foot and pedal to be lost at any time. It was further argued that by using spikes in running and click pedals or toe clips in cycling, the athlete is no longer forced to coordinate his muscles in such a way that slip (running) or contact loss (cycling) does not occur; phrased more generally, removal of a constraint on intermuscular coordination (such as “ensure that your foot does not slip”) by technical measures is likely to lead to improved performance and in theory cannot be detrimental to performance. For example, toe clips have been shown to result in increased maximal power output during all-out sprints on a bicycle ergometer (Capmal & Vandewalle, 1997). In van Soest and Hofmijster (2009), it was argued that a similar issue is present in rowing, as a rower must maintain the contact between the sliding seat and the buttocks under all circumstances, while it is quite possible for a rower to exert muscle forces that result in lift-off of the buttocks. In that study, it was suggested that by strapping the rower to the sliding seat, contact loss between the sliding seat and the buttocks can no longer occur, irrespective of the forces exerted by the rower. This implies that in the strapped situation (in contrast to the normal situation), there is no upper limit on the pulling force exerted by the rower on the oar, which led to the suggestion that performance may well be improved by strapping the rower to the sliding seat. In line with this suggestion, it was found that performance during ergometer rowing was improved in the strapped condition. In fact, the improvement in performance was surprisingly large: for example, average mechanical power output of the rower increased by 12% during the 5-cycle ergometer starts investigated in that study.

Even though these results convincingly confirmed the validity of the proposed concept, it remains to be investigated if the results obtained in a rowing ergometer experiment can be generalised to on-water rowing. It is not obvious that the answer to this question is affirmative because (1) a rowing ergometer is a good but not a perfect model of on-water rowing, (2) it is expected that the coordination requirements during on-water rowing are more subtle than during ergometer rowing and (3) the changed pattern in handle and footstretcher forces in the strapped condition may lead to additional boat movement that result in additional water resistance that is detrimental to boat forward velocity (Baudouin & Hawkins, 2002). It is conceivable that boat heating may change due to changes in the vertical acceleration profile of the rower’s centre of mass in the strapped condition; for example, the rower might move much more vigorously around the catch, resulting in a higher instantaneous vertical...
acceleration of the centre of mass, which in turn would result in changes in the vertical acceleration of the boat. Boat pitching may increase in the strapped condition due to changes in the sum of the moments of the vertical forces at the seat and footstretcher.

Thus, it is the aim of this study to establish the effect of strapping a single-scull rower to the sliding seat on performance during a maximal intensity on-water starts.

Methods

Outline of the experiment

Each participant performed four maximum-effort starts over a distance of 75 m, using a customised competitive single scull rigged with measurement equipment as described below. Two starts were made in the normal (N) condition and two in the strapped (S) condition in which the pelvis of the rower was tightly strapped to the redesigned sliding seat system (see Figure 1). In the strapped condition, the reaction force from seat + strap on rower could be directed downwards, which is impossible during normal rowing. The sequence of trials was either SNNS or NSSN, in an attempt to minimise time and sequence effects. All trials were completed in a single session.

Participants

Nine male rowers participated in this study. All were competitive rowers at national level with at least 2 years of rowing experience. None of the participants had experience with strapped rowing prior to the experiment. The experiment was approved by the Ethics Committee of the Faculty of Human Movement Sciences (Vrije Universiteit Amsterdam), and all participants provided written informed consent.

Experimental protocol

Participants were first allowed to familiarise themselves with the single scull used, which was equipped with the redesigned sliding seat system (see Figure 1) in both conditions. Next, participants performed their normal warming-up routine, while instructed to incorporate six practice starts (three in the normal condition, three in the strapped condition). The four experimental trials (sequenced either as SNNS or as NSSN) immediately followed this warming-up routine. After initiation of the data acquisition, one of the experimenters performed a countdown audible to the rower, who was instructed to reach the 75 m mark in minimal time. Ample time for recovery was inserted between trials, but in order to minimise potential changes in environmental conditions (air velocity, water flow, temperature), the four trials for a participant were completed within 30 min.

Redesigned sliding seat and strap system

In order to accommodate strapped rowing, low-friction sliding of the seat must be possible when an upward force is exerted on the seat (which is not possible in the standard layout of the rail-seat system). To achieve this, the mechanical interface between the hull-fixed rail and the sliding seat was redesigned. In particular, additional stainless steel ball bearings were fitted, resulting in low-friction rolling contact both under compression and under traction. A design drawing of this system is shown in Figure 1. In terms of mechanical properties, the redesigned interface is indistinguishable from the standard interface under normal conditions. The pelvis of the rower is strapped to the seat by Velcro strips running from a belt worn around the waist, over the lateral aspect of the hips, to Velcro counterstrips attached to the sliding seat (see Figure 1). In designing the Velcro strap system, utmost care was taken to ensure that in case of an emergency, rowers can release the strap within seconds without using their hands. Apart from the added Velcro strip that allows quick release, the strap system was identical to that used in the previous study on ergometer rowing (van Soest & Hofmijster, 2009). It is possible to integrate the Velcro strap system in the clothing of the rower, but this possibility was not used in this study. Introduction of the redesigned rail-seat system and the Velcro strap system resulted in an increase in mass of about 0.1 kg.

Equipment

The experiment was carried out using a racing single scull (Filippi Lido SRL, Donoratico, Italy) and oars (Concept II, USA) equipped with a custom-built measurement system consisting of sensors, a data acquisition module and data storage facilities. For a full description of this system, see Hofmijster, de Koning, and van Soest (2010). In short, hull acceleration was measured using a 3D accelerometer (ADXL204, Analog Devices, USA), and hull pitch angular velocity was measured using a gyroscope (ADXRS300, Analog Devices, USA), positioned in the waterproof compartment about 2 m from the stern of the scull. The horizontal-plane angle between the parts of the oars near the oarlocks, and the boat was measured using servo-potentiometers (FCP12-AC, Feteris Components, the Netherlands) mounted in each of the oarlocks. The horizontal-plane force on the pin was measured using custom-made strain-gauge force transducers integrated in each of the oarlocks. From these oarlock sensor data, the force component between oar and oarlock that is perpendicular to the face of the oarlocks was reconstructed. Vertical seat force was measured using strain-gauge force transducers.
Table 1. Key performance characteristics in the normal and strapped conditions.

|                  | Normal          | Strapped        | \( \Delta \) | Rel. \( \Delta \) (%) | CI of \( \Delta \) | Cohen's \( d \) |
|------------------|-----------------|-----------------|---------------|------------------------|------------------|-----------------|
| \( T_{75m \_1} \) [s] | 18.19 ± 0.74    | 17.71 ± 0.57    | -0.48 ± 0.33  | -2.6 ± 1.8             | (-0.75) – (-0.21) | -1.36           |
| \( T_{75m \_2} \) [s] | 18.19 ± 1.04    | 17.78 ± 0.97    | -0.41 ± 0.52  | -2.3 ± 2.9             | (-0.84) – (0.01)  | -0.74           |
| \( T_{S \_2 \_10} \) [s] | 13.32 ± 0.51    | 12.94 ± 0.42    | -0.38 ± 0.46  | -2.8 ± 3.5             | (-0.75) – (-0.00) | -0.77           |
| \( \Delta X \_p \_5s \) [m] | 13.42 ± 0.85    | 13.75 ± 0.80    | 0.33 ± 0.31   | 2.5 ± 2.3              | (0.08) – (0.99)   | 1.01            |
| \( \Delta X \_p \_10s \) [m] | 35.58 ± 2.44    | 36.74 ± 2.10    | 1.16 ± 1.10   | 3.3 ± 3.1              | (0.26) – (2.05)   | 0.99            |
| \( \Delta X \_p \_15s \) [m] | 59.58 ± 4.08    | 61.45 ± 3.80    | 1.87 ± 1.75   | 3.1 ± 2.9              | (0.44) – (3.30)   | 1.01            |

\( T_{75m \_1} \) and \( T_{75m \_2} \) are the time required to travel 75 m, as determined by stopwatch and from boat acceleration, respectively; \( T_{S \_2 \_10} \) is the time from start of stroke cycle 2 to end of stroke cycle 10; the final three rows represent boat forward displacement at \( \Delta X \_p \_5s \), \( 10 \) \( \Delta X \_p \_10s \) and \( 15 \) \( \Delta X \_p \_15s \) seconds after the start. Values represent mean ± SD (between participants). \( \Delta \) represents the difference between strapped and normal conditions. Significant differences are denoted by an asterisk; note that the repeated-measures statistical analysis is only concerned with the distribution of \( \Delta \). CI of \( \Delta \) represents the 95% confidence interval for \( \Delta \). Cohen’s \( d \) also concerns \( \Delta \) and is given as a measure of effect size.

(Tdea-Huntleigh Model 1022, VPG transducers, USA), mounted between the seat and the frame supporting it. All sensor data were sampled at 1000 Hz and stored on-board on a data acquisition computer (PC 104 Prometheus, Diamond Systems, USA). After the experiment, the data were transferred to a PC.

**Determination of time over 75 m**

Time taken to complete the 75 m start was determined using two independent methods. The first method is based on stopwatch readings, the second method is based on double integration over time of the boat acceleration in the direction of travel. For a description of the way in which boat displacement was calculated from the accelerometer signals, see below under “Data analysis”. Regarding stopwatch timing, the following procedure was adopted. The experimenter located at the starting line started the stopwatch at the end of the verbal countdown, that is, at the instant she gave a verbal start signal to the participant and stopped the stopwatch when a second experimenter, located at the 75 m line, quickly lowered her extended arm to indicate that the bow of the boat crossed the 75 m line. In order to facilitate judgement at the 75 m line, buoys were placed in the water to demarcate the 75 m line. All stopwatch timings were carried out by the same experimenters, who practised this procedure prior to the actual measurements. No attempt was made to quantify the reliability of this procedure; based on results reported by Hetzler, Stickley, Lundquist, and Kimura (2008), average absolute error is expected to be in the order of 0.15 s.

**Data analysis**

Off-line analysis was carried out using Matlab R2013b (Mathworks, USA). Before analysis, all signals were filtered using a bidirectional low-pass Butterworth filter with a cut-off frequency of 20 Hz. Total perpendicular pin force was defined as the sum of the left and right pin force components perpendicular to the oar. The catch, that is, the start of a drive phase, was defined as the instant at which the oar angular velocity became positive. The finish, that is, the end of a drive phase, was defined as the instant at which the total perpendicular pin force dropped below 15 N. Oar angle was defined as the top-view angle between the oar at the pin and the boat. Oar angular velocity (positive during the drive phase) was calculated numerically as the 3-point derivative of the oar angle. Vertical seat force was defined as the force from seat on rower (upward positive) and was obtained from the force transducer mounted under the sliding seat. After careful correction for offset and determination of gain, boat acceleration in the direction of travel was integrated numerically using the trapezoidal rule to obtain boat velocity and was integrated once more to obtain boat displacement. In order to analyse heaving and pitching of the boat, data from the gyroscope measuring boat pitch angular velocity (i.e., rotation around a lateral axis) were integrated numerically using the trapezoidal rule to obtain boat pitch angle, and vertical boat acceleration was integrated numerically using the trapezoidal rule twice to obtain accelerometer vertical displacement. Pitch angle and vertical displacement were then high-pass filtered (cut-off frequency 0.2 Hz) in order to focus on within-stroke-cycle variations in these variables, and within-stroke-cycle variations in these variables were then analysed.

**Statistical analysis**

Paired Student’s t-tests were performed to investigate statistical significance of differences between the normal and strapped conditions. In addition, confidence intervals and Cohen’s \( d \) are reported for the dependent variables that are directly related to performance (Table 1). For all dependent variables, in the statistical analysis, the average of the values obtained in the two trials in the normal condition was compared to the average of the values obtained in the two trials in the strapped condition, except for the strapped condition in one participant, for which only one trial in the strapped condition was available due to a problem in data acquisition. In all statistical tests, the significance level was set at \( P = 0.05 \).

**Results**

In Figure 2 (top panel), vertical seat force as a function of time is presented for a typical participant for stroke cycles 4–6 of one start under normal conditions and one start in the strapped condition. It is seen that in the strapped condition, the minimum value of the vertical seat force is slightly lower in each of the stroke cycles shown and is marginally negative in two out of three stroke cycles, indicating that the participant pulls on the seat, which is clearly impossible in the normal condition.

In Figure 2 (bottom panel), total perpendicular pin force as a function of time is presented for the same stroke cycles of
the same trials. It is seen that in the strapped condition, the maximal total perpendicular pin force is higher in each of the stroke cycles shown. Furthermore, it is seen from comparison of both panels of Figure 2 that the maximum in the total perpendicular pin force occurs slightly later than the minimum in the vertical seat force, although the time difference between these events is smaller than that observed in the previous study on ergometer rowing (van Soest & Hofmijster, 2009).

The key question is if the slightly higher total perpendicular pin force results in better performance in terms of boat displacement over time. Data for the first 10 stroke cycles of one start in the strapped condition are compared to the normal condition in Figure 3 for the same typical participant. It is seen that towards the end of the corresponding time period, boat displacement is about 1.5 m larger in the strapped condition, indicating that average velocity over this time period is approximately 2.5% higher. It is further seen that stroke rate is slightly higher in the strapped condition.

The suggestions following from the typical example presented above are confirmed by statistical analysis of the results of all nine participants. In Table 1, the final time over 75 m as obtained from stopwatch data ($T_{75m-1}$) and from boat acceleration ($T_{75m-2}$), as well as boat displacement $\Delta X$ after 5, 10 and 15 s are reported. For all these except $T_{75m-2}$ (for which $P = 0.06$), the difference between normal and strapped condition is significant, and the corresponding effect size (reported in terms of Cohen’s $d$) would generally be qualified as large. On average, the displacement after 15 s is 1.87 m larger in the strapped condition, and the 75 m line is reached about 0.45 s earlier in the strapped condition, implying that average boat velocity is about 2.5% higher in the strapped condition. Furthermore, it is seen that a substantial part of this increase in velocity is due to a decrease in the time taken to complete stroke cycles 2–10, that is, to an increase in average stroke rate over these (non-steady-state) stroke cycles from 40.5 in the normal condition to 41.7 in the strapped condition.

Results per stroke cycle for selected dependent variables are presented in Table 2. The change in oar angle ($\Delta \phi_{drive}$), the maximal oar angular velocity ($\max(\omega_{drive})$) and the drive-to-recovery ratio are not different between normal and strapped conditions in any of the first 10 stroke cycles, confirming that stroke cycle execution is not drastically changed in the strapped condition. In contrast, maximal total perpendicular pin force ($\max(F_{pin})$) and minimal vertical seat force ($\min(F_{seat})$) are significantly different in 8 out of the 10 first stroke cycles; differences in these forces are very consistent, although mean differences are not large, and the pulling forces on the seat are small. Furthermore, mean stroke cycle duration is 2–4% shorter in the strapped condition in each of the first 10 cycles; total duration of stroke cycles 2–10 is significantly shorter in the strapped condition (Table 1), and duration per stroke cycle is significantly shorter in 3 stroke cycles (Table 2).

To quantify within-cycle variations in boat heaving and pitching, the standard deviation (for each stroke cycle) of the vertical position and pitch angle of the accelerometer was...
Table 2. Key mechanical characteristics per stroke cycle in the normal (N) and in the strapped (S) condition, and the relative difference (%) between N and S conditions.

| Stroke cycle number | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|---------------------|------|------|------|------|------|------|------|------|------|------|
| \(\Delta \phi_{\text{drive}}\) [rad] | N    | 1.29 | 1.34 | 1.54 | 1.64 | 1.71 | 1.75 | 1.76 | 1.78 | 1.80 |
|                     | S    | 1.29 | 1.34 | 1.54 | 1.64 | 1.71 | 1.73 | 1.75 | 1.76 | 1.78 |
| rel. \(\Delta\) (%) | N    | 0.4  | 0.0  | 0.4  | 0.7  | 0.1  | 0.4  | 1.1  | 1.1  | 1.7  |
|                     | S    | 2.51 | 2.88 | 3.04 | 3.21 | 3.26 | 3.35 | 3.49 | 3.37 | 3.42 |
| max(\(\omega_{\text{drive}}\)) [rad \cdot s\(^{-1}\)] | N    | 1.94 | 2.51 | 2.93 | 3.16 | 3.25 | 3.32 | 3.39 | 3.33 | 3.30 |
|                     | S    | 1.87 | 2.51 | 2.93 | 3.16 | 3.25 | 3.32 | 3.39 | 3.33 | 3.30 |
| rel. \(\Delta\) (%) | N    | 3.9  | 0.1  | 1.9  | 3.6  | 1.1  | 1.3  | 0.9  | 4.2  | 2.9  |
|                     | S    | 2.06 | 1.11 | 1.14 | 1.13 | 1.11 | 1.10 | 1.08 | 1.09 | 1.10 |
| DR-ratio            | N    | 2.06 | 1.21 | 1.14 | 1.10 | 1.12 | 1.11 | 1.10 | 1.10 | 1.10 |
|                     | S    | 0.0  | 2.2  | 0.0  | 2.9  | 1.0  | 2.2  | 3.2  | 1.7  | 1.9  |
| max(\(F_{\text{seat}}\)) [N] | N    | 1070 | 1057 | 1023 | 993  | 975  | 965  | 956  | 948  | 939  |
|                     | S    | 1100 | 1115 | 1085 | 1048 | 1025 | 1016 | 1001 | 990  | 976  |
| rel. \(\Delta\) (%) | N    | 2.8  | 4.5  | 6.0  | 5.6  | 6.2  | 5.5  | 4.9  | 5.3  | 4.4  |
|                     | S    | 0.0  | 2.2  | 0.0  | 2.9  | 1.0  | 2.2  | 3.2  | 1.7  | 1.9  |
| \(T_{\text{cycle}}\) [s] | N    | 1.86 | 1.41 | 1.42 | 1.45 | 1.49 | 1.50 | 1.50 | 1.51 | 1.52 |
|                     | S    | 1.83 | 1.36 | 1.36 | 1.40 | 1.43 | 1.45 | 1.47 | 1.48 | 1.49 |
| rel. \(\Delta\) (%) | N    | 1.7  | 3.6  | 3.7  | 3.1  | 3.9  | 3.8  | 2.2  | 1.5  | 1.6  |
|                     | S    | 0.0  | 2.2  | 0.0  | 2.9  | 1.0  | 2.2  | 3.2  | 1.7  | 1.9  |

\(\Delta \phi_{\text{drive}}\) is the change in oar angle during the drive phase; max(\(\omega_{\text{drive}}\)) is the maximal oar angular velocity during the drive phase; DR-ratio is the ratio of drive phase duration to recovery phase duration; max(\(F_{\text{seat}}\)) is the maximum value of the component of the total pin force that is perpendicular to the oar; min(\(F_{\text{seat}}\)) is the minimum value of the vertical seat force; \(T_{\text{cycle}}\) is the duration of the stroke cycle. Due to the sign change in min(\(F_{\text{seat}}\)), the relative difference in this variable is not meaningful and is therefore not reported. All relative differences were obtained by averaging the individual relative differences. Significant differences are denoted by an asterisk.

calculated, as outlined in the methods section (data not shown). It was found that neither of these standard deviations differed significantly between normal and strapped conditions in any of the stroke cycles; averaged over stroke cycles, the difference was negligibly small.

Discussion

In this study, it was found that strapping a rower to his sliding seat significantly improves performance during maximum-effort 75 m single scull starts: the 75 m line is reached about 0.45 s earlier in the strapped condition, corresponding to a 2.5% difference in average boat velocity. Furthermore, no indications were found that stroke cycle execution is disrupted by strapping the rower to his sliding seat. These results provide further support to our notion that externally imposing a desired kinematic feature through technical means is likely to lead to improved performance and convincingly show that our previous findings relating to ergometer rowing (van Soest & Hofmijster, 2009) generalise to maximum-effort on-water starts in a single scull.

In this study, it was found that the minimum in vertical seat force occurs shortly after the sign change of the oar angular velocity (defined as the catch in this study), and that the maximum in the total perpendicular pin force occurs slightly later in the drive phase, with both the minimal vertical seat force and the maximal total perpendicular pin force reaching more extreme values in the strapped condition (see Table 2). These results suggest that, around the instant of the catch, the strap was primarily used to generate a higher footstretcher force on the rower, resulting in a higher acceleration of the rower’s centre of mass in the direction of travel of the boat. This higher acceleration of the rower around the catch is likely to be related to the slightly higher stroke rate in the strapped condition. Somewhat later into the drive phase, the total perpendicular pin force peaked at a higher value in the strapped condition, suggesting that the certainty that contact loss between buttocks and seat could not occur due to the presence of the strap, led the rower to pull harder on the oar than in the normal condition. This is in line with the results of a previous study on the effect of the strap during ergometer starting (van Soest & Hofmijster, 2009), where the suggestion of a higher footstretcher force around the catch was indeed confirmed in the data; in this study, we cannot confirm this suggestion because footstretcher force was not measured.

This study was limited to single scull rowing. Although there is no reason to expect that the effects of strapping are very different during sweep rowing, this is an area for further research. From a technical point of view, we expect that the current strapping system and the redesigned mechanical interface between rail and sliding seat as used in this study can be used during sweep rowing with no or minimal adjustments.

Participants in this study had at least 2 years of rowing experience, were well-trained and were involved in competition at the national level at the time of the experiments. It is an open question if similar results would be obtained in elite rowers. This is an area for future research.

The most direct measure of performance in this study is the time taken to displace the boat over a distance of 75 m. This is why two independent measures of this time were used, both having their limitations, however. Stopwatch timing is reported to have an absolute mean error in the order of 0.15 s (Hetler et al., 2008); in order to optimise the accuracy of stopwatch timing, the same two experimenters were involved in the stopwatch timing in all measurements; these experimenters practised the procedure prior to the actual measurements, and clear visual markers (red buoys) marked the 75-m line. The second method was based on double integration over time of the forward acceleration of the hull, as obtained from a 3D accelerometer fixed to the hull. Temperature sensitivity of the accelerometer played a
negligible role because, for each participant, trials in the strapped and normal conditions took place in a time period that was so short that large temperature changes did not occur; furthermore, the accelerometer was not directly exposed to the sun. Variations in orientation of the accelerometer (equalling orientation changes of the hull) were limited to about 2°, which results in negligible errors in the estimated acceleration in the direction of travel of the hull. The accuracy of the accelerometer-based method depends critically on the integration constant for velocity, as an error in this integration constant may result in substantial integration drift. This integration constant was based on the accelerometer data obtained in the seconds prior to the start, where average boat velocity can safely be assumed to equal zero. To check for integration drift, the cycle-to-cycle boat velocity changes towards the end of each trial were checked, and no indications of substantial integration drift were observed.

It is interesting to compare the results in performance reported here to those reported for maximum-effort 5-stroke starts in ergometer rowing (van Soest & Hofmijster, 2009). In the latter study, mechanical power output of the rower, averaged over the first 5 stroke cycles, was 12% larger in the strapped condition. Although mechanical power output was not directly determined in the current study, it is straightforward to estimate the relative changes in two key power terms: the average mechanical power spent on increasing the kinetic energy of boat and rower, and the average mechanical power spent on boat drag. The relative difference in the latter term was estimated using the commonly adopted assumption that power lost to boat drag is proportional to boat velocity cubed (Baudouin & Hawkins, 2002; Cabrera, Ruina, & Kleshnev, 2006). For stroke cycles 2–10, due to higher boat velocity, the mechanical power lost to boat drag was estimated to be between 5% and 10% higher in the strapped condition, averaging 7% over the full 75 m start. Average power spent on increasing the kinetic energy of boat plus rower (calculated from the boat speed averaged over a full cycle) at the end of the 75 m start was found to be 7% higher in the strapped condition. Lacking any information on power loss at the blades, it is impossible to accurately estimate the mechanical power output of the rower in absolute terms; however, based on the information on power terms that is available, it is plausible that the relative increase in the mechanical power output of the rower in the strapped condition during on-water rowing is smaller than the 12% reported previously for ergometer starting (van Soest & Hofmijster, 2009).

One possible explanation for the finding that use of a strap leads to a performance gain during ergometer rowing that is larger than the performance gain observed during on-water rowing might be related to boat motion. In particular, one might argue that in the on-water strapped condition, additional forces are exerted on the hull that may lead to undesirable motion of the hull, that is, heaving and pitching; the argument being that additional heaving and pitching lead to additional boat drag, in turn leading to a reduced average boat velocity. The analysis of within-cycle variations in heaving and pitching carried out in this study provided no indication that heaving and pitching are indeed exaggerated in the strapped condition.

In our view, a more likely explanation for the smaller gain in mechanical power output in the strapped condition during on-water rowing is related to the rower’s intermuscular coordination. More precisely, we expect that, although general stroke cycle characteristics in ergometer rowing do not differ from those in on-water rowing (e.g., Lamb, 1989), the required intermuscular coordination is more subtle in on-water rowing and is in fact most critical during the first few strokes during the start. We suggest that the required subtle coordination in on-water rowing compromises the positive effect of the strap to some extent. This suggestion is supported by the finding that in this study, only a small fraction of the lead in the strapped condition was achieved during the first part of the start (Table 1); the average lead after 5 s was only 0.33 m in this study, whereas it was estimated to be about 1 m in our previous ergometer study.

It is remarkable that a positive effect of strapping a rower to the sliding seat is observed after just a few minutes of exposure of the participants to the strapped situation. One might expect the positive effect of the strap to be further enhanced, perhaps in particular during the coordination-critical first part of the start, when the rowers involved would be exposed to the strapped situation for a prolonged period of time. This is an area for future research.

Given the positive results of this study, it would now be interesting to investigate to what extent strapping results in improved performance over a prolonged period of time. At this time, it is unclear if rowers are at all able to generate a higher mechanical power output over a longer time period: it may well be that even though rowers are mechanically able to exert higher forces during a few stroke cycles in the strapped condition, the additional physiological load is in fact detrimental to performance over the more relevant time period corresponding to a 2 km race. We intend to address this question in a future study.

In conclusion, we have shown that strapping rowers to their sliding seat results in improved performance during the start of single scull on-water rowing; average boat velocity is increased by about 2.5%, implying that strapped rowing results in a lead of about 1.87 m at 15 s after the start. No additional heaving and pitching of the single scull under strapped conditions was observed. It remains to be investigated if performance during strapped rowing can be further improved through training, and if the gain in performance during the starting phase is maintained over a 2000 m race.

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Disclosure statement
No potential conflict of interest was reported by the authors.
References

Baudouin, A., & Hawkins, D. A. (2002). Biomechanical review of factors affecting rowing performance. British Journal of Sports Medicine, 36, 396–402. doi:10.1136/bjsm.36.6.396

Cabrera, D., Ruina, A., & Kleshnev, V. (2006). A simple 1+ dimensional model of rowing mimics observed forces and motions. Human Movement Science, 25, 192–220. doi:10.1016/j.humov.2005.11.002

Capmal, S., & Vandewalle, H. (1997). Torque-velocity relationship during cycle ergometer sprints with and without toe clips. European Journal of Applied Physiology and Occupational Physiology, 76, 375–379. doi:10.1007/s004210050264

Hetzler, R. K., Stickley, C. D., Lundquist, K. M., & Kimura, I. F. (2008). Reliability and accuracy of handheld stopwatches compared with electronic timing in measuring sprint performance. Journal of Strength and Conditioning Research, 22, 1969–1976. doi:10.1519/JSC.0b013e318185f36c

Hofmijster, M. J., de Koning, J. J., & van Soest, A. J. (2010). Estimation of the energy loss at the blades in rowing: Common assumptions revisited. Journal of Sports Sciences, 28, 1093–1102. doi:10.1080/02640414.2010.495994

Lamb, D. H. (1989). A kinematic comparison of ergometer and on-water rowing. The American Journal of Sports Medicine, 17, 367–373. doi:10.1177/036354658901700310

van Ingen Schenau, G. J., & Cavanagh, P. R. (1990). Power equations in endurance sports. Journal of Biomechanics, 23, 865–881. doi:10.1016/0021-9290(90)90352-4

van Soest, A. J., & Hofmijster, M. J. (2009). Strapping rowers to their sliding seat improves performance during the start of ergometer rowing. Journal of Sports Sciences, 27, 283–289. doi:10.1080/02640410802495336