Muscle Synergy of Collegiate Rowers During 6 Min Maximal Rowing on Fixed and Slides Ergometer

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Abstract—**The purpose of this study was to evaluate the muscle synergy of collegiate rowers during 6 min maximal rowing on different stretcher mechanisms: fixed (FE) and slides ergometer (SE). The association of muscle synergy to rowing economy and physiological variables was further quantify by statistical analysis. Method: Ten collegiate rowers were recruited at the end of their competitive season. Muscle synergy was extracted from 16 rowing specific muscles using principal component analysis with varimax rotation. 6 min maximal rowing test was performed on Concept 2 FE and SE. Rowing performance and physiological variables were analyzed. Results: Rowers showed similar rowing performance on FE and SE in terms of total distance covered. Rowers rowed faster at shorter strokes when rowing on SE compared than rowing on FE. Greater maximal heart rate, energy expenditure and rowing economy were achieved on SE rowing. Three muscle synergies were extracted in both rowing conditions. Significant association was found between Synergy #1 and rowing economy. Discussion: Muscle synergy was robust between two rowing conditions. Rowing economy was highly associated with muscle synergy. As there was no significant difference in muscle synergy pattern and rowing performance during rowing on FE and SE, both ergometers could be utilized by experienced rowers.**

Index Terms—**muscle synergy, sport biomechanics, rowing, principal component analysis**

I. Introduction

Muscle synergy is defined as a specific and consistent spatiotemporal pattern of muscle activations that leads to similar joint trajectories [1] 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 [2]. Some researchers observed that temporal recruitment patterns were robust across various mechanical constraints while the muscle weightings varied across subjects or test conditions [3], [4]. These studies showed that muscle synergies were stable across tasks and yet flexible enough to allow inter-individual variability and accommodate errors or changes.

The modulation of muscle recruitment patterns following training was another indication of the flexibility of muscle synergy composition [5]. As an example, [6] found alterations of the synergy vectors following five days of postural training. On the contrary, a study of maximal rowing on fixed ergometer (FE) observed a great similarity between the muscle synergy of experienced rowers (10 years of competitive rowing) and untrained subjects [7]. They concluded that expertise in rowing was linked to a better ability in adjusting the mechanical output of the muscle synergy rather than the differences of temporal aspect muscle synergy. The discrepancy of results could be due to the differences in the tasks studied (i.e postural versus rowing tasks) and the types of synergy adaptation (i.e chronic versus acute training). However, both studies neglected the physiological variables that could gain further insights regarding the effect of training on muscle synergy. This is particularly important in rowing because as a power-endurance sport that recruits 70% of total muscle mass [8], [9], rowers need to have enhanced physiological capacity coupled with efficient muscle synergy.

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 [10], [11], [12], evaluation [10] and team selection [13], [11]. Although rowing on slides ergometer (SE) was

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hypothesized to be less physiologically demanding than FE rowing [14], 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 [15].

On the other hand, [10] 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 [10]. Hence, the differences between force profiles on FE and SE may have implications on the pattern of muscle recruitment, coordination [10], [16] and adaptation [17].

Despite the importance of muscle coordination on rowing performance [18], [19], no studies have been conducted comparing the muscle synergy of trained rowers during FE and SE rowing. As the muscle activity is a large determinate of metabolic rate during maximal effort activities [20] 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 undertaken in an attempt to investigate the association of muscle synergy and physiological variables in collegiate rowers when rowing on SE and FE.

II. Methods

A. Subjects

Ten collegiate male rowers (age: 20.36 ± 3.4 years, mass: 79.47 ± 8.1 kg, height: 1.82 ± 0.1 m) were recruited at the end of their competitive season. At least three years of experience in competitive rowing was needed to be included in the study. All rowers were physically healthy without any musculoskeletal injuries. A written informed consent was obtained from participants prior to the experiments. All procedures were complied with the ethical code of University of Delaware Internal Review Board.

B. Experimental Setup

Experiments were carried out on a Concept 2 model D ergometer (Morrisville, Vermont, USA). Drag factor was adjusted according to the body weight of each rower to resemble the resistance effect during on-water rowing [21]. 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.

The muscle activity was recorded using wireless Noraxon Telemyo DTS Desk Receiver (Noraxon, Scottsdale, AZ). 16 rowing-specific muscles were evaluated on the right side of the body: Soleus (SOL), Gastrocnemius Lateralis (GL), Tibialis Anterior (TA), long head of Biceps Femoris (BF), Semitendinosus (ST), Rectus Femoris (RF), Vastus Lateralis (VL), Erector Spinae (ES), Lattisimus Dorsi (LD), Trapezius Medialis (TRAP), Deltoid Medius (DM), Triceps Lateralis (TRI), Abdominis (AB), Pectoralis Major (PEC), Biceps Brachialis (BB) and Brachioradialis (BR). 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 [22] for all muscle, except for LD and BR, which were not referenced by SENIAM. For LD, we followed the suggestion of [23] by positioning the electrodes on the muscular curve at T12 and along a line connecting the posterior axillary fold and the S2 spinous process. 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 [24]. 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).

The metabolic variables such as oxygen consumption (VO_2), carbon dioxide production (VCO_2), ventilation (VE) and respiratory exchange ratio (RER) were measured by Cortex MetaMax3B portable metabolic system (MM3B, Leipzig, Germany). The system was determined to provide reliable and valid measurements of metabolic demands for rowing physiological tests [25]. The breath-by-breath MetaMax3B measurements were averaged over 30s interval. The heart rate was measured continuously (Polar, Electro Oy, Finland) in synchrony of the data from the ergospirometer system. Energy expenditure (kJ/ min) was calculated following Brockway et al (1987) formula:

$$\text{Energy expenditure} = 21\ V\Delta O_2 \qquad (1)$$

where V was the ventilation rate and ΔO_2 was the oxygen concentration difference from the resting value. The rowing economy was defined as net energy expenditure divided by power output [26]. Common rowing economy definition which was dividing the mean power output by volume of oxygen consumed during sustained state (R < 1.0) [15], [21], [27] was disregarded because during maximal intensity exercise, it was very unlikely to obtain the sustained state of respiratory quotient (e.g ratio of eliminated carbon dioxide to oxygen consumed) less than 1.0.

Energy expenditure and rowing economy were calculated according to comparable time representation of EMG synergy extraction for each subject. For 6 min maximal rowing test, data were analyzed starting from the third minute of rowing up to 40 consecutive rowing cycles because the peak value of oxygen consumption was often achieved between the second and fourth minutes of exercise [28]. The $VO_{2\ peak}$ was defined as the highest VO_2 value that met two out of these three criteria [29], [30]: (i) 90% of age-predicted maximum heart rate; (ii) respiratory exchange ratio 1.2; and (iii) a plateau of VO_2 (less than 0.15 L/min increase in VO_2).

C. Protocol

6 min maximal rowing on SE and FE were randomized among participating subjects. Care was taken to reduce the circadian effect on physiological data by ensuring the subjects to perform around the same time of the day with at least 48 hours interval between the tests. Subjects were asked to refrain from food and beverages (except water) for two hours before testing. They wore their own shoes and skin-tight Lycra shorts to facilitate accurate markers and electrodes placement. The experiment consisted of: i) 5 min warm up on the ergometer, ii) 6 min maximal test, and iii) 5 min cool down. Subjects were told to keep their stroke rate within 28 to 36 strokes per minute. The overall protocol took approximately 90 min including the preparation time.

D. Data Analysis

EMG signals were band-pass filtered (20-400 Hz, zero-lag 6-th order Butterworth filter), fully rectified and low-pass filtered (8 Hz, zero-lag 2-nd order Butterworth filter) to create linear envelopes. Then, linear envelopes were split into individual rowing cycles and time-normalized to a 100-point time base. Next, 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. These patterns were subsequently normalized to their peak value. All analyses were conducted using custom MATLAB code (The Mathworks, Inc., Natick, MA).

E. Factor Analysis

Principal Component Analysis (PCA) was applied to extract the muscle synergy as suggested by [4]. PCA was chosen to analyze the underlying factors or associations in a huge 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 [4], [31]. The Kaiser-Meyer Olsen (KMO) [32] 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 [33]. Once we had checked that all the prerequisite tests were met, 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 [3], [4]. 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 [32], (ii) to retain those eigenvalues that occurred before the inflection point of the scree plot [34], (iii) Parallel Analysis (PA) [35], 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) [36] 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 [3], [4] of the factors related to the physiological function.

F. Statistics

The inter-group indices of similarity were computed on Z-transforms of individual EMG patterns and synergy activation coefficients [3], [7]. Paired T-test was used to compare the subjects' characteristics, rowing performance, physiological variables and each muscle weightings between the rowing tests. The association of muscle weightings from Synergy #1 and rowing economy was tested using non-parametric Friedman's test because the data violated the assumption of homogeneity of variance. Wilcoxon post-hoc test with Bonferroni correction was applied when any significant was detected. Significance value was set to $\alpha = 0.05$. All statistical tests were carried out in IBM SPSS Statistics v20.0 (IBM Corp., Armonk, NY).

III. RESULTS

A. Rowing Variables

The rowers were able to cover about the same rowing distance and exert similar power output during both (SE and FE) rowing conditions (Table I). There was no significant difference of oxygen consumption in both rowing conditions. However, rowing on SE was more intense as evidenced by greater maximal heart rate ($p < 0.05$) and energy expenditure ($p < 0.01$) compared to FE rowing. The rowers exhibited different rowing strategy following different type of ergometers. They rowed faster at shorter strokes on SE and slower with longer strokes on FE. This strategy could be the reason of better rowing economy achieved during rowing on SE ($p < 0.05$).

B. EMG Patterns

The ensemble averages of the EMG linear envelopes showed no distinct differences in the muscle waveforms between rowing conditions which was indicated by high similarity index of waveform pattern (Pearson *r*) for each muscle between rowing conditions which range from 0.85 to 0.996 (except for TA, = 0.665).

TABLE I. ROWING PERFORMANCE VARIABLES DURING ROWING ON SE AND FE.

	SE	FE	*p* value
Total distance (m)	1741.1 (47.8)	1731.4 (64.1)	0.49
Power (Watts)	317.47 (38.1)	313.6 (33.8)	0.32
Stroke rate (spm)	30.9 (2.7)	28.9 (1.5)	0.03
Stroke length (mps)	9.32 (0.8)	10.41 (0.7)	0.01
$VO_{2\,peak}$ (L/min)	5.78 (0.7)	5.33 (0.9)	0.10
$VO_{2\,peak}$ (L/kg/min)	71.33 (12.2)	67.8 (14.4)	0.23
Heart rate $_{max}$ (bpm)	180.67 (6.9)	172.4 (10.5)	0.05
Energy $_{expenditure}$ (kJ/min)	105.9 (13.5)	80.5 (15.4)	0.01
Economy (%)	33.57 (4.02)	29.7 (3.4)	0.01

SE, slides ergometer; FE, fixed ergometer; m, meter; spm, strokes per minute, mps, meter per stroke; VO_2, oxygen consumption; L, liter; min, minute; kg, kilogram; kJ, kilojoule; %, percentage.

C. Muscle Synergy

Data from both SE and FE rowing showed adequate KMO statistics (0.617 ± 0.04 and 0.619 ± 0.06 respectively). Therefore PCA was applied and following Kaiser's criterion, scree plot, PA and MAP analysis, we observed that three synergies were sufficient to explain 90% of total Variance Accounted For (VAF) in both rowing conditions. These synergies showed moderate similarity index between rowing ergometers (0.957, 0.73, and 0.609 for Synergy #1, Synergy #2 and Synergy #3 respectively) with high Cronbach's α value showing repeatability of data (Table II). Muscles with factor loading greater than 0.55 [37] were considered as contributors for a specific synergy. Synergies activation coefficients and muscle loadings were depicted in Fig. 1 and Fig. 2 respectively.

TABLE II. CRONBACH'S Α FOR MUSCLE SYNERGIES DURING ROWING ON SE AND FE

Cronbach's α	SE	FE
Synergy #1	0.954 (0.03)	0.957 (0.02)
Synergy #2	0.695 (0.17)	0.821 (0.14)
Synergy #3	0.726 (0.13)	0.787 (0.14)

For rowing on SE, the Synergy #1 consisted of the main force generator muscles during rowing such as the SOL, GL, BF, ST, VL, ES, LD, TRI, and PEC. The GL, BF and TRI were multi joint muscles which also functioned as efficient force distributors while ES and LD were postural muscles which have large cross sectional area. Synergy #1 was dominant during the first half of the drive phase where most propulsive force was generated. Next, the force from Synergy #1 was transferred to Synergy #2 that comprised of arm muscles (BB and BR) and AB which occurred during the second half of drive phase. Synergy #3 was contributed by TA, RF, TRAP and DM. Synergy #3 was initiated during the second half of drive phase and was crucial during the transition of rowing stroke from catch to finish position. The muscles that made up the Synergy #3 functioned as movement refiner (e.g TRAP for maintaining the posture and DM for shoulder abductor) and force distributor (e,g TA transferred the force generated from foot stretcher to the leg and RF transferred the force from the thigh to the hip).

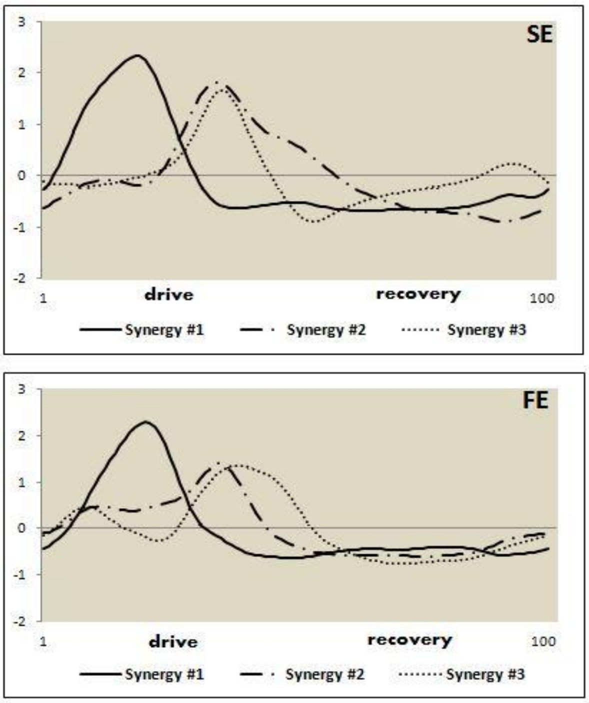

Figure 1. Synergy activation coefficients and muscle synergy vectors depicted for rowing on SE and FE. Synergy activation coefficients were averaged across the subjects for the three extracted synergies and expressed as a function of percentage of the rowing cycle (0% to 50% represent drive phase and 51% to 100% represents recovery phase). SE, slides ergometer: FE, fixed ergometer.

There were small differences in terms of muscle loadings and synergies activation coefficient between SE and FE rowing. For FE rowing, the Synergy #1 involved the TRAP as addition to other similar muscles of Synergy #1 in SE. Synergy #2 consisted of TA, BB and BR while the Synergy #3 comprised of RF, DM and AB. There was a slight timing coefficient differences from SE rowing such that the rowers tend to acquire cumulative effect of muscle forces by combining Synergy #1 and #2 at the start of drive phase. Meanwhile, the Synergy #3 was predominant during the transition from drive to recovery phase.

D. Muscle Synergy and Rowing Economy

The association of muscle loadings on Synergy #1 and rowing economy was tested using analysis of variance (ANOVA) adopting method by [20]. As Synergy #1 accounted for almost half of total VAF synergies (49.36 ± 5.6 for SE; 48.12 ± 7.4 for FE), the effect on rowing economy should be detectable. However, the data violated the assumption of homoscedasticity (Levene's test $p < 0.05$), therefore we adopted non-parametric Friedman's test and post-hoc Wilcoxon sign-rank test with Bonferroni correction whenever significance was detected. We found that Synergy #1 of both rowing conditions showed significance association of muscle loadings and rowing economy (SE and FE, $p = 0.001$). The post hoc tests revealed significant association of each muscle loadings to rowing economy (SE, $p < 0.006$; FE, $p < 0.005$).

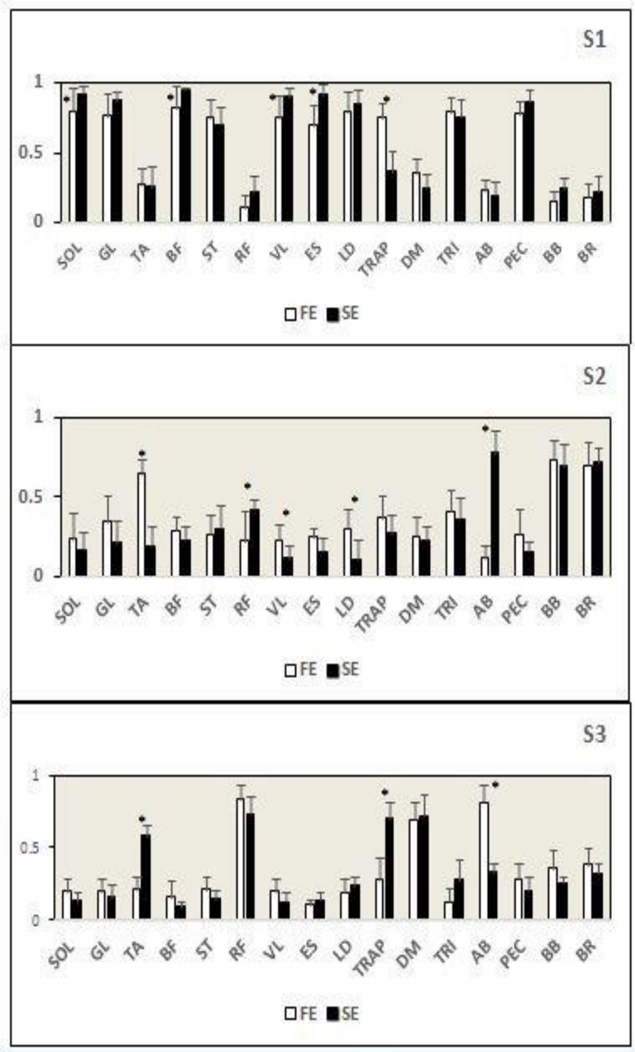

Figure 2. Muscle synergy vectors depicted for rowing on SE and FE. The muscle synergy vectors were averaged across the subjects for the three extracted synergies. Individual muscle weightings are depicted for each muscle within each synergy. SE, slides ergometer: FE, fixed ergometer. Asterisks indicate significant difference of muscle loadings between rowing conditions ($p < 0.05$).

IV. Discussion

It is important for the rower to develop an effective coordination between upper and lower body [38], since a non-optimal strategy could limit the power output and the efficiency of the limb motion [39]. These observations suggest a fundamental role of muscle synergy during rowing. In our analysis, PCA was capable of extracting three muscle synergies during maximal intensity of rowing, similar to previous rowing studies that applied non-negative matrix factorization [7], [40], [41]. Our basic finding, namely, that three component factors (e.g. muscle synergies) were accounted for the activation of muscles during rowing, was reported earlier by [41] who extracted synergies from 23 muscles in nine subjects. They observed the same basic patterns across varying power outputs [40], fatiguing condition [41], and expertise level [7]. We have extended these results by showing that the basic patterns were conserved across different stretcher mechanisms (i.e., FE and SE). Besides, by including physiological variables, our study showed that the association of muscle synergies to rowing economy was substantial.

The similarity in the composition of three extracted synergies in both rowing conditions was accompanied by different emphasis on particular muscles, showing the robustness of the neuromotor control to adapt to various mechanical constraints. We observed that the inventory of rowing tasks was achieved through modification of muscle activation vectors but not synergy activation coefficient (e.g the temporal structure), which was in agreement with synergies studies on locomotion [4] and cycling [42]. Rather, the rowers seem to utilize the innate synergies and sharpen the muscle activation levels to adapt to the different type of ergometers.

Additionally, our results on mechanical variables were in line with previous studies [15], [43]. Subjects preferred to row faster with shorter stroke length on SE, because the slides mechanism provided ease of movement during the recovery phase [43]. Greater 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 [44]: the distance taken to reduce the kinetic energy will be further when the kinetic energy is higher. The lack of motion of the FE has two important consequences: (i) increase in total work, because the rower needs to accelerate and decelerate his center of mass at the end of each stroke [45], 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 [13]. On the other hand, the power delivered to the handle can be increased by up to 18% when subjects rowed on ergometers that allowed their center of mass to remain relatively stationary [46] (i.e., rowing on SE) which explained better rowing economy [45] on SE compared to FE.

V. Conclusion

The main finding of this study is the robustness of muscle synergies pattern of collegiate rowers during 6 min maximal rowing on FE and SE. Statistical analyses revealed that muscle synergies (especially Synergy #1) were highly associated to rowing economy in both rowing. Despite the differences in rowing strategy (e.g row faster at shorter strokes on SE but slower and longer strokes on FE), the rowers showed similar level of rowing performance in terms of total distance covered and power output exerted in both rowing conditions and displayed high similarity between muscle synergies patterns in both rowing conditions. This could be due to their experience in rowing which may offset any differences of rowing techniques on ergometers. Hence, for experienced rowers, training on both type of ergometers are recommended.

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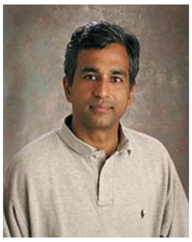

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