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Research article

Muscle Synergies of Untrained Subjects during 6 min Maximal Rowing on Slides and Fixed Ergometer

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Abstract
The slides ergometer (SE) was an improvisation from fixed ergometer (FE) to bridge the gap of mechanics between ergometer rowing and on-water rowing. The specific mechanical constraints of these two types of ergometers may affect the pattern of muscle recruitment, coordination and adaptation. The main purpose of this study was to evaluate the muscle synergy during 6 minutes maximal rowing on slides (SE) and fixed ergometers (FE). The laterality of muscle synergy was also examined. Surface electromyography activity, power output, heart rate, stroke length and stroke rate were analyzed from nine physically active subjects to assess the rowing performance. Physically active subjects, who were not specifically trained in rowing, were chosen to exclude the training effect on muscle synergy. Principal component analysis (PCA) with varimax rotation was applied to extract muscle synergy. Three muscle synergies were sufficient to explain the majority of variance in SE (94.4 ± 2.2 %) and FE (92.8 ± 1.7 %). Subjects covered more rowing distance, exerted greater power output and attained higher maximal heart rate during rowing on SE than on FE. The results proved the flexibility of muscle synergy to adapt to the mechanical constraints. Rowing on SE emphasized on bi-articular muscles contrary to rowing on FE which relied on cumulative effect of trunk and upper limb muscles during propulsive phase.

Key words: Muscle synergy, rowing, principal component analysis.

Introduction

Muscle synergy is defined as a specific and consistent spatiotemporal pattern of muscle activations that leads to similar joint trajectories (Ting and McKay, 2007) and have been proposed as a neural strategy for simplifying the neuromuscular control. These synergies can be identified from electromyographic (EMG) patterns recorded from numerous muscle decomposition algorithms (e.g principal component analysis, PCA) based on two components, (i) "muscle synergy vectors" which corresponds to the relative loading of each muscle within each synergy; and (ii) "synergy activation coefficient" which represents the temporal activity of the muscle synergy (Frére and Hug, 2012). Some researchers observed that temporal recruitment patterns were robust across various mechanical constraints while the muscle weightings varied across subjects or test conditions (Cappellini et al., 2006; Ivanenko et al., 2004). These studies showed that muscle synergies were stable across tasks and yet flexible enough to allow inter-individual variability and accommodate errors or changes.

Working out on sculling ergometers, either on fixed (FE) or slides ergometer (SE), was a crucial training component for competitive rowers. The slides ergometer (SE) was an improvisation from fixed ergometer (FE) to bridge the gap of mechanics between ergometer rowing and on-water rowing. For Concept 2, the SE consists of a rail that was mounted underneath the fixed ergometer. Both types of ergometers were widely utilized by rowers for training (Colloud et al., 2006; Maestu et al., 2005; Secher, 1993), evaluation (Colloud et al., 2006) and team selection (Elliott et al., 2002; Maestu et al., 2005). Although rowing on slides ergometer (SE) was hypothesized to be less physiologically demanding than FE rowing (Mahony et al., 1999), recent findings indicated that physiological variables (i.e., maximal heart rate, peak lactate concentration and peak aerobic capacity) were not significantly different on both rowing ergometers except for anaerobic capacity (Holsgaard-Larsen and Jensen, 2010).

On the other hand, Colloud et al. (2006) reported significant difference in force curve profiles (i.e., handle and stretcher force) during SE and FE rowing. A large anterior-posterior force at the stretcher was produced by the rower to move his center of mass in the positive and negative directions when rowing on FE. This causes considerable amount of contact force and external power (i.e., the product of the force exerted on the handle by its velocity) during the catch and the finish phases. Conversely, low inertial force was necessary to accelerate the rower's center of mass on SE ergometer (Colloud et al., 2006). Hence, the differences between force profiles on FE and SE may have implications on the pattern of muscle recruitment, coordination (Colloud et al., 2006; Green and Wilson, 2000) and adaptation (Roth et al., 1993).

Muscle synergy is particularly important in rowing because as a power-endurance sport that recruits 70% of total muscle mass (Steinacker et al., 1998; Roberts et al., 2005), rowers need to have enhanced physiological capacity coupled with efficient muscle synergy. Despite the importance of muscle coordination on rowing performance (Rodriguez et al., 1990; Tachibana et al., 2007), no studies have been conducted comparing the muscle synergy during FE and SE rowing. As the muscle activity is a large determinate of metabolic rate during maximal effort activities (Wakeling et al., 2010) such as 6 min maximal rowing, and muscle synergy is a strategy to simplify neuromuscular control, it is thus compelling to explore the underlying relationships. Therefore, this study was under-

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taken in an attempt to evaluate the muscle synergy during 6 minutes maximal rowing of physically active untrained males. The subjects were not specifically trained in competitive rowing to exclude the effect of training bias on muscle synergy. Our second aim was to evaluate the laterality of muscle synergy between the right and the left sides of the body as the previous studies only assumed the symmetries of muscle synergy on sculling ergometer rowing (Turpin et al., 2011a; Nowicky et al., 2005; So et al., 2007).

Methods

Subjects

There is no a-priori power analysis test for PCA analysis, however, based on previous studies of muscle synergy (Hug et al., 2011; Ivanenko et al., 2004; Turpin et al., 2011a; 2011b; 2011c; Wakeling and Horn, 2009) we decided to recruit nine physically active males (age: 26.78 ± 2 years, mass: 80.61 ± 11.48 kg, height: 1.81 ± 0.07 m). The group consisted of competitive triathletes, long distance runners, cyclists and rugby players who had never been involved in competitive rowing. A separate familiarization session was undertaken before the real experiment to ensure the safety of the subjects and to reduce potential risks. For each subject a written informed consent was obtained. All tests and scientific experiments comply with the ethical code of University of Delaware Internal Review Board.

Experimental setup

Experiments were carried out on a Concept 2 model D ergometer (Morrisville, Vermont, USA). The slides system consists of a pair of rails that can be attached to the ergometer to simulate OW rowing mechanics. Drag factor was manually adjusted relative to the subjects' body weight which resembled the resistance effect during OW rowing (Kane et al., 2008). Simultaneous visual feedback was provided to subjects through an attached display that showed data on heart rate, stroke length, stroke rate, power output, distance covered and time. Stroke-to-stroke data were assessed using the RowPro v2.006 software (Digital Rowing) in conjunction with the Concept 2 interface. These data were averaged into 30s intervals.

Eight rowing-specific muscles were evaluated bilaterally: Gastrocnemius Lateralis (GL), long head of Biceps Femoris (BF), Rectus Femoris (RF), Erector Spinae (ES), Lattisimus Dorsi (LD), Brachioradialis (BR), Triceps Lateralis (TR) and Deltoid Medius (DM). The muscles activity was recorded using wireless Noraxon Telemyo DTS Desk Receiver (Noraxon, Scottsdale, AZ). Pairs of surface Ag/AgCl wet gel electrodes (Noraxon, Scottsdale, AZ) were attached to the skin with a fixed 20 mm inter-electrode distance. Before the electrodes were applied, the skin was shaved and cleaned with alcohol to minimize impedance. Electrode placement followed the recommendations by SENIAM (Hermens et al., 2000) for all muscles, except for LD and BR, which were not referenced by SENIAM. For LD, the electrode was placed on the muscular curve at T12 (de Sèze and Cazalets, 2008) and for BR, the electrode was placed at 1/6 of the distance from the midpoint between the cubital fossa to the lateral epicondyle of the ulna (Muceli et al., 2010). Raw EMG signals were recorded at sampling rate of 1500 Hz.

The position and orientation of the wrist joint projected along the longitudinal axis of the ergometer (i.e., the rowing direction) was analyzed to define the rowing cycle. Their three-dimensional trajectories were captured using ten infrared cameras (Vicon MX, Oxford, UK). The spatial accuracy of the system is better than 1 mm (root mean square). The rowing cycle was defined as the time between two successive local maxima. The points of local maxima and minima indicated catch and finish positions, respectively. These were used to identify the drive phase (i.e., from catch to finish position) and the recovery phase (i.e., from finish to catch position). The position data were sampled at 100 Hz, filtered (Butterworth filter, cutoff frequency: 5Hz) and synchronized to electromyography (EMG) data through Vicon Nexus Workstation v4.5 (Vicon, Oxford, UK).

Protocol

The order of rowing on either FE or SE was randomized with at least one week interval in between. The tests were conducted around the same time of day to eliminate circadian effect. Subjects were asked to refrain from food and beverages (except water) from two hours before testing. They wore their own shoes and skin-tight lycra shorts to facilitate accurate markers and electrodes placement. The overall protocol took approximately 90 min including the preparation time. The experiment consisted of: i) 5 min warm up on the ergometer, ii) 6 min maximal test, iii) 5 min cool down. The 6 min maximal rowing test is a common test to simulate a 2000 meters OW race (Holsgaard-Larsen and Jensen, 2010). Subjects were encouraged to cover as much rowing distance as they could during the 6 min period.

Data analysis

EMG signals were band-pass filtered (20-400 Hz, zero-lag 4-th order Butterworth filter), fully rectified and low-pass filtered (8 Hz, zero-lag) to create linear envelopes. Then, linear envelopes were split into individual rowing cycles and time-normalized to a 100-point time base. The time-normalized technique was crucial to ensure robust comparison by avoiding the biased of transition time between subjects (Hug et al., 2011). Then, a set of 40 consecutive cycles starting from the third minute of the maximal rowing test was averaged to obtain a representative pattern for each muscle. The third minute was chosen because the peak value of oxygen consumption was often achieved between the second and fourth minutes of exercise (Hagerman, 1984). These patterns were subsequently normalized to their peak value. All analyses were conducted using custom MATLAB code (The Mathworks, Inc., Natick, MA).

Factor analysis

Principal Component Analysis (PCA) was applied to extract the muscle synergy as suggested by Ivanenko et al (2004). PCA was chosen to analyze the underlying factors or associations in a large dataset of muscle activity. Rejection of the hypothesis of the Bartlett's test signifies latent factors in the data and was therefore a requirement for PCA (Ivanenko et al., 2004). The Kaiser-Meyer Olsen (KMO) (Kaiser, 1974) test measured the adequacy of the sample size for the factor analysis and a value greater than 0.6 indicated a good sampling size for PCA (Kline, 1994). After meeting all the prerequisite tests, PCA with varimax rotation was applied. Varimax was an orthogonal rotation method which constrained the analysis to uncorrelated factors and commonly adopted in factor analysis for muscle synergy studies (Cappellini et al., 2006; Ivanenko et al., 2004). The robustness of the number of factors to be retained from PCA was ensured through several statistical methods: (i) to retain factors that have eigenvalues greater than 1 (Kaiser, 1974), (ii) to retain those eigenvalues that occurred before the inflection point of the scree plot (Cattell, 1966), (iii) Parallel Analysis (PA) (Glorfeld, 1995) which compared the obtained eigenvalues with randomly generated eigenvalues, thus the obtained eigenvalues must be larger than the random data, and finally (iv) Minimum Average Partials (MAP) (Velicer, 1976) which was an iterative procedure that examined successive partial correlation matrices. In muscle synergy studies, an additional important aspect to decide the number of factors to retain was the interpretability (Cappellini et al., 2006; Ivanenko et al., 2004) of the factors related to the physiological function.

Statistical analyses

The intra-group indices of similarity were computed on Z-transforms of individual EMG patterns and synergy activation coefficients as done in previous studies (Cappellini et al., 2006; Ivanenko et al., 2004; Turpin et al., 2011a). These indices correspond to the averaged Pearson's correlation coefficient (r) between each pair of values within the same group. Such indices were used as indicators of the waveform consistency within a rowing condition. The use of Pearson's correlation coefficient (r) on Z-transform data excluded the differences in-phase and frequency between the correlated signals. All statistical tests were carried out in IBM SPSS Statistics v20.0 (IBM Corp., Armonk, NY). Paired Student's t-test was applied to compare rowing performance, and muscle loadings between two rowing conditions. Significance value was set to $\alpha = 0.05$.

Results

Rowing performance

Overall, better rowing performance was observed during 6 min maximal rowing on SE compared to rowing on FE (Table 1). The subjects were able to exert more powerful strokes ($p < 0.001$), cover longer distance ($p < 0.001$) and attain higher maximal heart rate ($p = 0.045$) during rowing on SE compared to rowing on FE. Besides, subjects preferred to row faster ($p < 0.001$) with shorter strokes ($p < 0.001$) on SE compared to rowing on FE.

EMG patterns

The averaged EMG patterns were first compared bilaterally to test muscle symmetry during rowing. All subjects of this study were right-hand dominant. For each muscle, the Z-transformed EMG patterns were averaged across subjects compared bilaterally through Pearson's correlation tests (Table 2). All muscles showed high value of Pearson's r (e.g., for SE the r ranged from 0.86 to 0.95 while for FE the r ranged from 0.82 to 0.95) which indicate symmetrical muscle activation during rowing. Therefore, we presented results on right side only.

Table 1. Rowing performance on slides and fixed ergometer. The values are in mean (standard deviation) (n = 9).

	SE	FE
Max HR (bpm)	177 (8.1)	172 (6.5) *
Stroke rate (spm)	38 (5.9)	30 (4.3) ***
Stroke length (mps)	7 (1.7)	8 (1.6) ***
Power (W· kg$^{1/3}$)	50 (13.6)	41 (11.3) ***
Total distance (m)	1517 (103.9)	1420 (106.6) ***

SE, slides ergometer; FE, fixed ergometer; HR, heart rate; bpm, beats per minute; spm, strokes per minute; mps, meter per stroke; W· kg$^{1/3}$, Watt per corrected body weight. * $p < 0.05$, *** $p < 0.001$.

Table 2. Averaged Pearson's correlation coefficients (r) comparing the right and left sides for eight muscles during SE and FE rowing. The values are in mean (standard deviation) (n = 9).

Muscle	SE	FE
Gastrocnemius Lateralis (GL)	.92 (.06)	.81 (.03)
Biceps Femoris (BF)	.93 (.04)	.81 (.05)
Rectus Femoris (RF)	.94 (.04)	.84 (.02)
Erector Spinae (ES)	.87 (.07)	.86 (.08)
Latissimus Dorsi (LD)	.93 (.01)	.90 (.02)
Brachioradialis (BR)	.94 (.01)	.95 (.01)
Triceps Lateralis (TR)	.95 (.03)	.88 (.06)
Deltoid Medius (DM)	.86 (.10)	.82 (.07)

SE, slide ergometer; FE, fixed ergometer.

The ensemble averages of the EMG linear envelopes for the eight muscles investigated during both rowing conditions were depicted in Figure 1. Comparing rowing on SE to FE, subjects showed different timing and strategy of muscle recruitment especially during the propulsive drive phase (i.e., from 0% to 50% of the rowing cycle). For rowing on SE, five muscles (GL, BF, RF, ES and LD) contributed predominantly during the drive phase, while the other three muscles (TR, BR and DM) were primarily recruited during the recovery phase. On the other hand, for rowing on FE, all muscles contributed to some degree during the drive phase. Table 3 illustrates the intragroup similarity indices of waveforms for each muscle. Values range from 0.64 to 0.81, indicating moderate variability of the waveforms.

Table 3. The intra-group indices of waveform similarity for each muscle during both rowing conditions.

Muscle	SE	FE
Gastrocnemius Lateralis (GL)	.65 (.08)	.64 (.07)
Biceps Femoris (BF)	.65 (.12)	.75 (.12)
Rectus Femoris (RF)	.68 (.12)	.72 (.14)
Erector Spinae (ES)	.74 (.13)	.81 (.06)
Latissimus Dorsi (LD)	.68 (.16)	.76 (.05)
Brachioradialis (BR)	.73 (.09)	.73 (.05)
Triceps Lateralis (TR)	.67 (.13)	.66 (.06)
Deltoid Medius (DM)	.63 (.06)	.75 (.09)

SE, slide ergometer; FE, fixed ergometer.

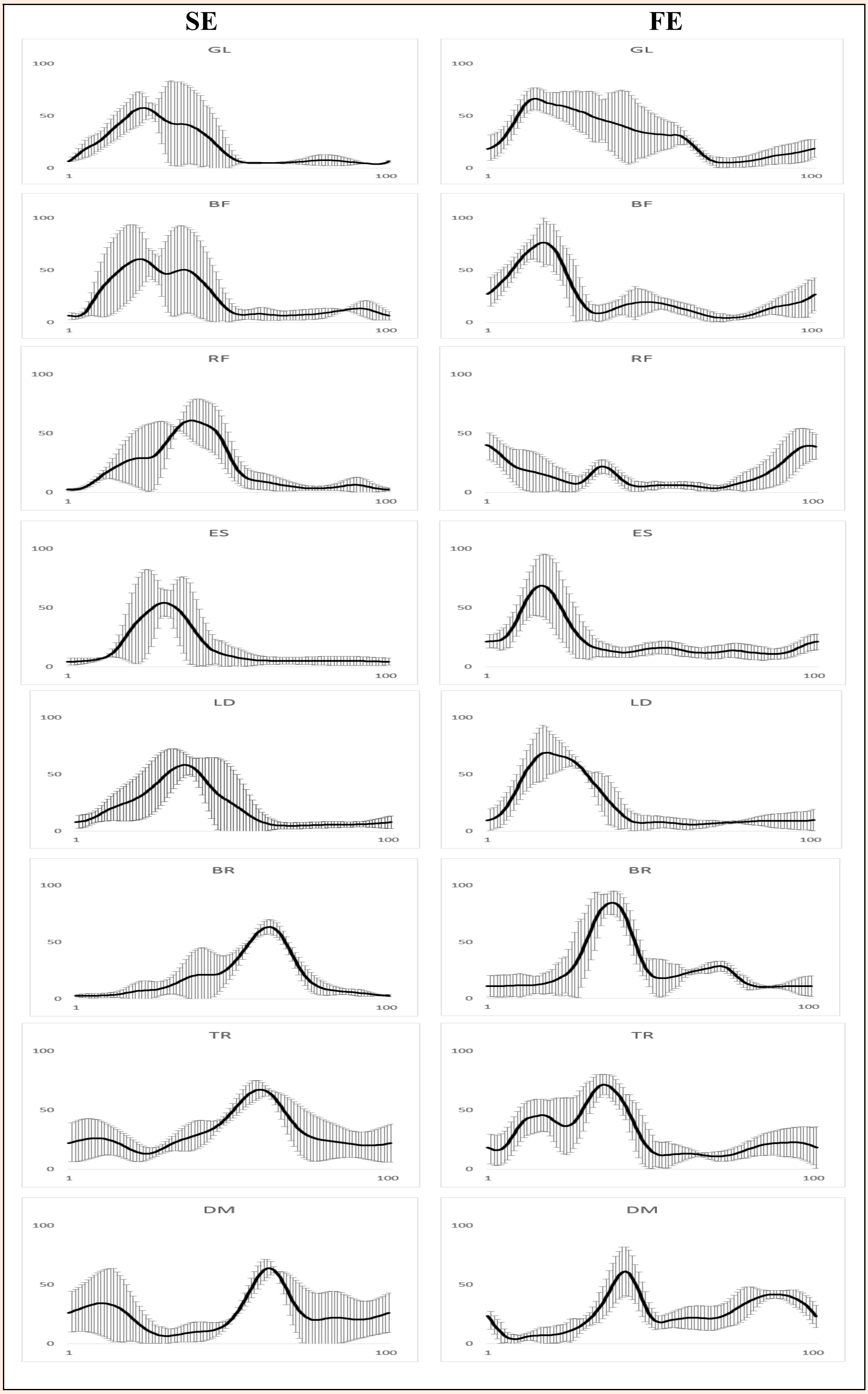

Figure 1. **Ensemble averages of normalized EMG patterns of the 8 recorded muscles during rowing on SE and FE. Rowing phase from 0% to 50% indicates drive phase and from 51% to 100% signifies the recovery phase. Muscle abbreviations are described in the text.**

Muscle synergy

Results from Bartlett's Test of Sphericity on each subject indicated that the correlation matrix significantly diverged from the identity matrix (df = 28, p = 0.001), suggesting that muscle activations were not orthogonal. The KMO statistic (ranging from 0.625 to 0.7 for SE and ranging from 0.614 to 0.767 for FE) was always larger than the minimum value of 0.6 suggested by Kline (Field, 2013), hence data were appropriate for PCA.

Kaiser's criterion, the scree plot, PA and MAP analysis pointed to a three-factor solution. The three factors solution satisfied requirements for simple structure, meaning that all muscles were loaded on one specific factor (Kline, 1994; Tabachnick and Fidell, 2007). The muscles with factor loadings greater than 0.55 (Comrey and Lee, 1992) were considered as contributors for a specific factor. We defined these factors as synergies. Hence, three muscle synergies were extracted for all subjects during rowing on SE and FE. The total Variance Accounted For (VAF) SE rowing was 94.4 ± 2.2 % (ranged 90% to 96.9%) and the total VAF for FE rowing was 92.8 ± 1.7 % (ranged 90.3% to 94.9%). Therefore, three muscle synergies were sufficient to reproduce EMG patterns for all subjects.

The overall results of the three muscle synergies for both conditions were depicted in Figure 2. The comparison of muscle loadings between rowing conditions were illustrated in Figure 3. For rowing with SE: (i) Synergy #1 involved all bi-articular leg muscles (GL, BF and RF) and was associated with the drive phase, (ii) Synergy #2 comprised upper limb muscles (BR, TR and DM) and was activated during first half of the recovery phase, and (iii) Synergy #3 engaged the dorsal trunk muscles (LD and ES) and was dominant between the transition of drive and recovery phases.

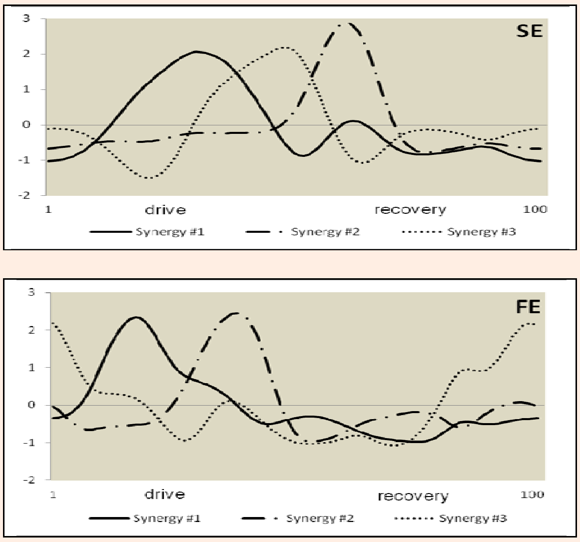

Figure 2. Muscle synergies of untrained subjects during 6 minutes maximal rowing on slides (SE) and fixed ergometer (FE).

Although three synergies were identified in the FE rowing mode, these consisted of different muscles: (i) Synergy #1 involved ES, LD, TR and GL, and was activated during the first half of drive phase, (ii) Synergy #2 was active during the second half of the drive phase and was contributed by BR and DM, and (iii) Synergy #3 engaged the bi-articular thigh muscles (BF and RF) and was associated with the second half of the recovery phase and the starting of the drive phase. Additionally, the intragroup indices of similarity showed acceptable values of the synergies waveforms for both rowing conditions (Table 4), indicating some variability of synergies among subjects.

Table 4. Intra-group indices of waveform similarity of synergies. The values are in mean (standard deviation).

	SE	FE
Synergy #1	.66 (.14)	.64 (.13)
Synergy #2	.64 (.17)	.62 (.21)
Synergy #3	.51 (.26)	.68 (.09)

SE, slide ergometer; FE, fixed ergometer.

Discussion

It is important for rowers to develop an effective coordination between upper and lower body (Shephard, 1998), since a non-optimal strategy could limit the power output and the efficiency of the limb motion (Hug et al., 2011).These observations suggest a fundamental role of muscle synergies during rowing. In our analysis, PCA was capable of extracting three synergies, similar to previous studies that applied non-negative matrix factorization (Turpin et al., 2011a; Turpin et al., 2011b; Turpin et al., 2011c). Our basic finding, that three component factors were accounted for muscle synergies during rowing, was reported earlier by Turpin et al. (2011b) who extracted three synergies from 23 muscles in nine subjects. They found the same basic patterns across different skill levels (Turpin et al., 2011a), fatiguing conditions (Turpin et al., 2011b), and power outputs (Turpin et al., 2011c). We have extended these results by showing that the basic patterns were conserved across different stretcher mechanisms (i.e., FE and SE).

The similarity in the composition of three extracted synergies in both rowing conditions was accompanied by different emphasis on particular muscles, which indicated the robustness of the neuromuscular control to adapt to various mechanical constraints. We observed that the inventory of rowing tasks was achieved through modification of muscle loadings but not muscle synergy structure, which was in agreement with synergies studies on locomotion (Ivanenko et al., 2004), cycling (Wakeling and Horn, 2009) and rowing (Turpin et al., 2011a).

The varimax factors were proposed to represent motor programs for groups of muscles that perform specific function during locomotion (Ivanenko et al., 2004). Some evidence for such functional grouping (i.e. leg drive for Synergy#1, arm pull for Synergy#2 and trunk swing for Synergy#3) was seen in our SE data. For instance, during SE rowing, the bi-articular leg muscles explained up to 60% of total VAF and were active during the propulsive phase (Synergy #1). Thigh muscles were the main power sources during rowing (Guével et al., 2011; Nowicky et al., 2005) and as multi-joint muscles they also play a role in transferring force generated from the stretcher to the trunk (Hofmijster et al., 2008). Next, the force generated was distributed to Synergy #3 (i.e., back muscles) which were active from the middle of drive

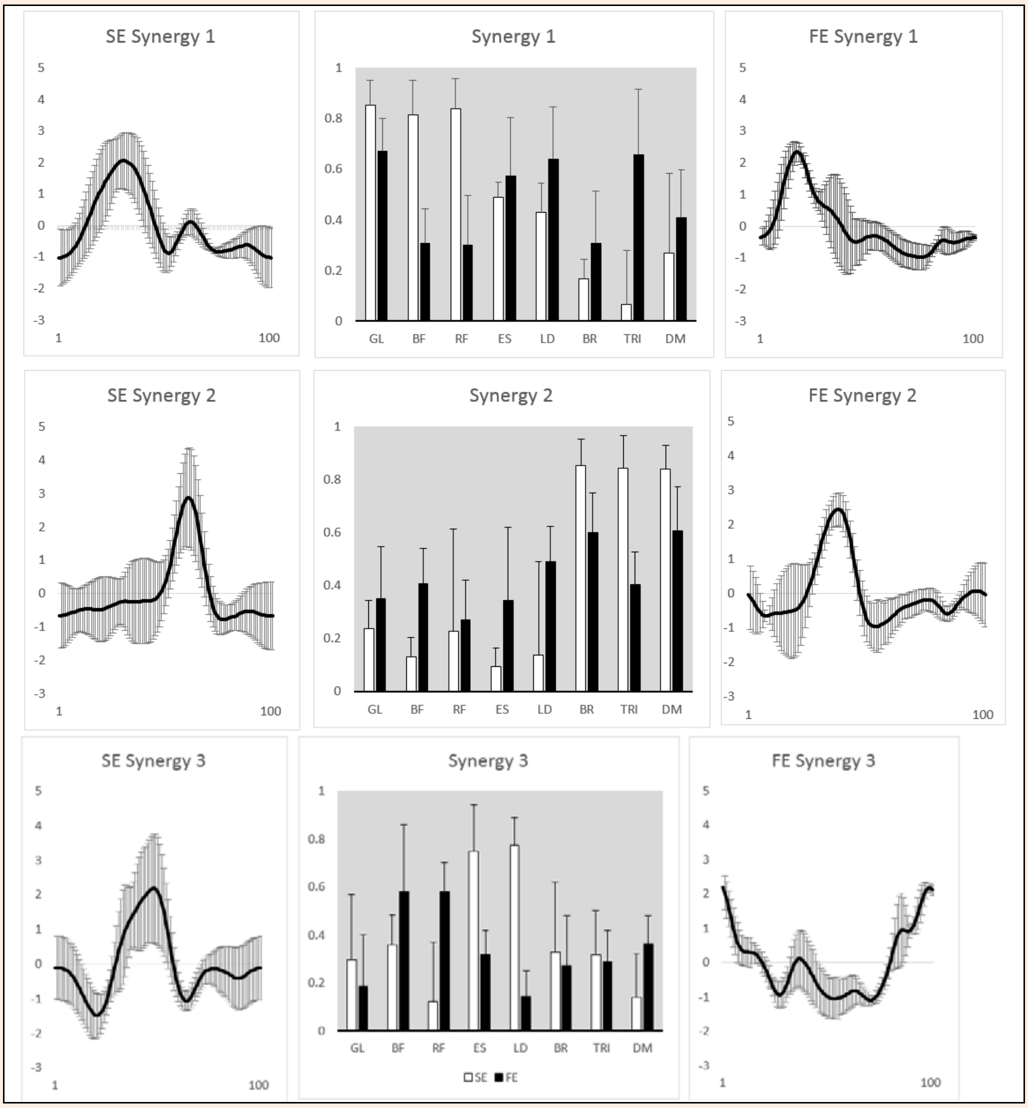

Figure 3. Synergy activation coefficients and muscle synergy vectors depicted for rowing on SE and FE. Synergy activation coefficients were averaged across the subjects for the three extracted synergies and expressed as a function of percentage of the rowing cycle (0% to 50% represent drive phase and 51% to 100% represents recovery phase). The muscle synergy vectors were averaged across the subjects for the three extracted synergies. Individual muscle weightings are depicted for each muscle within each synergy. SE, slides ergometer: FE, fixed ergometer.

phase up into early recovery phase. The trunk swing transferred the force generated by the leg extension (Hofmijster et al., 2008) to the Synergy#2, which consisted of three arm muscles. The arms synergy was active after the legs were fully extended to conserve the force continuity to the handle. Hence, by emphasizing leg drive, rowing on SE allows effective force transfer (Kleshnev, 2011).

On the contrary, rowing on FE recruited a larger percentage of total muscle mass (Synergies #1 and #2) than rowing on SE due to cumulative force production during the drive phase. However, despite their huge cross sectional area, postural muscles were slow to transfer the force generated. Hence, reliance on back muscles prevented a quick increase of propulsive force, thus making the temporal structure of the drive less effective (Kleshnev, 2011). This explained the absence of clear distinction between legs, back and arms functional muscle synergy as observed in SE rowing. Meanwhile, due to the lack of motion of FE, separate Synergy #3 was activated to control the body movement during stroke transition. These synergies were similar to a previous study that analyzed muscle synergies on FE rowing (Turpin et al., 2011a).

Additionally, our results on rowing variables were in line with previous studies (Holsgaard-Larsen and Jensen, 2010; Mello et al., 2009). Subjects preferred to row faster with shorter stroke on SE, because the slides mechanism reduced the inertial force between changing of strokes position (Mello et al., 2009). Longer stroke length was observed when rowing on FE to dissipate the rower's momentum and reverse its direction, as explained by the work-energy theorem (Bernstein et al., 2002). The lack of motion of FE yielded two important consequences: (i) increased in total work, because the rower had to accelerate and decelerate his body at the end of each stroke (Martindale and Robertson, 1984), and (ii) minimal propulsive force loss, as force was transferred from the fixed stretcher to the rower's body equally and in the opposite direction to which it was applied (Elliott et al., 2002). On the other hand, the power delivered to the handle can increased by up to 18% when subjects rowed on ergometers that allowed their center of mass to remain relatively stationary (Harrison, 1970) (i.e., rowing on SE). This probably explained better total energy savings (Martindale and Robertson, 1984), more power output and distance covered on SE compared to FE.

On the other hand, the Concept2 ergometers only allowed symmetrical movements that resemble sculling, and investigators who focused on sculling had restricted measurements of the muscle activity to one side of the body (Nowicky et al., 2005; So et al., 2007). Under such experimental conditions, the detection of possible asymmetries in muscle activation between the two sides was not possible (Janshen et al., 2009). Therefore, we decided to check the laterality of muscle activity on eight rowing-related muscles bilaterally. The high Pearson's *r* on index of waveform similarity for all muscles during the two rowing conditions indicated that muscle activity was indeed symmetrical.

There were several limitations in our study. The only device that measured physiological attributes was a heart rate monitor, which limited our understanding in terms of muscle synergy and energy efficiency. As stated by d'Avella and Pai (2010), the robustness of muscle synergies should include consistency across various mechanical and physiological constraints. Also, the number and the choices of selected muscles did influence the patterns muscle synergy extracted (Steele et al., 2013). The lack of kinetic profile measurement and analysis reduced our insights regarding force transferred during rowing.

Conclusion

The purpose of this study was to evaluate the muscle synergy during 6 minutes maximal rowing on FE and SE for physically active untrained males. Despite the number of published studies that compared the two rowing ergometers in terms of rowing performance, physiological variables, kinematics, force profiles, and individual EMG patterns, this study was the first to focus on muscle synergies related to the two stretcher mechanisms. Besides, the muscle synergies that were extracted in this study excluded the bias of training and circadian cycle, with enhancement of PCA method. Rowing on SE and FE showed the same number of muscle synergies, but the muscle loading on each synergy were different. Rowing on SE relied mostly on bi-articular leg muscles, while rowing on FE emphasized on recruiting a huge percentage of muscle area for cumulative force production. The findings of this study could improve our current understanding regarding the strategy of the CNS to remain efficient in different mechanical constraints. As different stretcher mechanisms emphasized on different muscle synergies, selecting a suitable ergometer for novice rowers is crucial. Considering the emphasized of leg drive by SE, it may provide a better training tool which possibly reduce back pain in novice rowers.

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Key points

- Three muscle synergies were extracted during maximal rowing on both fixed and slides ergometer
- Untrained subjects emphasized leg muscles while rowing on SE
- Untrained subjects focused on back muscles during FE rowing

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