MUSCLE SYNERGIES IN DIFFERENT PHYSIOLOGICAL DEMANDS DURING ROWING

by

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ABSTRACT

Muscles synergy is a strategy of central nervous system (CNS) to improve redundancy at musculoskeletal level. The study of muscle synergy and its association to energy capacity is crucial for rowing as huge muscle mass are recruited during high intensity exercise. Due to close link that exists between the state of energy supply and types of muscle fibers being recruited, the muscle synergy was hypothesized to enhance rowing economy and further improve rowing performance. Although the robustness of muscle synergy has been extensively studied across tasks, mechanical constraints, training effect, and posture, the robustness of muscle synergy across different physiological demands was still an open question. Therefore, this body of work was designed to fulfill the gap in muscle synergy literature.

The pilot study was the starting point to evaluate the muscle synergy in two different stretcher mechanisms (i.e fixed and slides ergometer) in untrained subjects during 6 min maximal rowing test. Untrained subjects were chosen to avoid the training effect bias on synergy. The same protocol was further repeated with collegiate rowers. As the slides system provides a close resemblance to on-water rowing, Wingate anaerobic and $VO_{2\ max}$ test were conducted on slides ergometer for both untrained subjects and collegiate rowers. Wingate anaerobic test was an assessment of anaerobic power and $VO_{2\ max}$ test was applied to evaluate aerobic capacity. As a power endurance sport, both energy pathways (i.e aerobic and anaerobic) were crucial for maximum rowing performance. The 6 min maximal rowing test was a simulation of a typical rowing event where interplay of all energy pathways were highlighted.

Muscle synergy was extracted from 16 rowing specific muscles using Principal Component Analysis with varimax rotation. Parallel Analysis (PA) and Minimum Average Partial (MAP) were

computed to further enhance the extraction method. Surface electromyography, kinematics, rowing performance, and energy metabolism were quantified from 10 collegiate rowers and 10 physically active untrained (e.g not specifically trained in rowing) subjects. All rowing tests were conducted on Concept 2 rowing ergometer. Appropriate statistical tests were applied to find the association of muscle synergy and rowing economy and its effect on rowing performance.

Three muscle synergies were sufficient to explain the majority of variance for both untrained and rowers groups across three rowing tests (e.g. Wingate anaerobic test, $VO_{2\,max}$ test, 6 minutes maximal rowing test). Despite small differences in muscle contributions to specific synergy, overall, for both subject groups, Synergy #1 was activated during the first half of the drive phase, Synergy #2 was engaged during the second half of the drive phase and Synergy #3 was predominant during the transition of strokes positions (e.g from recovery to catch). Synergy #1 always gained largest contribution from the leg, back and chest muscles, Synergy #2 was typically made of upper limb muscles and synergy #3 comprised of Rectus Abdominis (AB), Rectus Femoris (RF) and Tibialis Anterior (TA) with minor variations in different experimental tests. Based on these results, we were able to show that muscle synergy is robust across different physiological demands.

Through the statistical analysis, we found that Synergy #1 (which comprised about half of total variance accounted for all synergies) was highly correlated to rowing economy. However, rowing economy is not the main predictor of rowing performance as revealed by Multiple Linear Regression. Both collegiate rowers and untrained groups exhibited similar rowing strategy in different stretcher mechanisms. They tended to row faster with shorter strokes when rowing on slides ergometer (SE), but slower with longer strokes when rowing on fixed ergometer (FE). However, when compared across the groups in similar rowing condition (i.e SE rowing), the rowers tended to row slower with longer strokes compared to untrained subjects. This strategy is an indicator of practice-related adaptation that was suggested to reduce energy cost. Due to this rowing technique, the rowers were able to exert more energy with better rowing economy compared to the untrained subjects in any tests.

The results proved the flexibility of muscle synergy to adapt to the mechanical constraints (e.g different stretcher mechanisms) and different physiological demands. The findings of this study could guide the rowers and their coaches to enhance the training regime. As there is no difference in muscle synergy pattern and rowing performance during rowing on FE and SE, both ergometers could be utilized by the experienced rowers. Expertise in rowing is not related to sequence of synergies activation but to the ability to adjust the muscle activation economically. As rowers have to sustain high aerobic intensity during a rowing event, they could apply our findings by focusing the training on the synergies refinement (particularly Synergy #1), which will improve their rowing economy.

Chapter 1

INTRODUCTION

1.1 Dissertation Focus

High levels of physiological functions are a prerequisite for high performance in rowing races which includes peak oxygen uptake (Secher et al.,1993; Cosgrove et al., 1999; Ingham et al., 2012), power output (Bourdin et al., 2004; Ingham et al., 2007, Gabarren et al., 2010), muscle mass (Roth et al., 1983, Owen et al., 2002, Drarnitsyn et al., 2009, Gabarren et al., 2010), maximal isometric muscle strength (Secher et al., 1993; Steinacker et al., 1986, Gabarren et al., 2010), and maximal power (Ingham et al., 2007, Drarnitsyn et al., 2009).

Of our particular interest is the energy pathways contribution to rowing performance. In fact, many studies have investigated the energy contribution (Hagerman et al. 1978; Mickelson and Hagerman 1982; Russel et al. 1998; Pripstein et al. 1999) during ergometer rowing. They noted that during rowing races, the rowers utilize about 12% to 30% of anaerobic metabolism of total energy metabolism (Pripstein et al., 1999; Russel et al., 1998; Secher et al., 1993) while, aerobic metabolism contributes about 70-86 % of total energy (Russel et al., 1998; Pripstein et al., 1999; Messonnier et al. 2005). Huge contributions from both energy pathways entitle the rowing to be called a power endurance sport (Peltonen and Rusko, 1993).

According to Roberts et al., (2005), rowing engages most of the principal muscle groups of the upper and lower body such that a larger fraction of total muscle mass is recruited when rowing compared to cycling (30 kg muscle mass compared to only 15 kg in a 70 kg male). Hence, the recruitment of a greater muscle mass could potentially compromise muscle perfusion, particularly during heavy exercise where a larger fraction of maximal cardiac output is utilized

(Volianitis and Secher, 2002). Therefore, to overcome the compromising effect of muscle perfusion, rowing economy could be the determining factor. Muscle synergy is a way of central nervous system to reduce the degrees-of-freedom at musculoskeletal level. Although a lot of studies have been done to evaluate the robustness of muscle synergies across tasks and mechanical constraints, the energetic effects on muscle synergies have been overlooked. We hypothesized that the muscle synergies could affect rowing economy by letting the muscles to remain efficient across different physiological demands.

1.2 Specific Aims

The goal of this dissertation is to gain understanding of muscle synergies and their adaptation to different physiological demands during rowing. By filling this gap in the literature, we will have better insights regarding motor control in sports which will specifically improve rowing training. The results could also yield insights into a wider spectrum of human movements because rowing utilizes whole body muscles and different types of energy metabolisms. This study could also impact synergy-based exercise designs by providing knowledge regarding physiological efficiency of human movements. We test the functional hypotheses in physically active untrained subjects and collegiate rowers. To achieve the goals set forth in this dissertation, the following aims were proposed:

1.2.1 Aim 1: Determine muscle synergies during fixed (FE) and slides ergometer (SE) rowing.

Muscle synergies during rowing were extracted from eight rowing-specific muscles bilaterally. 6 minutes maximal rowing tests were conducted on physically active untrained subjects in two conditions: a) rowing with and b) without the attachment of slides on the ergometer. Statistical tests were applied to measure the reliability of synergies extraction method. This aim is addressed in Chapter 3 (for untrained subjects) of this dissertation. Our hypotheses were:

H1.1: There will be no difference in muscle activation patterns bilaterally.

H1.2: Different synergies will be used during rowing with and without slides.

H1.3: The synergies extraction method is reliable and valid.

Our pilot study determined the muscles that needed to be extracted, the best extraction method and the physiological variables to measure. We then repeat the same test for collegiate rowers but with added rowing-specific muscles and physiological variables. This is addressed in Chapter 5 of the dissertation.

1.2.2 Aim 2: Quantify muscle synergies during slides ergometer (SE) rowing in specific physiological tests.

Three physiological tests were carried out emphasizing particular energy metabolism: $VO_{2\ max}$ test to evaluate the aerobic capacity, Wingate test to reflect the anaerobic capacity and the 6 minutes maximal test to simulate the energy metabolism during races. The results were then compared between the collegiate rowers and untrained subjects. This aim is addressed in Chapters 6, 7 and 8 of the dissertation.

H2.1: The rowers have higher aerobic capacity compared to untrained subjects.

H2.2: The rowers have higher anaerobic capacity compared to untrained subjects.

H2.3: The rowers have better rowing performance compared to untrained subjects.

1.2.3 Aim 3: Evaluate the effect of muscle synergies on rowing economy and performance.

The principal component analysis (PCA) was applied on EMG signals to obtain the muscle synergies over all physiological tests. Multiple linear regression (MLR) was then applied to study the association of muscle synergies on rowing economy in different physiological tests and to predict the effect of rowing economy on rowing performance. This aim is addressed in Chapters 6, 7 and 8 of the dissertation.

H3.1: The synergies are associated with rowing economy.

H3.2: Rowing economy is one of the rowing performance predictor.

H3.3: The rowers expressed energy-efficient synergies compared to untrained subjects.

Chapter 2

BACKGROUND

2.1 Significance

2.1.1 Physiological demands during rowing

Endurance of athletes is usually quantified through their aerobic capacity. As a highly ranked endurance sport, rowers need to have large aerobic capacity to hold the high intensity of rowing. This slow energy system is continuously sufficient in oxidative condition. Therefore, aerobic system contributes to a large percentage of energy sources during rowing.

Anaerobic metabolism could yield faster and more readily available energy compared to aerobic metabolism but it lasts only for a short period of time. Therefore, the anaerobic contribution is the key metabolism during the starting section of the long distance rowing race to overcome the inertia of the rowing shell (Drarnitsyn et al, 2009).

Skill and technique is another important aspect in rowing (Baudoin et al., 2004; Maestu et al., 2005; Smith et al., 2002; Soper and Hume 2004). According to Smith (2002), quality and consistency of strokes are crucial for competent rowing. This is because rowing is a periodic movement that consists of catch, drive, finish and recovery phases (Figure 2.1). The catch involves force buildup phase by placing the blade of an oar in the water. In this phase, the muscle action is to extend the ankle, knee, hip and lumbar joints and flex the shoulder, elbow and wrist joints. The latter joints (i.e shoulder, elbow and wrist joints) control the drive phase which follows the catch. The removal of the blade from the water defines the finish phase. Finally, the recovery phase is the return of the rower from the extended position of the finish to the flexed crouched posture of the catch. This combination of actions must be repeated precisely for more than 200 strokes during a rowing competition. Hence, the consistency of strokes among the crew members and also within each crew member is crucial to ensure the optimal velocity of the boat.

The body capability to change muscle activation strategy is known as bio-compensation strategy (So et al., 2007). This technique is crucial for the muscles to maintain a given effort (Duchene and Goubel et al., 1990), minimize energy usage (Sparto et al., 1999) and also to reduce risk of injury (Nyland et al., 1994). In a recent wavelet study of cyclists, the authors (Blake and Wakeling, 2012) observed bio-compensation strategy where changes in coordination patterns could provide rest to the primary power-producing muscles and avoid performance reductions from fatigue. The same result was obtained by So et al., (2007) where the elite rowers were able to produce repeatable patterns of bio compensation compared to less experienced rowers. These studies proved that the muscles were able to adapt at particular times when physiological demands increase. These results also showed that experienced rowers have different synergy strategies compared to inexperience rowers.

However, most studies on muscle synergies and sports (Turpin et al. 2011; Hug et al., 2011; Wakeling et al., 2009; So et al., 2007) focused on overall effect of fatigue rather than focusing on specific energy metabolism. The effect of energy metabolism on muscle synergies is a gap in the literature which we attempt to address.

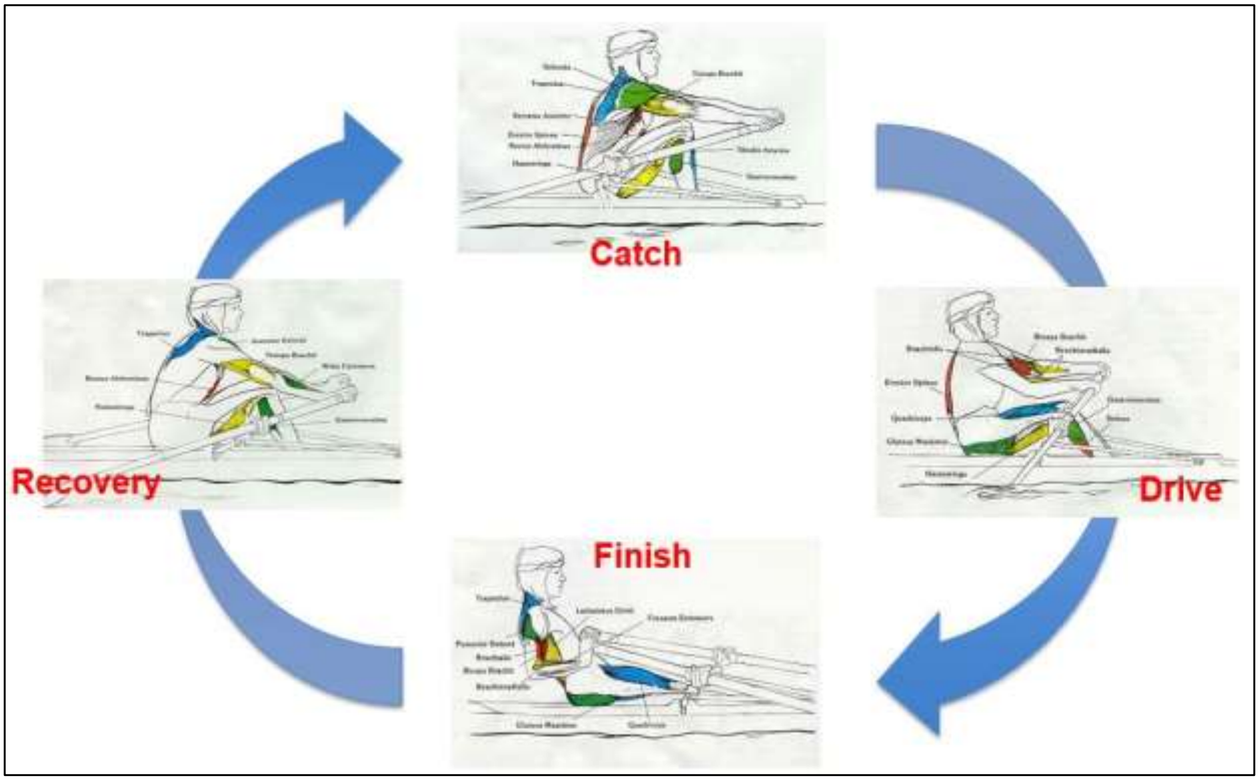


Figure 2.1: The rowing cycle.

2.1.2 Muscle synergies in rowing

The theory of degrees-of-freedom (DOF) proposes a neural strategy for simplifying the neuromuscular control by coupling output variables at the kinematic level (Bernstein, 1967). It aims to achieve repeatable multi-joint coordination. This motor redundancy also exists at the musculature level due to multiple muscles crossing each joint. Thus, muscle synergy is defined as a specific and consistent spatiotemporal pattern of muscle activations that leads to similar joint trajectories (Ting et al., 2007).

Each muscle synergy is presumed to be controlled by a single neural command signal that modulates the magnitude of the muscle activation pattern. The synergies should be robust and yet still accommodate flexible mixing between the synergies (Ting et al., 2007). As an example, by simply changing the proportion of contribution of each muscle synergy during a balance test, we can observe different stance configurations. This is caused by the changes in muscle activation and forces produced (Macpherson, 1994; Torres-Oviedo et al., 2006).

Synergy studies of human movement have been extensively studied such as in balance (Ting et al., 2007), cycling (Wakeling et al., 2009; Hug et al., 2011), walking (Ivanenko et al., 2004), running (Cappellini et al., 2006) and even rowing (Turpin et al., 2011). A number of movement studies showed the robustness of synergies by changing the mechanical load (Hug et al., 2011), speed (Ivanenko et al., 2004, Wakeling et al., 2009), force direction (Ting et al., 2007), effect of aging (Monaco et al., 2010) and training (Asaka et al., 2008), but no studies yet have compared the change of synergies related to energy metabolism. This is a gap in literature that we want to address.

In conclusion, the understanding of muscle synergies during different energy metabolism is crucial in rowing performance because it provides us an insight into the compensatory strategies used by neuromuscular system when faced with different physiological demands.

2.2 Innovations

A number of movement studies have tested the mechanical robustness of muscle synergies (Ivanenko et al., 2004; Ting et al., 2007; Hug et al., 2011). However, no studies have been done yet that tested the specific energy metabolism robustness of muscle synergies. The main reason synergies exist is to increase efficiency of central nervous system (CNS) to control the output variables at kinematic and musculoskeletal level. A number of studies have proved that physiological demands impose changes at musculoskeletal levels in order to maintain the task output (Duchene and Goubel et al., 1990; Sparto et al., 1999). However, these changes are directly related to the efficiency of the metabolic system which is not addressed yet in current literature.

Rowing is a unique exercise that not only utilizes whole body muscles but also utilizes all types of energy metabolism. Therefore, the knowledge that will be obtained through this study is particularly useful for rowers and coaches and can also be applied to create a better design in rehabilitation and sports research. These synergy-based designs will utilize the natural capability of neuromuscular control of movement. A number of robotic studies have already applied findings from synergy studies to develop state-of-the-art designs. Brown et al., (2007) presented a novel mechanism design which combines 17 degrees-of-freedom of robotic hand coordination. They showed that the complexities of hand movements can be reduced to only two patterns of synergies which are derived using Principal Component Analysis (PCA) method. By combining the results from synergy studies, they created a robotic hand that includes inter-finger coordination compared to other robotic hand designs that commonly couple the intra finger joints (Brown et al., 2007; Bicchi et al., 2010). On the other hand, muscle synergy analyses are increasingly being used to evaluate altered neuromuscular control in clinical populations (e.g stroke and cerebral palsy patients) and supplement movement rehabilitations (Cheung et al., 2012; Safavynia et al., 2011).

Therefore, the insights gained from this study will enrich the field of motor control in human movement in sports or rehabilitation strategies. Specifically, synergy-based-designs can further be enhanced by including the effect of energy metabolism contribution from our study.

Chapter 3

PILOT STUDY: MUSCLE SYNERGY OF UNTRINED SUBJECTS DURING 6 MIN MAXIMAL ROWING ON FIXED AND SLIDES ERGOMETER

3.1 Abstract

Introduction: Muscles synergies are crucial to reduce musculoskeletal redundancy and enhance rowing performance. The slides system provides a close resemblance to on-water rowing. The study aims to evaluate the muscle synergies during 6 minutes maximal rowing on fixed and slides ergometers. We hypothesized that the number of synergies would be the same in both conditions due to the robustness of neuromuscular control, but with different contribution of muscles.

Methods: Surface electromyography, kinematics, power output, heart rate, stroke length and stroke rate were collected from nine physically active non-rower males to assess the rowing performance. Principal component analysis with varimax rotation was applied to identify muscle synergies.

Results: Three muscle synergies were sufficient to explain the majority of variance in both conditions. More rowing distance was covered during rowing on slides ergometer (SE) than on fixed ergometer (FE).

Discussion: The timing coefficients and muscle loadings variability proved the flexibility of muscle synergies to adapt to the mechanical constraints. Rowing on SE emphasized bi-articular muscles in contrast to rowing on FE which relied on cumulative effect of trunk and upper limb muscles during propulsive phase.

3.2 Introduction

Rowing is one of the most comprehensive exercises, as it involves whole body muscles and utilizes both types of energy metabolisms (i.e., aerobic and anaerobic) (Secher, 1993). It is also a unique power-endurance sport, because rowers not only need physical strength to achieve high power per stroke, but also high endurance to sustain this power until the end of a rowing race (Secher, 1993). This is further complicated by influences from the environment such as rain, wind and cold.

Rowing ergometers provide a viable alternative for training (Secher, 1993), evaluation (Colloud, Bahuad, Doriot, Champely, & Cheze, 2006) and team selection (Elliott, Lyttle, & Birkett, 2002; Maestu, Jurimae, & Jurimae, 2005) in a more controlled environment. Among the existing models, a popular rowing ergometer is the Concept 2 (Nowicky, Burdett, & Horne, 2005; Maestu et al., 2005). Although the kinematics of lower limbs and trunk during ergometer rowing are similar to on-water rowing (Lamb, 1989), rowing on fixed ergometer (FE) represents a poor simulation of real on-water (OW) rowing. Typically, throughout the recovery phase of OW rowing, the boat slides underneath the rower, which is the opposite of what happens in rowing on FE, where the rowers need to move their whole body mass during each rowing stroke (Holsgaard-Larsen, & Jensen, 2010).

Recent innovation in ergometer slide system has made it possible to resemble OW rowing mechanics (Holsgaard-Larsen, & Jensen, 2010; Mahony, Donne, & O'Brien, 1999; Mello, Bertuzzi, Grangeiro, & Franchini, 2009; Nowicky et al., 2005) by moving the ergometer back and forth. For Concept 2, the system consists of a rail that is mounted underneath the ergometer (Figure

3.1), allowing it to move in the opposite direction of the rower, similar to the boat's displacements relative to the rower during OW rowing (Mello et al., 2009).

A number of studies have been conducted comparing the kinematics (Lamb, 1989), kinetics (Martindale & Robertson, 1984), force profile (Colloud et al., 2006), physiological variables (Mello et al., 2009; Secher, 1993) and muscle activity (Guével et al., 2011; Nowicky et al., 2005; Rodriguez, Rodriguez, Cook, & Sandborn, 1990) of rowing on ergometers with those of on water rowing. Rowing on slides ergometer (SE) was hypothesized to be less physiologically demanding than FE rowing (Mahony et al., 1999), since the effort required to move the ergometer (~26 kg) should be smaller than the one required to move the rower's body mass (~70kg). However, except for anaerobic capacity (Holsgaard-Larsen, & Jensen, 2010; Steinacker, 1993), other physiological variables (i.e., maximal heart rate, peak lactate concentration and peak aerobic capacity) were not significantly different in both rowing conditions. Furthermore, rowing on both types of ergometers yields closely similar aerobic power values to those obtained on water (Mello et al., 2009; Secher, 1993; Steinacker, 1993). Although mechanical efficiency is greater in OW rowing compared to ergometers rowing (Steinacker, 1993), the physiological similarity between the two indicated that the ergometer could be utilized as a training device.

Colloud et al. (2006) reported significant differences in force curve profiles (i.e., handle and stretcher force) during SE and FE rowing. The rower must produce larger anterior-posterior force at the stretcher to accelerate his center of mass in the positive and negative directions when rowing on FE. This causes larger contact forces and external power (i.e., the product of the force exerted on the handle by its velocity) during the catch and the finish phases. However, low inertial forces are necessary to accelerate the segments of the rower's body on SE ergometer (Colloud et al., 2006). Despite closely similar pattern of flexion/ extension range of motion of the whole body in both rowing conditions (Lamb, 1989), the differences between force profiles may have implications for the pattern of muscle recruitment (Colloud et al., 2006; Green, & Wilson, 2000) and adaptation (Roth, Schwanitz, Pas, & Bauer, 1993). Muscular coordination may also differ according to the stretcher mechanism used (Colloud et al., 2006).

As an intense sport that recruits almost 70% of the total muscle's mass (Steinacker, Lormes, Lehmann, & Altenburg, 1998), rowing requires an efficient musculoskeletal system. Muscle synergy is a strategy of the central nervous system (CNS) to reduce the redundancy at the musculoskeletal level (Bernstein, 1967). Despite the importance of muscles coordination on rowing performance (Rodriguez, Rodriguez, Cook, & Sandborn, 1990; Tachibana, Yashiro, Miyazaki, Ikegami, & Higuchi, 2007), no studies have been conducted comparing the synergies of the upper and lower body muscles during FE and SE rowing. This is crucial to understand the strategy of the CNS to remain efficient in diverse mechanical constraints. Since ergometer training represents a significant fraction of the rowers' training regimen (Colloud et al., 2006; Maestu et al., 2005; Secher, 1993), we investigated the muscle recruitment patterns and coordination on SE and FE rowing. The purpose of this study is to evaluate muscle synergies during 6 minutes maximal rowing of untrained males. We hypothesized that the number of synergies would be the same in both conditions due to the robustness of neuromuscular control, but with different contribution of muscles.

3.3 Methods

Subjects. There was no a-priori power analysis test for PCA analysis, however, based on previous studies on muscle synergies (Hug, Turpin, Couturier, & Dorel, 2011; Ivanenko, Poppele, &

Lacquaniti, 2004; Turpin, Guével, Durand, & Hug, 2011a; Turpin, Guével, Durand, & Hug, 2011b; Turpin, Guével, Durand, & Hug, 2011c; Wakeling, & 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). They were not specifically trained in rowing, hence, prior to the experiment each subject was shown a video explaining proper rowing technique to ensure safety and 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, Figure 3.1). The slides system consists of a pair of rails that can be attached to the ergometer to simulate OW rowing mechanics. Drag factor can be manually adjusted according to body weight by means of a dial to resemble the resistance effect during OW rowing (Kane, Jensen, Williams, & Watts, 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 time-aligned and averaged into 30s intervals.

Ten infrared cameras (Vicon MX) were positioned around the ergometer to measure rowers' motion. 27 reflective markers were attached on bilateral bony landmarks as suggested by Rab and co-workers (2002). Kinematic data were sampled at 100 Hz and were synchronized to electromyography (EMG) data through Vicon Nexus Workstation v4.5 (Vicon, Oxford, UK). Kinematic data were filtered, interpolated and analyzed using Visual3D (C-motion, Inc., Germantown, MD). The human body was modeled as an interconnected chain of rigid segments: hand, arm, upper arm, torso, pelvis, thigh, leg, and foot. To define the rowing cycle, we analyzed the position of the seventh cervical vertebra marker (C7) projected along the longitudinal axis of the ergometer (i.e., the rowing direction). 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).

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 2.0 cm 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, Freriks, Disselhorst-Klug, & Rau, 2000) for all muscles, except for LD and BR, which are not referenced by SENIAM. For LD, we followed the suggestion of de Sèze and Cazalets (2008) 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 (Muceli, Boye, d'Avella, & Farina, 2010). Raw EMG signals were recorded at sampling rate of 1500 Hz.

Protocol. Each subject performed an identical protocol for both rowing conditions (i.e., FE and SE) around the same time of the day with at least one-week interval. 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 and familiarization with the ergometer, ii) 6 min maximal test, iii) 5 min cool down. The 6 minutes maximal rowing test is a commonly used test to simulate a 2000 meters OW race (Holsgaard-Larsen, & Jensen, 2010). The warm up and cool down phases were added for safety reasons. Subjects were told to cover as much rowing distance as they could during the 6 min period. Considering that subjects were non-rowers, we decided not to impose any stroke rate range, instead, self-pace was chosen as it poses reduced metabolic challenge (Lander, Butterly, & Edwards, 2009).

Data Analysis. EMG signals were band-pass filtered (30-300 Hz, zero-lag 6-th order Butterworth filter), fully rectified and low-pass filtered (4 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). Then, Principal Component Analysis (PCA) was applied to extract the muscle synergies as suggested by Ivanenko et al (2004).

Factor Analysis. A number of methods have been proposed to extract muscle synergies in biomechanics: Non-Negative Matrix Factorization (NNMF) (Lee, & Seung, 1999), independent component analysis (ICA) (Bell, & Sejnowski, 1995) and principal component analysis (PCA) (Cappellini, Ivanenko, Poppele, & Lacquaniti, 2006; Ivanenko et al., 2004). A study comparing the reliability of the methods mentioned above proved that they all yield the same number of synergies (Cappellini et al., 2006). Therefore, we decided to apply PCA to extract muscle synergies, since the method can be easily set-up and run using standard statistical software packages.

For the data to be adequate for PCA, a number of prerequisites should be met: all variables should have raw correlation coefficients ≥0.3 (Tabachnick, & Fidell, 2007), the variables should not be orthogonal (Bartlett's test of sphericity) (Bartlett, 1954) and the Kaiser-Meyer Olsen (KMO) (Kaiser, 1974) magnitude should be more than 0.5. The Bartlett's test checks if the observed correlation matrix diverges significantly from the identity matrix, which indicates that the variables do not correlate with one another (Bartlett, 1954; Ivanenko et al., 2004). Rejection of the hypothesis signifies latent factors in the data and is therefore a requirement for PCA. The KMO test measures the adequacy of the sample size for the factor analysis and a value greater than 0.6 indicates a good sampling size for PCA (Kline, 1994). Once we had checked that all the prerequisites were met, PCA with varimax rotation was applied. Varimax is an orthogonal rotation method which constraints the analysis to uncorrelated factors and is commonly adopted in factor analysis for muscle synergies studies (Cappellini et al., 2006; Ivanenko et al., 2004).

Several statistical tests were applied to confirm the number of factors to retain. We adopted the criterion suggested by Kaiser (1974) to only retain factors that have eigenvalues greater than 1 because smaller values indicate noise. Each eigenvalue represents the total variance accounted by all the variables that load on a particular factor (Kaiser, 1974). We applied Cattell's scree test (Cattell, 1966), which plots all the eigenvalues obtained from PCA, and only retained those eigenvalues that occurred before the inflection point of the scree plot. Parallel Analysis (PA) (Glorfeld, 1995) is a hypothesis testing which compares the obtained eigenvalues with randomly generated eigenvalues: the obtained eigenvalues must be larger than random data. Minimum Average Partial (MAP) (Velicer, 1976) is an iterative procedure to examine successive partial correlation matrices. At each step, the average squared partial correlation of the observed correlation matrix is plotted on a graph. The number of factors to retain is indicated by the graph point where the averaged squared correlation reaches its lowest value. All these methods are commonly used in factor analysis to further confirm the number of factors to retain and often their results are contradictory. In practice, an additional important aspect to decide the number of factors to retain is interpretability (Cappellini et al., 2006; Ivanenko et al., 2004) of the factors related to the physiological function. In our analysis, several solutions were examined, and the one that made the best 'sense' was chosen (Ivanenko et al., 2004).

Statistics. 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., 2011). These indices correspond to the averaged Pearson's correlation coefficient (*r*) between each pair of subjects within the same group. Such indices were used as indicators of the waveform consistency within a rowing condition. All statistical tests were carried out in IBM SPSS Statistics v20.0 (IBM Corp., Armonk, NY). Paired Student's t-test was used to compare rowing performance and muscle symmetry between two rowing conditions. Significance value was set to $\alpha = 0.05$.

3.4 Results

Rowing variables

Overall, better rowing performance was observed during 6 min maximal rowing on SE compared to rowing on FE (Table 3.1). Subjects tended to row faster (38 strokes/min, p = 0.001) with shorter strokes (7 meter/stroke, p = 0.001) on SE because the slide system provides ease in movement during the recovery phase. Furthermore, by increasing the rowing pace rather than lengthening the stroke, the center of mass was kept closer to the body. This strategy is more energy efficient, as proven by the ability of the subjects to achieve and maintain higher maximal heart rate (177 beats/min, p = 0.045). With better efficiency, the subjects were able to exert more powerful strokes (50 Watt/corrected body weight, p = 0.001) and cover longer distance (1517m, p = 0.001) compared to rowing without slides. These findings are in line with previous studies (Holsgaard-Larsen, & Jensen, 2010; Mello et al., 2009), which indicate that rowing on SE is more intense compared to rowing on FE.

The rowing performance variables were evaluated separately for each minute of testing, and plotted against time to observe their trend (Figure 3.2). For both rowing conditions, distance covered in 1 minute, average stroke rate, power output and heart rate were normalized to the corresponding values at the first minute of rowing. Since the assumption of sphericity was not met in any of the variables (Machy's test, $p < 0.05$), we adopted a non-parametric test (Friedman test) and used Wilcoxon signed rank test with Bonferroni correction for post-hoc comparisons where appropriate.

Distance and power output significantly decreased with time for the SE condition ($p = 0.036$), whereas the same variables were approximately constant for the FE condition ($p > 0.05$).

Stroke rate did not change significantly in either condition, whereas heart rate increased significantly with time ($p < 0.0001$) for both SE and FE. Post-hoc comparisons did not evidence significant changes between minute 1 and all the other sessions, except for the heart rate.

EMG patterns

The averaged EMG patterns were first compared bilaterally to test muscle symmetry during rowing. All the subjects included in this study were right-hand dominant. For each muscle, Pearson's correlation coefficients of EMG patterns were averaged across subjects and compared bilaterally using Student's paired t-test (Table 3.2). No significant difference was found, indicating symmetrical contribution from each muscle during both rowing conditions. Therefore, we presented results on right side only.

The ensemble averages of the EMG linear envelopes for the eight muscles investigated during both rowing conditions are depicted in Figure 3.3. Comparing rowing on SE to FE, subjects showed different timing and strategy of muscle recruitment especially during the drive phase (i.e., from 0% to 50% of the rowing cycle), when the main propulsive force is exerted. 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 3.3 illustrates the intragroup similarity indices of waveforms for each muscle. Values range from 0.64 to 0.81, indicating moderate variability of the waveforms. This result is probably due to subjects' lack of experience in rowing (Turpin et al., 2011c).

Muscle synergies

All variables showed bi-variate correlations larger than 0.3. 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 (1994). Kaiser's criterion and the scree plot indicated a three-factor solution, but the PA and MAP analysis pointed to a two-factor solution. We decided to opt for the three-factor solution, based on the interpretability of the salient factors (Cappellini et al., 2006; Ivanenko et al., 2004), the overfactoring rule (Field, 2013) and results from similar previous studies (Turpin et al., 2011a; Turpin et al., 2011b; Turpin et al., 2011c).

The three factors satisfied requirements for simple structure, in that all muscles showed appreciable factor loadings and most of the muscles were loaded only on one factor (Kline, 1994; Tabachnick, & Fidell, 2007). Muscles with factor loadings greater than 0.55 (Comrey, & Lee, 1992) were considered as contributors for a specific factor. We defined these factors as synergies. Three synergies were extracted for all subjects while rowing in both conditions. The total Variance Accounted For (VAF) SE rowing was 94.4 ± 2.2 % (range 90% to 96.9%) and the total VAF for FE rowing was 92.8 ± 1.7 % (range 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 are depicted in Figure 3.4. For rowing with SE, these synergies can be explained as follows:

- Synergy #1 involves all bi-articular leg muscles (GL, BF and RF) and is associated with the drive phase.
- Synergy #2 comprises upper limb muscles (BR, TR and DM) and is active during first half of the recovery phase.
- Synergy #3 engages the dorsal trunk muscles (LD and ES) and is active between the interchange of drive and recovery phase.

Although three synergies were identified also in the FE mode, these consisted of different muscles:

- Synergy #1 involves ES, LD, TR and GL, and is active during the first half of drive phase.
- Synergy #2 is active during the second half of the drive phase and is contributed by BR and DM.
- Synergy #3 engages the bi-articular thigh muscles (BF and RF) and is associated with the second half of the recovery phase and the starting of the drive phase.

The intra-group indices of similarity showed acceptable values of the synergies waveforms for both rowing conditions (Table 3.4), indicating some variability of synergies among subjects.

3.5 Discussion

The purpose of this work is to study the muscle synergies during 6 minutes maximal rowing on SE and FE. A number of studies have been conducted comparing both rowing conditions in terms of rowing performance, physiological variables, kinematics, force profile, and individual EMG patterns. However, to our knowledge, this study is the first attempt to understand the muscle synergies related to different stretcher mechanisms.

In general, our results on mechanical variables are in line with previous studies (Holsgaard-Larsen, & Jensen, 2010; Mello et al., 2009). Subjects tend to row faster with shorter stroke length on SE, because of the ease of movement during the recovery phase provided by the slides mechanism (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, Webber, & Woledge, 2002): 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 body at the end of each stroke (Martindale, & Robertson, 1984) (ii) minimal propulsive force loss, as force is 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 increase by up to 18% when subjects row on ergometers that allow their center of mass to remain relatively stationary (Harrison, 1970) (i.e., rowing on SE). This explains better total energy savings (Martindale, & Robertson, 1984), more power output and distance covered on SE compared to FE.

The rowing performance showed a different trend for the two rowing conditions across 6 minutes of maximal rowing. Power and distance did not show any significant changes from the first minute of test during FE rowing, conversely, time significantly affected the same quantities in SE rowing. Decreases in mean power similar to these measured in SE were reported in previous studies on OW rowing (Guével et al., 2011). The fact that such decrements were not observed in FE further indicates that SE rowing resembles OW rowing more closely than FE (Bernstein et al., 2002). In summary, rowing on SE yielded better rowing performances compared to FE, but these were harder to maintain across the 6 minutes of test. These findings are in line with previous studies (Holsgaard-Larsen, & Jensen, 2010; Mello et al., 2009) indicating that rowing on SE is more intense compared to rowing on FE.

The Concept2 only allows 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, Tse, & Wong, 2007). Under such experimental conditions, the detection of possible asymmetries in muscle activation between the two sides was not possible (Janshen, Mattes, & Tidow, 2009). Therefore, we decided to check the symmetries of muscle activity on eight rowing-related muscles. The high Pearson's r for all muscles during the two rowing conditions indicated that muscle activity was indeed symmetrical (Table 3.2) despite all the subjects being right-handed.

The bi-articular muscles (GL, BF and RF) yielded interesting results in both rowing conditions. GL was the earliest to activate, as plantar flexion is used prominently in the drive phase of rowing (Gerzevic, Strojnik, & Jarm, 2011). As a bi-articular muscle, GL also enables force transfer from the foot stretcher to the thigh muscles, which explains the high level of muscle activity during the drive phase on both rowing conditions. RF was recruited next, to assist the other quadriceps muscles to produce drive power (Guével et al., 2011) and remained active until the end of the drive phase. Guével et al (2011) suggested that the RF activity on OW rowing serves also to control trunk extension. This seems to be confirmed in SE rowing, where activity of RF is concomitant to those of the trunk extensors ES and LD. Conversely, a second burst of RF activity was observed in FE rowing, which did not correspond to major activity of the trunk extensors, thus suggesting a different role of the muscle. We hypothesize that the second burst of RF assisted the abdominals to bring the flexed body forward. This role was not observed in SE rowing, since lower inertia had to be overcome by the thigh muscles to pull the body forward from the finish position (Colloud et al., 2006). In FE, both thigh muscles were recruited earlier (i.e. at the end of the recovery phase) than in SE rowing to pull the rower back to catch position, and both remained active during the drive phase as observed by Janshen et al (2009). BF was active for the whole drive phase for SE rowing, similar to OW rowing (Guével et al., 2011). Both BF and RF maintained activation after full extension of the knee (middle of the drive phase), to transmit the generated force to the trunk (Tachibana et al., 2007).

By linking upper and lower limbs, back muscles act as a rigid lever to transfer the driving forces from the legs up to the hands on the oar handle (Caldwell, McNair, & Williams, 2003). Although these segments contribute significantly less to the overall power of the stroke compared to lower limbs, their concomitant timing (Sprague, Martin, Davidson, & Farrar, 2007) is crucial for force transmission to the handle (Baudoin & Hawkins, 2004; Hofmijster, Van Soest, & De Koning, 2008). Trunk swing was immediately followed by arm flexion in both rowing conditions. During SE rowing, both LD and ES were active during drive phase while the arm muscles (BR, TR and DM) were recruited as soon as the activity of back muscles declined. Then, the arm muscles remained active until the first half of recovery phase. During FE rowing, instead, early peak activity was observed for LD and ES. The shifting of the activation and peak activity of thigh muscles caused the back muscles to be activated earlier compared to SE rowing to continue generating force. The shifting was then compensated by the arm muscles which were activated during the second half of drive phase and declined before the recovery phase begun. However, it should be noted that due to the self-return mechanism of the handle, neither rowing conditions simulate all aspects of the upper body motion occurring in OW rowing (Nowicky et al., 2005; Rodriguez et al., 1990; Shepard, 1998). Despite these limitations, our results suggest that differences in sequential loading (Baudoin & Hawkins, 2004) and compensation strategies in muscles between SE and FE rowing can affect the power output.

Thus, it is important for the rower 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 NNMF (Turpin et al., 2011a; Turpin et al., 2011b; Turpin et al., 2011c). Our basic finding, namely, that three component factors can account for the activation of muscles during rowing, was reported earlier by Turpin et al. (2011b) who extracted synergies from 23 muscles in nine subjects. They found the same basic patterns across varying power outputs (Turpin et al., 2011a), fatiguing condition (Turpin et al., 2011b), and expertise level (Turpin et al., 2011c). We have extended these results by showing that the basic patterns are conserved across different stretcher mechanisms (i.e., FE and SE).

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 (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 are 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 energy from the stretcher to the trunk (Hofmijster et al., 2008). Next, the force generation was distributed to the Synergy #3 (i.e., back muscles) which are active from the middle of drive phase up into early recovery phase. The trunk swing transfers 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 on leg drive, rowing on SE allows quicker increase of the force and effective drive timing (Kleshnev, 2011).

On the contrary, rowing on FE recruited a bulk of muscles (Synergies #1 and #2) for cumulative force production during the drive phase. However, despite their huge cross sectional area, postural muscles are slow. Hence, reliance on back muscles prevents a quick increase of propulsive force, thus making the temporal structure of the drive less effective (Kleshnev, 2011). This explains 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, Synergy #3 was activated to accelerate and decelerate the body mass at the end of each stroke. These findings are similar to a previous study that analyzed synergies on FE rowing (Turpin et al., 2011a).

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 CNS to adapt to various mechanical constraints. We observed that the inventory of rowing tasks was achieved through modification of muscle recruitment but not muscle synergy structure, which is in agreement with synergies studies on locomotion (Ivanenko et al., 2004) and cycling (Wakeling,

& Horn, 2009). As suggested by Tresch and Jarc (2009), the use of similar muscle synergies associated with different kinematic and kinetic patterns would provide evidence that the CNS produces movement through flexible combination of muscle synergies. However, the findings should be interpreted with caution, as no studies have been done on muscle synergies during OW rowing. While FE and SE may be useful for training physical fitness, their effect on the coordination of the muscles used in OW rowing is still an open question (Elliott et al., 2002; Torres-Moreno, Tanaka, & Penney, 2000).

There are several limitations in our study. The only device that we utilized to measure physiological attributes was a heart rate monitor, which limited our understanding in terms of synergies 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. The onset and cessation of the EMG patterns were not analyzed, although the timing of the muscles activation would provide deeper insights regarding muscle synergies. Future studies of muscle synergies conducted during actual OW rowing will definitely clarify our understanding.

3.6 Conclusion

The purpose of this work was to study the muscle synergies during 6 minutes maximal rowing under two conditions: fixed ergometer (FE) and ergometer mounted on sliders (SE). Despite the number of published studies that compared the two rowing conditions in terms of rowing performance, physiological variables, kinematics, force profiles, and individual EMG patterns, this study was the first one to focus on muscle synergies related to the two mechanisms. Rowing on SE and FE showed the same number of muscle synergies, but the muscles contributing to each synergy were different. Rowing with SE relied mostly on bi-articular leg muscles, which are more energy efficient, and hence enabled rowers to cover more distance and exert higher power output compared to rowing on FE which emphasized on recruiting a bulk of muscles 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 rowing in both conditions resulted in different strategies, more studies should be conducted to develop a training regime that resembles the muscle synergies of OW rowing more closely.

TABLES

Table 3.1: Rowing performance on slides and fixed ergometer. (N = 9)

	SE	FE	*p* value
Max HR (bpm)	177 (8.1)	172 (6.5)	**0.045**
Stroke rate (spm)	38 (5.9)	30 (4.3)	**0.001**
Stroke length (mps)	7 (1.7)	8 (1.6)	**0.001**
Power (W/ $kg^{1/3}$)	50 (13.6)	41 (11.3)	**0.001**
Total distance (m)	1517 (103.9)	1420 (106.6)	**0.001**

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; m, meter. The values are in mean (standard deviation).

Table 3.2: Averaged Pearson's r correlation coefficients comparing the right and left sides for eight muscles during SE and FE rowing. (N = 9)

Muscle	SE	FE
Gastrocnemius Lateralis (GL)	0.92 (0.06)	0.81 (0.03)
Biceps Femoris (BF)	0.93 (0.04)	0.81 (0.05)
Rectus Femoris (RF)	0.94 (0.04)	0.84 (0.02)
Erector Spinae (ES)	0.87 (0.07)	0.86 (0.08)
Latissimus Dorsi (LD)	0.93 (0.01)	0.90 (0.02)
Brachioradialis (BR)	0.94 (0.01)	0.95 (0.01)
Triceps Lateralis (TR)	0.95 (0.03)	0.88 (0.06)
Deltoid Medius (DM)	0.86 (0.10)	0.82 (0.07)

SE, slide ergometer; FE, fixed ergometer. The values are in mean (standard deviation).

Table 3.3: The intra-group indices of similarity for each muscle during both rowing conditions. (N = 9)

Muscle	SE	FE
GL	0.65 (0.08)	0.64 (0.07)
BF	0.65 (0.12)	0.75 (0.12)
RF	0.68 (0.12)	0.72 (0.14)
ES	0.74 (0.13)	0.81 (0.06)
LD	0.68 (0.16)	0.76 (0.05)
BR	0.73 (0.09)	0.73 (0.05)
TR	0.67 (0.13)	0.66 (0.06)
DM	0.63 (0.06)	0.75 (0.09)

SE, slide ergometer; FE, fixed ergometer. The values are in mean (standard deviation). Muscle lists are abbreviated as in Table 3.2.

Table 3.4: Intra-group indices of similarity and internal consistency of synergies. (N =9)

	SE	FE
Synergy #1	0.66 (0.14)	0.64 (0.13)
Synergy #2	0.64 (0.17)	0.62 (0.21)
Synergy #3	0.51 (0.26)	0.68 (0.09)

SE, slide ergometer; FE, fixed ergometer. The values are in mean (standard deviation).

FIGURES

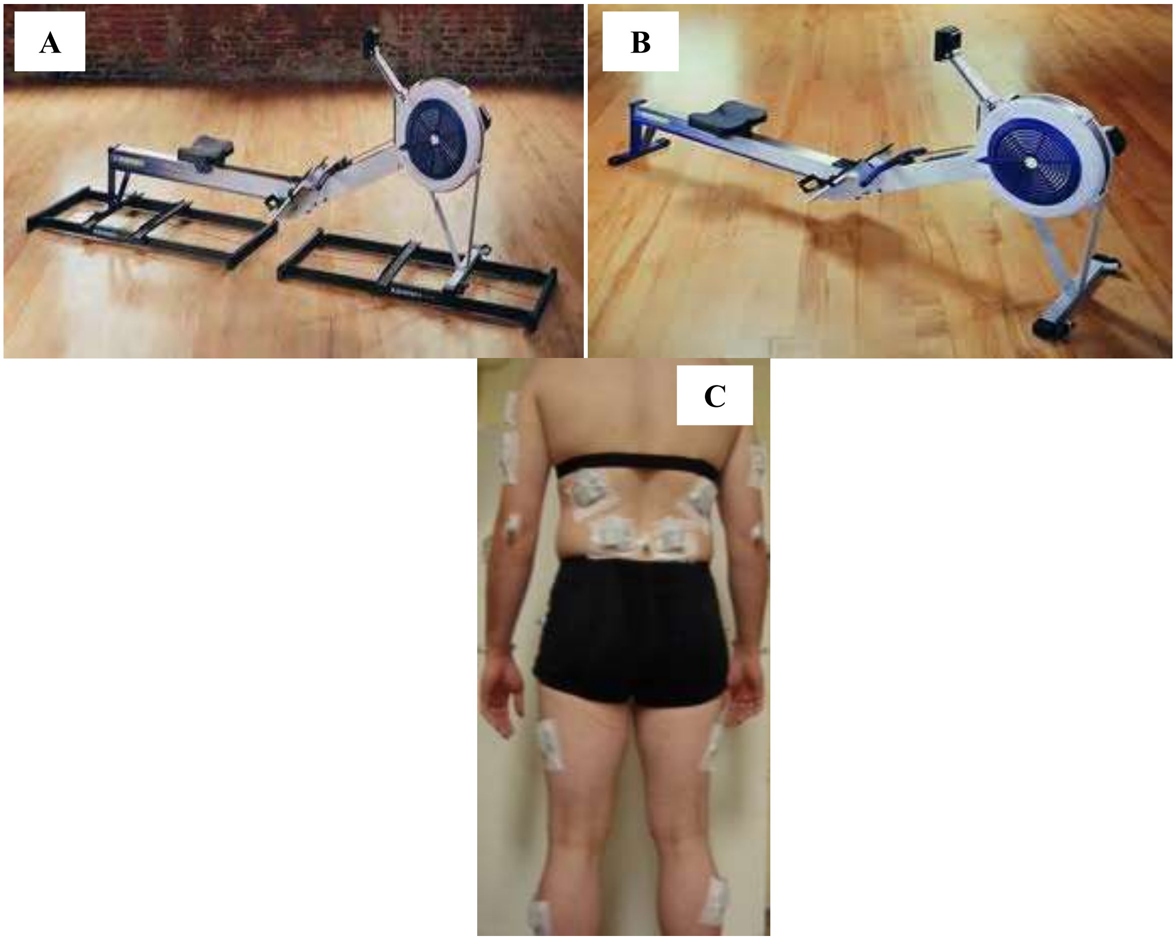


Figure 3.1. Concept 2 Model D Ergometer: A) with the slides system and B) the fixed ergometer (pictures courtesy of www.concept2.com) C) a subject with EMG electrodes

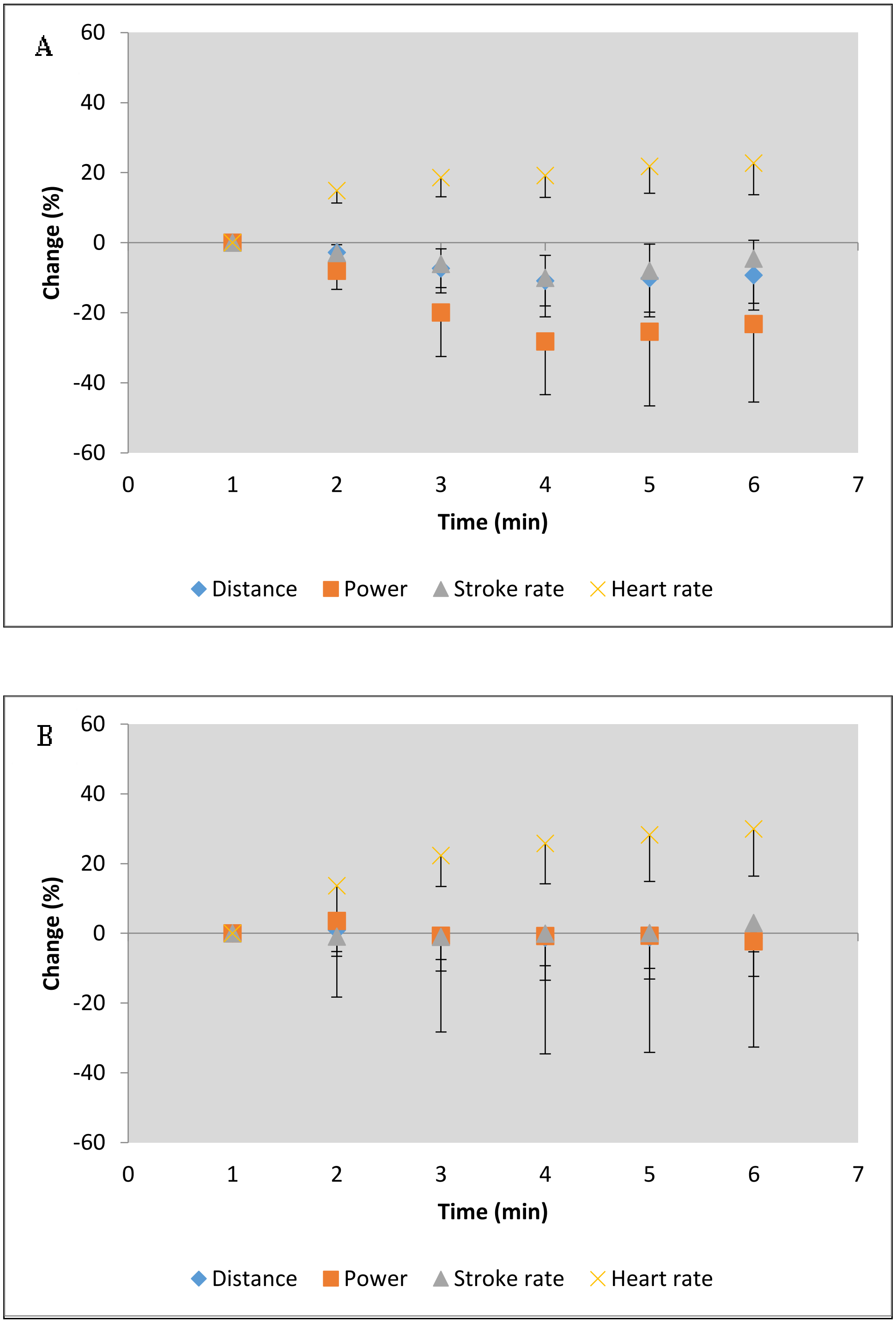


Figure 3.2: Percentage of changes of rowing performance variables: A) SE rowing, B) FE rowing.

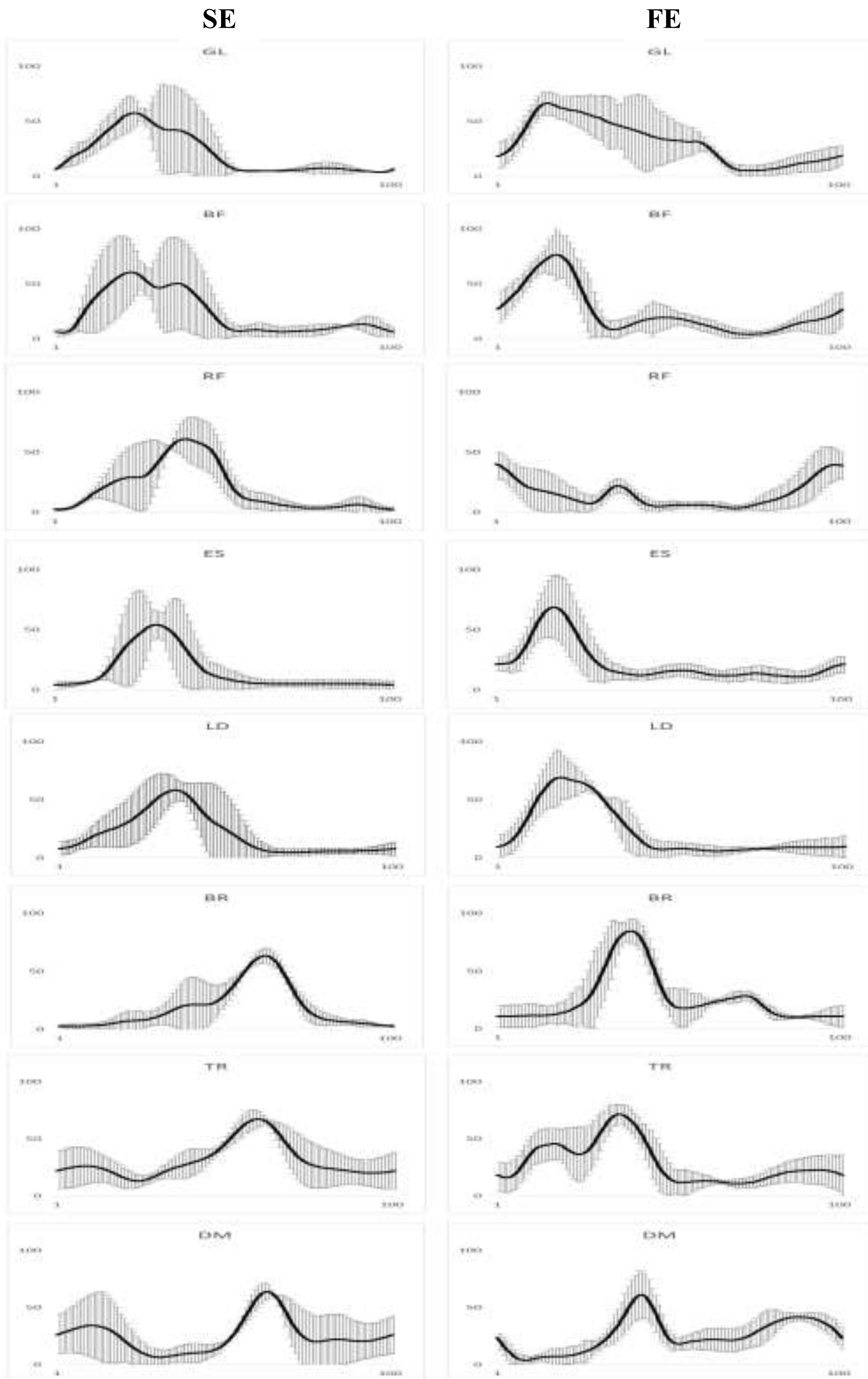


Figure 3.3: Ensemble averages of normalized EMG patterns of the 8 recorded muscles during rowing on SE and FE. Rowing phase from 0% to 50% indicates drive phase and from 51% to 100% signifies the recovery phase. Muscle abbreviations are described in Table 3.2.

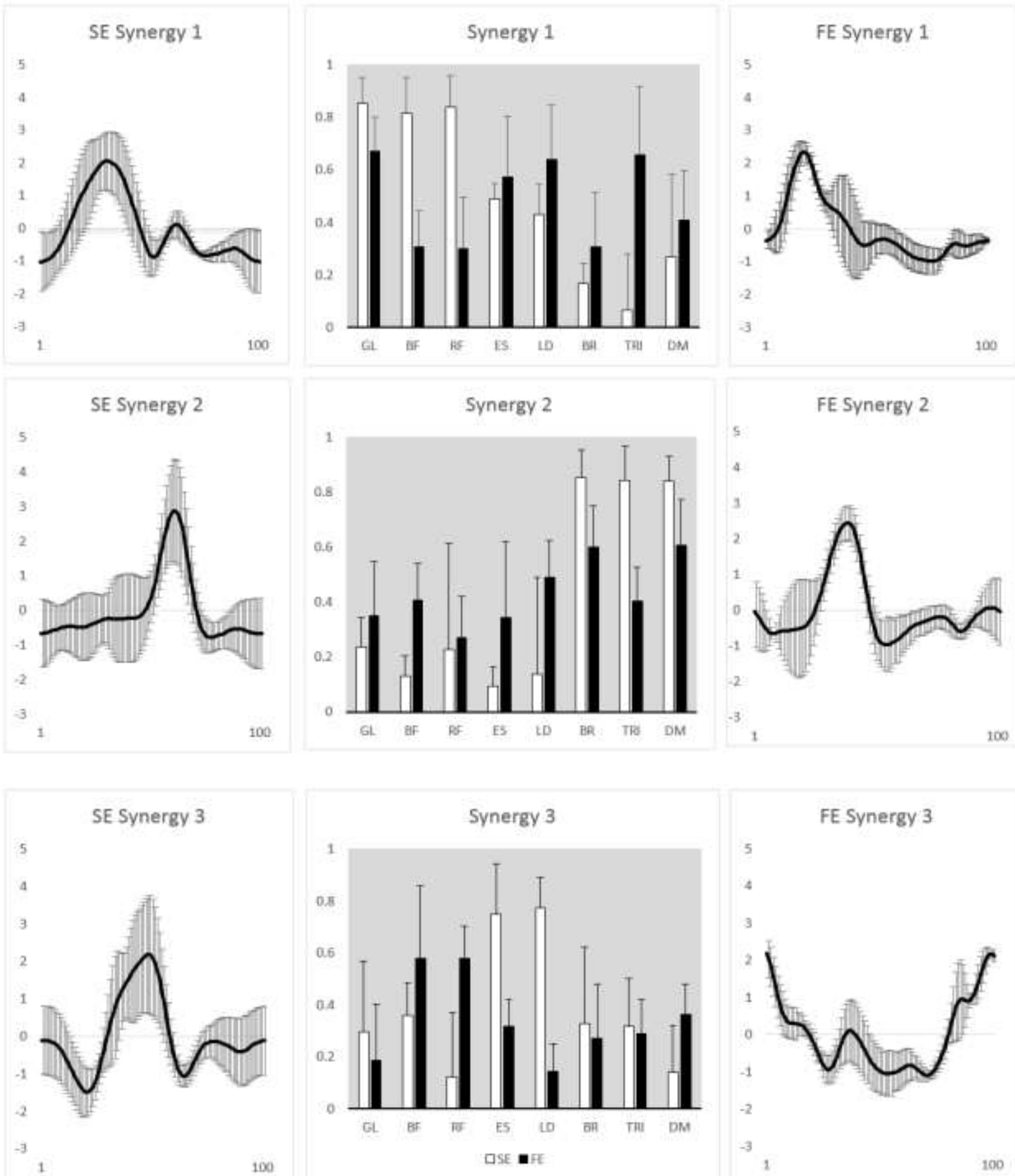


Figure 3.4: Synergy activation coefficients and muscle synergy vectors depicted for rowing on SE and FE. Synergy activation coefficients were averaged across the subjects for the three extracted synergies and expressed as a function of percentage of the rowing cycle (0% to 50% represent drive phase and 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.

Chapter 4

METHODS

This chapter describes our methods for the next three studies. A few additions were made following the findings from the pilot study (Chapter 3).

4.1 Subjects

Ten physically active males (age: 26.78 ± 2 years, mass: 76.56 ± 8 kg, height: 1.81 ± 0.1 m) and ten collegiate male rowers (age: 20.36 ± 3.4 years, mass: 79.47 ± 8.1 kg, height: 1.82 ± 0.1 m: 3 heavyweight) were recruited. The rowers are significantly younger than the untrained group with about the same height and mass. The non-rowers group consisted of recreational athletes in various sports such as triathlon, cycling, running, swimming and rugby. The collegiate team was recruited at the end of their competitive season after winning 4th place in Dad's Vail Regatta. Inclusion criteria includes competitive rowing training for at least three years (for rowers) and physically healthy without any musculoskeletal injuries. 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.

4.2 Experimental setup

We retained the setup and data analysis of EMG, kinematic variables and rowing ergometer as in the pilot study (i.e Chapter 3). Our pilot study showed that there is no difference in muscle pattern bilaterally. Therefore, 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 (TR), Abdominis (AB), Pectoralis Major (PEC), Biceps Brachialis (BB) and Brachioradialis (BR).

Another new addition to our research following the pilot study was oxygen consumption analysis. 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 (Vogler et al., 2000). The breath-by-breath MetaMax3B measurements were averaged over 30 s interval. The heart rate was measured continuously (Polar, Electro Oy, Finland) which read the data simultaneously into the ergospirometer system software. Energy expenditure (kJ/ min) was calculated following Brockway et al (1987) formula:

$$\text{Energy expenditure} = 21\ V\Delta O_2$$

where V is the ventilation rate and ΔO_2 is the oxygen concentration difference from the resting value. In our study we decided to follow definition by Sparrow and Newell (1998) as net energy expenditure divided by power output. We did not follow common rowing economy definition by dividing the mean power output by volume of oxygen consumed during sustained state ($R < 1.0$) (Holsgaard-Larsen and Jensen, 2010; Kane et al., 2008; Kane et al., 2013). This is because for maximal intensity exercise, it is very unlikely to obtain the sustained state of respiratory quotient (e.g ratio of eliminated carbon dioxide to oxygen consumed). Therefore the common rowing economy ratio do not satisfy our experimental need. Energy expenditure and economy were calculated according to comparable time representation of EMG synergies extraction for each subject. As such for 6 min maximal rowing test and $VO_{2\ max}$ test, data were analyzed starting from the third minute of rowing up to 40 consecutive rowing cycles following suggestion by Hagerman (1984) that the peak value of oxygen consumption was often achieved between the second and fourth minutes of exercise. Meanwhile for Wingate test, data were analyzed from the start of the sprint test until the end of the test (about 30 s). The $VO_{2\ max}$ is defined as the highest VO_2 value that met two out of these three criteria (Bergstrom 2013; Robergs et al. 2010): (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). Anaerobic threshold (AT) was detected automatically by the ergospirometer system software following Wasserman et al., (1984) and was expressed as percentage of $VO_{2\ max.}$ Anaerobic threshold is defined as the point when the anaerobic component initiates the increment of lactate concentration, blood acidosis and respiratory CO_2. High anaerobic threshold indicates the ability of athletes to perform optimal exercise intensity for extended period (Mikulic et al., 2011) and thus determines their overall respiratory fitness.

4.3 Protocol

Series of experiments (Wingate anaerobic, VO_{2max} and 6 min maximal rowing tests) were randomized among participating subjects. Following our findings in the pilot study, all tests were conducted on sliding ergometer (SE). Another set of experiment comparing the effect of fixed ergometer (FE) and SE was repeated for rowers only. 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.

Wingate anaerobic test: The experiment consisted of: i) 5 min warm up with intermittent sprint at self-pace, ii) 30-s all out sprint test, iii) 5 min cool down, following protocol as suggested by Mandic et al., (2004), Mikulic et al., (2010) and Riechman et al., (2002). However, contrary to these studies which applied maximum drag factor during sprint test for all subjects, we applied drag factor according to each subjects' body weight. This is because the performance on the Wingate anaerobic power test was correlated to body mass (Mandic et al., 2004). To reduce the effect of inertia at the start of the sprint test, subjects rowed without load for a constant pace for 10s and then the researcher manually adjusted the drag factor to initiate the test. Subjects were told to achieve maximal power output during the test. Stroke rate was not imposed and no verbal encouragement was given during the test. The overall protocol took approximately 60 min including the preparation time.

$VO_{2\ max}$ test: The experiment was conducted as follows: i) 5min warm up, ii) incremental ramp test starting at 25W with increment of 25W for every 30s and continued until volitional exhaustion or until power output reduced by 10% of the target power for 5 consecutive strokes (Ingham et al., 2012), iii) 5min cool down. Constant drag factor was applied during the incremental test according to the subjects' body weight. Stroke rate were not imposed. The overall protocol took approximately 90 min including the preparation time

6 min maximal rowing test: The experiment consisted of: i) 5 min warm up and familiarization with the ergometer, ii) 6 min maximal test, iii) 5 min cool down. Subjects were told to cover as much rowing distance as they could during the 6 min period with stroke rate within 28 to 36 strokes per minute. For rowers, test was conducted on both SE and FE. The overall protocol took approximately 90 min including the preparation time.

4.4 Statistics

The inter-group indices of similarity were computed on Z-transforms of individual EMG patterns and synergy activation coefficients (Cappellini et al., 2006; Turpin et al., 2011). These indices correspond to the averaged Pearson's correlation coefficient (r) between each pair of subjects between the two groups. Factor analysis (PCA with varimax rotation, PA and MAP) was applied and explained in detail in Chapter 3. T-test was used to compare subjects' characteristics, rowing performance, physiological variables and muscle weightings between the groups. 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 $\alpha = 0.05$. Rowing economy, VO_2 max, heart rate, and power output were then submitted to Multiple Linear Regression (MLR) as predictors of rowing performance. For Wingate anaerobic test, peak power output was the criterion of rowing performance. Total distance covered was the criterion for 6 min maximal rowing test and absolute maximal oxygen consumption value (VO_{2max} in L/min) was selected as the criterion for VO_{2max} test. All statistical tests were carried out in IBM SPSS Statistics v20.0 (IBM Corp., Armonk, NY).

Chapter 5

MUSCLE SYNERGY OF COLLEGIATE ROWERS DURING 6 MIN MAXIMAL ROWING ON FIXED AND SLIDES ERGOMETER

5.1 Abstract

Introduction: The purpose of this study is to evaluate the muscle synergies of collegiate rowers during 6 minutes maximal rowing on different stretcher mechanisms: fixed (FE) and sliding ergometer (SE). The association of muscle synergies to rowing economy will further quantify by statistical analysis. Although the robustness of muscle synergies has been extensively studied (across tasks, mechanical constraints, training effect, and posture), the robustness of muscle synergies across different physiological demands is still an open question.

Method: Ten collegiate rowers were recruited at the end of their competitive season. Muscle synergies were 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, kinematic and physiological variables were analyzed.

Results: Rowers showed similar rowing performance in terms of total distance covered. Rowers rowed faster at shorter strokes when rowing on SE. Higher 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. Multiple linear regression revealed that mean power output is the only important predictor of rowing performance for FE rowing only.

Discussion: Although rowing economy is highly associated with muscle synergies (especially Synergy #1), it is not the main predictor of rowing performance for 6 minutes maximal rowing on FE and SE. The findings of this study could guide the rowers and their coaches to enhance the training regime. As there is no difference in muscle synergy pattern and rowing performance during rowing on FE and SE, both ergometers could be utilized by the experienced rowers.

5.2 Introduction

Muscle synergy is defined as a specific and consistent spatiotemporal pattern of muscle activations that leads to similar joint trajectories (Ting et al., 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 PCA, ICA, NNMF) based on two components "muscle synergy vectors" which correspond to the relative loading of each muscle within each synergy; and a "synergy activation coefficient" which represents the temporal activity of the muscle synergy (Frére and Hug, 2012). Some researchers observed that temporal recruitment patterns are robust across various mechanical constraints while the loadings vary across subjects or test conditions (Cappellini et al., 2006; Ivanenko et al., 2004, 2005). These studies proved that muscle synergies is stable across tasks and yet flexible enough to allow inter-individual variability.

The modulation of muscle recruitment patterns following training is another indication of the flexibility of muscle synergies composition (Carson et al., 2006). As an example, Asaka et al. (2008) 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 in the muscle synergies of experienced rowers (10 years of rowing) and untrained subjects (Turpin et al., 2011). They concluded that expertise in rowing is linked to a better ability in adjusting the mechanical output of the muscle synergies rather than the differences in shape and timing of muscle activations. This discrepancy of results could be due to the difference in tasks studied and the different types of synergies adaptation (i.e chronic versus acute training). However, both studies did not take into account the physiological variables that could gain further insights regarding the effect of training on synergies.

As the muscle activity is a large determinate of metabolic rate during maximal effort activities (Wakeling et al., 2010), and muscle synergy is a way of CNS to reduce redundancy of motor control, it is thus compelling to investigate the underlying relationship. Therefore, as an extension of previous study in Chapter 3, we included more rowing-specific muscles and oxygen consumption analyzer to further investigate the association of muscle synergies and physiological variables in collegiate rowers. In parallel with our findings in previous chapter, we hypothesized that rowing on sliding ergometer (SE) is more efficient than rowing on fixed ergometer (FE).

5.3 Results

Rowing variables

Contrary to the untrained subjects, the rowers were able to cover about the same distance and exert similar power output during both (SE and FE) rowing conditions (Table 5.1). There was also no significant difference in oxygen consumption in both rowing conditions. However, rowing on SE was more intense as evidenced by higher maximal heart rate (p = 0.05) and energy expenditure (p = 0.01) compared to FE rowing. The most interesting part was that the rowers also exhibited similar rowing strategy as the untrained subjects, where they rowed faster at shorter stroke on SE and slower with longer stroke on FE. This strategy could be the reason of better economy achieved during rowing on SE.

The rowing variables were further evaluated to observe their trends (Figure 5.1). For both rowing conditions, distance covered, stroke rate and power output of each minute were normalized to the corresponding values at the first minute of rowing. As the homoscedasticity assumption was not met (Levene's test, $p < 0.05$), we adopted a non-parametric test (Friedman test) and applied

Wilcoxon signed rank test with Bonferroni correction for post-hoc comparisons wherever appropriate. All variables significantly decreased over time for both rowing conditions ($p = 0.001$), however post-hoc comparison did not detect any significant changes between one minute-sessions.

EMG patterns

The ensemble averages of the EMG linear envelopes for 16 muscles investigated are presented in Figure 5.2. Contrary to untrained subjects, there were no distinct differences in the muscle waveforms between rowing conditions. This 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).

Muscle synergies

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 group (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 5.2). Muscles with factor loading greater than 0.55 (Comrey, & Lee, 1992) were considered as contributors for a specific synergy. Muscle loadings and synergies coefficients were depicted in Figure 5.3.

For rowing on SE, the Synergy #1 consisted of the main force generator muscles during rowing such as the soleus (SOL), gastrocnemius lateralis (GL), biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL), erector spinae (ES), latissimus dorsi (LD), triceps long-head (TRI), and pectoralis major (PEC). The GL, BF and TRI are multi joint muscles which also an efficient force distributor while ES and LD are postural muscles which have large 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 #1 which comprised of arm muscles (biceps brachii, BB; and brachioradialis, BR) which occurred on the second half of drive phase. Synergy #3 was contributed by tibialis anterior (TA), rectus femoris (RF), middle trapezius (TRAP) and deltoid medius (DM). Synergy #3 initiated during the second half of drive phase and was crucial during the transition of stroke from catch to finish position. The muscles that made up the Synergy #3 function as movement refiner (e.g TRAP for 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 hip).

Small differences in muscle contributions to synergies and synergies timing coefficient during FE rowing were noted. For Synergy #1 the rowers recruited the middle trapezius (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.

Muscle synergies and rowing economy

To test our hypothesis that muscle synergies could improve rowing performance, the effect of muscle loadings of Synergy #1 on rowing economy was tested using analysis of variance (ANOVA) adopting method by Wakeling et al. (2010). 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 of variance (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, $p = 0.001$). Post hoc revealed significance association of each muscle loadings to rowing economy (SE, $p < 0.006$; FE, $p < 0.005$). As we want to evaluate the association of all muscle loadings to rowing economy (not a pairwise comparison between each muscle loading and rowing economy), post hoc results were not studied further.

Next, data were further analyzed using a direct-entry (standard) multiple regression analysis (MRA) to predict the variables effect on rowing performance. Multivariate associations are generally superior to univariate correlations because they better capture the full network of relations among predictors and criteria (Tabachnick, & Fidel, 2007). Maximal oxygen consumption (VO_2), maximal heart rate, mean power output and rowing economy served as predictors. Total rowing distance was utilized as the criterion. For 6 minutes maximal rowing, total distance covered is the indicator of rowing performance.

For SE, MLR failed to detect any significance of the predictors on rowing performance. For FE, the overall association was statistically significant, $p = 0.0001$. However, only mean power output made statistically significant, unique contribution to the estimation of total rowing distance covered ($p < 0.05$). The relative contribution of significant independent variables was evaluated through the interpretation of squared semi-partial coefficients (sr^2) (Tabachnick, & Fidel, 2007). We obtained sr^2 for mean power output, however as it is the only significant predictor, we could not calculate its unique contribution to rowing performance relative to other predictors. Effect sizes were calculated for the two significant predictors using Cohen's (1988) f^2, where values of 0.02 represent a small effect, values of 0.15 equal a medium effect, and values more than 0.35 denote a large effect. The only significant predictor in our model showed large effect sizes.

5.4 Discussion

As hypothesized, rowing on SE is more intense physiologically but more energy efficient (as shown by high percentage of rowing economy) compared to rowing on FE. Contrary to the untrained subjects (in previous chapter), the rowers showed similar 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. Surprisingly, the rowers adopted similar rowing strategies as the untrained subjects, which is to row faster at shorter strokes on SE but slower and longer strokes on FE. Statistical analyses revealed that muscle synergies (especially Synergy #1) were highly associated to rowing economy in both rowing conditions although rowing economy is not the main predictor of rowing performance.

Although Ingham et al., (2007) suggested that economy of movement may be a crucial physiological characteristics of performance, our findings did not share similar view. This could be due to difference in our definition of economy, where we defined it according to Sparrow and Newell (1998), the energy expenditure per power output. Meanwhile, Ingham et al., (2007) defined it according to kinetics of oxygen uptake. However, our result showed similarity with Bourdin et al. (2002), where in the study rowing economy was not the main predictor of rowing performance. In their study, rowing gross efficiency only accounted for 12.3% of variation in 2-km rowing test compared to peak power output, which explained 84.6% of total rowing performance. On the other hand, our regression results showed that mean power output is the main predictor of rowing performance on FE during 6 min maximal rowing test. This finding is in-line with Riechman et al., (2002) who noted that mean power accounted for 75.7% of variance in 2-km rowing performance time on similar ergometer.

To our knowledge, this study is the first attempt to find the association of muscle synergies to rowing economy in different stretcher mechanisms. Although the robustness of muscle synergies have been widely studied across mechanical constraints (Ivanenko et al., 2004), training effect (Asaka et al., 2008), and posture (Hug et al., 2011), there are currently no studies that attempt to evaluate the robustness of muscle synergies in physiological constraints. We also enhance the PCA technique to extract muscle synergies by applying a number of VAF detection tests (e.g PA and MAP). These analyses were common techniques in statistics but have never been used in synergies extraction.

The limitation of this study is the application of non-parametric statistical test to evaluate the association of muscle loadings from Synergy #1 to rowing economy. We adopted the method from Wakeling et al., (2010), who applied ANOVA and found significant association of muscle intensity loadings (through wavelet and PCA method) across difference pedaling coordination. However, since our data violated the homoscedasticity of variance, ANOVA could not be applied. Although, non-parametric statistical tests are less powerful than parametric tests, but typically the overall findings are similar (Field, 2013).

The findings of this result could guide the rowers and their coaches to enhance the training regime. As there are no differences in muscle synergies pattern and rowing performance during rowing on FE and SE, both ergometers could be utilized by the experienced rowers. However, for beginners or novice rowers, rowing on SE is a better option (as shown from previous chapter) to develop efficient muscle synergies.

TABLES

Table 5.1: Rowing performance on slides (SE) and fixed (FE) ergometer. (N = 10)

	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 (L/min)	5.78 (0.7)	5.33 (0.9)	0.10
VO_2 (kg/L/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.

Table 5.2: Cronbach's α for synergies extracted during rowing on FE and SE. (N = 10)

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)

SE, slides ergometer; FE, fixed ergometer.

Table 5.3: Multivariate linear regression was used to investigate the relationship between variables to rowing performance ($R^2 = 0.99$) on FE (N = 10)

	β	***p*-value**	**sr^2**	**f^2**
Mean power output	0.996	**0.0001**	**0.68**	**0.67**
Rowing economy	0.003	0.835		
Heart rate $_{max}$	-0.02	0.145		
$VO_{2\,max}$	0.028	0.095		

$VO_{2\,max}$, maximal oxygen consumption; β, standardized beta coefficient; sr^2, semi partial coefficients; f^2, effect size.

FIGURES

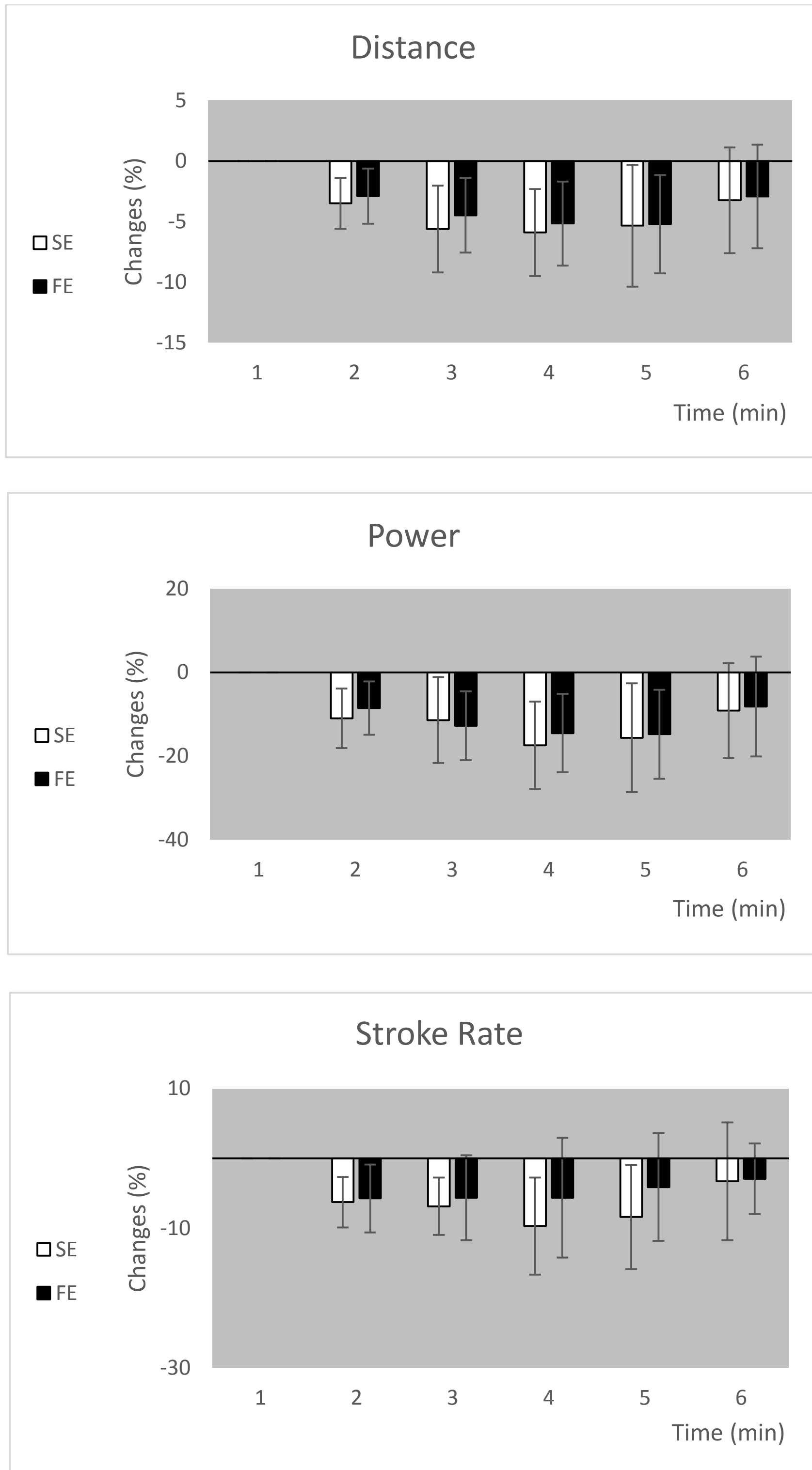
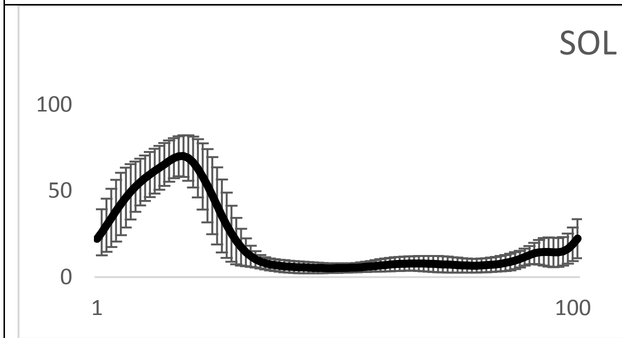
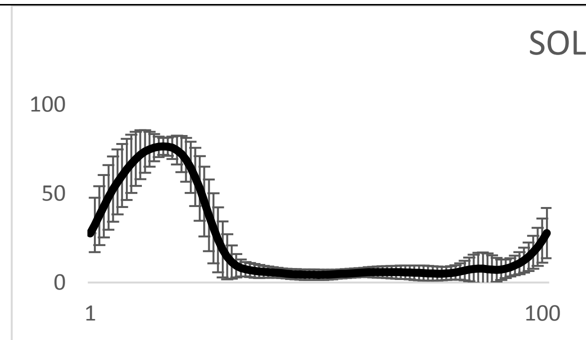
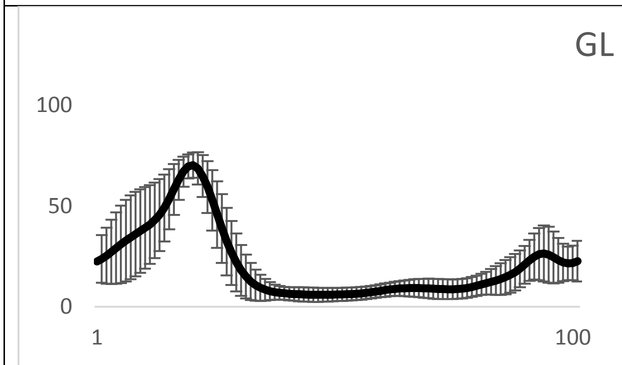
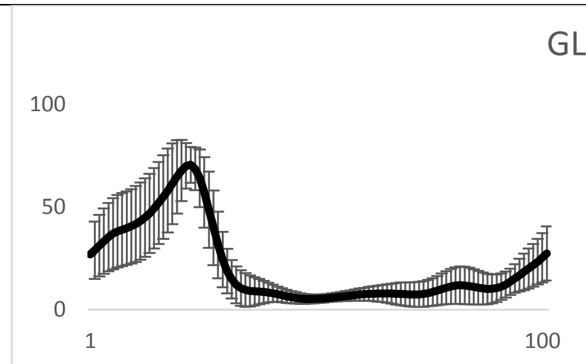
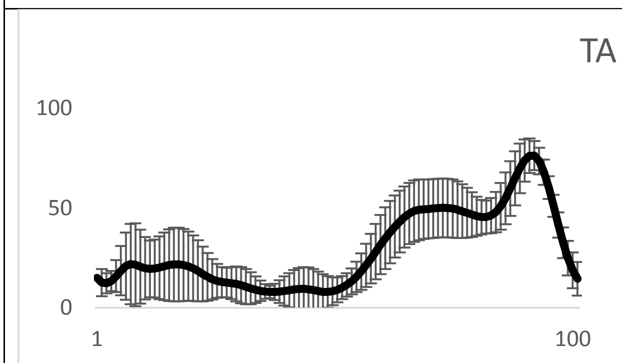
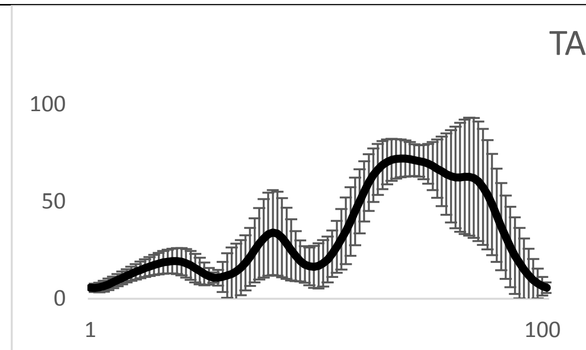
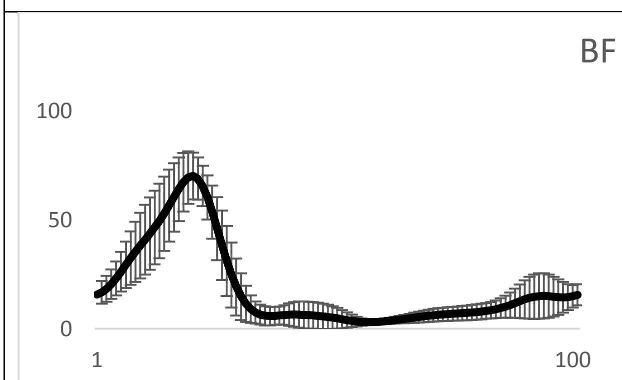
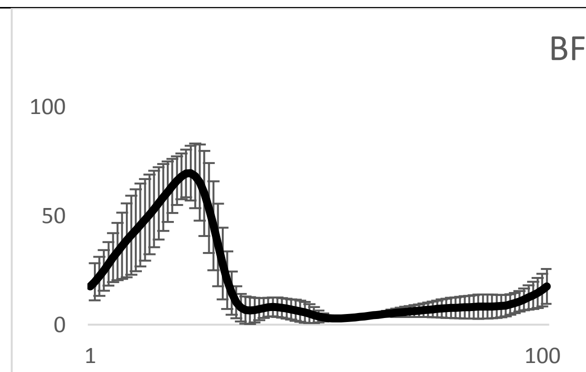
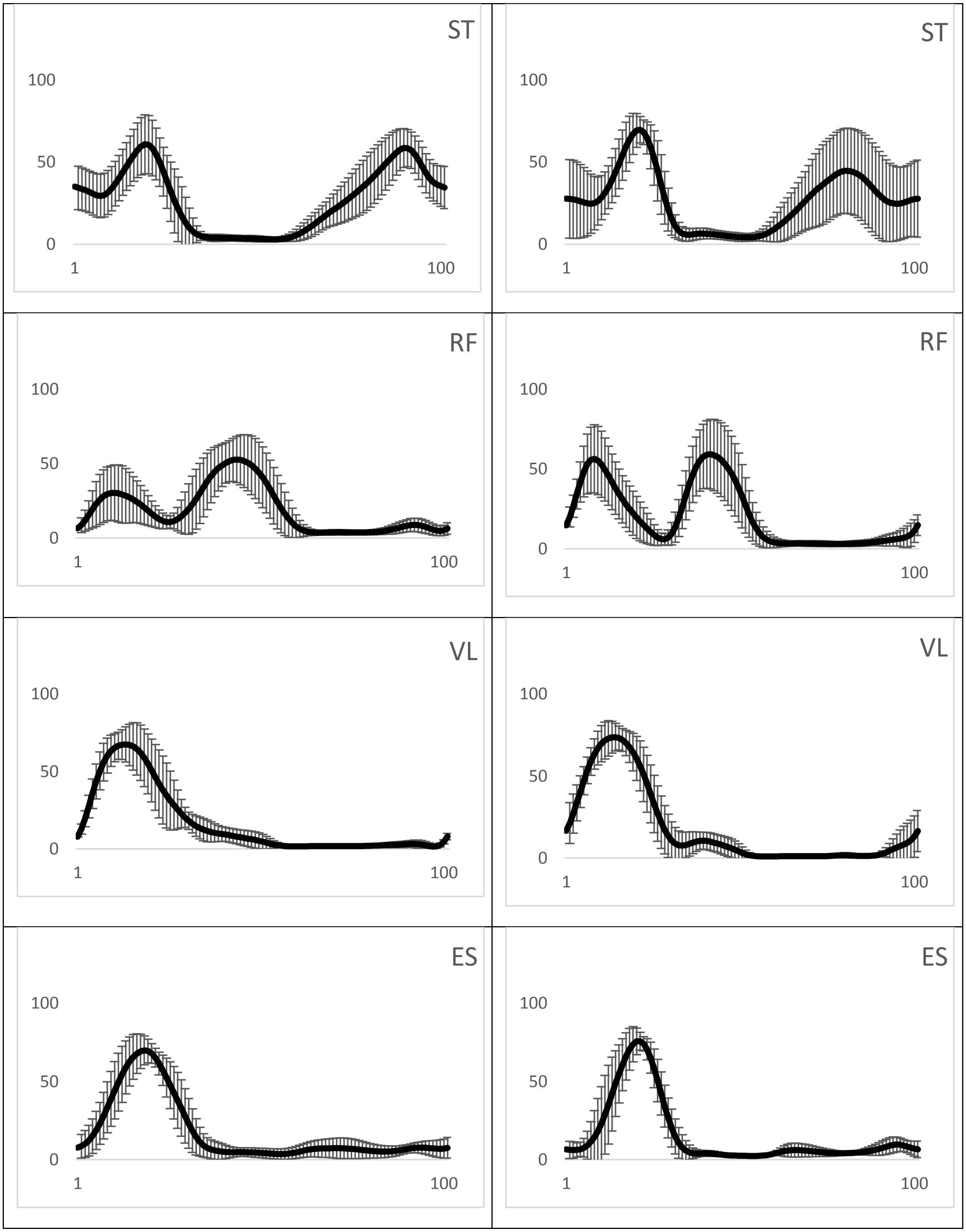


Figure 5.1: The percentage of changes of rowing variables from the initial minute.

SE	FE
SOL 100 50 0 1 100	SOL 100 50 0 1 100
GL 100 50 0 1 100	GL 100 50 0 1 100
TA 100 50 0 1 100	TA 100 50 0 1 100
BF 100 50 0 1 100	BF 100 50 0 1 100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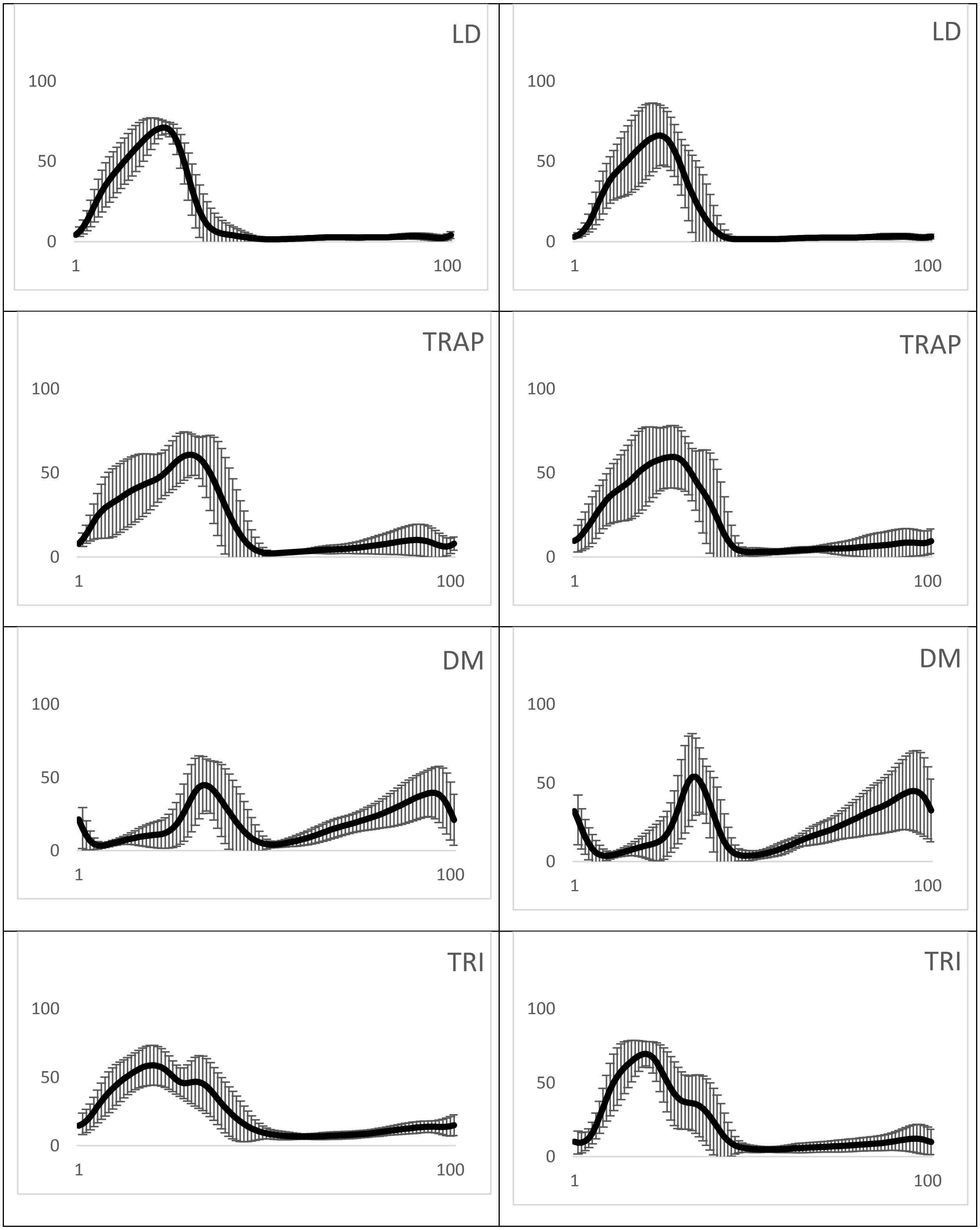
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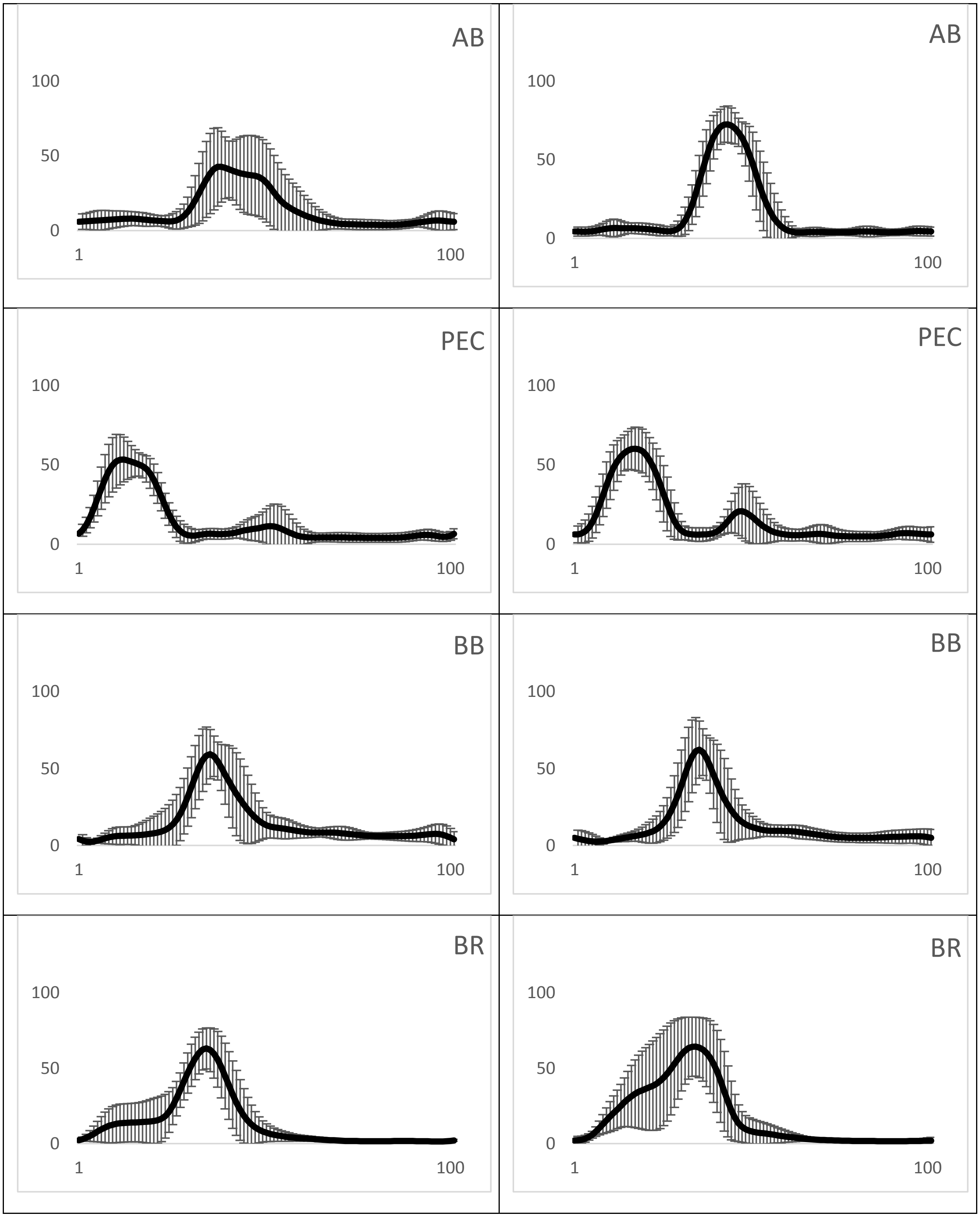


Figure 5.2: Ensemble averages of normalized EMG patterns of the 16 recorded muscles during rowing on SE and FE. Rowing phase from 0% to 50% indicates drive phase and from 51% to 100% signifies the recovery phase. Muscle abbreviations are described in text (Methods section).

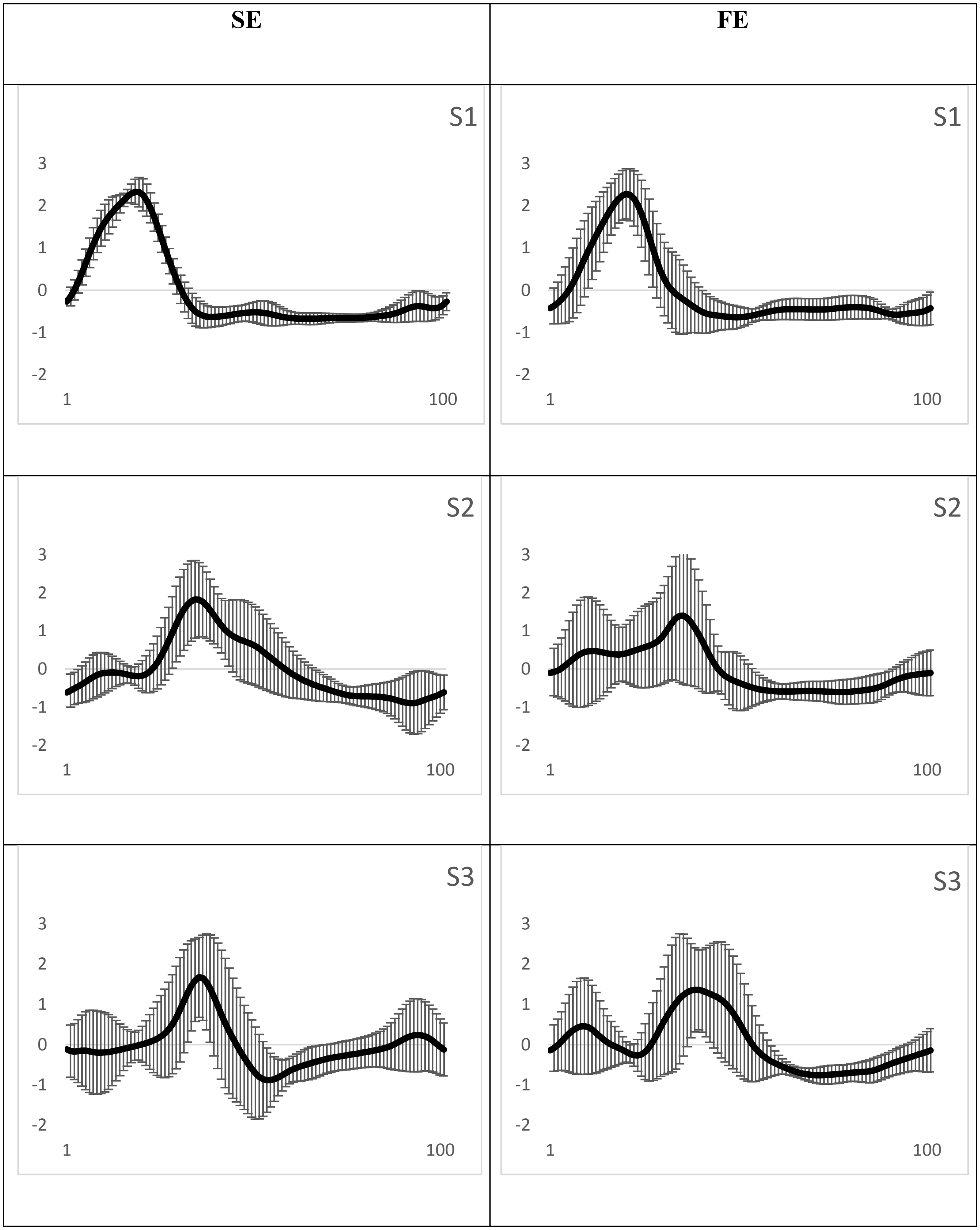


Figure 5.3: Synergy activation coefficients and muscle synergy vectors depicted for rowing on SE and FE. Synergy activation coefficients were averaged across the subjects for the three extracted synergies and expressed as a function of percentage of the rowing cycle (0% to 50% represent drive phase and 51% to 100% represents recovery phase). SE, slides ergometer: FE, fixed ergometer.

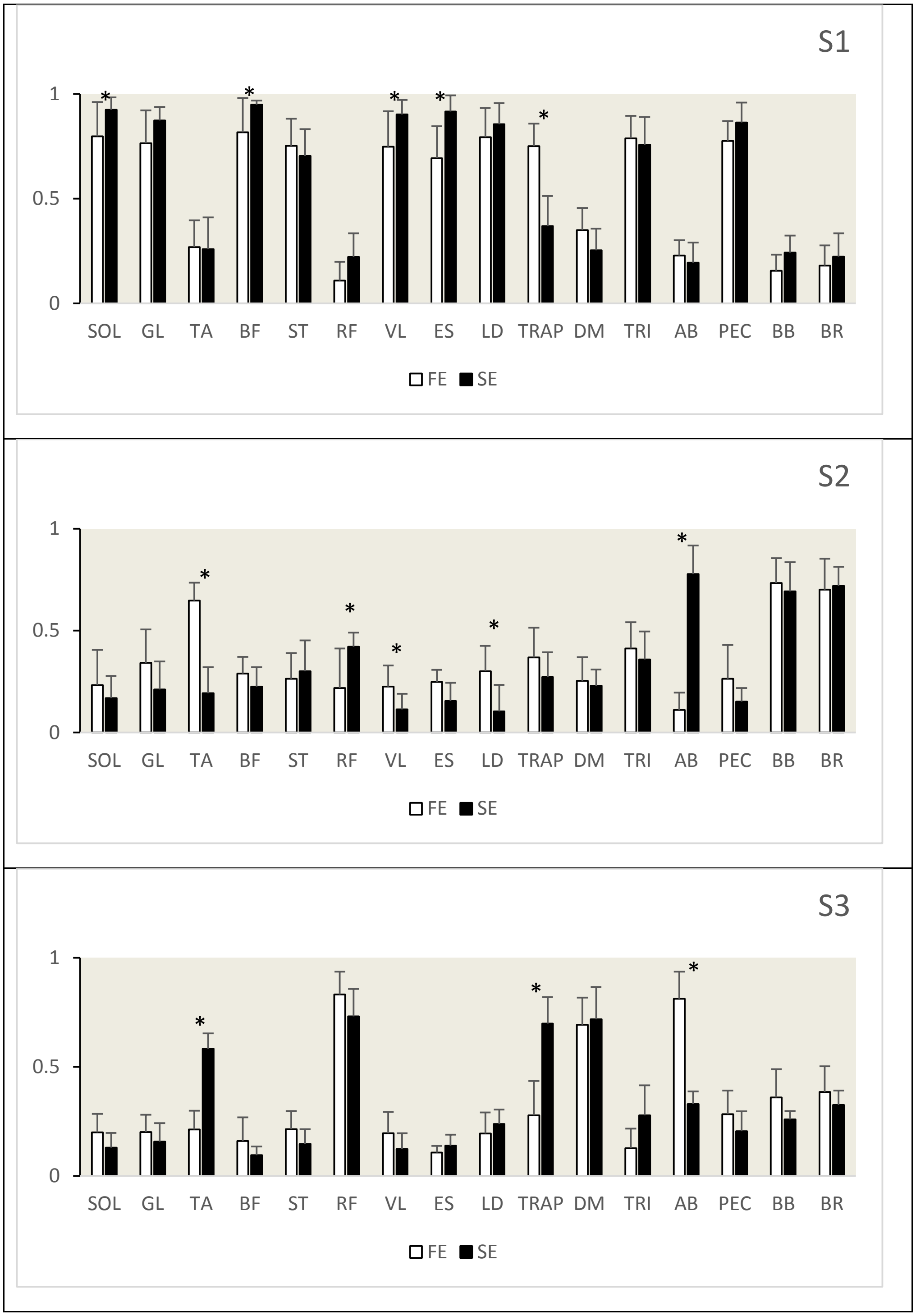


Figure 5.4: Muscle synergy vectors depicted for rowing on SE and FE. The muscle synergy vectors were averaged across the subjects for the three extracted synergies. Individual muscle weightings are depicted for each muscle within each synergy. SE, slides ergometer: FE, fixed ergometer. Asterisks indicate significant difference of muscle loadings between rowing conditions ($p < 0.05$).

Chapter 6

MUSCLE SYNERGY DURING WINGATE ANAEROBIC TEST FOR ROWERS AND UNTRAINED SUBJECTS

6.1 Abstract

Introduction: The purpose of this study is to evaluate the effect of muscle synergies on rowing economy during anaerobic Wingate test. As a power endurance sport, high anaerobic capacity is one of the determinant of rowing performance. Due to close link that exists between the state of energy supply and types of muscle fibers being recruited, the muscle synergies were hypothesized to enhance rowing economy and thus further improve rowing performance.

Method: Ten physically active males and ten collegiate male rowers were recruited. Muscle synergies were extracted from 16 rowing specific muscles using Principal Component Analysis (PCA) with varimax rotation. All out anaerobic Wingate test was performed on Concept 2 sliding ergometer. Rowing performance, kinematic and physiological variables were analyzed.

Results: Rowers showed better rowing performance in terms of peak power output, mean power output, distance covered, max oxygen consumption, energy expenditure and rowing economy. Three muscle synergies were extracted from both groups. Significant association was found between synergy #1 and rowing economy. Multiple linear regression revealed that mean power output and rowing economy are important predictors of rowing performance for untrained subjects only.

Discussion: Expertise in rowing does not affect the sequence of synergies activation but it is rather related to the ability to adjust the muscle activation level during intense anaerobic burst. We

conclude that training to enhance the muscle synergies (particularly synergy #1) might improve the rowing economy during anaerobic test. The rowers could apply the results from this study to reduce the energy cost especially during the start of the rowing race, where anaerobic metabolism is predominant.

6.2 Introduction

A distinctive attribute of the rowing activity is the unique pattern of energy utilization (Hagerman 1978). Rowing races begin with a surge of intense anaerobic activity, followed by sustained maximum effort at 90-95% of aerobic capacity until the final sprint to the finish (Huntsman et al., 2011). In 2000m indoor rowing test, 75.7% of the variance in rowing performance time was accounted for by mean power during the Wingate test and only 12.1% of variance was related to VO_2max (Riechman et al., 2002). Therefore, high anaerobic capacity is crucial to succeed in this 'power endurance' sport (Peltonen and Rusko 1993).

The intensity (all out sprint) and duration (30 s) of Wingate test allows the evaluation of the metabolism underlying the rate of the high-energy phosphagens (adenosine triphosphate, ATP and phosphocreatine, PCr) and the glycolytic energy contribution (glycolysis/ glycogenolysis) to power generation. Typical variables for Wingate are peak power and mean power outputs. The peak power output is generated during the first 5 s of the test and indicates the high energy phosphagens turnover. Mean power output is the average of power output over the entire 30 s of the test, and it estimates energy contribution from the glycolytic system (Mandic et al., 2004). However, it should be noted that the energy release mechanism during Wingate test is not exclusively anaerobic: the aerobic component supplies about 20-30% of the total energy (Beneke et al., 2002; Beneke et al., 2007; Mikulic et al., 2010). Despite being the easiest field test and non-invasive method compared to other anaerobic quantifying method, the Wingate test is only a reflection of the anaerobic capacity.

Moritani suggested that a close link exists between the state of energy supply and types of muscle fibers being recruited (Moritani et al., 1992). Hence, extensive studies were conducted to relate the effect of anaerobic metabolism on electromyographic (EMG) signals. One particular method consists in the identification of the neuromuscular fatigue threshold (NMFT) by plotting the oxygen consumption and the EMG threshold (EMGT) of the particular muscle that contributes the most to force production in a specific task (i.e., the Vastus Lateralis during cycling). This method attempts to relate the local neuromuscular fatigue to systemic fatigue and further detect the transition of aerobic metabolism to anaerobic metabolism (Hug et al.2003; Hug et al., 2004). However, it is known that EMGT is not always detectable for all muscles and does not account for the synergies of muscles. This is particularly important, considering that the coordination pattern of muscles limits the power output from a limb (Wakeling et al., 2010), and thus could be a determining factor of performance.

In this work, we attempt to fill the gap in literature regarding muscle synergies and anaerobic metabolism. Our specific aim is to evaluate the effect of muscle synergies on rowing economy during anaerobic Wingate test.

6.3 Results

Rowing variables

Overall, rowers exerted greater $VO_{2\ max}$ values, maximal heart rate, peak and mean power while covering more distance in 30 s Wingate rowing test (Table 6.1). However, absolute $VO_{2\ max}$ (oxygen consumption in L/min) is more important to rowing because the body weight is supported by the boat (or ergometer in this case) (Mahler et al., 1984). Therefore, the rowers have better absolute $VO_{2\ max}$ than untrained subjects although there was no difference in anaerobic threshold (AT). AT is the threshold of lactate accumulation in bloodstream. Higher values of AT indicates the ability to maintain exercising at high intensity which means better overall physiological fitness.

As the AT value is not significantly different between groups, it shows that the subjects have comparable physiological fitness. Thus, physiological fitness can be excluded as confounding factor of our synergies results. Energy expenditure was calculated by taking the net difference of oxygen consumption at the end of the test from resting values. The rowers exerted higher energy expenditure than untrained subjects probably due to lower resting oxygen consumption values exhibited by the rowers. The rowing economy was significantly higher in rowers.

EMG patterns

The ensemble averages of the EMG linear envelopes for 16 muscles investigated for both groups are presented in Figure 6.1. All muscles showed high inter-group index of similarity with Pearson r ranging from 0.874 to 0.96 (except for TA, $r = 0.75$).

Muscle synergies

Both groups have acceptable KMO statistics (untrained: 0.606 ± 0.03; rowers: 0.609 ± 0.04) which means data were adequate for PCA. Therefore PCA with varimax rotation 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 groups. Three synergies explained 90% of VAF for both groups as shown on Figure 6.2. The indices of similarity for synergies waveform between groups were acceptable for all the synergies (Synergy #1 = 0.832; Synergy #2 = 0.854; and Synergy #3 = 0.676). High Cronbach's α value showed the repeatability of data (Table 6.2). Muscles with factor loading greater than 0.55 (Comrey, & Lee,

1992) were considered as contributors for a specific synergy. Muscle loadings and synergies coefficients were depicted in Figure 6.3 and Figure 6.4.

The rowers recruited total of nine muscles for Synergy #1 which is the most important synergy as it accounted about half of total variance of overall synergies. The muscles recruited for Synergy #1 were: SOL, GL, BF, ST, VL, ES, LD, TRI, and PEC which were activated on the first half of drive phase. Next the force generated by the muscles from Synergy #1 was transferred to the upper arm muscles (TRAP, DM, BB and BR) which constituted the Synergy #2. The Synergy #3 was the made up of force distributor and movement refiner muscles (i.e TA, RF and AB) and was activated during the rowing phase transition. The force generated by the synergies were transferred efficiently as the rowers recruited the Synergy #1 and #2 successively during the first and half part of drive phase.

On the other hand, less muscles were recruited in Synergy #1 (SOL, GL, BF, ST, VL, ES, LD) of the untrained subjects. In terms of timing coefficient similar synergies recruitment strategy by the rowers was not evidenced in the untrained group. They tend to recruit Synergy #1 and #2 (TRAP, DM, TRI, BB, BR) simultaneously during the whole drive phase, which is an attempt to direct an accumulative force. This probably explains the higher value of rowing economy and power output of rowers compared to the untrained subjects. The Synergy #3 was contributed by TA, RF, AB and PEC which function as force distributor and occurred during the changes of rowing phase.

Muscle synergies and rowing economy

To test our hypothesis that muscle synergies could improve rowing performance, the effect of muscle loadings of Synergy #1 on rowing economy was tested using analysis of variance (ANOVA) adopting method by Wakeling et al. (2010). As Synergy #1 accounted for almost half of total VAF synergies (54.17 ± 6.9 for untrained; 50.3 ± 6.1 for rowers), the effect on rowing economy should be detectable. However, the data violated the assumption of homoscedasticity of variance (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 (untrained and rowers, $p = 0.001$). Post hoc revealed significance association of each muscle loadings to rowing economy for untrained subjects ($p < 0.007$), but not all muscle loadings showed significant association to rowers' economy ($p > 0.005$). As we want to evaluate the association of all muscle loadings to rowing economy (not a pairwise comparison between each muscle loading and rowing economy), post hoc results were not studied further.

Next, data were further analyzed using a direct-entry (standard) multiple regression analysis (MRA) to predict the variables effect on rowing performance. Multivariate associations are generally superior to univariate correlations because they better capture the full network of relations among predictors and criteria (Tabachnick, & Fidel, 2007). Maximal oxygen consumption ($VO_{2\ max}$), maximal heart rate, mean power output and rowing economy served as predictors. Peak power output was utilized as the criterion. For Wingate test, peak power output is the indicator of rowing performance.

For rowers, MLR failed to detect any significance of the predictors on rowing performance. For untrained subjects, the overall association was statistically significant, $p = 0.006$ (Table 6.3). Only mean power output and rowing economy made statistically-significant, unique contribution to the estimation of peak power output during a Wingate test ($p < 0.05$). The relative contribution of significant independent variables was evaluated through the interpretation of squared semi-partial coefficients (Tabachnick, & Fidel, 2007). Results showed that mean power output made the largest unique contribution and that its predictive efficacy was over twice larger than that for the rowing economy (i.e 0.32/ 0.15 = 2.13). Effect sizes were calculated for the two significant predictors using Cohen's (1988) f^2, where values of 0.02 represent a small effect, values of 0.15 equal a medium effect, and values more than 0.35 denote a large effect. Both predictors showed medium effect sizes.

6.4 Discussion

The purpose of this study is to evaluate the effect of muscle synergies on rowing economy during anaerobic Wingate test for untrained subjects and collegiate rowers. We observed that although both groups attained comparable level of fitness, the rowers exhibited higher values of rowing economy. Through Friedman's non-parametric test we noted that rowing economy is highly associated with Synergy #1, which comprises about half of VAF from total synergies. Therefore, we concluded that muscle synergy does relate to rowing economy for both untrained and rowers groups. However, through regression analysis, rowing economy is a less influential factor compared to mean power output to predict rowing performance during Wingate test. Besides, with negative value of β coefficients from regression analysis, it means that rowing economy is inversely related to performance during Wingate test. Surprisingly, the regression analysis is only significant for untrained groups. None of the predictors we listed (i. e: $VO_{2\ max}$, maximal heart rate, mean power output and rowing economy) was significant to predict peak power output that rowers could exert during Wingate anaerobic test. We hypothesized that through intense training, the rowers have developed skills and the technique that could be the key variable for peak performance. However, our study failed to capture this variable, hence further analyses is suggested.

Comparing the muscle synergies pattern between untrained subjects and collegiate rowers, our results are in agreement with Turpin et al. (2011). As the waveform patterns for individual muscles and extracted synergies exhibited high indices of similarity between groups, we hypothesized that expertise in rowing is not related to sequence of synergies activation, but the activation level of synergies (Turpin et al., 2011). Particularly in Wingate anaerobic test, the rowers recruited nine muscles for Synergy #1, compared to only seven muscles recruited by the untrained subjects. We hypothesized that the ability to adjust the muscle activation level following high demands of Wingate test is the distinguishing factor of rowers and untrained subjects.

The main limitation of this study is we did not include blood lactate collection, and thus we could not developed energy profile following calculations by Beneke et al., (2002 and 2004). Although Wingate anaerobic test is a valid and reliable test (Riechman et al., 2002), non-invasive and easily applied during field testing, it only assumed that anaerobic capacity is fully exhausted due to its intensity and duration (Mandic et al., 2004). Therefore, Wingate test is only a reflection of anaerobic capacity rather than the exact quantification of anaerobic metabolism derived from phosphagens and alactic energy pathways.

As an initial attempt to study the association of muscle synergies to rowing economy, we succeeded to find the relationship in both untrained subjects and collegiate rowers. Therefore, from this finding, we conclude that training to enhance the muscle synergies (particularly Synergy #1) could improve the rowing economy during anaerobic test. The rowers could apply the results from this study to reduce the energy cost especially during the start of the rowing race, where anaerobic metabolism is predominant.

TABLES

Table 6.1: Rowing performance and physiological variables of untrained subjects and collegiate rowers during Wingate test.

	Untrained	Rowers	*p* value
Peak power (Watts)	622.78 (106)	732 (53.6)	**0.003**
Mean power (Watts)	469.88 (61.5)	584.97 (95.57)	**0.001**
Stroke length (mps)	7.06 (0.81)	8 (0.61)	**0.003**
Stroke rate (spm)	44.78 (5.02)	48.22 (7.64)	0.111
Distance covered (m)	175.44 (25.98)	241.89 (25.65)	**0.001**
Max heart rate (bpm)	181.33 (5.3)	186 (7.1)	**0.047**
$VO_{2\ max}$ (L/min)	3.79 (0.7)	5.01 (1.4)	**0.017**
$VO_{2\ max}$ (L/kg/min)	49.9 (12.9)	62.33 (16.9)	**0.032**
AT (% of VO_2)	40.56 (17.31)	42.67 (16.1)	0.384
$Energy_{\ expenditure}$ (kJ/min)	55.4 (12)	76.37 (9.6)	**0.001**
Economy (%)	11.73 (1.6)	13.31 (2.5)	**0.044**

spm, strokes per minute, mps, meter per stroke; m, meter; bpm, beats per minute; VO_2, oxygen consumption; L, liter; min, minute; kg, kilogram; AT, anaerobic threshold; kJ, kilojoule; %, percentage.

Table 6.2: Cronbach α for each muscle synergy for both groups.

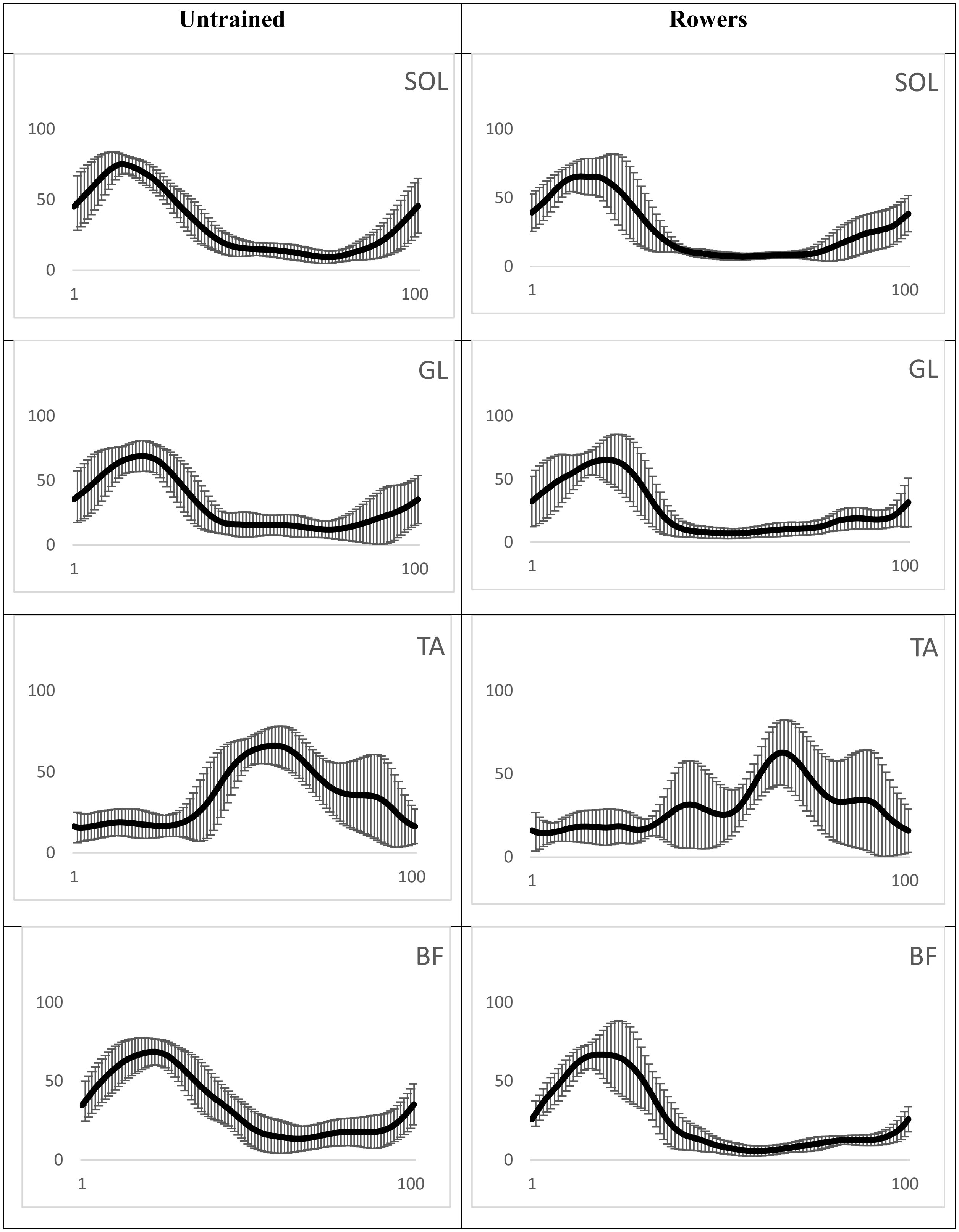
Cronbach α	Untrained	Rowers
Synergy #1	0.951 (0.03)	0.935 (0.03)
Synergy #2	0.876 (0.14)	0.869 (0.1)
Synergy #3	0.726 (0.19)	0.711 (0.19)

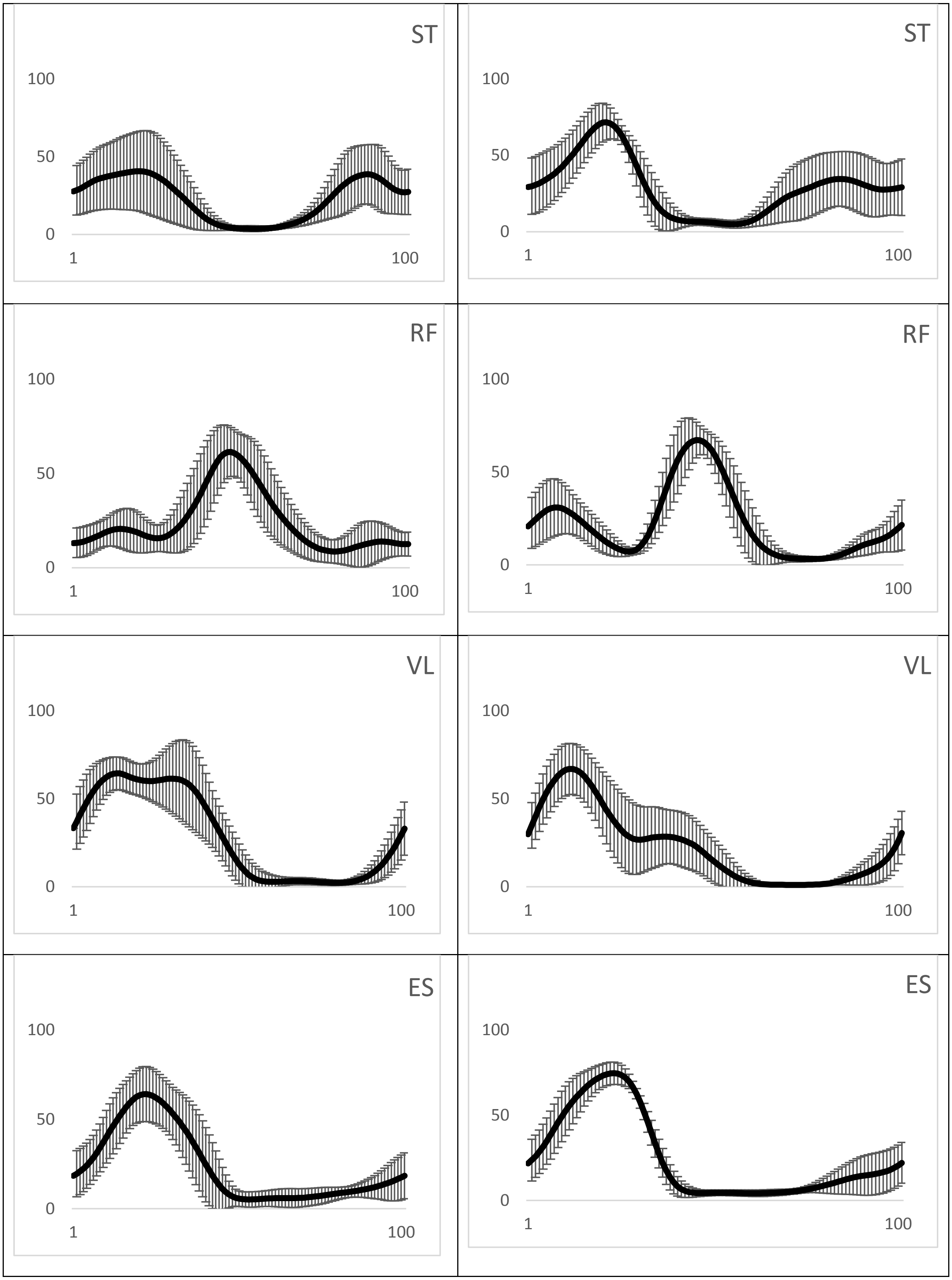
Table 6.3: Multivariate linear regression was used to investigate the relationship between variables to peak power ($R^2 = 0.884$) for untrained subjects during Wingate test

	β	***p*-value**	***sr^2***	***f^2***
Mean power output	0.705	**0.007**	**0.32**	**0.13**
Rowing economy	-0.588	**0.032**	**0.15**	**0.28**
Heart rate $_{max}$	0.359	0.129		
$VO_{2\ max}$	0.053	0.781		

$VO_{2\ max}$, maximal oxygen consumption; β, standardized beta coefficient; sr^2, semi partial coefficients; f^2, effect size.

FIGURES

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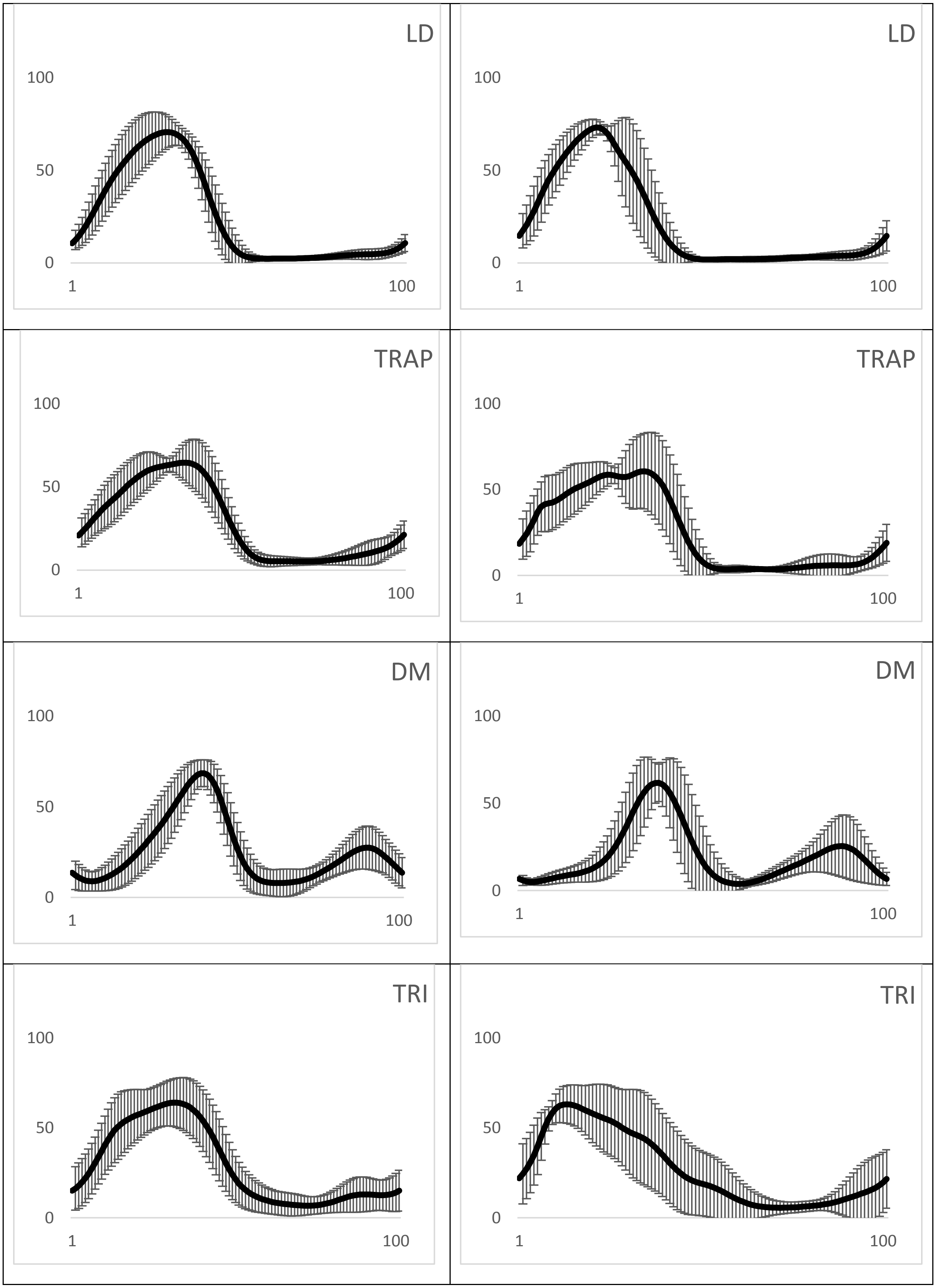
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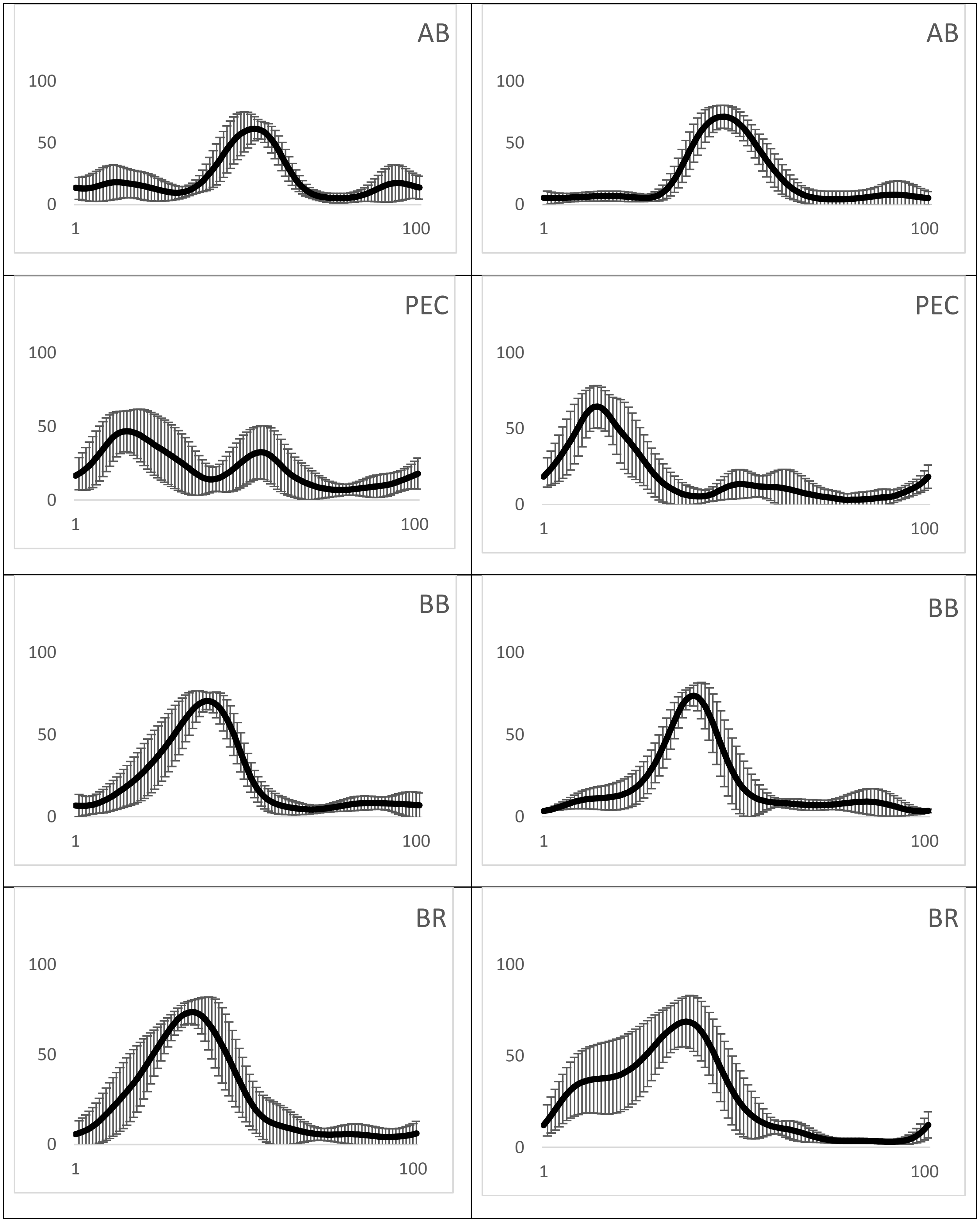


Figure 6.1: Ensemble averages of normalized EMG patterns of the 16 recorded muscles during Wingate rowing test for untrained subjects and collegiate rowers. Rowing phase from 0% to 50% indicates drive phase and from 51% to 100% signifies the recovery phase. Muscle abbreviations are described in text (Methods section).

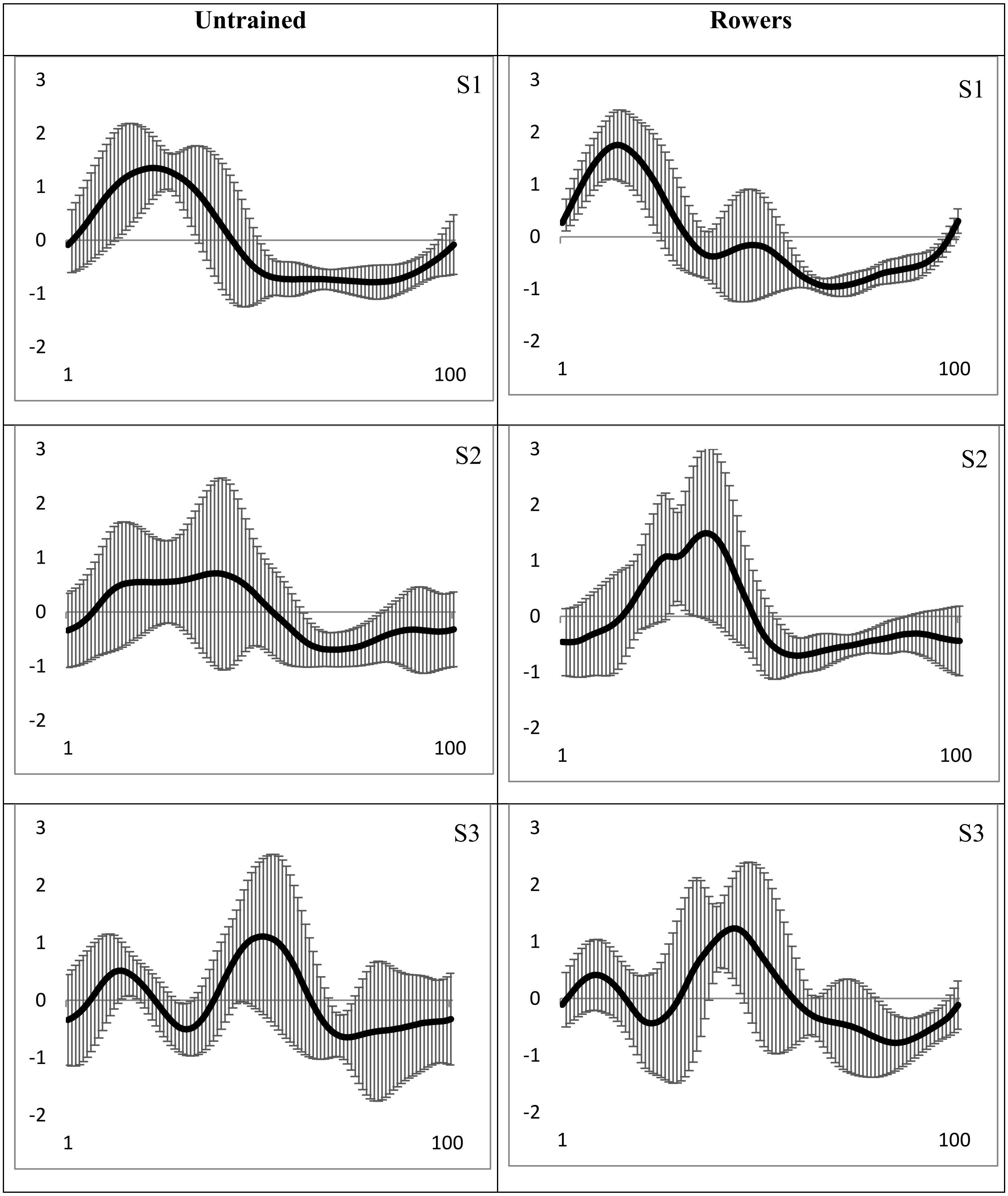


Figure 6.2: Synergy activation coefficients and muscle synergy vectors depicted for Wingate rowing test of untrained subjects and collegiate rowers. Synergy activation coefficients were averaged across the subjects for the three extracted synergies and expressed as a function of percentage of the rowing cycle (0% to 50% represent drive phase and 51% to 100% represents recovery phase).

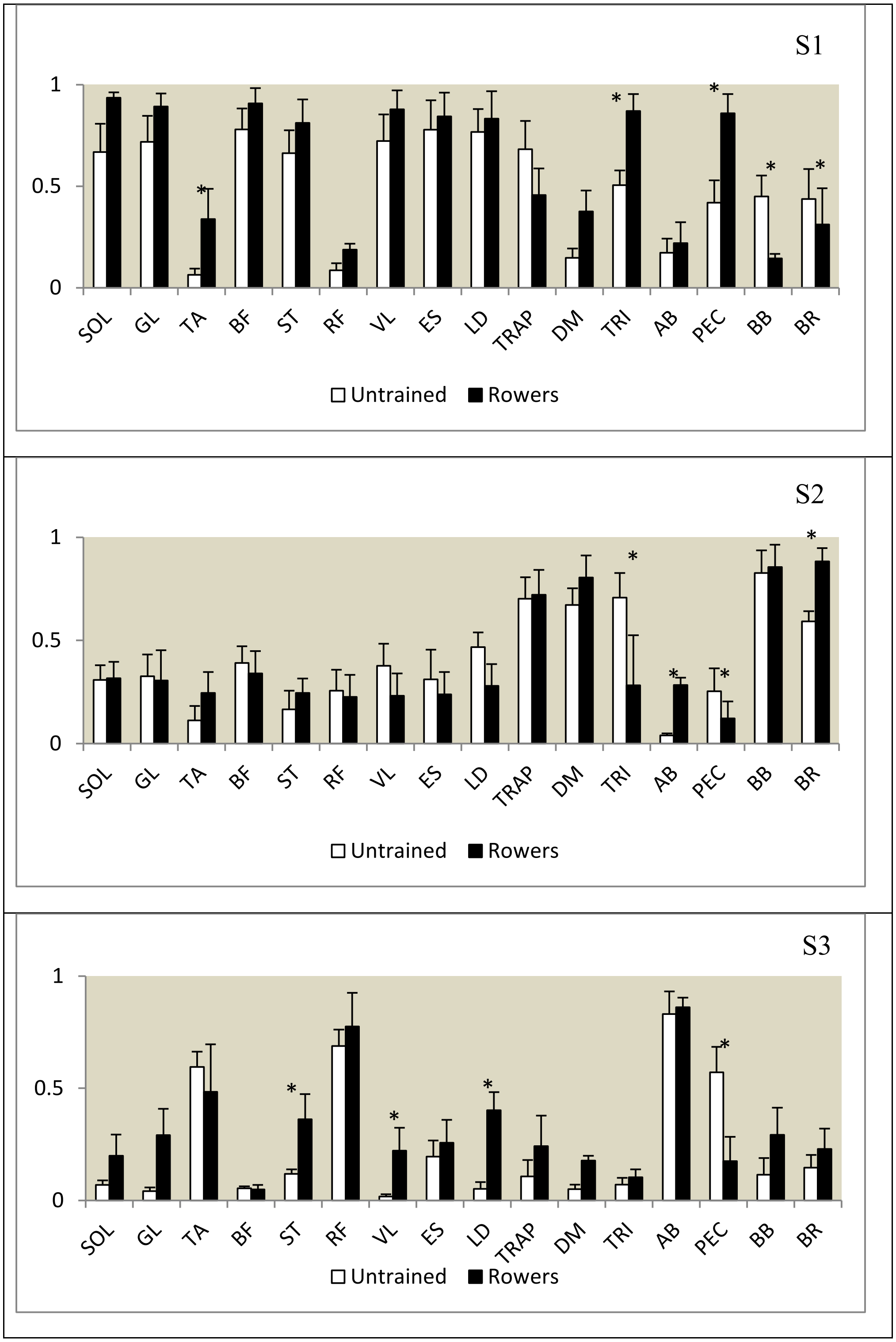


Figure 6.3: Muscle synergy vectors depicted for Wingate rowing test of untrained subjects and collegiate rowers. The muscle synergy vectors were averaged across the subjects for the three extracted synergies. Individual muscle weightings are depicted for each muscle within each synergy. Asterisks indicate significant difference of muscle loadings between rowing conditions ($p < 0.05$).

Chapter 7

MUSCLE SYNERGY DURING VO_{2max} TEST FOR ROWERS AND UNTRAINED SUBJECTS

7.1 Abstract

Introduction: The purpose of this study is to evaluate the muscle synergies during incremental volitional $VO_{2\,max}$ test. High aerobic capacity is one of the key factors to determine rowing success while muscle synergy is a strategy of central nervous system (CNS) to improve redundancy at musculoskeletal level. We hypothesized that muscle synergy is associated with rowing economy and eventually impacts the rowing performance of collegiate rowers and untrained subjects.

Method: Ten male collegiate rowers and ten physically active males were recruited. Muscle synergies were extracted from 16 rowing specific muscles using principal component analysis with varimax rotation. Incremental ramp $VO_{2\,max}$ ramp test was performed on Concept 2 SE. Rowing performance, kinematic and physiological variables were analyzed.

Results: Rowers exerted higher power output, more energy expenditure and better rowing economy compared to untrained subjects. Rowers tend to row slower with longer strokes compared to the untrained subjects. Three muscle synergies with high indices of pattern similarity were extracted in both groups. Significant association was found between Synergy #1 and rowing economy. Multiple linear regression revealed that rowing economy is not an important predictor of rowing performance during $VO_{2\,max}$ test.

Discussion: Although rowing economy is highly associated to muscle synergies (especially Synergy #1) for both groups of subjects, it is not the predictor of rowing performance for $VO_{2\,max}$

test. The findings of this study showed that muscle synergies is robust during aerobic-dominant exercise for collegiate rowers and physically active males. As rowers have to sustain high aerobic intensity during a rowing event, rowers and coaches could utilized our findings by focusing training to enhance the coordination (particularly the muscles that contributed to Synergy #1), which will enhance their rowing economy.

7.2 Introduction

Rowing races typically begin with a burst of intense anaerobic capacity. Next, effort at 90-95% of maximum aerobic capacity is sustained until the finish line, which is at least 4 minutes (Huntsman et al., 2011). The ability to sustain high aerobic capacity while exerting maximum stroke power is the most impressive physiological character in a rower (Hagerman et al., 1978). In line with this thought, a number of studies proved that $VO_{2\ max}$ is one of the most important predictor of competition success (Cosgrove et al., 1999; Hagerman et al., 1984)

One would expect metabolic and ventilator changes to be associated with muscular changes (Hug et al., 2003). Linear regression analyses showed that muscle activation patterns are associated with metabolic cost during inclined walking (Slider et al., 2012) and typical ground walking for young adults and elderly (Hortobagyi et al., 2011). It was further suggested that the changes in motor unit recruitment, muscle perfusion, neuromuscular fatigue due to changes in exercise intensity could affect the muscle coordination pattern (Wakeling and Horn, 2009).

Since rowing involves about 70% of muscle mass (Maestu et al., 2005; Shepard et al., 1998), the endeavor of reducing metabolic cost through sufficient muscle coordination is crucial. As muscle synergy is a strategy of central nervous system (CNS) to reduce redundancy at musculoskeletal system (Bernstein, 1967), it is compelling to assume that synergies could also reduce the metabolic cost. However, to the best of our knowledge, there are no studies that attempt to associate muscle synergies and aerobic capacity during rowing.

Therefore, we aim to evaluate the muscle synergies during incremental volitional $VO_{2\ max}$ test. We hypothesized that the muscle synergies will affect the energy cost during the test and eventually further impact the rowing economy of collegiate rowers and untrained subjects.

7.3 Results

Rowing variables

All subjects completed the test at their maximum oxygen consumption as they met all the $VO_{2\ max}$ requirement. As shown on Table 7.1, the rowers covered more distance and exerted higher power output compared to the untrained subjects despite their similar level of relative $VO_{2\ max}$ (oxygen consumption in L/kg/min). When body weight was not considered as in absolute $VO_{2\ max}$ (oxygen consumption in L/min), the rowers showed better level of fitness with ability to retain higher value of maximal heart rate and exerted more energy with better rowing economy. Contrary to the results from our previous work on 6 min maximal rowing and Wingate anaerobic test, both groups utilized different rowing strategy during $VO_{2\ max}$ test. The rowers tend to row slower with longer strokes while the untrained subjects row faster at shorter strokes. The stroke rate and length were the average of the entire session, which included the lowest level at 25W up to volitional exhaustion achieved (375W for rowers; 325W for untrained)

EMG patterns

The ensemble averages of the EMG linear envelopes for 16 muscles investigated for both groups are presented in Figure 6.1. All muscles showed high inter-group index of similarity with Pearson *r* ranging from 0.719 to 0.98 except for TA (r = 0.237).

Muscle synergies

Both groups have acceptable KMO statistics (untrained: 0.605 ± 0.04; rowers: 0.601 ± 0.03) which means data were adequate for PCA. Therefore PCA with varimax rotation 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 groups. Three synergies explained 90% of VAF for both groups as shown on Figure 7.2. The indices of similarity for synergies waveform between groups were acceptable for all the synergies (Synergy #1 = 0.97; Synergy #2 = 0.798; and Synergy #3 = 0.703). High Cronbach's α value showed the repeatability of data (Table 7.2). Muscles with factor loading greater than 0.55 (Comrey, & Lee, 1992) were considered as contributors for a specific synergy. Muscle loadings and synergies coefficients were depicted in Figures 7.3 and 7.4.

For rowers, Synergy #1 consisted of the power house muscles such as SOL, GL, BF, ST, VL, ES, LD, TRI and PEC which dominated the first half of the drive phase. Next, the force generated by these muscles were transmitted to Synergy #2 which comprised of upper arm muscles such as TRAP, DM, BB and BR which activated at the second half of drive phase. Meanwhile Synergy #3 was contributed by the movement refiner and force distributor muscles (i.e TA, RF and AB) and occurred during the transition of rowing phases. Surprisingly, the untrained subjects showed almost similar pattern in terms of synergies temporal aspect and the muscles loadings. The only exception was the untrained subjects preferred to recruit TRAP for Synergy #1 rather than TRI by the rowers.

Muscle synergies and rowing economy

To test our hypothesis that muscle synergies could improve rowing performance, the effect of muscle loadings of Synergy #1 on rowing economy was tested using analysis of variance (ANOVA) adopting method by Wakeling et al. (2010). As Synergy #1 accounted for about half of total VAF synergies (50.43 ± 4.3 for untrained; 50.48 ± 5.9 for rowers), 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 (untrained and rowers, $p = 0.001$). Post hoc revealed significant association of each muscle loadings to rowing economy for untrained subjects ($p < 0.0055$), and rowers ($p < 0.006$). As we want to evaluate the association of all muscle loadings to rowing economy (not a pairwise comparison between each muscle loading and rowing economy), post hoc results were not studied further.

Next, data were further analyzed using a direct-entry (standard) multiple linear regression (MLR) analysis to predict the variables effect on rowing performance. Multivariate associations are generally superior to univariate correlations because they better capture the full network of relations among predictors and criteria (Tabachnick, & Fidel, 2007). Maximal heart rate, mean power output and rowing economy served as predictors. Maximal oxygen consumption (absolute VO_2) was utilized as the criterion of rowing performance.

The omnibus test of MLR failed to detect any significance ($p > 0.05$) of the predictors on rowing performance for both groups (Sig. F change: untrained = 0.317, rowers = 0.108). Therefore, no further analysis was conducted.

7.4 Discussion

Our results showed that there is an association of muscle synergies, in particular Synergy #1, to rowing economy during incremental $VO_{2\ max}$ test for both untrained subjects and collegiate rowers. However, rowing economy is not one of the predictors of rowing performance during aerobic capacity test. The rowers showed different rowing strokes compared to the untrained subjects, which was slower and longer. It should be noted that the stroke rate and length measurements was averaged from whole test where the subjects have to gain 25W of power output until volitional exhaustion. As stroke rate was not restricted, the subjects managed to self-pace themselves to achieve varying power output as the test proceed. This strategy had lower metabolic cost than imposed work rate (Sparrow et al., 1987). Despite having almost similar synergies pattern, the rowers utilized different rowing strategy. They preferred to row slower with longer stroke length compared to the untrained subjects. Therefore, from muscle synergies perspective we did not manage to explain the tendency of choosing longer-slower type of stroke by the rowers. Rather, longer-slower movement indicates typical training-adaptation motor learning which increase the stability of the movement while attempting to reduce energy wasted. Rowers were capable to manipulate and adjust their rowing strokes to fulfill the demand of rowing task efficiently.

$VO_{2\ max}$ test is a reliable test to assess the aerobic capacity (Ingham et al., 2012). By comparing between untrained and rowers group, we observed large similarities of muscle synergies pattern in terms of the synergies activation coefficient (e.g., the temporal profile) and the muscle weightings on each synergy. The only difference of muscle weightings were observed in TRI and TRAP muscles, where the rowers recruited TRI for Synergy #1 and TRAP for Synergy #2, but the untrained subjects recruited the muscles otherwise. Hence, our results showed the robustness of muscle synergies during $VO_{2\ max}$ test (which is predominantly aerobic), across rowers and untrained subjects.

To our knowledge, this study is an initial attempt to associate muscle synergies to rowing economy and further analyzed the robustness of muscle synergies across different physiological demands. As we only recruited physically active males, our results showed that the $VO_{2\ max}$ values of these untrained subjects was comparable to the rowers, hence we reduced the physiological fitness biased across subjects. Compared to previous studies regarding energy expenditure and rowing (Bourdin et al., 2002;), which focused on gross rowing efficiency, we obtained the net value of energy expenditure (by subtracting from the resting values). This further reduced the bias of our results as the rowers typically have lower resting oxygen consumption values compared to the untrained despite having similar maximal oxygen consumption. We also raised concerns regarding rowing economy calculations and definition which are not standardized in previous studies and thus results were hard to interpret. As an example Bourdin et al., (2002) and Lay et al., (2002) defined rowing economy (or interchangeably defined as rowing efficiency in Bourdin et al., (2002)) as power output exerted per oxygen (in liter) consumed. However, Mahler et al., (1994) defined rowing economy as oxygen consumed per power output, while Nevill et al., (2011) assessed oxygen cost of movement by calculating the mean oxygen uptake per power output of submaximal stages. Therefore, we adopted the equation by Sparrow and Newell (1998) which is the amount of energy expended to exert a quantifiable power output. This equation makes more sense as higher economy means more energy was directed towards exerting rowing power.

Although rowing on SE showed larger similarity to on-water (OW) rowing (details in Chapter 3 Introduction) and $VO_{2\ max}$ test is a valid and reliable test for rowers, the findings of this study are somewhat limited to rowing on SE ergometer. As the blood lactate concentration was not measured, energy profile (contribution of phosphagens, alactic and aerobic metabolism) was not possible to quantify.

The findings of this study could further enhance our insights regarding muscle synergies during aerobic activities. As rowers have to sustain high aerobic intensity during a rowing event, rowers and coaches could utilize our findings by focusing training to enhance the synergies (particularly Synergy #1), which will enhance their rowing economy.

TABLES

Table 7.1: Rowing performance and physiological variables of untrained subjects and collegiate rowers during $VO_{2\ max}$ test.

	Untrained	Rowers	*p* value
Total distance (m)	1600.33 (352.3)	2109.22 (228.35)	**0.01**
Power (Watts)	205.71 (25.7)	213.33 (19.6)	**0.01**
Stroke rate (spm)	33.79 (4.5)	27.23 (0.9)	**0.01**
Stroke length (mps)	6.78 (0.92)	10.13 (1.3)	**0.01**
$VO_{2\ max}$ (L/min)	4.65 (0.9)	5.36 (0.9)	**0.04**
$VO_{2\ max}$ (kg/L/min)	63.33 (9.7)	67.78 (15.2)	0.21
Heart rate $_{max}$ (bpm)	177.78 (4)	183.11 (7.5)	**0.02**
Energy $_{expenditure}$ (kJ/min)	85.69 (13.9)	106.91 (18)	**0.01**
Economy (%)	42.01 (7.6)	50.24 (8.4)	**0.01**

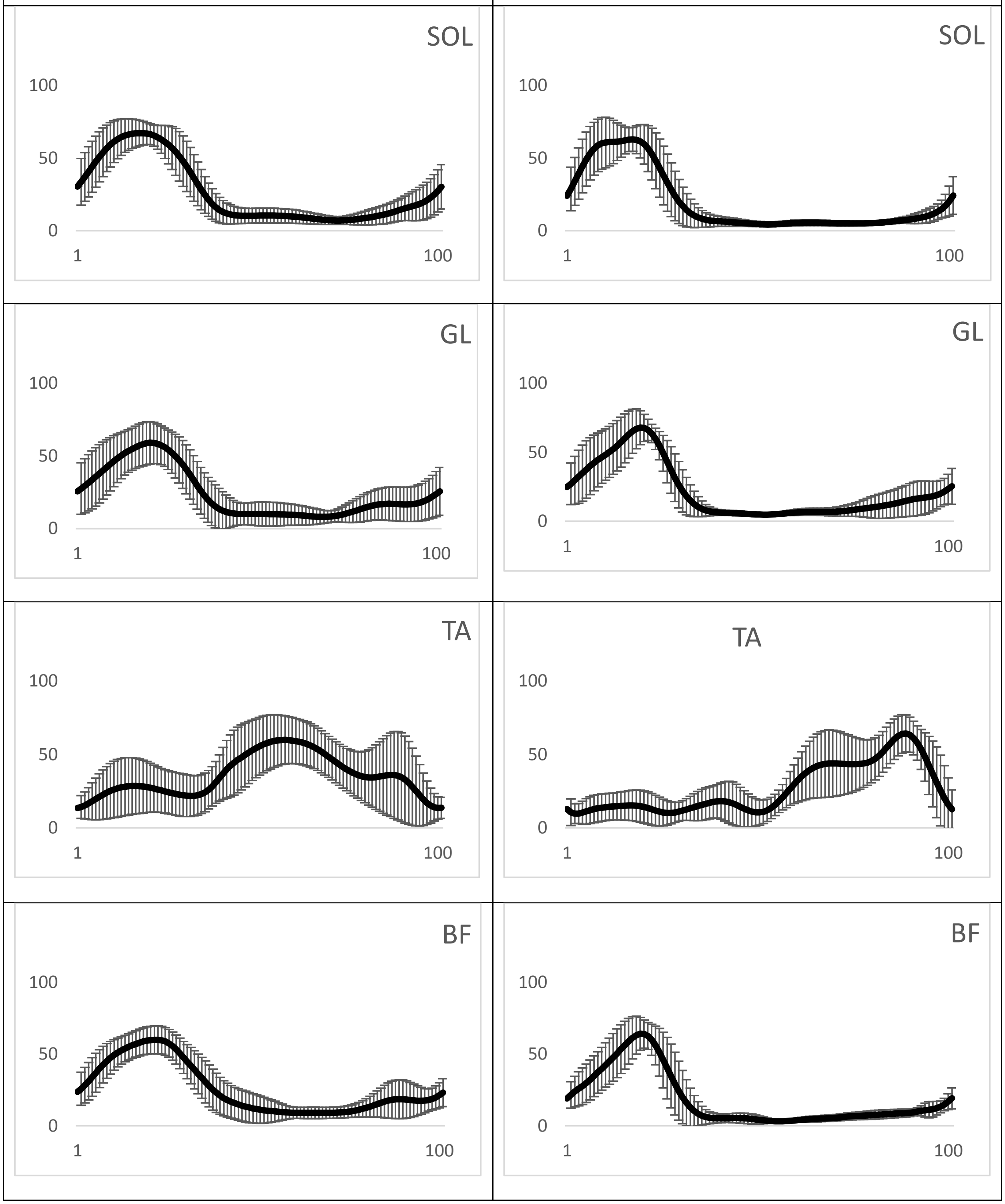
m, meter; spm, strokes per minute, mps, meter per stroke; VO_2, oxygen consumption; L, liter; min, minute; kg, kilogram; bpm, beats per minute; kJ, kilojoule; %, percentage.

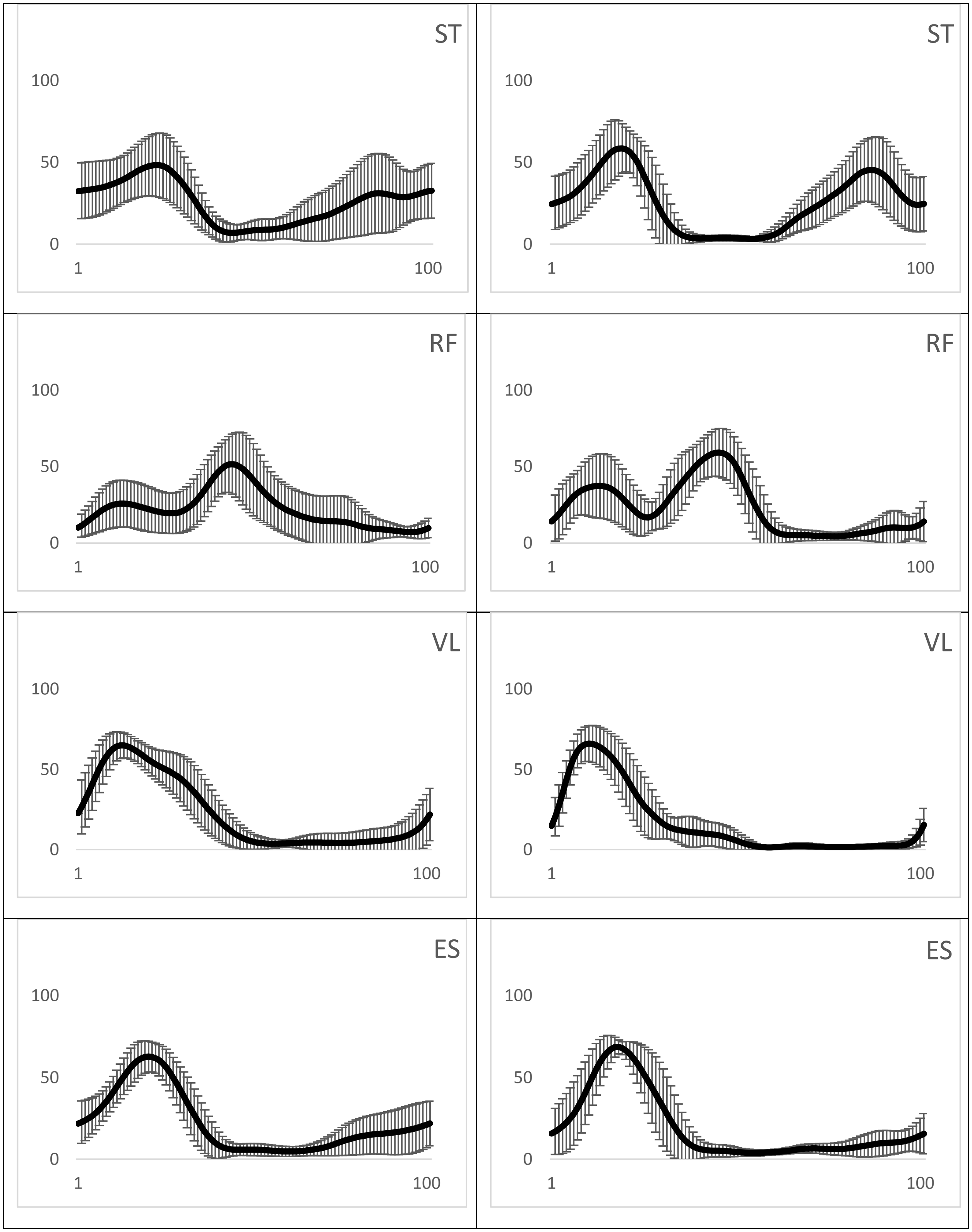
Table 7.2: Cronbach's α for synergies extracted from untrained and rowers groups.

Cronbach's α	Untrained	Rowers
Synergy #1	0.93 (0.05)	0.956 (0.02)
Synergy #2	0.921 (0.05)	0.792 (0.18)
Synergy #3	0.791 (0.13)	0.73 (0.19)

FIGURES

Untrained	Rowers

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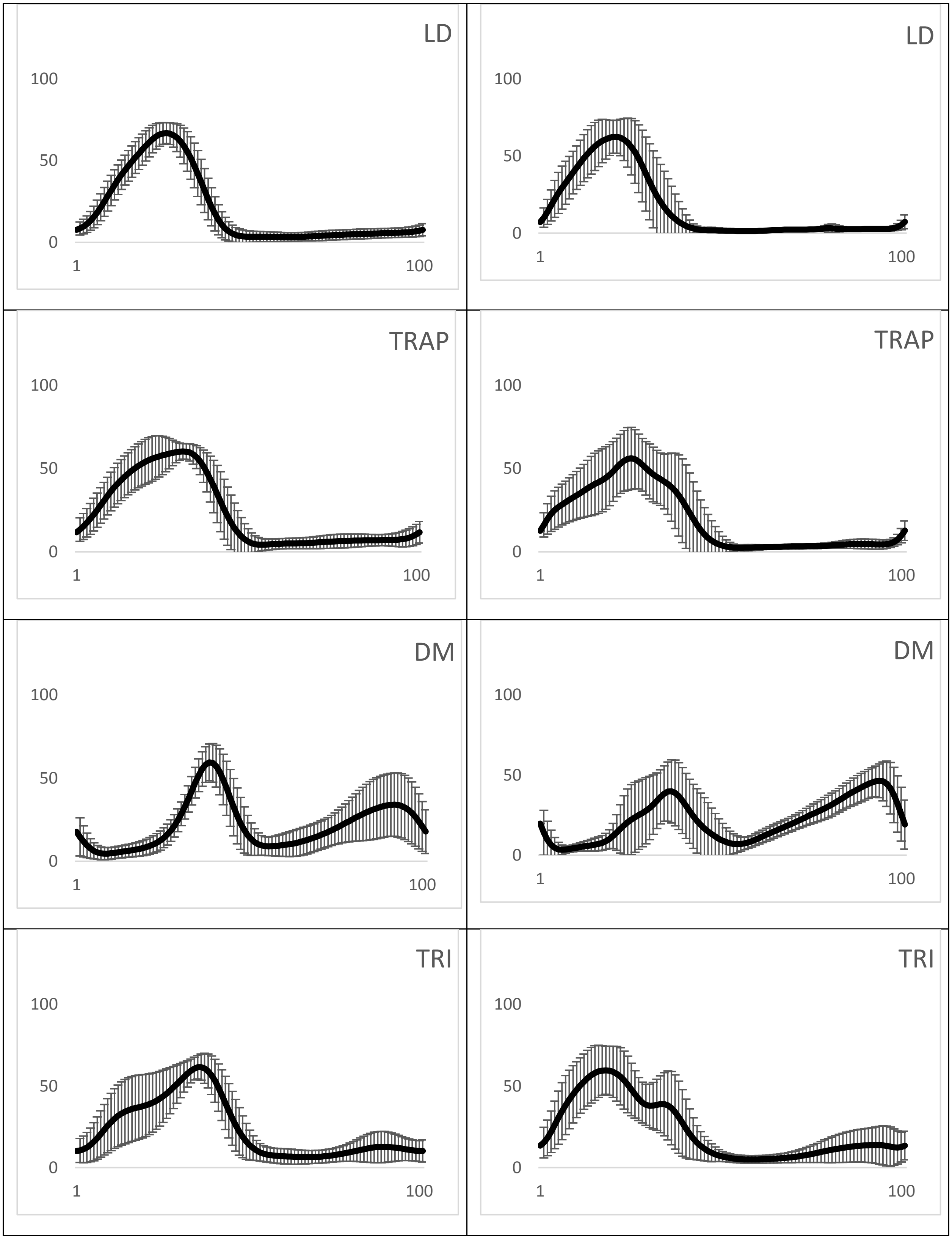
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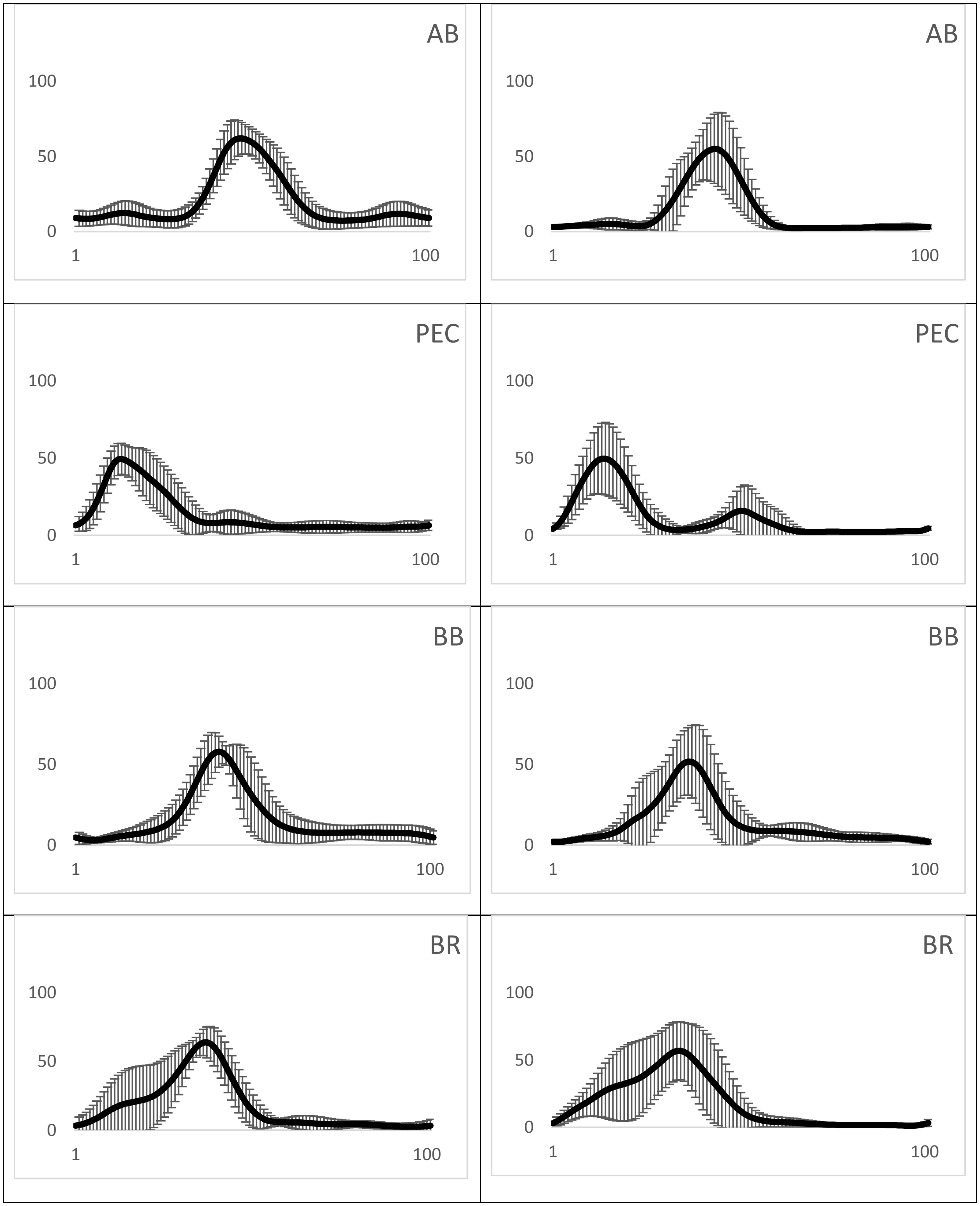


Figure 7.1: Ensemble averages of normalized EMG patterns of the 16 recorded muscles during $VO_{2\,max}$ for untrained subjects and collegiate rowers. Rowing phase from 0% to 50% indicates drive phase and from 51% to 100% signifies the recovery phase. Muscle abbreviations are described in text (Methods section).

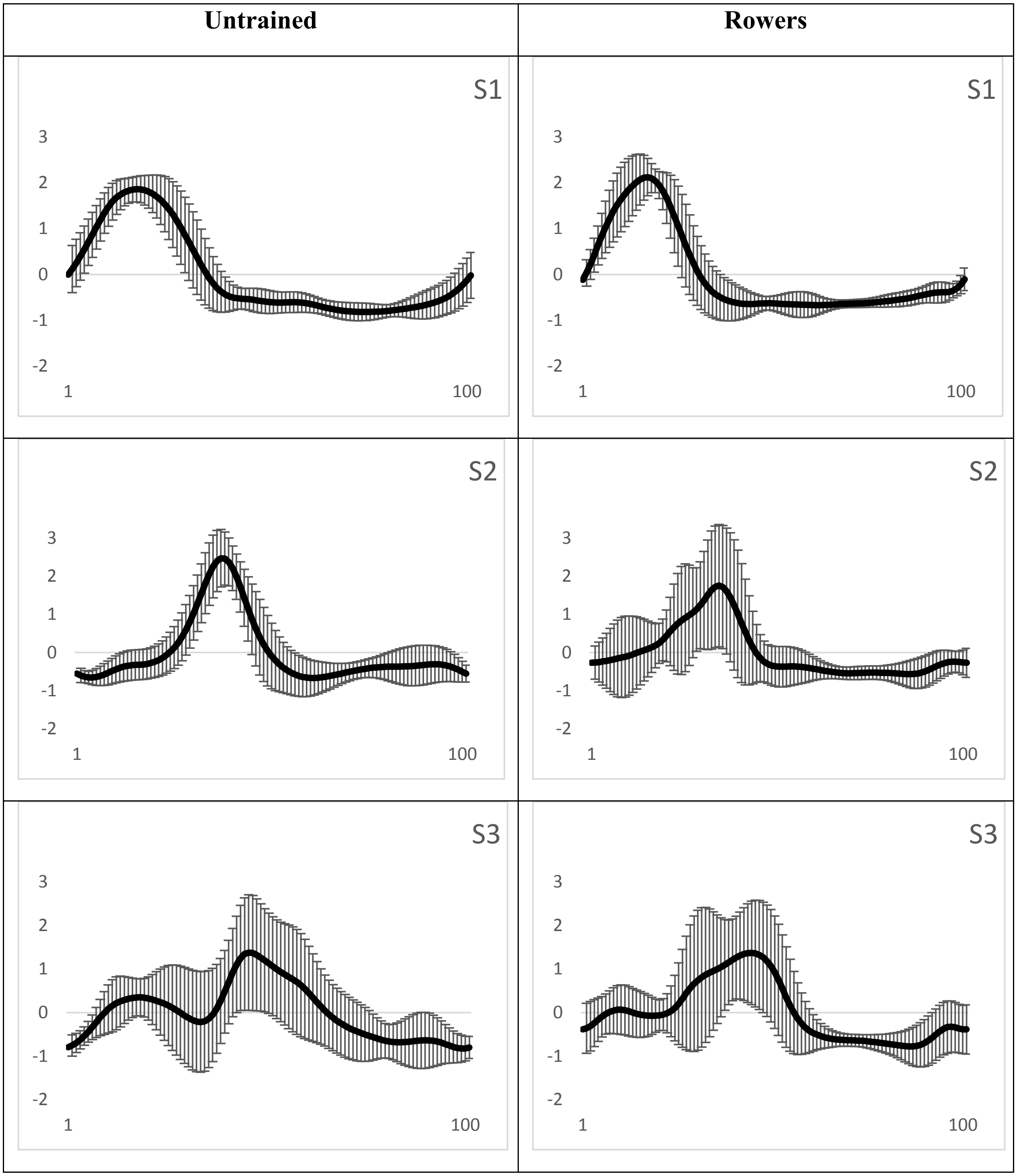


Figure 7.2: Synergy activation coefficients and muscle synergy vectors depicted for $VO_{2\ max}$ test of untrained subjects and collegiate rowers. Synergy activation coefficients were averaged across the subjects for the three extracted synergies and expressed as a function of percentage of the rowing cycle (0% to 50% represent drive phase and 51% to 100% represents recovery phase).

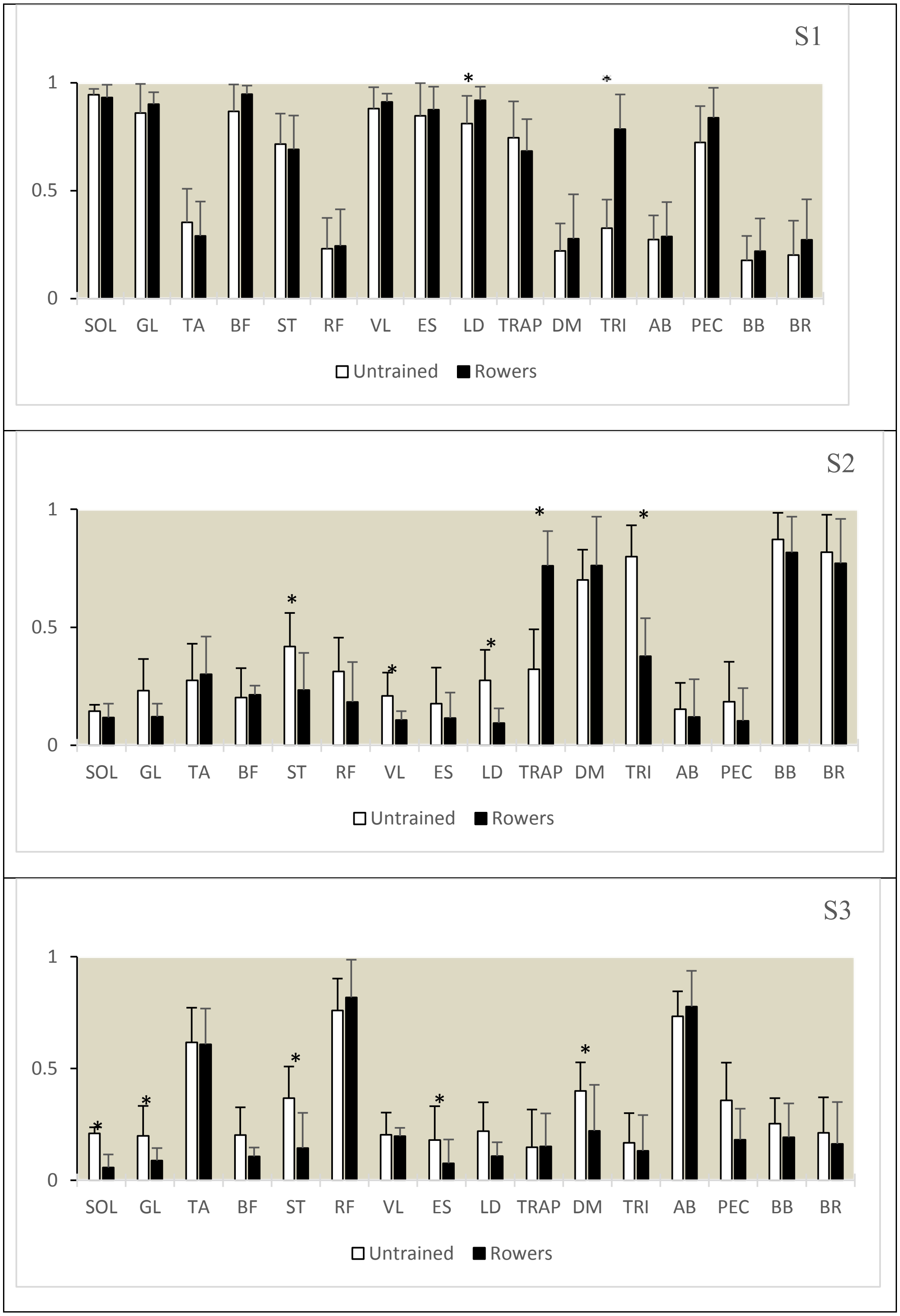


Figure 7.3: Muscle synergy vectors depicted for $VO_{2\ max}$ test of untrained subjects and collegiate rowers. The muscle synergy vectors were averaged across the subjects for the three extracted synergies. Individual muscle weightings are depicted for each muscle within each synergy. Asterisks indicate significant difference of muscle loadings between rowing conditions ($p < 0.05$).

Chapter 8

MUSCLE SYNERGY DURING 6 MIN MAXIMAL ROWING FOR ROWERS AND UNTRAINED SUBJECTS

8.1 Abstract

Introduction: The purpose of this study is to examine the muscle synergies during 6 min maximal rowing on sliding ergometer (SE) for untrained subjects and collegiate rowers. The study of muscle synergies and its association to energy capacity is crucial for rowing as huge muscle mass are recruited during high intensity exercise. As a strategy of central nervous system (CNS) to improve redundancy at musculoskeletal level, we hypothesized that muscle synergy is associated with rowing economy and eventually impact on the rowing performance.

Method: Ten collegiate rowers and ten physically active males were recruited. Muscle synergies were extracted from 16 rowing specific muscles using principal component analysis with varimax rotation. Subjects were told to cover as much distance during 6min rowing test on Concept 2 SE with imposed stroke rate. Rowing performance, kinematic and physiological variables were analyzed.

Results: Despite showing equivalent level of fitness on physiological variables (i.e absolute and relative values of $VO_{2\ max}$), rowers managed to cover more distance, expended more energy and power output at better rowing economy compared to untrained subjects. Three muscle synergies with high indices of pattern similarity were extracted in both groups. Significant association was found between Synergy #1 and rowing economy. Multiple linear regression revealed that rowing economy is inversely related to rowing performance of untrained subjects only.

Discussion: Although rowing economy is highly associated with muscle synergies (especially Synergy #1) for both groups of subjects, it is not the predictor of rowing performance for rowers. The findings of this study showed that muscle synergies is robust across level of expertise during 6min maximal rowing.

8.2 Introduction

Rowing is a sport placing high demands on both the anaerobic and aerobic energy systems, as 70% of total muscle mass (Maestu et al., 2005) have to perform at high power output (350–400 W) (Kokalas et al., 2004) for about 6 min during a typical 2-km rowing competition (Hagerman 1984). Realizing the importance, training programs in rowing seek to find the right balance between developing muscle power, maximizing aerobic and anaerobic performance (Fukuda et al., 2010).

Green and Patla (1992) have proposed that the accumulation of metabolites could raise inhibitory feedback signals from working muscles, which would result in a reduction in neural drive. Following the concomitant changes in global surface electromyography (SEMG) energy and oxygen uptake in exercise, Hug et al., (2004) agreed with the existence of adaptive mechanisms originating in contracting muscles which function to minimize the recruitment of motor units at a given oxygen uptake. In addition to muscle activation variables in previous studies, Figuerdo et al., (2013) observed that swimming intensity also induced changes in stroke mechanics suggesting coordinative and metabolic boundary between moderate and heavy intensity domains during exercise.

Given that there are many behavioral options for the motor system in meeting task demands, optimal metabolic and energy criteria may offer an intriguing alternative in selecting the most adaptive coordination (Galna et al., 2010). It was observed that the refinement of coordination across a range of cyclic motor tasks (i.e cycling, rowing) is an indicator of movement economy (Lay et al., 2005; Sparrow and Newell, 1998; Sparrow et al., 2005). Results of those studies showed that changes in coordination are consistent with low metabolic energy demands.

Nevertheless, these studies only investigate the kinematic coordination and not the muscle synergies. As muscle synergy is a mechanism of central nervous system (CNS) to reduce the degree of freedom at musculoskeletal level, we hypothesized that it would indirectly reduce the energy cost during task demand.

Hence, the study of muscle synergies and its association to energy capacity is crucial for rowing where large muscle mass is being recruited during high intensity exercise. Therefore, we aim to study the muscle synergies during 6 min maximal rowing on sliding ergometer (SE) for untrained subjects and collegiate rowers. We hypothesized that the interplay between aerobic and anaerobic metabolism could affect the synergies adopted by both groups which will further reveal their rowing economy and performance.

8.3 Results

Rowing variables

As expected, rowers covered more distance, achieved higher maximal heart rate value and exerted higher power output over the course of 6 min maximal rowing test on slides ergometer (SE) (Table 8.1). The rowers tend to row slower at longer strokes compared to the untrained groups. Despite being not specifically trained for rowing, the untrained groups showed comparable level of aerobic fitness capacity to rowers. However, the advantage of years training in rowing prevailed as the rowers were able to exert more energy and better rowing economy compared to the untrained subjects.

EMG patterns

The ensemble averages of the EMG linear envelopes for 16 muscles investigated from untrained and rowers are presented in Figure 8.1. All muscles showed high inter-group index of similarity with Pearson r ranging from 0.802 to 0.98 (except for TA, $r = 0.445$).

Muscle synergies

Both groups have acceptable KMO statistics (untrained: 0.602 ± 0.04; rowers: 0.619 ± 0.06) which means data were adequate for PCA. Therefore PCA with varimax rotation 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 groups. Three synergies explained 90% of VAF for both groups as shown on Figure 8.2. The indices of similarity for synergies waveform between groups were acceptable for all the synergies (Synergy #1 = 0.967; Synergy #2 = 0.98; and Synergy #3 = 0.539). High Cronbach's α value showed the repeatability of data (Table 8.2). Muscles with factor loading greater than 0.55 (Comrey, & Lee, 1992) were considered as contributors for a specific synergy. Muscle loadings and synergies coefficients were depicted in Figures 8.3 and 8.4.

The rowers recruited the power house muscles (SOL, GL, BF, ST, VL, ES, LD, TRI, PEC) for Synergy #1 during first part of drive phase. Next, the force generated by these muscles was further transferred to Synergy #2 which consisted of AB, BB and BR. BB and BR are force generator muscles during the second half of the drive phase, while AB was crucial for trunk flexion and transfer the force from hip to chest. Synergy #3 which consisted of TA, TRAP, RF and DM occurred almost simultaneously with Synergy #2. However, the main function of Synergy #3 is to refine the movement during the changing of strokes position.

Meanwhile for the untrained groups, they recruited almost similar muscles with the rowers' Synergy #1, except they preferred TRAP over TRI muscles. This could be the distinguishing factor of rowers and untrained rowing strokes. By emphasizing on TRI muscles during drive phase, the rowers were able to have longer strokes which further improved the follow-through of their strokes. Probably the untrained subjects emphasized on TRAP (e.g middle part) for postural stability and scapular retraction. This further explained the preference of the untrained subjects to recruit DM (e.g for shoulder abduction following scapular retraction by TRAP) for Synergy #2 compared to the rowers who recruited the DM in Synergy #3. The force generated from the Synergy #1 was transferred to Synergy #2 which consisted of upper arm muscles (DM, TRI, BB, BR). Synergy #2 and #3 occurred almost simultaneously during the second half of drive phase. The Synergy #3 consisted of TA, RF and AB functions as movement refiner during changing of rowing phases.

Muscle synergies and rowing economy

To test our hypothesis that muscle synergies could improve rowing performance, the effect of muscle loadings of Synergy #1 on rowing economy was tested using analysis of variance (ANOVA) adopting method by Wakeling et al. (2010). As Synergy #1 accounted for almost half of total VAF synergies (49.96 ± 7.4 for untrained; 50.3 ± 6.1 for rowers), 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 applied 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 (untrained and rowers, $p = 0.001$). Post hoc revealed significance association of each muscle loadings to rowing economy for untrained subjects ($p < 0.0055$), but not all muscle loadings showed significant association to rowers' economy ($p > 0.0055$). As we want to evaluate the association of all muscle loadings to rowing economy (not a pairwise comparison between each muscle loading and rowing economy), post hoc results were not studied further.

Next, data were further analyzed using a direct-entry (standard) multiple regression analysis (MRA) to predict the variables effect on rowing performance. Maximal oxygen consumption ($VO_{2\ max}$), maximal heart rate, mean power output and rowing economy served as predictors. Total rowing distance covered was utilized as the criterion to indicate rowing performance during 6min maximal test. Unfortunately, the omnibus test of MLR failed to detect any significance ($p > 0.05$) of the predictors on rowing performance for both groups (Sig. F change: untrained = 0.814, rowers = 0.392). Therefore, no further analysis was conducted.

8.4 Discussion

The main findings of this study are: 1) Rowers exerted more energy and power output and covered more distance with better rowing economy than untrained subjects, 2) Rowers tend to row slower at longer strokes compared to the untrained group, 3) Three muscle synergies with high indices of similarity for muscle loadings and synergy activation coefficients were extracted from both groups, 4) Muscle synergies are highly associated with rowing economy (especially Synergy #1) for both groups.

In line with Turpin et al., (2011) which is currently the only study focusing on muscle synergies during rowing, our results showed that the level of expertise did not distinguish the synergies characteristic. Rather, the rowers seem to utilize the innate synergies and sharpen the muscle activation levels. Although there was no effect of expertise level on muscle synergies, we observed that the subjects managed to scale their rowing strokes which is related to energy-reducing adaptation (Sparrow et al., 2000, 2007). According to the authors (Sparrow et al., 2007), the subjects initially adopted low-amplitude high-frequency (shorter faster) movement, which was the observed strategy used by the untrained subjects. However, the longer-slower movements appeared to be a characteristic of practice-related adaptation that decreases energy expenditure (Sparrow et al., 200) which was seen in the collegiate rowers. Hence, we concluded that the rowers were able to express better rowing economy due to their rowing strokes strategy.

By recruiting physically active males we reduced the bias on the results as their aerobic capacity is equivalent to the rowers. Therefore, the results can be emphasized on the muscle synergies and its association to rowing economy without being influenced by physiological fitness. To our knowledge, this is the first study that attempts to find the association of muscle synergies and physiological demands during rowing.

The study is limited to rowing performance on SE. In agreement with Bazucchi et al., (2012), direct comparisons of neuromuscular and physiological responses during rowing OW and ergometers are scarce. Although there were a number of similarities between SE and on water rowing (Introduction Chapter 3), a similar study conducted on OW rowing would definitely provide better insights.

As a suggestion to rowers and coaches, by emphasizing on synergies training (especially Synergy #1) will further help to improve rowing economy. Although for beginners, focusing on mean power output would be a better approach to improve the rowing performance.

TABLES

Table 8.1: Rowing performance and physiological variables of untrained subjects and collegiate rowers during 6 min maximal rowing on SE.

	Untrained	Rowers	*p* value
Total distance (m)	1503 (156.47)	1741.1 (47.8)	**0.01**
Power (Watts)	259.11 (44.2)	317.47 (38.1)	**0.01**
Stroke rate (spm)	35.01 (3.6)	30.9 (2.7)	**0.01**
Stroke length (mps)	7.23 (1.0)	9.32 (0.8)	**0.01**
$VO_{2\ max}$ (L/min)	5.02 (1.2)	5.78 (0.7)	0.05
$VO_{2\ max}$ (L/kg/min)	68.1 (12.9)	71.33 (12.2)	0.29
Heart rate $_{max}$ (bpm)	175.8 (5.1)	180.67 (6.9)	**0.04**
Energy $_{expenditure}$ (kJ/min)	73.38 (19.1)	105.9 (13.5)	**0.01**
Economy (%)	28.43 (5.9)	33.57 (4.02)	**0.02**

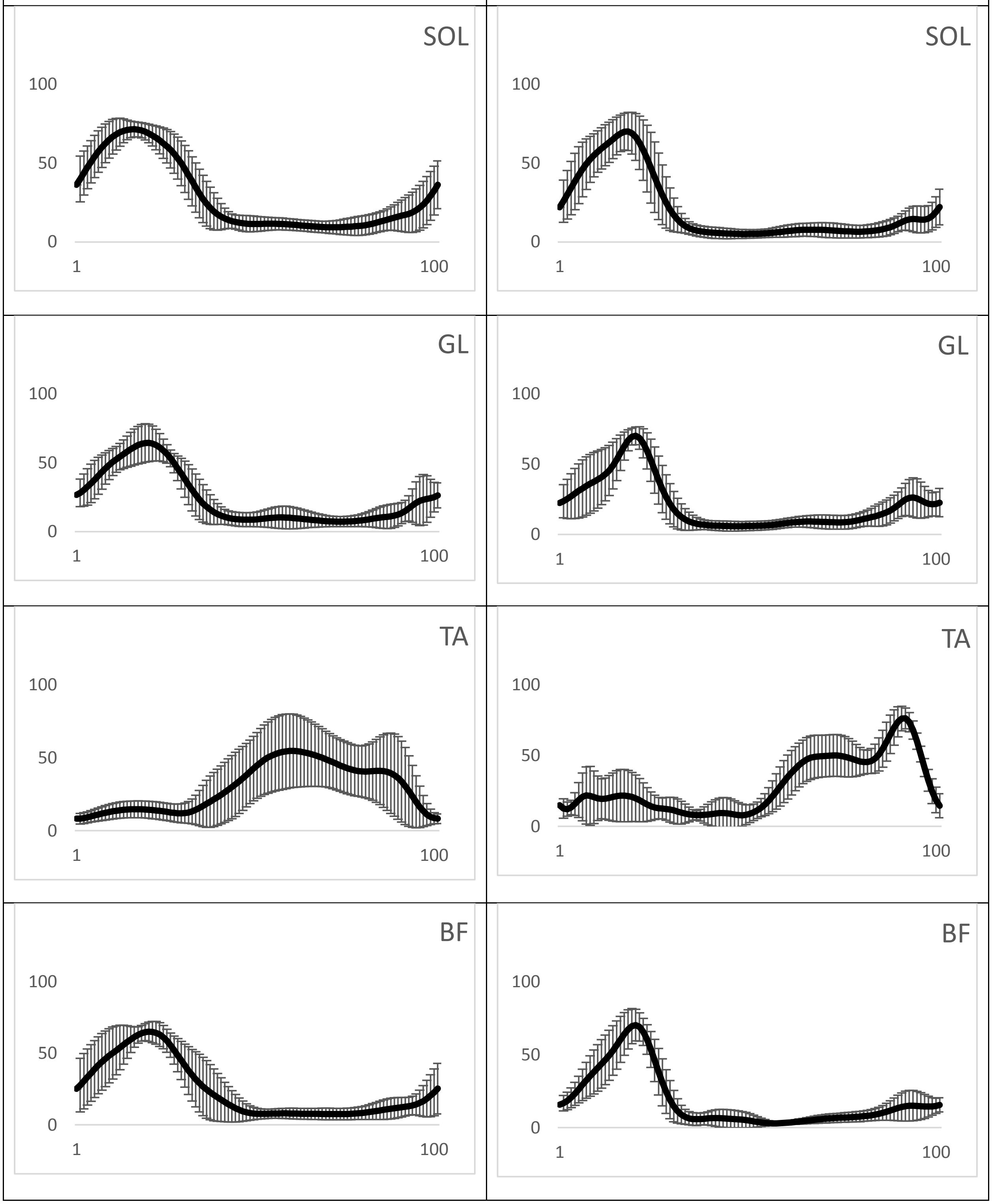
m, meter; spm, strokes per minute, mps, meter per stroke; VO_2, oxygen consumption; L, liter; min, minute; kg, kilogram; bpm, beats per minute; kJ, kilojoule; %, percentage.

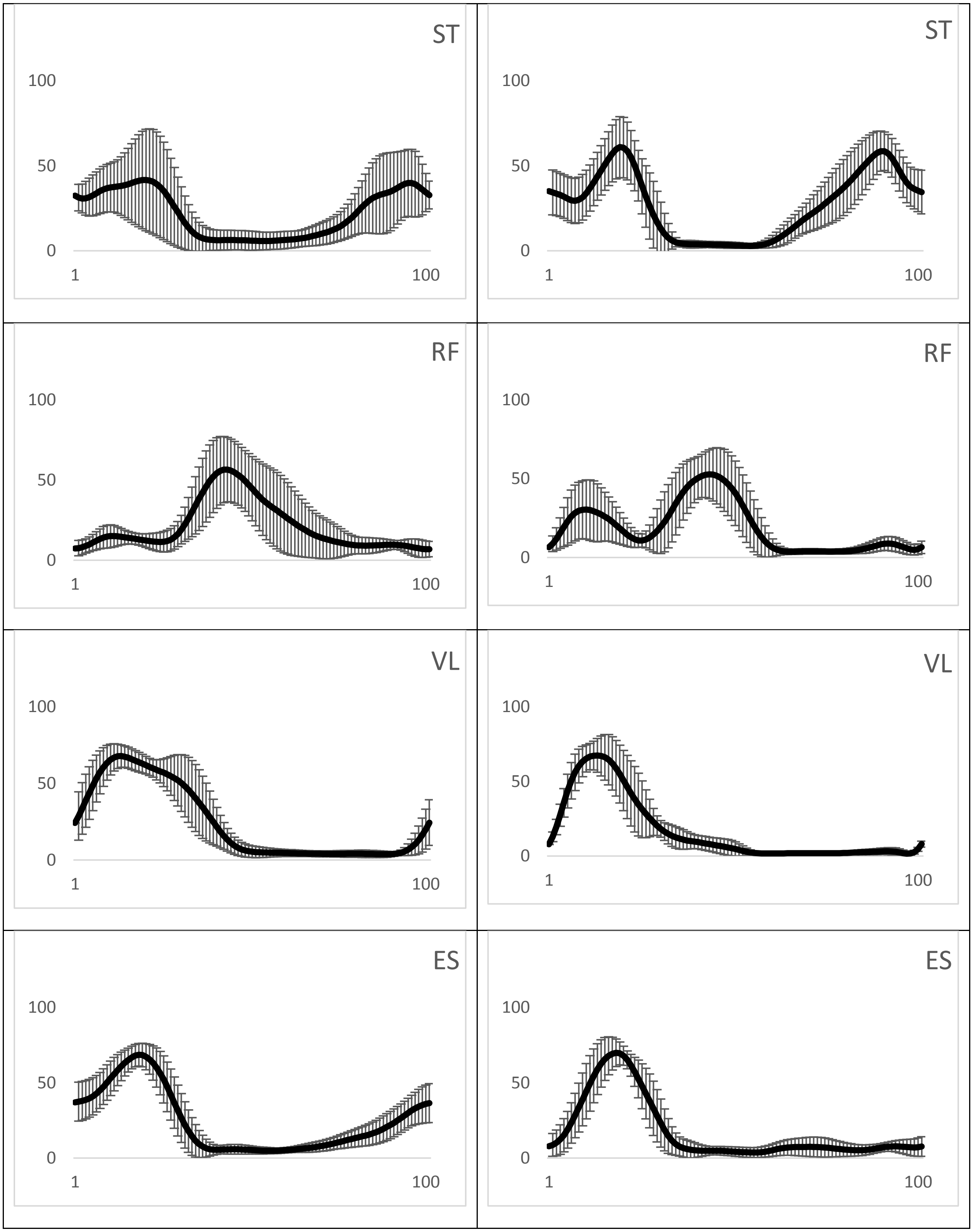
Table 8.2: Cronbach's α for synergies extracted from untrained and rowers groups.

Cronbach's α	Untrained	Rowers
Synergy #1	0.906 (0.11)	0.954 (0.03)
Synergy #2	0.936 (0.18)	0.695 (0.17)
Synergy #3	0.951 (0.13)	0.726 (0.13)

FIGURES

Untrained	Rowers

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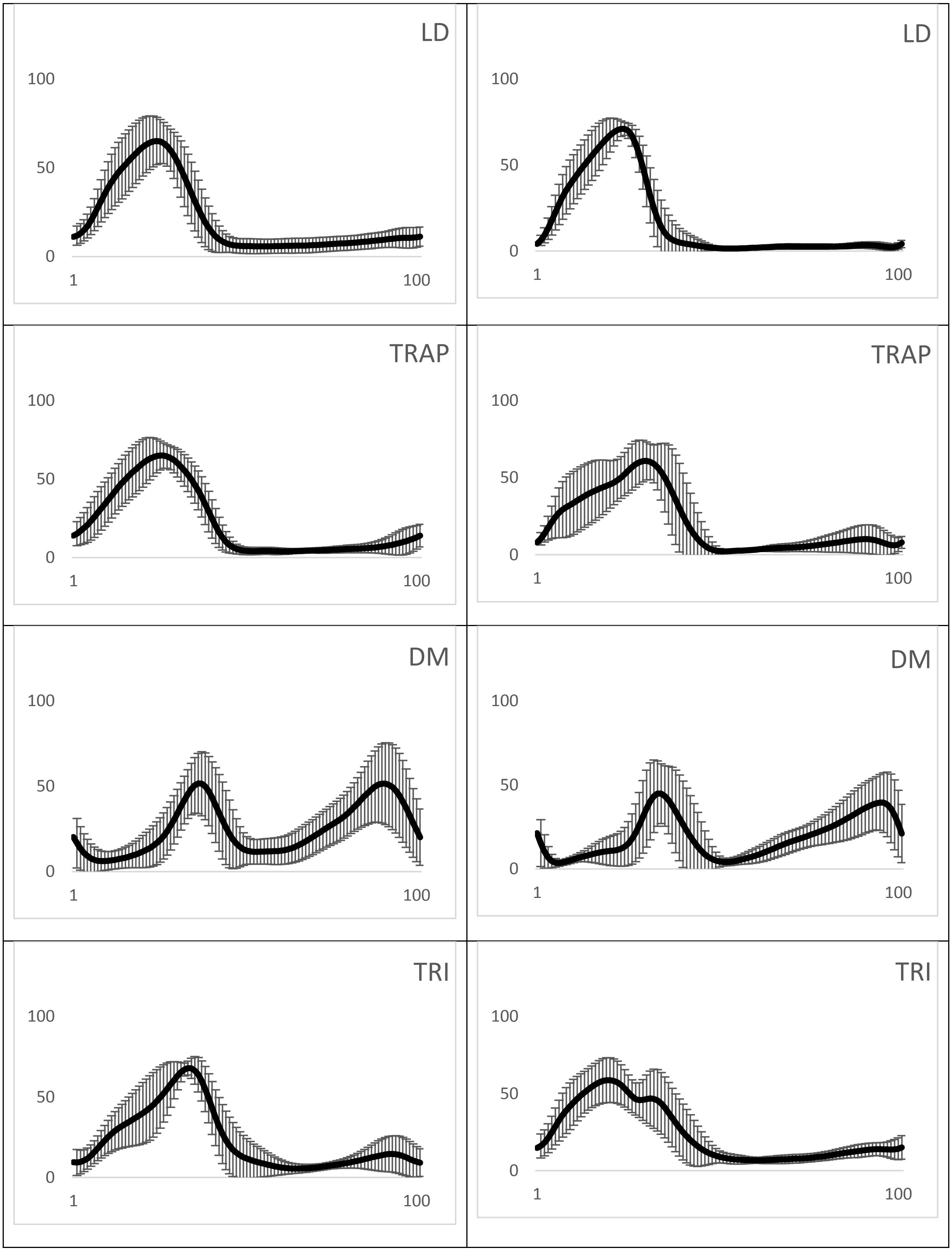
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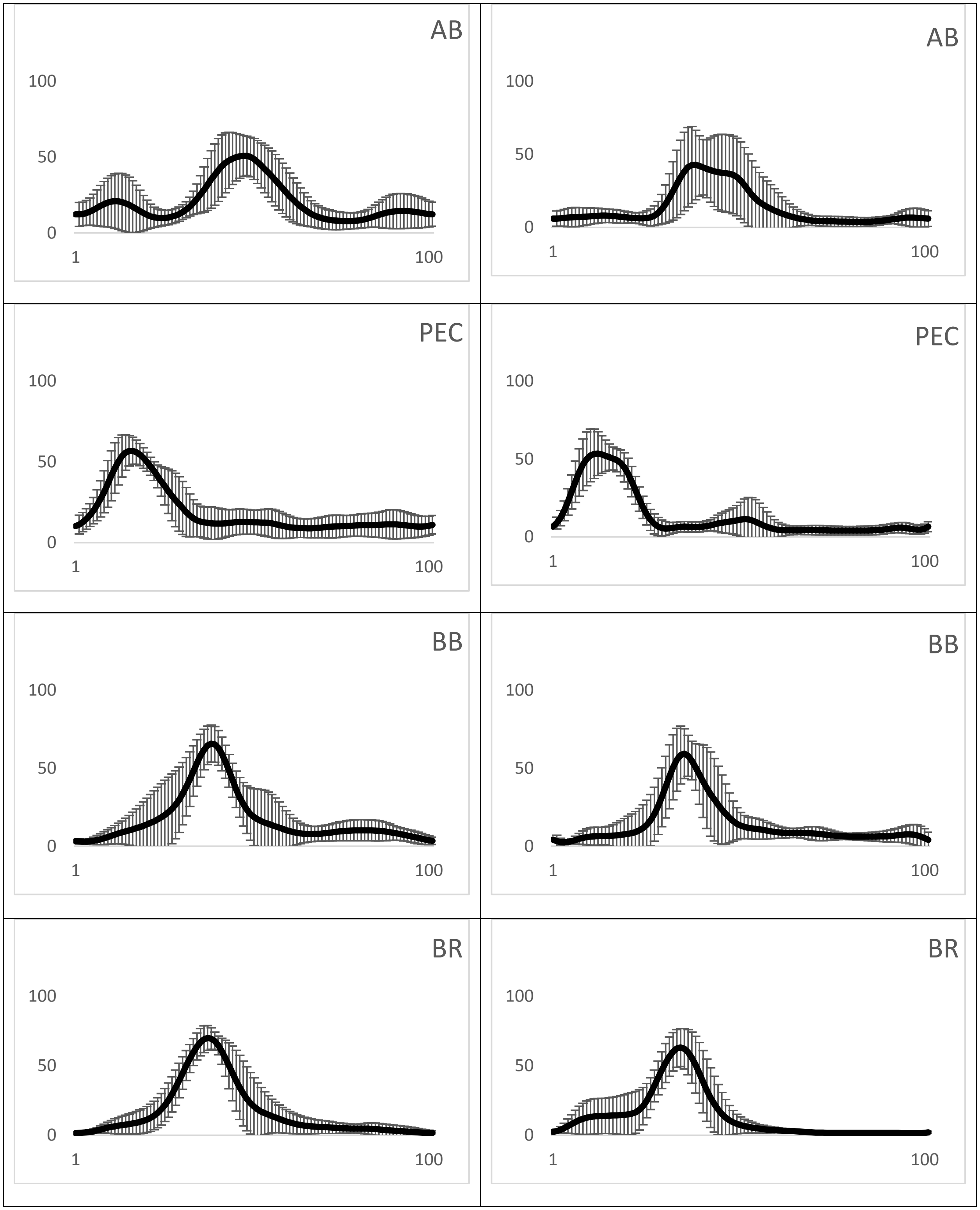

Figure 8.1: Ensemble averages of normalized EMG patterns of the 16 recorded muscles during 6 min maximal rowing test on SE for untrained subjects and collegiate rowers. Rowing phase from 0% to 50% indicates drive phase and from 51% to 100% signifies the recovery phase. Muscle abbreviations are described in text (Methods section).

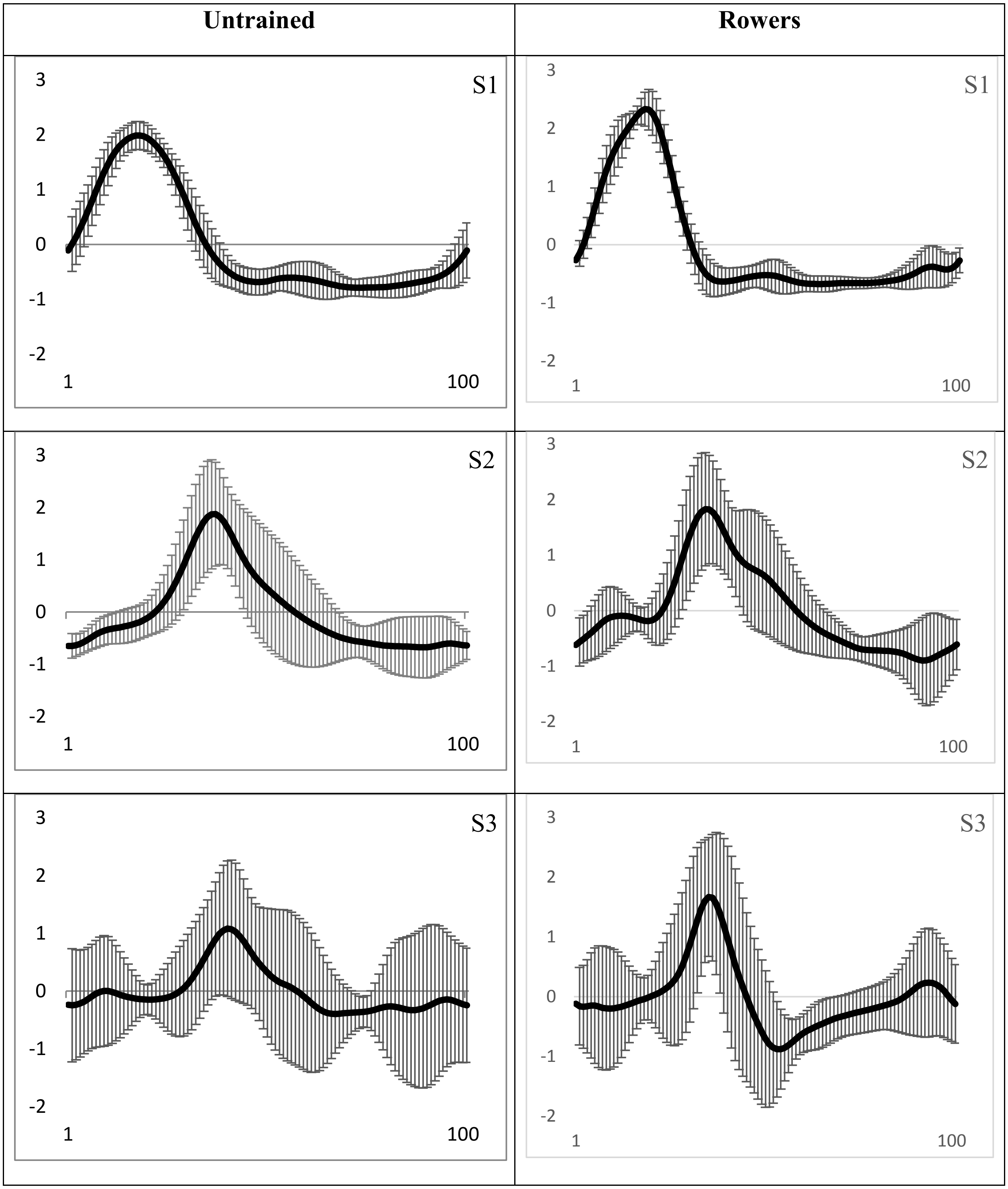

Figure 8.2: Synergy activation coefficients and muscle synergy vectors depicted for 6min maximal rowing on SE of untrained subjects and collegiate rowers. Synergy activation coefficients were averaged across the subjects for the three extracted synergies and expressed as a function of percentage of the rowing cycle (0% to 50% represent drive phase and 51% to 100% represents recovery phase).

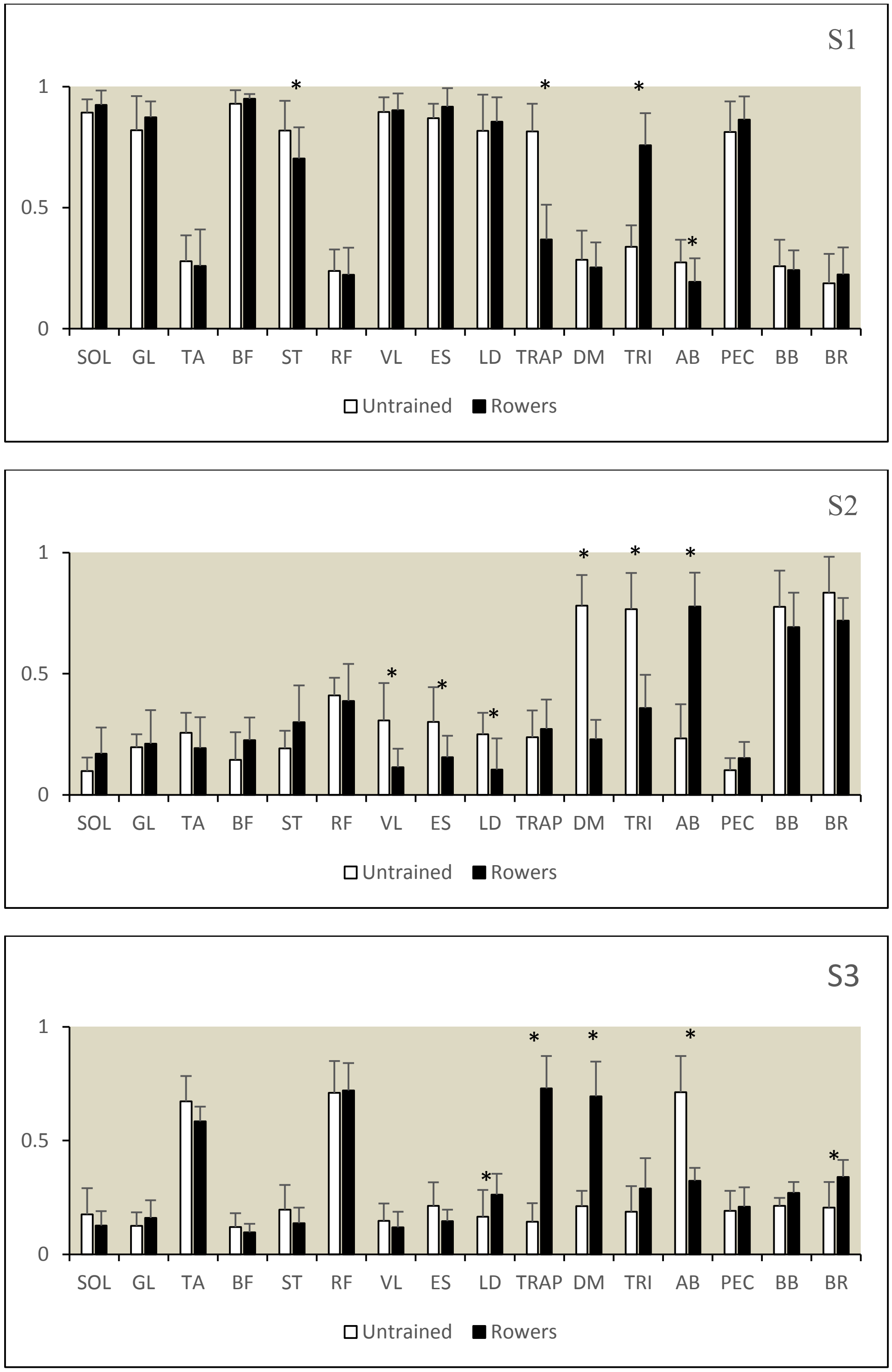

Figure 8.3: Muscle synergy vectors depicted for 6min maximal rowing on SE of untrained subjects and collegiate rowers. The muscle synergy vectors were averaged across the subjects for the three extracted synergies. Individual muscle weightings are depicted for each muscle within each synergy. Asterisks indicate significant difference of muscle loadings between rowing conditions ($p < 0.05$).

Chapter 9

CONCLUSION

9.1 Major Findings

We succeed to prove the robustness of muscle synergies across different physiological demands (e.g aerobic and anaerobic energy pathways), expertise level (e.g collegiate rowers and physically active untrained subjects) and mechanical constraints (fixed and slides ergometer). Three muscle synergies were extracted across these physiological demands, expertise level and mechanical constraints, but some variability were observed in terms of timing coefficients and muscle loadings. This further indicates the stability of muscle synergies. The strengths of our dissertation work are the ability of removing physiological fitness as the confounding factor between the groups of subjects studied and multiple robust statistical tools to enhance synergies extraction methods. The major findings are summarized as follows for each chapter:

9.1.1 Pilot study: Muscle synergy of untrained subjects during 6 min maximal rowing on fixed and slides ergometer

Three functional muscle synergies were sufficient to explain majority of variance during maximal rowing in both stretcher mechanisms. The synergies consisted of groups of muscles that function at specific phases of rowing cycle. 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 are the main power house during rowing (Nowicky et al., 2005) and as multi-joint muscles they also contributed to energy transfer from the stretcher to the trunk (Hofmijster et al., 2008).

Next, the force generation was attributed to the Synergy #3 (i.e., back muscles) which are dominant from the middle of drive phase up into early recovery phase. The trunk swing transfers 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. By emphasizing on leg drive, rowing on SE allows quicker increase of the force and effective drive timing (Kleshnev, 2011).

On the contrary, rowing on FE recruited a bulk of muscles (Synergies #1 and #2) for cumulative force production during the drive phase. Despite their huge cross sectional area, postural muscles are slow. Therefore, reliance on back muscles prevents a quick increase of propulsive force, thus making the temporal structure of the drive less effective (Kleshnev, 2011). This explains 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, Synergy #3 was activated to accelerate and decelerate the body mass at the end of each stroke.

Because of the differences in muscle synergies utilization in both stretcher mechanisms, the rowing performance and strokes varied. Subjects tended to row faster with shorter strokes on SE compared to FE rowing. Although energy metabolism was not quantified in this part of the study, we postulated that rowing on SE is more energy efficient than rowing on FE. This finding was concluded from the ability of subjects to cover more distance while maintaining higher maximal heart rate while rowing on SE. Based on the results, we suggested that it is beneficial for beginner (i.e novice rowers) to train efficient muscle synergies on SE.

9.1.2 Muscle synergy of collegiate rowers during 6 min maximal rowing on fixed and slides ergometer

Following the findings of the pilot study, we decided to recruit more rowing specific muscles on unilateral side of the body and to add oxygen consumption analyses. The same protocol was applied for the rowers comparing the muscle synergies in different stretcher mechanisms. Due to the addition of more muscles, different muscle weightings were loaded to three functional muscle synergies pattern. Hence, contrary to previous findings, the synergies of the rowers did not show significant difference in both stretcher mechanisms. Overall, Synergy #1 was activated during the first half of the drive phase, Synergy #2 was engaged during the second half of the drive phase and Synergy #3 was predominant during the transition of strokes positions (e.g from recovery to catch). Synergy #1 always consisted of the leg, back and chest muscles. Synergy #2 was typically made up of upper limb muscles and some small variation was noticeable in synergy #3. As Synergy #1 contributed to half of total synergies, the association of Synergy #1 to rowing economy also implied that muscle synergies are highly correlated to rowing economy. However, rowing economy is not a main predictor of rowing performance for both SE and FE rowing.

The rowers utilized similar rowing strategy as the untrained subjects in pilot study. They rowed faster and shorter on SE compared to FE. There was no significant difference of total distance covered in both rowing conditions, but the rowers were able to expend more energy at higher economy while rowing on SE compared to FE. As there are no differences in muscle synergies pattern and rowing performance during rowing on FE and SE, both ergometers could be utilized by the experienced rowers for their training regime.

9.1.3 Muscle synergy during Wingate anaerobic test for rowers and untrained subjects

In 30 s rowing sprint test, the rowers exhibited greater peak and mean power, covered more distance, and achieved higher value of $VO_{2\ max}$, energy expenditure and rowing economythan untrained subjects. There was no significant difference in anaerobic threshold (AT) between both groups.

Three muscle synergies were extracted with high index of waveform pattern of similarity between groups. Similar to previous chapter, in both groups, the Synergy #1 were primarily contributed by leg, thigh, and back muscles. This synergy comprised about half of total synergies and was engaged during the first half of drive phase. Meanwhile Synergy #2 consisted of upper limb muscles was activated during the second half of drive phase. Synergy #3 was made of TA, RF and AB and was involved during the strokes transition phase. Although Synergy #1 was highly correlated to rowing economy, it is inversely related to anaerobic rowing performance of untrained subjects. This means that during highly anaerobic rowing (such as at the start of the rowing event), rowing economy could deteriorate the ability of novice to sprint. For untrained subjects, mean power output is the determinant of rowing performance. However, similar results were not observed in rowers. Hence, we suggested that for novice it is crucial to improve mean power output during sprints training.

9.1.4 Muscle synergy during $VO_{2\ max}$ test for rowers and untrained subjects

Despite recruiting physically active untrained subjects, the rowers showed better level of fitness with ability to retain higher value of maximal heart rate and exerted more energy with better rowing economy. Contrary to the results from our previous work on 6 minutes maximal rowing and Wingate anaerobic test, both groups utilized different rowing strategy during $VO_{2\,max}$ test. The rowers tend to row slower with longer strokes while the untrained subjects row faster at shorter strokes. According to Sparrow and Newell (1998), longer and slower movement indicated training-related adaptation, where the experts are capable to achieve refined movement at low energy cost.

Similar to previous findings, three functional muscle synergies were extracted for both groups. Synergy #1 was constituted by leg, thigh, back and chest muscles, Synergy #2 was made of upper limb muscles and Synergy #3 was contributed by TA, RF and AB for both groups of subjects. Synergy #1 was highly associated to rowing economy although it is not a main predictor in aerobic part of rowing performance.

9.1.5 Muscle synergy during 6 min maximal rowing for rowers and untrained subjects

The longer and slower movement which indicate training-related adaptation was an obvious rowing strategy for collegiate rowers. The rowers covered more distance, exerted higher power out and energy with better rowing economy compared to the untrained subjects.

Three muscle synergies were extracted for both groups from almost similar muscle contributions. Synergy #1 (consisted of legs, thigh, back and chest muscles) was dominant during the first half of drive phase, Synergy #2 (contributed by upper limb muscles) was active during the second half of drive phase while Synergy #3 engages during the stroke transitions. Synergy #1 was highly associated to rowing economy although economy is not the main predictor of rowing performance.

Therefore, from the findings of each dataset, we concluded that muscle synergy is 1) highly associated with rowing economy and 2) robust across different physiological demands during rowing. The novice rowers could implement our findings by emphasizing the triceps muscles for more shoulder extension at the end of drive phase. Slides ergometer is a better training device for novices compared to fixed ergometer as it helps the novice to achieve similar synergies of experienced rowers. For more experienced rowers training that emphasized on strengthening the muscles in Synergy #1 could improve their overall power output.

9.2 Limitations

Despite extensive studies regarding muscle synergies and its robustness, there is little proof to suggest that the extracted muscle synergies have real physiological significance and could be utilized more than a description of the studied data (Ajiboye and Weir, 2009). Due to this lack of evidence in predictive framework of muscle synergies, a number of researchers (Kutch et al., 2008; Valero-Cuevas et al., 2009) claimed that muscle synergies better reflect task constraints rather representing the underlying neural control. Although we managed to test the robustness of muscle synergies across physiological demands during rowing for rowers and untrained subjects, we did not explore the predictive characteristic of the synergies extracted. According to Ajiboye and Weir (2009), "demonstrating a predictive framework is a more powerful assertion, and would more strongly suggest that muscle synergies are a reasonable governing paradigm of neural control by the central nervous system".

The physiological tests (Wingate anaerobic and $VO_{2\,max}$ test) relied on assumption rather than explicitly quantifying the energy profile based on three pathway metabolisms (phosphagens, alactic and aerobic metabolism). This is because of the lack of blood sampling or other non-invasive methods (e. g. magnetic resonance spectroscopy) available to measure the blood lactate concentration following exercise. By including lactate concentration, energy profile from three pathway metabolism can further be calculated using equation from Beneke et al., (2002, 2004).

9.3 Future Works

Detailed musculoskeletal models provide an ideal framework to investigate the biomechanical function of synergies across multiple tasks such as cycling Raasch and Zajac, 1999), walking (Neptune et al., 2009) and upper-extremity isometric force task (Steele et al., 2013). Based upon the posture, kinematics, and external forces for an experimental protocol, musculoskeletal simulation can be used to estimate expected muscle forces, test a priori the impact of experimental constraints (e.g the number of muscles included in the analyses) (Steel et et al., 2013), predict the functional impacts of altered synergies, examine the reliability of synergies identified from algorithms can control movement (Neptune et al., 2009; Allen and Neptune, 2012) and optimize synergies during sports performance by taking into account energy cost. Therefore, by using musculoskeletal model, the predictive framework of the muscle synergies can be quantified and hence further proved that it is a simplifying strategy from CNS rather than limited by certain tasks.

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APPENDIX A

INFORMED CONSENT FORM

Project Title: Muscle coordination and synergies in different physiological demands during rowing.

Investigators: Prof Sunil Agrawal

Shazlin Shaharudin

PURPOSE/ DESCRIPTION OF THE RESEARCH

You are invited to participate in this research study examining muscle coordination adaptations during rowing. You will be one of approximately 30 participants. There will be two groups of participants in this study, rowers and non-rowers. Your participation in this study is voluntary. If you agree, you will be asked to come to the University of Delaware, Mechanical Systems Laboratory for three separate testing sessions. In each session, you will be prepared with electrodes to record data from 16 muscles, reflective markers on bony landmarks and a breathing analyzer. Then you will row on a Concept II rowing machine. Each session is expected to last for an hour. There will be at least two days in between each session.

CONDITIONS FOR SUBJECT PARTICIPATION

To participate, you must be between 19 to 30 years old, have no high blood pressure, heart, respiratory or neurological problems. For rowers, you must have at least 3 years of rowing experience.

PROCEDURE

If you agree to participate, we will schedule a convenient time for you. In your first visit, you will need to answer the Medical History Questionnaire to the best of your knowledge. If you are a non-rower, you will be asked to watch a video regarding proper rowing techniques in your first visit. Then, you will be prepared for electrode placement. We will need to shave your body hair at specific body locations and an alcohol swab will be applied on the shaven skin. 16 muscles are chosen to be evaluated in this study: 4 leg muscles, 4 thigh muscles, 3 trunk muscles, 2 upper back muscles, and 4 arm muscles. A simple voluntary contraction test for each of these muscles will be conducted to locate the muscle accurately. Next, the reflective markers will be placed on your feet, legs, arms, back and chest. Then, you will be fitted with a breathing analyzer that consists of a facemask and a battery container. The facemask will cover your nose and mouth while the battery container will be strapped on your chest. This preparation procedure will be conducted in each session of the study.

Picture shows the rowing machine, the wireless electrodes and the breathing analyzer that will be equipped on you.

<u>Session 1: Maximal effort test</u>

For the first study session, you will be asked to row at your maximal effort. After preparing you with the electrodes, markers and breathing analyzer, you will be provided with 2 minutes self-directed warm up on the rowing machine. The load of the machine will be set differently according to your gender. The resistance will be increased by 10% from your baseline wattage in every stage. Each stage will last for 2 minutes and you will need to hold constant speed through each stage. Testing will be stopped when you can no longer hold a constant speed for 30 seconds. You will then be provided with 10 minutes of cool down on the rowing machine.

<u>Session 2: Sprint test</u>

At least two days after the first testing session, you will be asked to come back for the next session. For the second study session, you will be asked to do the rowing sprint test. After preparing you with the electrodes, markers and breathing analyzer, you will be provided with 2 minutes of self-directed warm up on the rowing machine with 4 short sprints followed by 2 minutes rest. Next, you will need to row for 1 minute at 65% of your maximal effort, followed by an ‘all out’ sprint for 30 seconds with verbal encouragement. You will then be provided with 10 minutes of cool down on the rowing machine.

Session 3: Race simulation

At least two days after the second testing session, you will be asked to come back for session three. For the third study session, you will be asked to do a 6 minutes race simulation test. After preparing you with the electrodes, markers and breathing analyzer, you will be provided with 2 minutes of self-directed warm up on the rowing machine. Then, you will row for 6 minutes at your maximal effort with a pre-determined stroke rate range. Next, you will be provided with 10 minutes of cool down on the rowing machine.

CONFIDENTIALITY

You will be identified by a subject number. No identifiable data will be shared publicly. The information will be used for research purposes only and will be encrypted in a password protected medium. The data will be retained by the researchers indefinitely and may be used in future research studies. Neither your name nor any identifying information will be used in any publication or presentation resulting from this study. Your permission will be required before taking any videos or photographs.

RISKS AND BENEFITS

Although risks associated with this study are low, it is possible that you may experience shortness of breath, low back pain, muscle soreness, or fatigue while participating in the study. For VO2max test, the risks includes abnormal blood pressure, fainting, irregular, fast or slow heart rhythm, and in rare instances, heart attack, stroke or death. Every effort will be made to minimize these risks by evaluation of preliminary information relating to your health and fitness and by careful observations during testing. We will provide you videos of proper rowing technique and enough time for warm up and cool down to reduce the related risks. In any unlikely event of injury, the experiment will be stopped immediately and first aid will be provided. The researcher is trained to provide CPR in emergency.

You will benefit from participation in this study by knowing your endurance, strength and cardiorespiratory levels of fitness. We will provide written reports of these tests to the rowers and their coaches. For non-rowers, we will provide verbal or written reports upon request. Your participation may also help the investigators better understand the physiology, movement and muscle coordination in rowing. If you are injured, you will receive first aid. If you require additional medical treatment, you will be responsible for the cost.

CONTACTS

Further information regarding this study may be obtained from Dr. Sunil Agrawal (302) 831-8049. Other questions about your rights as a research subject can be directed to the Chair of the Institutional Review Board, University of Delaware, at (302) 831-2137.

SUBJECT ASSURANCES

Participation in this study is voluntary and you may withdraw at any time without consequence.

Would you be willing to be contacted for future studies? ___ yes ___ no

I agree to participate in the research study described above.

Subject Signature: ______________________________ Date: _________________

Investigator Signature: __________________________ Date: _________________

I agree to recordings of my sessions by video or cameras as long as these are only used in scientific presentation of the material.

Subject Signature: ______________________________ Date: _________________

Investigator Signature: __________________________ Date: _________________

APPENDIX B

MEDICAL HISTORY QUESTIONNAIRE FOR VO_2MAX TEST

Personal Information

Gender: [ ] Male [ ] Female Age: _______

Address: ____ City: ________________________ State: _____ Zip: _______

Day Phone: (_____) _____ - _______ Evening Phone: (_____) _____ - ________ Email: ______________________________

Height: _____________ Weight: ______________________

Emergency Contact

Name: _______________________________________ Relationship: ____________________________________

Day Phone: (_____) _____ - ________ Evening Phone: (_____) _____ - ________

Primary Care Provider: _______________ Phone: (_____) _____ - _______

Medications

List any prescribed medications you are currently taking and reason for taking each medication:

____

____

____

List any self-prescribed medications you are currently taking (including herbal, supplements and NSAIDS such as Advil, Motrin, Tylenol, etc.):

____

____

____

ACSM CORONARY ARTERY DISEASE RISK FACTORS

Known Diseases Do you have any of the following? Please elaborate on any "yes" answers below.

Category	**Diseases**	**Yes**	**No**
Cardiovascular	Cardiac, peripheral vascular or cerebrovascular disease		
Pulmonary	Chronic obstructive pulmonary disease, asthma, interstitial lung disease, cystic fibrosis		
Metabolic	Diabetes mellitus (type I or II), thyroid disorders, renal or liver disease		

Comments: ____

____

Risk Factor To the best of your ability, please check the appropriate yes/no box for each of the following questions:

Risk Factor	**Defining Criteria**	**Yes**	**No**
Family History	• Has any of your family members had a heart attack, stroke, or died suddenly of heart disease before the age of 55?		
Cigarette Smoking	• Are you currently a cigarette smoker **OR** • Have you quit within the past 6 months?		
Hypertension	• Is your blood pressure over 140/90 mm Hg? • Are you on medication to control your blood pressure?		
Pre-diabetes	• Do you have diabetes mellitus?		
Sedentary lifestyle	• Are you physically inactive and/or sedentary (little physical exercise on the job or after work)?		
Obesity	• Is your **BMI** of > 30 kg/m2		

Comments: ____

____

____

Signs and symptoms Do you experience any of the following? Please elaborate on any "yes" answers below.

Symptom	**Yes**	**No**
• Have you experienced unusual pain or discomfort in your chest (pain due to blockage in coronary arteries of the heart)?		
• Have you experienced unusual shortness of breath during moderate exercise (such as climbing stairs)?		
• Have you had any problems with dizziness or fainting?		
• When you stand up, or sometimes during the night, do you have difficulty breathing?		
• Do you suffer from swelling of the ankles (ankle edema)?		
• Have you experienced a rapid throbbing or fluttering of the heart?		
• Have you experienced severe pain in your leg muscles during walking?		
• Has your doctor told you that you have a heart murmur?		
• Have you felt unusual fatigue or shortness of breath with usual activities		

Comments: ____

____

Musculoskeletal Please elaborate on any "yes" answers below.

Do you have any current musculoskeletal limitations that would impair your ability to perform maximal exercise (back pain; swollen, stiff, or painful joints; arthritis; etc.)?	Yes	No

Comments: ____

____

____

Other

Please list and explain any other significant medical problems that you consider important for us to know:

____

____

1. Purpose and Explanation of the Test

You will perform an exercise test on a rowing ergometer. The exercise intensity will begin at a low level and will be advanced in stages depending on your fitness level. We may stop the test at any time because of signs of fatigue or changes in your heart rate or symptoms you may experience. It is important for you to realize that you may stop when you wish because of feelings of fatigue or any other discomfort.

2. Attendant Risks and Discomforts

There exists the possibility of certain changes occurring during the test. These include abnormal blood pressure, fainting, irregular, fast or slow heart rhythm, and in rare instances, heart attack, stroke, or death. Every effort will be made to minimize these risks by evaluation of preliminary information relating to your health and fitness and by careful observations during testing. Emergency equipment and trained personnel are available to deal with unusual situations that may arise.

3. Responsibilities of the Participant

Information you possess about your health status or previous experiences of heart-related symptoms (such as shortness of breath with low –level activity, pain, pressure, tightness, heaviness in the chest, neck, jaw, back and/or arms) with physical effort may affect the safety of your exercise test. Prompt reporting of these and any other unusual feelings with effort during the exercise test itself are of great importance. You are responsible for fully disclosing your medical history, as well as symptoms that may occur during the test. You are also expected to report all medications (including non-prescription) taken recently and, in particular, those taken the day of testing, to the staff.

4. Use of Medical Records

The information that is obtained during testing will be treated as privileged and confidential. It will not be released or revealed to any person without your approval.

5. Inquires

Any questions about the procedures used in the exercise test or the results of our test are encouraged. If you have any concerns or questions, please ask us for further explanations.

BY MY SIGNATURE BELOW, I HAVE ANSWERED THE QUESTIONNAIRE TO MY BEST POSSIBLE KNOWLEDGE.

Print Name: ______________________Signature: ______________________Date: __________

APPENDIX C

RESEARCH OFFICE

210 Hullihen Hall
University of Delaware
Newark, Delaware 19716-1551
Ph: 302/831-2136
Fax: 302/831-2828

DATE:	February 17, 2012
TO:	Sunil Agrawal
FROM:	University of Delaware IRB
STUDY TITLE:	[291537-1] Muscle coordination and synergies in different physiological demands during rowing
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	February 17, 2012
EXPIRATION DATE:	February 14, 2013
REVIEW TYPE:	Full Committee Review

Thank you for your submission of New Project materials for this research study. The University of Delaware IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Full Committee Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate adverse event forms for this procedure. All sponsor reporting requirements should also be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office.

Please note that all research records must be retained for a minimum of three years.

Based on the risks, this project requires Continuing Review by this office on an annual basis. Please use the appropriate renewal forms for this procedure.