

Slide-based ergometer rowing: Effects on force production and neuromuscular activity

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Force production profile and neuromuscular activity during slide-based and stationary ergometer rowing at standardized submaximal power output were compared in 14 male and 8 female National Team rowers. Surface electromyography (EMG) was obtained in selected thoracic and leg muscles along with synchronous measurement of handle force and rate of force development (RFD). Compared to stationary conditions, slide-based peak force decreased by 76 (57–95) N (mean 95% CI) in males ($P < 0.001$) and 20 (8–31) N ($P < 0.05$) in females. Stroke rate increased (+10.7%) and late-phase RFD decreased (–20.7%) in males ($P < 0.05$). Neuromuscular activity in m. vastus lateralis decreased in the initial

drive phase from 59% to 51% of EMGmax in males and from 57% to 52% in females ($P < 0.01$ – 0.05), while also decreasing in the late recovery phase from 20% to 7% in males and 17% to 7% in females ($P < 0.01$). Peak force and maximal neuromuscular activity in the shoulder retractors always occurred in the second quartile of the drive phase. In conclusion, peak force and late-phase RFD (males) decreased and stroke rate increased (males) during slide-based compared to stationary ergometer rowing, potentially reducing the risk of overuse injury. Neuromuscular activity was more affected in leg muscles than thoracic muscles by slide-based ergometer rowing.

Ergometer rowing constitutes a relatively large part of the total training volume in international level rowing – up to 1/3 in Danish National Team rowers. The time spent on ergometer rowing has been reported to be related to the incidence of injuries in elite rowers (Wilson et al., 2010). Consequently, the type of ergometer used may have implications for both the risk of injury and the performance of elite rowers. The stationary Concept2 rowing ergometer (Concept2, Morrisville, VT, USA) is by far the most commonly used ergometer by elite and sub-elite competitive rowers. To achieve a more realistic “on-water-feeling,” the Concept2 ergometer can be placed on horizontal slides, which allows the ergometer to move back and forth during the rowing stroke. Investigations of biomechanical and physiological variables have indicated differences between slide-based ergometer rowing and stationary ergometer rowing (Holsgaard-Larsen & Jensen, 2010; Benson et al., 2011). The RowPerfect ergometer (RowPerfect, Hardenberg, the Netherlands) is another type of sliding rowing ergometer that has been used to investigate physiological and biomechanical characteristics of

sliding vs stationary ergometer rowing (Bernstein et al., 2002; Colloud et al., 2006). In this ergometer, the stretcher mechanism is mounted (and slides) on the same rail as the seat, which from a biomechanical perspective differs fundamentally from the placement of the entire Concept2 ergometer on slides. The inertial weight of the moving mass of the Concept2 ergometer placed on slides is approximately twice the weight of the sliding stretcher mechanism in the RowPerfect ergometer and, consequently, it can not be assumed that similar biomechanical responses to sliding can be observed in these two types of ergometers. In the RowPerfect ergometer, peak handle force and total power output were reduced compared to stationary ergometer conditions when rowing at a fixed stroke rate (Colloud et al., 2006) while mean handle force decreased and stroke rate increased when identical power outputs were compared (Bernstein et al., 2002). A similar trend was observed during slide-based vs stationary Concept2 ergometer rowing performed at race pace (Benson et al., 2011). While biomechanical differences between slide-based and stationary ergometer rowing have been indicated, it is

Table 1. Physical characteristics of the 22 elite rowers participating in the study (mean \pm SD)

	Age (years)	Years of training	Height (cm)	Weight (kg)	VO ₂ -max (l/min)	Max. power (W)	Max. HR (bpm)
Females (<i>n</i> = 8)	24.6 \pm 4.3	6.8 \pm 2.6	173.5 \pm 5.5	63.0 \pm 7.4	3.74 \pm 0.28	277.8 \pm 24.8	185 \pm 8
Males (<i>n</i> = 14)	27.0 \pm 4.9	8.3 \pm 4.6	186.8 \pm 7.3	78.9 \pm 10.3	5.38 \pm 0.37	418.4 \pm 33.3	183 \pm 10

Max. power, Max. HR and VO₂-max (average power output, maximal heart rate and maximal oxygen uptake obtained during a 6-min maximal rowing test), W, Watt; bpm, beats pr min.

unknown whether slide-based ergometer rowing has an effect upon the neuromuscular activity of the thoracic muscles.

Stationary ergometer analysis in competitive rowers has shown that propulsive handle force production is positively related to the magnitudes of compressive forces in the lumbar spine (Morris et al., 2000) as well as to the bending force at the ribs (Warden et al., 2003). Low back pain (LBP) has been reported as the most frequent injury type in rowing, while rib stress fractures (RSF) appear to be responsible for most of the time lost from training and competition in rowing (Rumball et al., 2005). Consequently, a reduction in peak handle force production for a given power production during ergometer rowing could potentially represent a reduced risk of overuse injury. Similarly, a potential change in the specific pattern (magnitude and timing) of neuromuscular activity during ergometer rowing could affect the risk of injury – especially with respect to RSF, where active muscle contraction forces have been suggested to be involved in the mechanism(s) of injury (Christiansen & Kanstrup, 1997; Karlson, 1998; Wajswelner et al., 2000; Warden et al., 2002; Vinthier et al., 2006). Specifically, the force vectors generated by the shoulder retractors and the resulting transmission of forces through the upper body and arms to the handle have been hypothesized to potentially induce detrimental rib cage compression that could lead to RSF (Warden et al., 2002).

The main aim of the present study was to test the hypothesis that, despite a high inertial mass of the Concept2 ergometer (compared to the RowPerfect ergometer), slide-based ergometer rowing would lead to increased stroke rate and decreased peak force production as well as reduced rate of force development (RFD) compared to stationary ergometer rowing at identical submaximal power output, as recently indicated by Benson et al. (2011) at race pace. Secondary aims were (a) to test the hypothesis that the change in kinetic profile (peak force production and RFD) would be accompanied by altered patterns of neuromuscular activity in selected thoracic and lower limb muscles; (b) to investigate the timing of neuromuscular activity relative to peak force production at the handle, as this information might provide insight into the etiology and potential prevention of musculoskeletal overuse injury resulting from intensive ergometer rowing; and (c) to investigate potential gender differences for the above factors during slide-based ergometer rowing.

Materials and methods

Subjects and test procedure

Eight female (5 lightweight) and 14 male (9 lightweight) Danish National Team rowers (Table 1) performed two trials of rowing on a Concept2 model D ergometer. The trials were performed with and without slides in randomized order at freely chosen stroke rate. During both trials the rowers maintained 75–80% of the average power output produced during a 6-min maximal (all-out) rowing test (Jensen, 2007), which was obtained on a separate occasion. While visual online feedback of power output was provided by the ergometer display, the rowers were blinded regarding stroke rate. Each trial lasted approximately 3 min and 30 s. In each subject, an identical resistance setting of the ergometer was used in all trials (mean drag factor females: 102 \pm 3, males: 113 \pm 5; \pm SD). A self-paced warm-up trial was performed prior to the first experimental trial. A rest period of 2–5 min was administered between trials. During the rest period, the slides were either blocked (stationary condition) or unblocked (sliding condition) in a randomized order. Prior to data recording in the second trial, the rowers were allowed 2–3 min of low-intensity rowing to allow for adequate familiarization to the new ergometer setup.

The present study was approved by the Regional Ethics Committee (H-A-2007-0031). All participating rowers gave their written informed consent and were free of injury at the time of testing.

Data measurements

A custom-made lightweight strain-gauge transducer was inserted between the handle and the chain to measure the force production while a commercially available potentiometer was used to measure the displacement of the handle (P6500 series, Novotechnik, Ostfildern, Germany). The output voltage of the strain gauge was checked at loads of 10, 20, 45, 55, 80, and 105 kg resulting in a highly linear ($r = 0.998$, $P < 0.001$) volt-to-newton relationship. Similarly, the potentiometer was calibrated at 0.2, 0.4, 0.6, 0.8 and 1 m of displacement resulting in a linear ($r = 0.995$, $P < 0.001$) volt-to-meter relationship. MATLAB (Mathworks, Natick, Massachusetts, USA) programming was used to process the recorded data and to calculate instantaneous (1 kHz) handle force and position. Digital fourth-order zero-lag Butterworth low-pass filters with cut-off frequencies of 15 Hz and 50 Hz were used to filter the potentiometer and force signals, respectively.

As previously described in detail (Vinthier et al., 2006), electromyographic (EMG) analysis was performed using bipolar surface EMG electrodes (Medicotest N-00-S, Oelstykke, Denmark) positioned on the following muscles (right body side) with a 2-cm inter-electrode distance: trapezius middle (TM) and lower (TL) fibers, serratus anterior (SA), and obliquus externus abdominis (OEA). In addition, bipolar EMG electrodes were placed on the following muscles: latissimus dorsi (LD), deltoideus posterior fibers (DP), vastus lateralis (VL), and tibialis anterior (TA). For these muscles electrode positionings were as follows: LD, one-third of the distance between the axilla and the spina iliaca posterior superior, posteriorly to the lateral superficial boundary of the

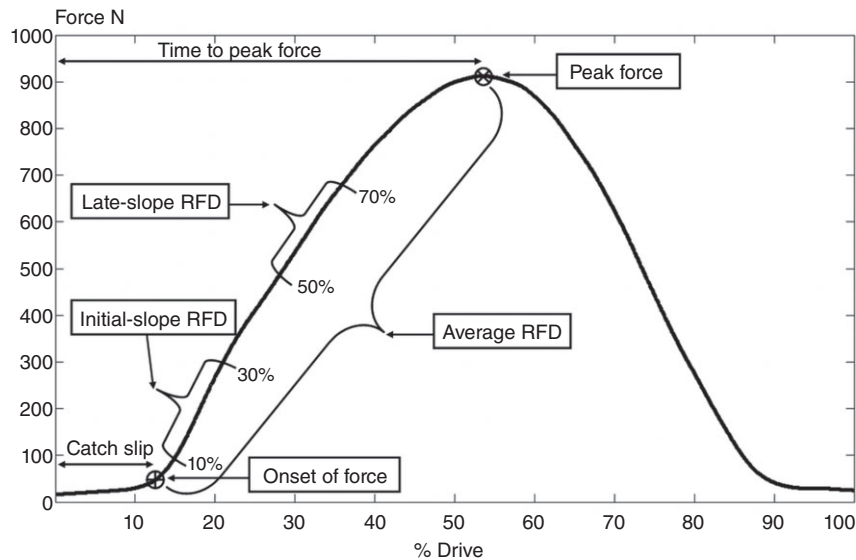


Fig. 1. Average force curve from one subject during stationary ergometer rowing illustrating the majority of the measured parameters. The x-axis represents the entire drive phase defined by the handle position: 0 = handle position closest to the flywheel denoted “The catch” and 100 = handle position the greatest distance from the flywheel denoted “The finish”.

muscle; DP, 4 cm below the posterior part of the acromion; VL, one-third of the distance between the proximal lateral part of the patella and the trochanter major; TA, one-third of the distance between apex patellae and the lateral malleolus. All bipolar electrode placements were aligned with the direction of the muscle fibers. The skin was shaved and cleaned with alcohol prior to electrode attachment to minimize skin impedance. Proper electrode placement and signal quality was checked continuously online prior to and during the warm-up. All signals were sampled synchronously (details listed below) and stored on a computer. During subsequent analysis, the EMG signals were digitally high-pass filtered using a fourth-order zero-lag Butterworth filter (5 Hz cut-off frequency) and subsequently rectified and low-pass filtered using a moving symmetrical RMS (root mean square) filter with a 50-ms time constant (Aagaard et al., 2002; Vinther et al., 2006). To enable comparison of neuromuscular activity between subjects and to minimize the effect of amplitude cancellation (Keenan et al., 2005), all EMG signals were normalized to the maximal RMS EMG amplitude (EMGmax). EMGmax was recorded in two trials of maximal ergometer rowing where the ergometer flywheel was accelerated from a complete standstill using maximal resistance, mimicking a race start (Vinther et al., 2006). During analysis, the maximal EMG signals were visually checked and maximal RMS EMG signal amplitudes arising from poor signal quality were discarded and replaced by the maximal amplitude from the alternative trial.

EMG, force, and potentiometer signals were synchronously recorded at a 1000 Hz sampling rate using a 12-bit analog-to-digital converter (BNC-2120, National Instruments, Austin, Texas, USA). Four separate sweeps of 6-s duration were recorded at each ergometer condition and stored on a computer. Data sampling was commenced approximately 30 s after the onset of each trial, during the phase of steady-state rowing. Each recorded data sweep always contained two complete drive phases and at least one complete recovery phase. Each sweep was visually checked during the analysis and only complete recovery phases were analyzed. Consequently, eight complete drive phases and 4–8 complete recovery phases were obtained for further analysis in each subject.

A Performance Monitor 4 display unit (Concept2 PM4, Morrisville, VT, USA) containing an ANT chip for wireless commu-

nication with a heart rate transmitter (Suunto, Vantaa, Finland) was used to monitor heart rate and ergometer power production.

Data analysis

Heart rate in the final phase (15 s) of each trial and average power output (watt) of each trial were recorded. From the potentiometer and force measurements, the following variables were averaged for the eight strokes sampled in each rower at each ergometer condition and subsequently ensemble averages were calculated: length of drive, duration of drive, time of recovery, stroke rate, peak force, time to peak force, onset of force, and RFD. The beginning and the end of each drive phase were defined by the handle displacement data. Consequently, the beginning and the end of the drive phase was defined as the time points when the handle was located at the shortest and the longest distance from the flywheel axis, respectively. The time to peak force was defined as the time elapsed from the beginning of the drive phase to the time of peak force. The onset of force was defined as the point in time when the handle force exceeded 1.5% of peak force in male rowers and 2.0% of peak force in female rowers (Fig. 1). Different values for male and female rowers were chosen to match the difference in absolute peak handle force between male and female rowers, which was confirmed by visual inspection of individual force curves. The rate of force impact was evaluated by calculating the rate of force development ($RFD = \Delta \text{force} / \Delta \text{time}$) as (a) average RFD from onset of force to peak force, (b) average RFD between 10–30% of time to peak force (initial slope), and (c) average RFD in 50–70% of peak force (late slope). These calculations were chosen to evaluate differences in total RFD as well as in early and late-phase RFD of the ascending part of the bell-shaped force curve that typically is observed during the drive phase of the rowing stroke (representative example is shown in Fig. 1). The time elapsed from the beginning of the drive phase to onset of force was denoted as the catch slip.

EMG analysis included determination of normalized average RMS EMG amplitude from each muscle during subsequent quartiles (0–25%, 25–50%, 50–75%, 75–100%) of the drive and recovery phases, respectively. This led to a greater number of

Table 2. Exercise intensity and biomechanical rowing stroke characteristics during slide-based and stationary ergometer rowing in male and female rowers. *P*-values are not corrected for multiple comparisons

	Slides Mean \pm SD	Stationary Mean \pm SD	Difference Mean (95% CI)	<i>P</i> -value
Males (<i>n</i> = 14)				
Power output (W)	321.2 \pm 24.6	318.6 \pm 26.3	2.6 (–1.1–6.3)	0.16
% of max. power	76.8 \pm 1.6	76.2 \pm 1.3	0.7 (–0.2–1.5)	0.13
Heart rate (bpm)*	157.2 \pm 9.7	155.1 \pm 8.7	2.2 (–0.2–4.5)	0.07
% of max. HR*	86.0 \pm 2.6	84.8 \pm 2.8	1.1 (–0.1–2.4)	0.07
Time to peak force (ms)	380 \pm 38	417 \pm 47	–36 (–52–21)	0.0002
Catch slip (ms)	46 \pm 11	70 \pm 21	–24 (–31–18)	0.000004
Length of drive (m)	1.57 \pm 0.05	1.59 \pm 0.05	–0.02 (–0.04–0.01)	0.005
Time of drive (ms)	876 \pm 23	905 \pm 31	–29 (–44–14)	0.001
Time of recovery (ms)	1224 \pm 118	1416 \pm 90	–192 (–249–135)	0.00001
Females (<i>n</i> = 8)				
Power output (W)	213.0 \pm 18.6	212.8 \pm 17.4	0.3 (–2.1–2.6)	0.81
% of max. power	76.7 \pm 1.6	76.7 \pm 1.4	0.1 (–0.8–1.0)	0.88
Heart rate (bpm)†	160.5 \pm 6.8	159.4 \pm 8.3	1.1 (–2.8–5.1)	0.50
% of max. HR†	86.2 \pm 5.0	85.5 \pm 5.1	0.6 (–1.5–2.7)	0.48
Time to peak force (ms)	389 \pm 42	426 \pm 44	–36 (–61–12)	0.01
Catch slip (ms)	56 \pm 18	87 \pm 24	–31 (–39–23)	0.00003
Length of drive (m)	1.56 \pm 0.03	1.56 \pm 0.02	0.00 (–0.02–0.01)	0.60
Time of drive (ms)	965 \pm 33	986 \pm 39	–22 (–39–5)	0.02
Time of recovery (ms)	1378 \pm 148	1425 \pm 158	–47 (–103–9)	0.09

P < 0.05 significant.

**n* = 13.

†*n* = 7.

analyzed time phases compared to previous reports where the entire stroke cycle was divided into six phases (Rodriguez et al., 1990; Vinther et al., 2006). In addition, average handle force production was calculated for the eight separate phases of the rowing stroke. Custom-made MATLAB-based analysis programs were used for all calculations. Ensemble averages for each ergometer condition were calculated separately for female and male rowers, respectively.

Statistical analysis

Due to limited availability of elite rowers (almost all National Team Rowers participated) no calculations of statistical power were made. All data are presented as group means \pm SD and all differences between ergometer conditions (trials) are presented as mean and 95% CI. Unpaired students *t*-testing was used to examine differences in the response to slide-based ergometer rowing (change in stroke rate and peak force) between male and female rowers. Specifically, differences between ergometer conditions for the main outcome measures stroke rate, peak force, and RFD were investigated using Bonferroni corrected paired *t*-tests for male and female rowers separately. An alpha level of 5% was chosen to indicate statistical significance and *P*-values for the main outcome measures were Bonferroni corrected. The variables related to exercise intensity and the biomechanical variables not related to the main aim were not included in the main analysis and *P*-values were therefore not corrected for multiple comparisons. The EMG data were analyzed using a more explorative approach based on paired or unpaired *t*-tests only when visible differences between ergometer conditions or gender were evident from visual inspection of the graphs displaying mean neuromuscular activity during the rowing stroke. This approach resulted in a limited number of pair-wise comparisons, and hence, no Bonferroni correction was applied for these results.

Results

Exercise intensity was successfully kept constant between slide-based and stationary ergometer rowing in both female and male rowers (Table 2). During slide-based ergometer rowing, peak force decreased more in male rowers (8.4 \pm 3.3%) compared to female rowers (3.1 \pm 2.2%; *P* < 0.01) and stroke rate increased more in males (10.7 \pm 5.6%; *P* < 0.01) compared to a small and statistically nonsignificant change in the females (2.9 \pm 3.1%). Consequently, male and female rowers were analyzed separately.

During slide-based ergometer rowing, all 14 male rowers consistently increased stroke rate and decreased peak force compared to stationary ergometer rowing (Table 3). Moreover, initial-slope RFD was greater (*P* < 0.05) and late-slope RFD smaller (*P* < 0.01) in slide-based than stationary ergometer rowing (Table 3). A less robust response to slide-based ergometer rowing was seen in female rowers, where only peak handle force decreased in the slide-based condition (Table 3). Time to peak force, duration of the drive, and recovery phases as well as the catch slip decreased in the slide-based ergometer condition compared to the stationary condition in both male and female rowers, while stroke length was found to change (decrease in the slide-based condition) in male rowers only (Table 2). Group mean force-time curves illustrating the differences in the timing and magnitude of force production between ergometer conditions are presented in Fig. 2a (males) and Fig. 2b (females).

Force and EMG in slide-based ergometer rowing

Table 3. Main outcome measures: Stroke rate, peak force, average, initial and late-phase rate of force development (RFD) during slide-based compared to stationary ergometer rowing in male and female rowers

	Slides Mean \pm SD	Stationary Mean \pm SD	Difference Mean (95%CI)	<i>P</i> -value*
Males (<i>n</i> = 14)				
Strokes per minute	28.7 \pm 1.7	25.9 \pm 1.2	-2.8 (-3.-2.0)	0.00005
Peak force (N)	811 \pm 74	887 \pm 87	76 (57-95)	0.000005
RFD (0-100%) (N/s)	2303 \pm 223	2436 \pm 234	133 (22-244)	0.11
RFD (10-30%) (N/s)	5098 \pm 1219	4701 \pm 1128	-397 (-67-123)	0.04
RFD (50-70%) (N/s)	2513 \pm 460	3216 \pm 376	703 (352-1054)	0.005
Females (<i>n</i> = 8)				
Strokes per minute	25.7 \pm 1.9	25.0 \pm 1.8	-0.7 (-1.-0.1)	0.16
Peak force (N)	612 \pm 52	632 \pm 53	20 (8-31)	0.02
RFD (0-100%) (N/s)	1723 \pm 245	1781 \pm 384	57 (-97-221)	1.0
RFD (10-30%) (N/s)	4370 \pm 1321	4045 \pm 1163	-325 (-594-56)	0.13
RFD (50-70%) (N/s)	1908 \pm 451	2431 \pm 660	522 (-65-1109)	0.37

*Bonferroni adjusted for multiple comparisons. *P* < 0.05 significant.

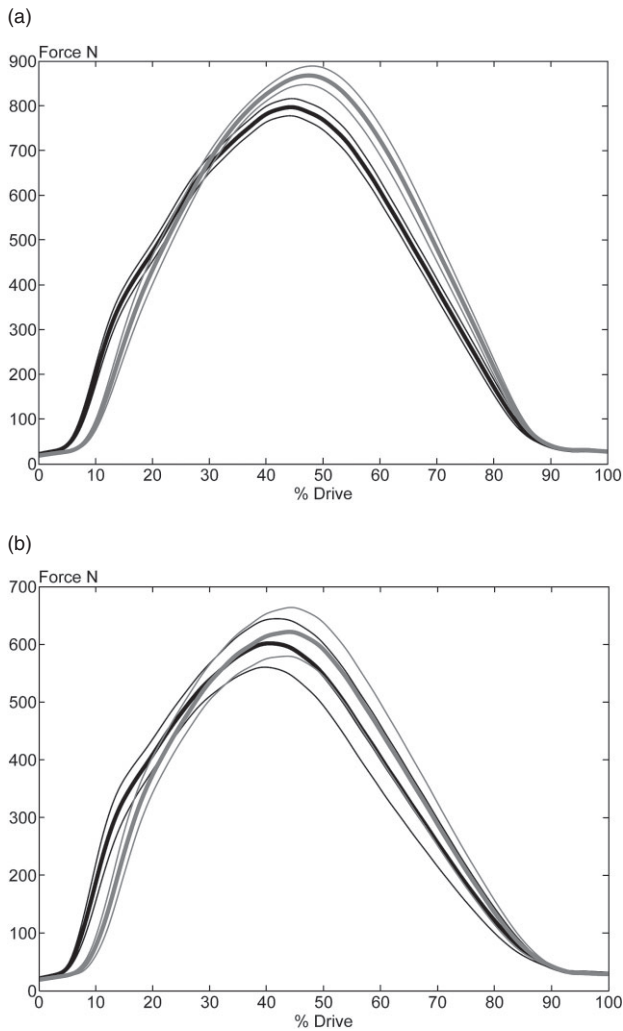


Fig. 2. (a) Average force \pm SEM at the handle during the drive phase (time normalized) on a stationary ergometer (gray line) and on a sliding ergometer (black line) in 14 male elite rowers. (b) Average force \pm SEM at the handle during the drive phase (time normalized) on a stationary ergometer (gray line) and on a sliding ergometer (black line) in 8 female elite rowers.

Male and female rowers generally exhibited identical patterns of neuromuscular activity in the investigated muscles, during both stationary and slide-based ergometer rowing (Fig. 3). However, a gender difference in SA muscle activity pattern was observed regardless of ergometer condition. The neuromuscular activity pattern in both males and females was characterized by an increase in activity in the second quartile of the drive phase, followed by a decrease toward the end of the drive phase and a gradual increase throughout the recovery phase. However, the increase observed in the second quartile of the drive phase was twofold larger (*P* < 0.05) in female than male rowers: female rowers, slides: $36.2 \pm 16.8\%$ EMGmax and stationary, $36.4 \pm 20.2\%$ EMGmax; male rowers, slides: $14.4 \pm 14.1\%$ EMGmax and stationary, $13.6 \pm 13.2\%$ EMGmax. Consequently, female rowers demonstrated peak neuromuscular activity in the second quartile of the drive, whereas in male rowers, peak neuromuscular activity occurred in the final quartile of the recovery phase (Fig. 3).

Neuromuscular activity did not differ between ergometer conditions for the shoulder retractors (m. trapezius middle fibers, m. trapezius lower fibers, m. latissimus dorsi fibers – TM, TL, and LD) and m. obliquus externus abdominis (OEA) in either male or female rowers (Fig. 3). During slide-based rowing, only males showed decreased neuromuscular activity in DP fibers during the third quartile of the drive phase and increased neuromuscular activity in SA during the third quartile of the recovery phase (*P* < 0.05; Fig. 3). Neuromuscular activity in VL and TA differed between ergometer conditions for both male and female rowers (*P* < 0.05). During slide-based ergometer rowing, VL activity decreased in the initial drive phase and late recovery phase, while TA activity increased and peaked later in the recovery phase for both genders (*P* < 0.05; Fig. 3).

As indicated by visual inspection of the ensemble EMG traces depicted in Fig. 3, the shoulder retractors

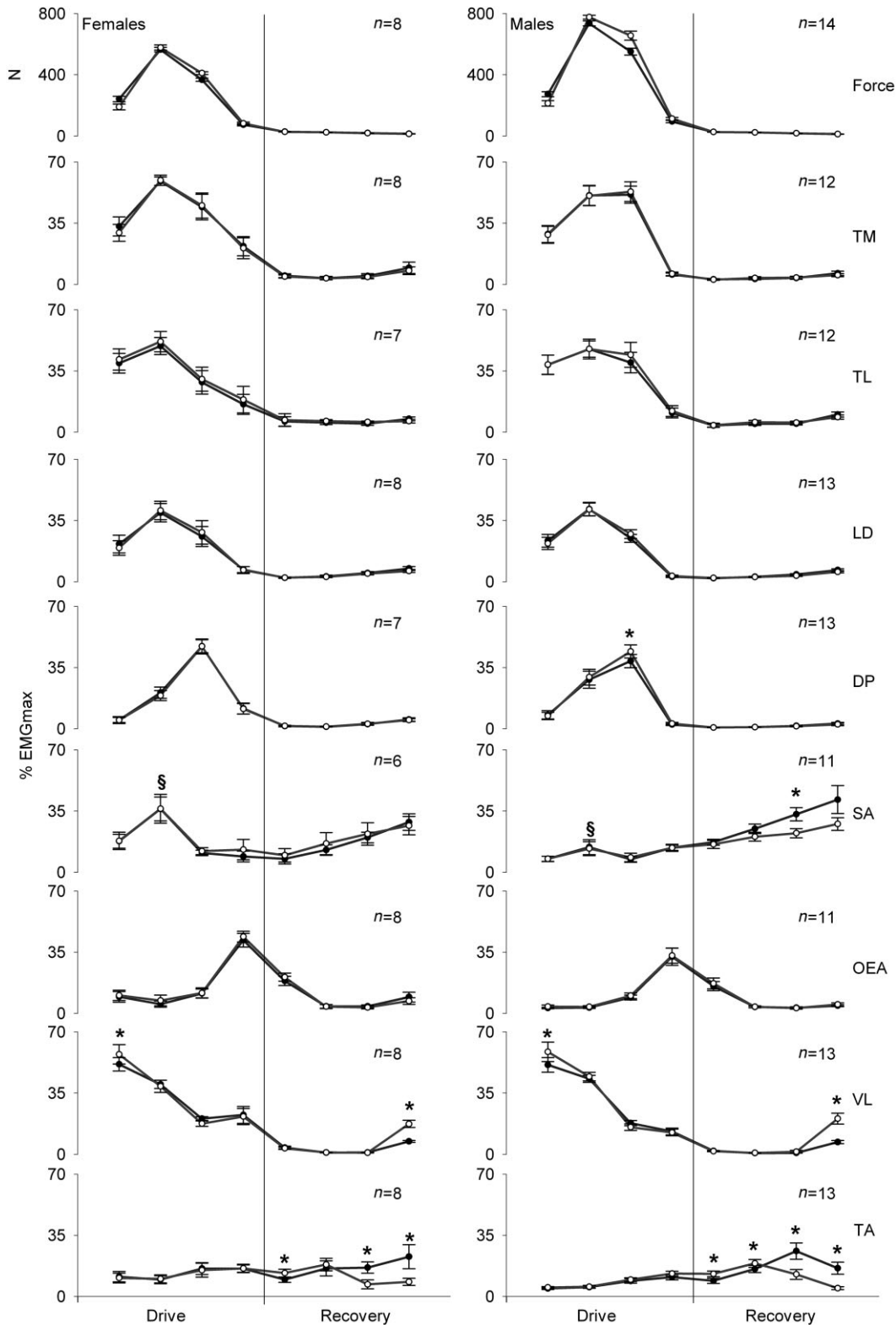


Fig. 3. Top panels: Average handle force production (N) illustrating the timing in handle force production. For statistical comparison between ergometer conditions, see Table 3. Mid and bottom panels: Average normalized neuromuscular activity (% of maximal EMG activity ± SEM) recorded in trapezius middle (TM) and lower fibers (TL), latissimus dorsi (LD), deltoideus posterior fibers (DP), obliquus externus abdominis (OEA), serratus anterior (SA), quadriceps vastus lateralis (VL), and tibialis anterior (TA) during successive quartiles of the drive and recovery phases of the rowing stroke, respectively. Slide-based ergometer rowing: black line, filled circles. Stationary ergometer rowing: gray line, open circles. Left panels: Female rowers. Right panels: Male rowers. *Significant difference between ergometer conditions ($P < 0.05$). § Significant difference between male and female rowers ($P < 0.05$). n indicates the number of rowers included in each analysis.

(TM, TL, LD) consistently showed peak neuromuscular activity in the second quartile of the drive phase, which coincided with the timing of peak handle force. This pattern was consistent across genders and ergometer conditions.

Discussion

The main result of the present study was that slide-based ergometer rowing led to decreased peak force production both in male and female elite rowers when compared to stationary ergometer conditions. In male rowers, sliding-based rowing was characterized by an increased stroke rate and decreased late-phase rate of force development measured as a reduced RFD during the final half of the rising force-time curve where handle force production was high to maximal. Neuromuscular activity in selected thoracic muscles was assessed for the first time during slide-based rowing ergometry, and as a novel finding slide-based ergometer rowing caused altered neuromuscular activity in leg muscles to a larger extent than in selected thoracic muscles. The timing of peak neuromuscular activity in the scapula retractors coincided with the instant of peak handle force production regardless of ergometer condition and gender. These findings and their potential relevance for overuse injury prevention are discussed below.

Force production at the handle and stroke rate

This study is the first to examine handle force impact rate, measured as the RFD, during ergometer rowing at various phases (early, late) of the rising force-time curve. Recently, Benson et al. (2011) observed a decrease in the grand mean RFD measured from onset of force to the instant of peak force in slide-based compared to stationary ergometer rowing performed at race pace. Although RFD measured in the same time interval did not differ between ergometer conditions in the present study, more detailed time analysis revealed that for male rowers, initial-slope RFD (at 10–30% of peak force) was 8.5% greater in the slide-based compared to the stationary condition, while a similar trend (7.8%) was indicated in female rowers albeit not reaching statistical significance ($P = 0.13$; Table 3). In summary, slide-based ergometer rowing led to a more rapid initial increase in force production in male rowers that was accompanied by a shorter catch slip (cf. Table 2). These findings are in strong agreement with the general shape of the force-time curves for slide-based vs stationary ergometer rowing (Benson et al., 2011) and for the RowPerfect ergometer in fixed vs sliding conditions (Colloud et al., 2006), exhibiting an earlier onset and sharper rise of the force production during sliding ergometer conditions. This also confirms the subjective sensation of a faster catch phase in the slide-based setting reported by the rowers of the present study (personal communication).

Force and EMG in slide-based ergometer rowing

Notably, a greater difference between ergometer conditions was observed for the load impact rate measured during the final phase of rising force production (late-slope RFD, recorded at 50–70% of peak force). During this phase, which was characterized by high propulsive force production, RFD decreased by 20.7% in male rowers during slide-based compared to stationary ergometer rowing (cf. Table 3).

The observed reciprocal trends in early-phase vs late-phase RFD between ergometer conditions may be explained by the fact that in the stationary condition, rowers have to accelerate their body mass to generate force at the handle, whereas in the slide-based condition, only the mass of the ergometer needs to be accelerated, hence reducing the time to onset of force (catch slip; Colloud et al., 2006). In the stationary condition, the “infinite” mass of the stationary ergometer (due to its fixed position on the floor base) allows the subject to sustain a high RFD in the late drive phase (probably due to the inertial mass of the rower) compared to the slide-based ergometer condition. The elevated load impact rate observed toward the mid-drive phase during stationary ergometer conditions could potentially result in a substantial difference in peak force production between ergometer conditions. In support of this notion, a 76 N (8.4%) reduction in peak force was observed in male rowers during slide-based ergometer rowing, which is very similar to the 80 N (~7%) reduction reported by Colloud et al. (2006) during sliding vs stationary RowPerfect ergometer rowing at race pace (fixed stroke rate of 35 strokes per minute, + 500 W). Bernstein et al. (2002) also compared RowPerfect ergometer rowing using fixed and sliding stretcher mechanisms and reported a 12.1% decrease in mean handle force in the sliding condition measured over the entire rowing stroke that was accompanied by ~9% increase in stroke rate at comparable sustained power output. These findings comply well with the 15.5% change in stroke frequency recently reported in male rowers using slide-based ergometry (Benson et al., 2011) and with the 11% increase in stroke rate observed in the male rowers of the present study for a given fixed power output. Therefore, evidence is accumulating to indicate that when either the entire rowing ergometer (Concept2) or the stretcher mechanism and flywheel (RowPerfect) are able to slide relative to the ground base of support, rowers demonstrate increased stroke rate and decreased handle force production for a given power output.

Similar trends tended to be observed in the female elite rowers of the present study, albeit their response to slide-based ergometer rowing was significantly smaller than that observed in male rowers. Likewise, Benson et al. (2011) observed an amplified response to slide-based ergometer rowing in male compared to female collegiate rowers and attributed this difference to differences in the familiarity with sliding ergometers between genders. In the present study however, all rowers were

experienced National Team rowers with prior experience with sliding ergometers. More likely therefore, the mass of the rower may affect the magnitude of the response since the mass of the moving ergometer (35 kg) constituted a substantially larger relative resistance (greater mass inertia relative to body mass) for the lightweight female rowers compared to the male rowers in the open weight class. Only two female rowers in the present study weighed more than 70 kg, which was comparable to the male lightweight rowers. Notably, they increased the stroke rate by 7% and 8% ~2 strokes per minute with corresponding decreases in peak force of 3% and 6%, respectively, during slide-based ergometer rowing, thus mimicking the response seen in male rowers.

Neuromuscular activity

Previously, Nowicky et al. (2005) observed no difference in neuromuscular activity for the extensors and flexors of the trunk and hip between stationary and sliding ergometer rowing (RowPerfect). Extending this analysis, the present study is the first to examine neuromuscular activity of thoracic muscles during slide-based ergometer rowing. The patterns of neuromuscular activity observed during the stationary rowing trial were in agreement with previous reports on neuromuscular activity in the abdominal muscles, the deltoids and the LD muscle (Rodriguez et al., 1990), LD and OEA (Pollock et al., 2009; Pollock et al. 2010), OEA and SA muscles (Wajswelner et al., 2000; Vinther et al., 2006), as well as in the TM and TL muscles (Vinther et al., 2006). The neuromuscular activity patterns presently observed for VL and TA conformed well to the observations by Jahnsen et al. (2009) although the VL pattern slightly differed from that reported by Rodriguez et al. (1990) where peak activity occurred later in the drive phase. Both female and male rowers demonstrated differences in neuromuscular activity for the VL and TA muscles between slide-based and stationary ergometer rowing. Notably, stationary ergometer rowing led to increased neuromuscular activity in the VL during the last quartile of the recovery phase as the rower moved forward to assume the catch position, and the knee extensors produced eccentric contraction force to decelerate the mass of the rower (Jahnsen et al., 2009). At the transition point, eccentric contraction was immediately followed by a concentric contraction, which was characterized by increased VL neuromuscular activity in the stationary condition that likely served to accelerate the mass of the rower during the initial drive phase. This type of forceful stretch-shortening-cycle knee extensor activity could not be performed to the same extent during slide-based ergometer rowing because of the lower inertial mass of the ergometer relative to the body mass of the rower. If vigorously performed, the movable ergometer would be pushed away and not allow the rower to assume an effective catch position. The observed difference in neu-

romuscular activity of the TA muscle was more related to the timing of the drive phase transition point where maximal neuromuscular activity in TA occurred later in the recovery phase in slide-based compared to stationary ergometer rowing (cf. Fig. 3). In the stationary condition, the body mass of the rower has to be continuously accelerated and decelerated while moving back and forth relative to the ergometer. Consequently, in the stationary condition, increased TA neuromuscular activity was observed in the initial recovery phase to initiate forceful forward-directed movement of the rower via ankle dorsi flexor contraction performed against the foot strap on the stretcher. In contrast, during slide-based rowing, the increase in TA neuromuscular activity in the late recovery phase likely served to prevent premature movement of the ergometer prior to the onset of the drive phase.

Male (but not female) rowers demonstrated increased SA neuromuscular activity during the late recovery phase during slide-based ergometer rowing (Fig. 3). Interestingly, the present female rowers exhibited peak SA neuromuscular activity in the second quartile of the drive phase, whereas the male rowers showed peak activity in the late recovery phase. The pattern observed in the female rowers resembled the pattern observed in a small ($n = 7$) mixed group of rowers with previous rib stress fractures (Vinther et al., 2006). Peak SA activity has previously been reported to occur in the final recovery phase in male rowers, female rowers, and a larger ($n = 22$) mixed group of rowers with a history of previous rib stress fractures (Wajswelner et al., 2000). Whether the increased neuromuscular SA activity in the mid-drive phase in the present female rowers reflects an increased need for scapular stabilization or merely represents a slightly different style of rowing remains unknown. Neuromuscular activity did not differ between ergometer conditions for TM, TL, LD, and OEA (cf. Fig. 3).

Timing of neuromuscular activity in relation to handle force production

As hypothesized by Warden et al. (2002) and illustrated in the present Fig. 3, maximal neuromuscular activity in the shoulder retractors (TM, TL, and LD) and peak handle force both occurred in the second quartile of the drive phase in both female and male rowers, regardless of ergometer condition. As suggested by Warden et al. (2002) the application of force to the handle will induce a forward-directed pull of the arms and shoulders that has to be resisted by the shoulder retractors, potentially resulting in a medially directed force vector causing rib cage compression. The present results clearly support such a scenario. Another important neuromuscular aspect relates to the increase in neuromuscular VL activity along with the increased force production observed in stationary ergometer conditions. It is well known that stretch-shortening-cycle contractions lead to increased muscle force production (Komi & Nicol, 2000), and it

therefore seems reasonable to speculate that in stationary ergometer rowing, the elevated neuromuscular activity in VL during the late recovery phase and initial drive phase, respectively, may have contributed to the increased force production (greater peak force and steeper late-slope RFD) seen in this condition. Thus, the “infinite” inertial mass of the ergometer in the stationary condition in combination with the more pronounced accelerations and decelerations of the rower in this condition require that greater forces are generated by the knee extensors in the catch (transition) phase as well as at the instant of peak handle force in the later drive phase.

Potential implications for risk of overuse injury – with emphasis on rib stress fractures

Rib stress fractures comprise a well-documented problem in elite rowing as summarized by Warden et al. (2002) and supported by more recent reports (Iwamoto & Tsuyoshi. 2003; Dragoni et al., 2007; Smoljanović et al., 2007). Stress fractures may develop over time when bone remodeling is unable to compensate for the accumulation of micro damages caused by repeated bone strains, high strain rates, large strain magnitudes, and limited periods of recovery between successive exposures to the bone strain (Warden et al., 2002). As a likely injury mechanism, detrimental rib cage compression may occur during the drive phase of the rowing stroke as a result of high contractile muscle forces produced by the shoulder retractors in combination with the application of force to the handle (Warden et al., 2002). This theory is supported by the present observations of a close timing between peak handle force production and peak neuromuscular activity in TM, TL, and LD, respectively. Consequently, the elevated peak force and rise in late-phase RFD measured at the handle during stationary ergometer conditions could potentially contribute to an increased magnitude and rate of bone strain induced to the ribs. Moreover, the observed gender difference in the timing and magnitude of neuromuscular activity in serratus anterior (SA) may provide some additional insight on the etiology of rib stress fractures in competitive rowers since SA is attached to the ribs and an increased incidence of rib stress fracture has been reported in female compared to male elite rowers (Hickey et al., 1997). Certainly, more research is needed to examine the

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influence of gender on the incidence of rib stress fractures and to further evaluate the potential negative role of SA in this type of injury. In anecdotal support of the potential importance of SA, the female rower who demonstrated the greatest normalized SA activity in the mid-drive phase subsequently developed a rib stress fracture after completion of this study.

Perspectives

The decreased peak force and attenuated impact rate (reduced late-phase RFD at 50–70% of peak force) measured during slide-based ergometer rowing may contribute to a diminished mechanical rib loading pattern, as elaborated in detail above. On the other hand, the elevated stroke rate increases the number of rib loading cycles per unit of exposure time. A recent study suggests that the magnitude of bone stress is more important than the repetitiveness of bone strain in the development of stress fractures of the tibia in distance runners (Edwards et al., 2009). Consequently, the potential protective effect of reduced magnitude and rate of bone loading may counterbalance the potential negative effect of an increased loading frequency. As ergometer power output, and thus, exercise intensity remained constant between ergometer conditions and no major differences in neuromuscular activity were observed, slide-based ergometer rowing may constitute a valid alternative to stationary ergometer training, as recently suggested by Holsgaard-Larsen and Jensen (2010). Prospective controlled studies are needed to elucidate if slide-based ergometer rowing may play a role in the prevention of overuse injuries in rowers.

Key words: Biomechanics, muscle, elite rowers, overuse injury, rib stress fractures.

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