©Journal of Sports Science and Medicine (2019) **18,** 264-270
http://www.jssm.org

Research article

Effect of Rowing Ergometer Compliance on Biomechanical and Physiological Indicators during Simulated 2,000-metre Race

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Abstract
This study compared biomechanical characteristics and physiological responses during rowing on three devices: (i) stable ergometer (STE), (ii) transversally compliant ergometer (TCE) and (iii) frontally compliant ergometer (FCE). Eleven young competitive rowers completed a 2000 meter simulated race under each of the ergometer conditions in a randomized order. Stroke rate, average force, power output, velocity and amplitude of the handle and stretcher or seat, heart rate and blood lactate were measured at 500 m intervals. Force and power at the stretcher were significantly lower ($p < 0.03$) for TCE, while stroke rate and velocities of the handle and the seat were higher ($p < 0.01$). No significant differences were observed between STE and FCE in biomechanical parameters. The lowest rowing performance was observed in FCE ($p = 0.007$), and was accompanied with the highest average heart rate ($p = 0.031$). Our findings indicate that in TCE, rowers modified their technique, but were able to maintain physiological strain and performance. In contrast, FCE had no effect on rowing biomechanics, but decreased rowing performance and increased physiological strain. It seems plausible that transversal, but not frontal compliance, elicited a biomechanical technique that might reduce the discrepancy between a rowing ergometer and on-water rowing.

Key words: Rowing, biomechanics, stability, power, velocity, technique.

Introduction

Competitive rowers frequently use rowing ergometers, particularly in wintertime to overcome various constraints of on-water training (e.g. weather, logistics). However, a concern has been raised regarding discrepancy between the biomechanical properties of on-water and ergometer techniques (Mäestu et al., 2005), as well as the resulting physiological stress. Moreover, a high volume of ergometer training volume is associated with an increased injury risk (Wilson et al., 2010), with lower back being the most frequently injured region (Wilson et al., 2014), perhaps due to a higher lumbar flexion range of motion during rowing on an ergometer as compared to on-water rowing (Wilson et al., 2013).

Compliant ergometers using slides or free-floating stretcher mechanisms have been developed to simulate on-water rowing. Such devices have been suggested as more suitable for the assessment of rowing performance with respect to physiological measures (oxygen uptake, heart rate and blood lactate concentrations), as they have been shown to elicit similar responses to on-water rowing (Mello et al., 2014; Urhausen et al., 1993). The use of a stable ergometer (STE) has shown comparable physiological responses, however, in the case of STE the activity of several muscles is increased compared to the on-water rowing (Bazzucchi et al., 2013). This phenomenon may occur because the central nervous system needs to direct more of its capacity towards additional stabilizing actions on-water.

Several studies have compared the differences in biomechanical and physiological responses between rowing on ergometers with different compliance and yielded ambiguous results (Attenborough et al., 2012; Benson et al., 2011; Bernstein et al., 2002; Colloud et al., 2006; Greene et al., 2013; Holsgaard-Larsen and Jensen, 2010; Mahony et al., 1999; Nowicky et al., 2005; Rossi et al., 2015; Shaharudin et al., 2014; Vinther et al., 2012). Rowing on a transversally compliant ergometer (TCE) using slide mechanisms elicited a higher heart rate, greater oxygen uptake and carbon dioxide production, lower blood lactate accumulation and lower net and gross efficiencies compared to rowing on a STE (Rossi et al., 2015). Rowing on a STE was also shown to produce higher maximal and average forces and power throughout the rowing cycle (Colloud et al., 2006) and higher forces with a concomitant lower stroke rate at a constant power output (Benson et al., 2011; Bernstein et al., 2002; Vinther et al., 2012). On the other hand, Mahony (1999) found no differences between STE and TCE regarding power output or physiological responses. De Campos Mello et al. (2009) demonstrated that on-water rowing is more metabolically demanding than ergometer rowing, however, no differences between STE and TCE were observed. Higher stroke rate on a TCE is probably beneficial, as it is associated with higher efficiency and reduced demand to the upper body (Attenborough et al., 2012). A study by Holsgaard-Larsen and Jensen reported higher maximal and average force whilst rowing at higher intensities on a STE (Holsgaard-Larsen and Jensen, 2010). Greene et al. (2013) reported higher joint moments and lower limb power output (particularly at the knee) during rowing on a STE compared to rowing on a TCE. Electromyographical measurements of untrained subjects showed they prioritized leg muscles during rowing on a TCE and back muscles during rowing on a STE (Shaharudin et al., 2014). However, some studies have

Received: 09 January 2019 / Accepted: 15 March 2019 / Published (online): 01 June 2019

reported unchanged electromyographical activity between both ergometer types (Nowicky et al., 2005), while lower activity of m. vastus lateralis and m. tibialis anterior during rowing on a TCE have also been documented (Vinther et al., 2012).

As the stability demands of movement increase, the ability to produce net force decreases (Cotterman et al., 2005; Lyons et al., 2010), with the magnitude of the effect being dependent on the specific motor task and involved muscles groups. While some discrepancies between the stable and compliant ergometers have already been observed, no studies have investigated different approaches to creating an unstable ergometer design so far. The purpose of this study was to provide further insight into discrepancies in biomechanical variables during rowing on different ergometers: (i) a classic, stable ergometer, (2) a transversally compliant ergometer using a sliding mechanism, and (iii) a frontally compliant ergometer (FCE) using a tilt-board attached under the device. Our aim was to explore the differences in forces and power output at the handle and the stretcher, the motion amplitude and velocity of the seat and handles, stroke rate, lactate concentration and heart rate during different distance points of a simulated 2,000-m race. We hypothesized that rowers will produce lower forces and power output on TCE and FCE, and that rowing on a FCE is the most physiologically demanding.

Methods

Participants and study design

Eleven healthy young male rowers (age: 16.8 ± 2.8 years; body height: 1.83 ± 0.09 m; body mass: 77.0 ± 12.1 kg; BMI: 22.8 ± 1.7 kg/m^2) participated in the study. All participants had undergone a physical examination by an experienced sports physician within 4 months of testing. Exclusion criteria were injury in the previous year and any medical condition that could be exacerbated by the protocol. All participants were recruited from local rowing clubs situated on the Slovenian coast. Underage participants required a parental consent to participate and all participants required consent of their coaches. The study protocol was confirmed by the Republic of Slovenia National Medical Ethics Committee (approval number: 157/02/14) and registered at ClinicalTrials.gov (ID: NCT03253900). Each participant was required to sign a written informed consent after being informed about the protocol, the aims of the study and possible risks related to participation. No participants that responded to our recruitment activities declined to participate. However, four participants were not eligible to participate due to injuries within the twelve-month period before the experiment. One participant dropped out of the study after completing the test in only one of the conditions.

A crossover repeated-measures design was used in this study as depicted on Figure 1. The test setting was simulation of a 2000 meter race. Testing the responses to different ergometers has previously been shown to be more reliable over 2000 meter simulations, compared to shorter distances (Soper and Hume, 2004). The measurements for each condition were performed during separate sessions, which were 7 to 10 days apart. The conditions were: (i) stable ergometer (STE), (ii) transversally compliant ergometer (TCE) and (iii) frontally compliant ergometer (FCE). As a warm-up activity, participants performed 10-minutes of low-intensity rowing on the same ergometer that was used for testing during that session. All participants used stable ergometers for their indoor trainings. The order of condition for each participant was randomized in a counter-balance order (generated by Research Randomizer Version 4 (Urbaniak and Plous, 2013)).

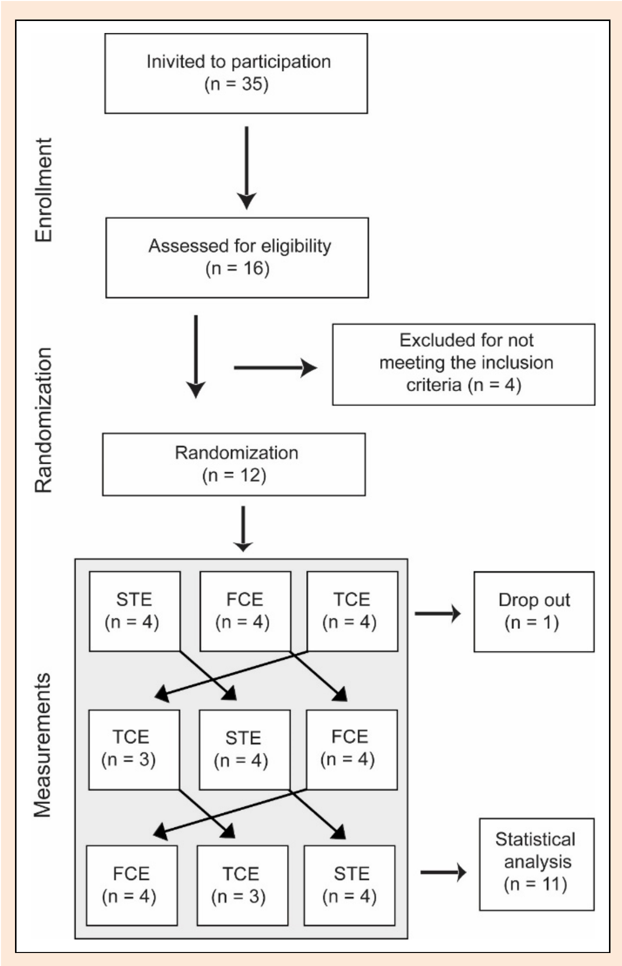

Figure 1. CONSORT diagram of the study. The order of conditions was counter-balance randomized between participants.

Measurements and equipment

The participants performed the simulated races on a Concept II rowing ergometer (Model D; Concept II Inc., Morrisville, VT, USA). Previous research has demonstrated the high reliability of physiological and biomechanical assessment using this ergometer (Schabort et al., 1999). In STE mode, the ergometer was fixed on the floor and the rower and the seat moved along the slide bar. When the ergometer was placed on slides (Concept Inc., Morrisville, VT, USA) for TCE mode, the body of the rower remained in nearly fixed position relative to the environment, while the ergometer itself moved. For the third condition (FCE), a tilt board was fixed under the ergometer to elicit frontal plane compliance (see Figure 2).

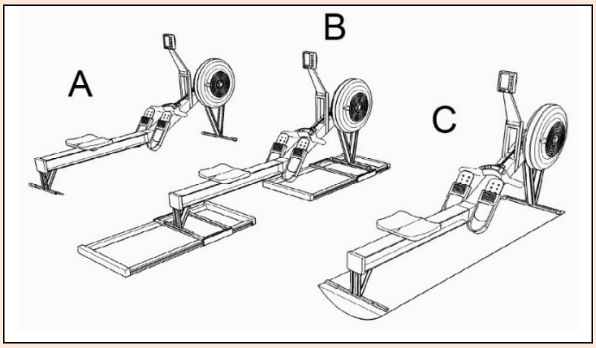

Figure 2. **Ergometer compliance was achieved by placing a STE (A) on slides that enabled transversal compliance (B) and on a wobble broad that induced frontal compliance (C).**

Biomechanical rowing outputs were assessed at five stages of the test (at 0, 500, 1000, 1500 and 2000 meters of the simulated race). For each stage, an interval of 10 strokes was recorded and average of the 10 strokes was calculated for further analyses. Movement of the handle was detected by an encoder (model RI 30-B; Hengstler, Aldingen, Germany) positioned on the axis of the flywheel. Force developed at the rowing handle was measured by a small strain gauge traction sensor (model U9B; Hottinger-Baldwin Messtechnik, Darmstadt, Germany) mounted between the handle and the chain connected to the flywheel. The signals were sampled at 1000 Hz by a data acquisition card (model NI USB 6212; NI, Austin, TX, USA). The locations of the sensors are depicted on Figure 3. Data was further analyzed using custom software (ARS Rowing, S2P Ltd., Ljubljana, Slovenia). The main outcome parameters were stroke rate, force, power output, velocity and amplitude of the movement of arms (handle) and legs (stretcher; seat for velocity and amplitude). Additionally, total race time was recorded. Heart rate was recorded throughout the race using a heart rate monitor (Polar V800 COMBO). Blood lactate was measured before and immediately after the race by analyzing the micro blood samples drawn from the earlobe. We used StatStrip Xpres lactate meter (NovaBiomedical, Cheshire, UK), following the manufacturer's instructions. The biosensors were first inserted into the device, then the biosensor was exposed to the blood sample.

Statistical analysis

All statistical analyses were done using SPSS 18.0 (SPSS Inc., Chicago, USA). Descriptive statistics were calculated and reported as mean ± standard error for all variables. The Shapiro-Wilk test was used to check for the normality of distribution. A two-way repeated measures ANOVA (condition (3) x distance (5)) was calculated to test for the effect of condition, distance and possible interactions, with Eta^2 value used to assess the effect size (ES). Two-tailed pairwise t-tests with Bonferroni corrections were used for pairwise comparison. The level of statistical significance was set at $p < 0.05$.

Results

The values for average forces, power outputs and velocities are depicted in Figure 4. The F-values, p-values and effect sizes are presented on Table 1. Average force and power outputs at the handle were significantly affected by distance ($p < 0.001$), but not by condition ($p = 0.527$-0.710; Figure 3). At the stretcher, average force and power outputs were significantly affected by both the ergometer mode ($p < 0.03$) and distance ($p < 0.001$) (Figure 3). The only significant condition × distance interaction effect was observed for the average power output at the stretcher ($p = 0.026$; Figure 3). Regarding velocity, significant main effects for condition and distance were observed at both the handle ($p < 0.001$) and the stretcher ($p < 0.01$), while a significant condition × distance interaction effect was observed only for velocity at the stretcher ($p < 0.001$; Figure 4).

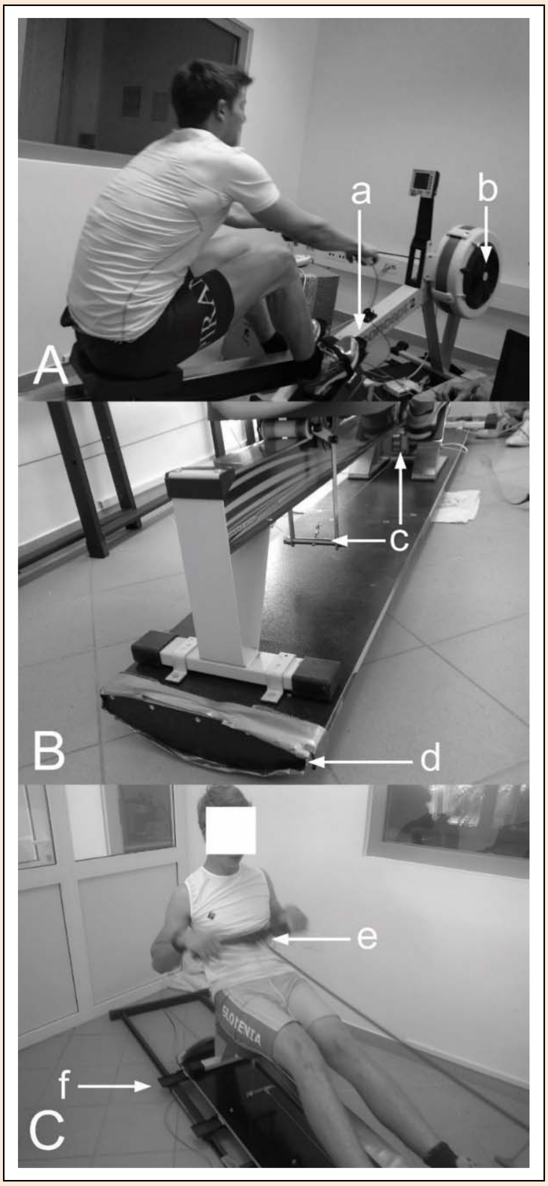

Figure 3. **Biomechanical parameters were recorded using: (a) force sensors at the stretcher, (b) an encoder measuring handle motion, (c) an encoder for measuring seat motion and (e) a force sensor at the handle. A wobble-board (d) eliciting frontal plane compliance and (f) slides enabling transverse compliance are also seen.**

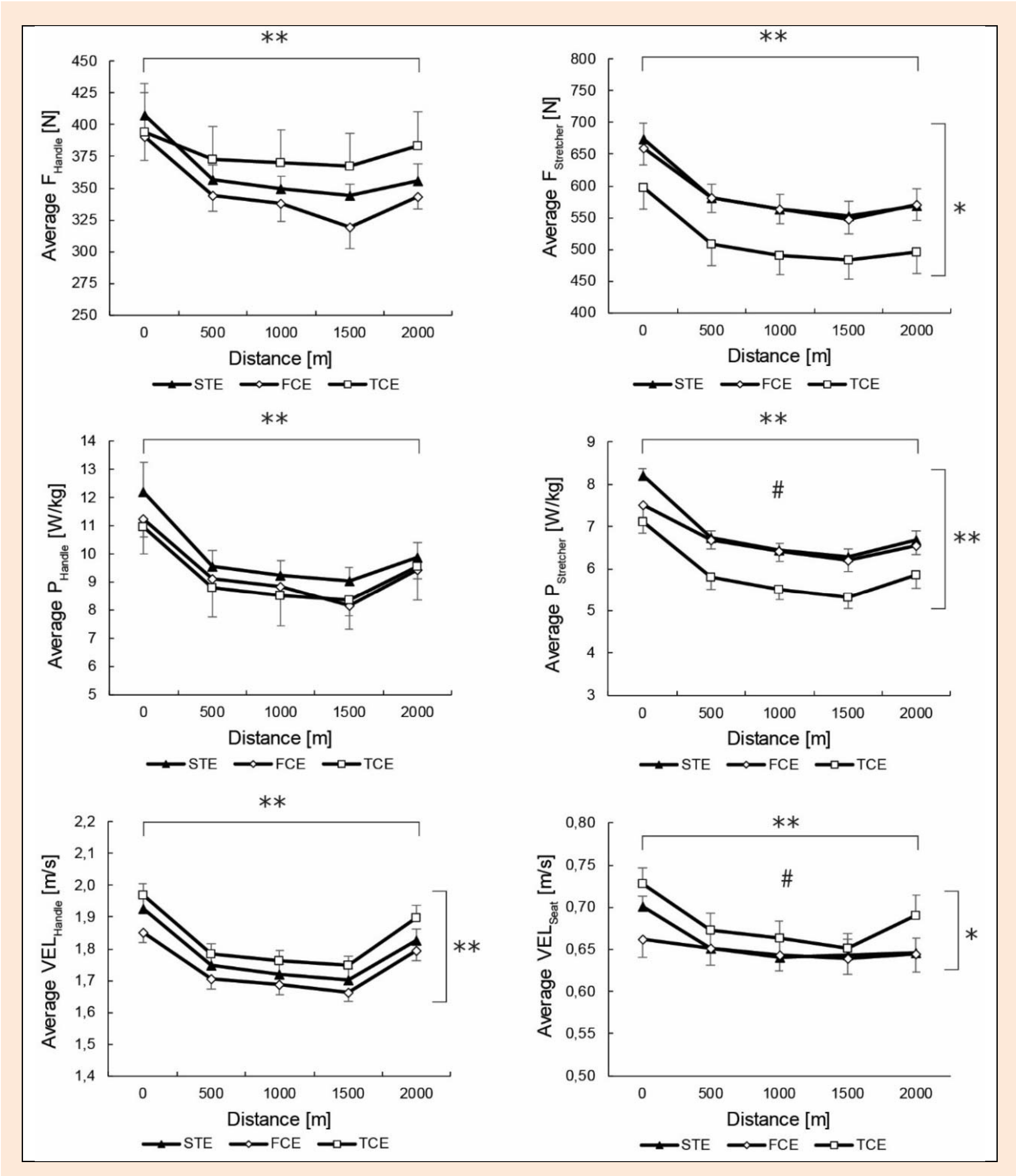

Figure 4. Average force, power output and velocity at the handle and the stretcher (seat for velocity) throughout the simulated race. The asterisks on the horizontal lines indicate a statistically significant effect of distance (* for $p < 0.05$ and ** for $p < 0.01$), while those on the vertical line indicate statistically significant effect of condition (ergometer type). The hash (#) indicates a statistically significant interaction between distance and condition.

Table 1. Summary of statistical outcomes for 2-way ANOVA.

	Condition (ergometer)			Distance			Interaction		
Parameter	**F**	**P-value**	**ES**	**F**	**P-value**	**ES**	**F**	**P-value**	**ES**
Handle - Average Force	0,66	0,527	0,062	19,9	**0,000**	0,66	1,05	0,403	0,09
Stretcher - Average Force	4,15	**0,031**	0,293	76,1	**0,000**	0,88	0,27	0,971	0,02
Handle - Average Power	0,34	0,710	0,034	39,0	**0,000**	0,79	0,40	0,916	0,03
Stretcher - Average Power	7,00	**0,005**	0,412	32,4	**0,000**	0,76	2,34	**0,026**	0,19
Handle - Average Velocity	15,3	**0,000**	0,605	51,5	**0,000**	0,83	0,44	0,888	0,04
Seat - Average Velocity	5,81	**0,010**	0,368	6,44	**0,000**	0,39	4,14	**0,000**	0,29
Rowing frequency	9,92	**0,001**	0,49	19,9	**0,000**	0,66	0,66	**0,720**	0,06

ES – Effect size. Statistically significant outcomes are in bold text.

The condition factor had no significant effect on the amplitude of the handle ($F(2) = 0.55$; $p = 0.584$; $ES = 0.05$) or the amplitude of the seat ($F(2) = 0.998$; $p = 0.386$; $ES = 0.091$). Distance had a statistically significant effect on the amplitude of the handle ($F(4) = 6.36$; $p < 0.001$; $ES = 0.38$), but not on the amplitude of the seat ($F(4) = 0.955$; $p = 0.443$; $ES = 0.087$). No significant condition × distance interaction effects were observed for two amplitude variables (handle: $F(2,4) = 1.36$; $p = 0.233$; $ES = 0.12$; seat: $F(2,4) = 1.01$; $p = 0.438$; $ES = 0.09$).

Significant main effects of both condition and distance were observed for stroke frequency, while their interaction effect was not statistically significant (Figure 5). Pairwise comparisons for condition showed statistically significant differences between STE and TCE ($p = 0.007$) and TCE and FCE ($p = 0.012$).

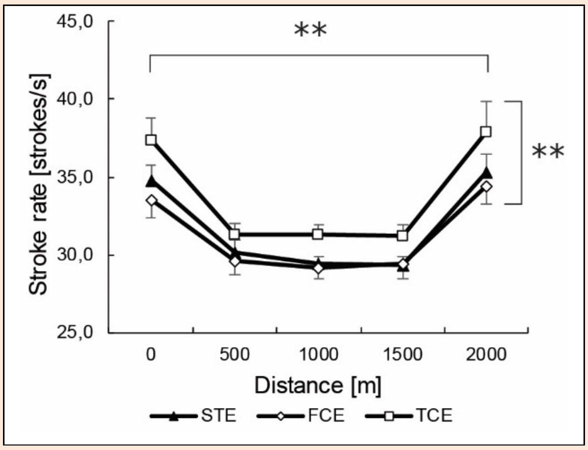

Figure 5. Average stroke rates throughout the race. The asterisks on the horizontal lines indicate a statistically significant effect of distance (* for $p < 0.05$ and ** for $p < 0.01$), while those on the vertical line indicate statistically significant effect of condition (ergometer type).

Race time (STE = 407.3 ± 7.1 s; TCE = 409.8 ± 7.5 s; FCE = 413.8 ± 6.8 s) was significantly affected by condition ($F(2) = 6.50$; $p = 0.007$; $ES = 0.39$). Pairwise comparisons revealed statistically significant differences in race time ($p = 0.022$) only between STE and FCE. Distance had a statistically significant effect on blood lactate concentration ($F(1) = 513.826$; $p < 0.001$; $ES = 0.981$), while no significant effect was observed for condition factor ($F(2) = 1.036$; $p = 0.373$; $ES = 0.094$), or condition × distance ($F(2,4) = 0.43$; $p = 0.658$; $ES = 0.04$). The average heart rate (STE = 174 ± 2 bpm; FCE = 176 ± 4 bpm; TCE = 169 ± 3 bpm) varied significantly between conditions ($F(2) = 4.691$; $p = 0.031$; $ES = 0.439$). Pair-wise comparisons revealed a statistically significant difference ($p = 0.044$) to be only between FCE and TCE. Maximal heart rate (STE = 196 ± 2 bpm; TCE = 194 ± 3 bpm; FCE = 194 ± 3 bpm) did not vary significantly between the conditions ($F(2) = 1.613$; $p = 0.234$; $ES = 0.187$).

Discussion

To our knowledge, this is the first study that compared kinematics, kinetics and physiological responses during rowing between stable, transversally and frontally compliant rowing ergometers. At the biomechanical level, our findings indicate that ergometer type significantly affected average force, velocity and power, as well as stroke rate. Specifically, in the TCE condition, rowers produced the lowest average force and power outputs at the stretcher. These differences were compensated for by (i) higher stroke rates, (ii) higher velocities at both the handle and the stretcher, and (iii) higher average forces at the handle (albeit not significant) during the last stages of the simulated race. No statistically significant biomechanical differences were observed between STE and FCE.

While previous studies indicated decreased average force both at the handle and the stretcher during rowing on a TCE (Benson et al., 2011; Colloud et al., 2006), we observed this phenomenon only for the stretcher in our study. Although not to a statistically significant level, the average force at the handle tended to be the highest during rowing on the TCE for most distance points, which is in contrast with previous findings. This increase was not observed at the first distance point, indicating that protocol duration and associated fatigue could be an important factor for handle forces. In particular, TCE could help the rowers to maintain higher forces for longer time periods. Indeed, we used longer study protocols than previous research (Colloud et al., 2006). Since it was shown that rowing on a slide-based simulator requires lower average force to maintain the same power output (Benson et al., 2011), we could expect a similar power output on both ergometers. However, in our study, power at the stretcher behaved in the same manner as force at the stretcher (i.e., concurrent decreased in force and power output on TCE).

Since average force and power outputs at the handle were unchanged among the conditions, we could assume that a higher percentage of the total load was placed on the upper extremities during rowing on the TCE. Previous electromyographic studies reported both lower (Vinther et al., 2012) and higher (Shaharudin et al., 2014) activity of the leg muscles during rowing on a slide-based simulator. In our study, TCE allowed higher stroke rates and velocities at the stretcher and the handle, which is consistent with previous findings (Benson et al., 2011). Similarly, when constant stroke rate is imposed, the forces are lower on TCE (Colloud et al., 2006). However, the best race times were nonetheless achieved on the STE ergometers, despite higher efficiency reported with increased stroke rate (Attenborough et al., 2012). The additional stabilizing actions may have increased the amount of additional muscle work to produce an overall loss of energy spent on rowing activities Interestingly, the seat and handle amplitudes were similar across conditions, suggesting none of the ergometers could decrease the associated lumbar range of motion and potentially reduce the incidence of lower back pain. One of the few interaction effects between ergometer type and distance was observed for seat velocity. Participants were able to increase seat velocity during the final stage of the race on a TCE more than on the other two ergometers.

While TCE caused the mechanics of the rowing stroke to change, no effect was observed for FCE compared to STE, except for the handle velocity, which was lowest on the FCE. Regarding the biomechanical parameters, adding frontally compliant materials to increase stability demands did not seem to cause any meaningful differences in rowing on a STE.

At the physiological and performance levels, our findings indicate that the lowest rowing performance (i.e., highest race time) was observed on a novel, custom built FCE, and was accompanied with the highest physiological strain during the race (i.e., the highest average heart rate). The remaining two indicators of physiological strain (i.e., post-test lactate concentrations and maximal heart rate) did not differ between the conditions. Since the subjects exercised at their maximal effort at the end of the race, their anaerobic function probably explains the majority of the variance in lactate concentration. Performing a test at a constant power output could better reveal the associations between biomechanical and physiological changes induced using different ergometer types. However, average heart rate was significantly lower for the TCE than the FCE, which indicates lower efficiency imposed by frontal compliance. The FCE appears to be the least efficient ergometer; however, direct comparison of all three ergometers to on-water rowing is needed to reveal which ergometer best resembles on-water conditions. Previous studies showed substantially longer race times and higher metabolic demand for on-water rowing compared to both STEs and TCEs, with small difference between the two (de Campos Mello et al., 2009).

When considering all measured data together, our findings suggest a rather complex interaction between rowing technique, physiological load, and rowing ergometer performance. While rowers seem to be able to optimize their rowing technique and maintain performance during unstable conditions in the transverse plane, no such adjustments were observed when instability was introduced in the frontal plane. Given that on-water condition challenges the stability of the boat in both frontal and transverse planes, further studies comparing different ergometers directly to on-water rowing are needed.

Limitations

A general limitation of the present study is lack of subject familiarity with the ergometers. The differences that we observed could have partially occurred because participants were not accustomed to rowing on unstable ergometers. While a warm-up was performed on a same ergometer that was used for testing in respective session and some level of familiarization could have occurred, our results should be interpreted with caution. Furthermore, ergometers are rarely used for racing, but rather for training. Therefore, generalizing these differences to training sessions, especially those done at lower intensities is limited.

Conclusion

In conclusion, the results of the present study indicated significant differences in rowing technique between rowing ergometers with various compliance levels. It was shown that a TCE elicits different rowing biomechanics than a STE, but there seems to be little difference between a STE and a FCE. As the adaptations to training seem to be specific to the imposed stability demands (Augustsson et al., 1998; Mayhew et al., 2010; F. E. Rossi et al., 2018; Wirth et al., 2016) our results provide an important step in optimizing off-season rowing trainings. Further investigations should compare more ergometer designs directly to on-water rowing.

Acknowledgements

The experiments comply with the current laws of the country in which they were performed. The authors have no conflicts of interests to declare.

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Key points

- Transversally compliant (slide-based) ergometers elicit biomechanical changes that might be favorable in comparison to stable ergometers.
- Rowing on a frontally compliant ergometer does not induce any biomechanical changes, however, it appears to be the most physiologically demanding.
- Seat and handle amplitudes were similar between stable and both compliant ergometers, suggesting none of the ergometers could decrease the associated lumbar range of motion and potentially reduce the incidence of lower back pain.

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