ABSTRACT

Title of Thesis:	MUSCULAR FATIGUE INFLUENCES MOTOR SYNERGIES DURING PUSH-UPS
	Elizabeth Bell, Master of Arts 2018
Thesis Directed By:	Jae Kun Shim, PhD, Department of Kinesiology

This research used the push-up as an experimental paradigm for the study of adaptations in motor synergies throughout the challenge of muscular fatigue. Fatigue was expected to lead to greater synchronization of power production (greater motor synergy) by the Central Nervous System (CNS). Greater between and within-limb synergies would be necessary to overcome the reduced force production of fatigued muscles. Different changes in joint power synergies were expected for eccentric and concentric phases due to muscle properties and direction of gravity. Eleven subjects performed push-ups repetitions to self-selected failure. Subjects initially performed push-ups using positive between and within-limb joint power synergies, however synergies reduced throughout reps. Congruent with hypotheses, between and within-limb synergy reduced at a lesser rate throughout eccentric movements. The strategy used relied on bilateral elbow and shoulder joint production. The CNS was not able to adapt control strategies, but instead the dominant strategy was affected throughout fatigue.

MUSCULAR FATIGUE INFLUENCES MOTOR SYNERGIES DURING PUSH-UPS

by

Elizabeth Mae Bell

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Arts
2018

Advisory Committee:
Professor Jae Kun Shim, Chair
Professor Ross H. Miller
Dr. Kyung Koh

Dedication

For my Step-grandmother, Sylvia who had the courage to be a female scientist in an era where it was rare, within a field where she faced frequent and apparent opposition.

Acknowledgements

I would like to express my sincere gratitude to the following people who have supported my desire to study Neuromechanics. First, I would like to recognize my family. Especially my love, my husband Morgan, who convinced me that I could quit my job and go back to school to achieve my graduate degree. I appreciate your sense of humor and patience with me. Thanks to my Mother, who quietly guided me into becoming the student I am today. She has always encouraged me to practice mathematics by sewing, baking, and playing musical instruments. To my Father, who boisterously imparted the “Nottingham perspective” upon me. So far, this outlook has helped immensely in my career.

Additionally, I would like to thank my advisors and my committee members. Particularly to Dr. Shim for patiently answering my repetitive questions, and always making me feel like an important part of “the best Neuromechanics lab in the world.” Thanks to Dr. Miller for being detail oriented, keeping his expectations of me high, and for helping me understand the mechanical and biomechanical perspective on joint power. Thanks to Dr. Koh for the hours he spent helping me become a stronger programmer and the advice he has given about finding my own research path in graduate school.

Lastly, thanks to the engineers, kinesiologists, and physical therapists who helped me learn so much during my time in the life sciences research industry and research labs.

I would especially like to thank my sister-in-law, Johanna, whom I admire as an engineer, author, and friend.

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Chapter 1: Introduction

General Introduction

Redundancy is common in human movements, as motor tasks can often be accomplished in an infinite number of ways by using extra degrees of freedom in the system. If you touch your finger to your nose you will notice that you can keep the finger in this location as you change positions of your arm. You can complete this pointing task with many different combinations of arm joint angles, or redundant solutions. This redundancy means that the central nervous system (CNS) needs to select from infinitely many motor solutions to complete a motor task. Recently, the mathematical problem of motor redundancy has been reinterpreted as the principle of motor abundancy (Latash, 2000; Latash, 2012). This reformulation suggests that having many solutions to a motor problem is an advantage which allows for flexibility by the CNS in selecting solutions to motor tasks. Solutions are thought to be selected by the CNS based on the stabilization of task specific performance variables (Latash, Scholz, & Schöner, 2002). The solutions are commonly called synergies. Specifically, the CNS can create motor synergies that organize elemental (input) variables that co-vary to stabilize sets of task-specific performance variables (output). Within motor abundancy it is thought that the existence of multiple synergistic solutions allows the CNS to solve the motor task even if there are changes within the elemental variable level.

Fatigue presents a unique challenge to the CNS that can be useful for understanding how abundant solutions to a motor task are used. Fatigue is an acute neuromuscular state commonly experienced in daily life. Muscle (peripheral) related fatigue processes (Westerblad, Allen, Bruton, Andrade, & Lannergren, 1998) lead to a decreased ability to produce high muscle forces, and increased variability of performance (Enoka & Stuart, 1992; Enoka & Duchateau, 2008). Fatigue alters muscular performance and inherently changes the available motor solutions within a motor task. However, in motor tasks that include a redundant set of elements, the neuromuscular system appears to adapt after fatigue to preserve goal-relevant features of motor tasks (Huffenus, Amarantini, & Forestier, 2006; Kruger, Hoopes, Cordial, & Li, 2007; Singh, Zatsiorsky, & Latash, 2010; Singh, Varadhan, Zatsiorsky, & Latash, 2010). Within the motor abundancy theory, it is not known how the shift in synergistic strategy is obtained. The CNS might progressively shift to a new synergistic task solution as the elemental variables face the challenge of fatigue. Motor synergies have not been systematically evaluated throughout the challenge of muscular fatigue. It is not known if the CNS alters control strategies to achieve performance goals throughout the fatiguing process.

In fact, limited investigations into the influence of fatigue on motor synergies exist in literature. Available studies focus on fatigue effects within low redundancy systems which perform clearly defined motor tasks. An example of a clearly defined task with limited redundancy is two fingers interacting to produce a targeted unidirectional force before and after the muscles in one finger are fatigued (Kruger et al., 2007;

Singh et al., 2010; Singh, Varadhan, et al., 2010). Results from this two-finger task suggest that fatigue causes the CNS to adjust its strategy by selecting a synergistic solution that preserves the performance of the force production. Specifically, variance increased among non-fatigued elements and greater synergistic force production was identified between the finger elements. The variance increased as the unfatigued element had to produce more force to compensate for the reduced ability of the fatigued element. Further research investigated fatigue within upper limbs through the examination of disk throwing strategy before and after fatigue of the elbow or wrist joint (Huffenus et al., 2006). Like the results of the finger pressing experiment, disk throwing task performance was preserved. Likewise, variance among non-fatigued elements increased and the synergies between the joint elements was greater after fatigue. The actions of the non-fatigued elements were more variable to compensate for the fatigue effects at the fatigued joints. Greater synergies within the elemental variables were seen in both these investigations. An increase in elemental synergy suggests that a new motor solution was obtained, a solution that relies more on the unfatigued motor elements. The results from these studies suggest that motor abundance is used by the CNS to compensate for the effects of fatigue. However, no investigations have looked at how the strategy changes throughout the process of fatigue. It is not known when the CNS is able to select a new motor solution to overcome the effects of fatigue. If the CNS progressively increases the synergies between elemental variables then abundancy could be an important aspect of endurance, or the ability to reach a motor task solution throughout the challenge of fatigue.

The conventional push-up is a popular exercise used to test muscular endurance of the upper limbs against fatigue (American College of Sports Medicine, 1991; Army, 2011). Specifically, this motor task requires controlled upward and downward movement of the body while in a plank position. This task requires a significant amount of power, or energy transfer, to be generated or absorbed by the upper limbs. This energy transfer can theoretically be achieved through an infinite combination of joint power production within and between the limbs, which presents motor abundancy to the CNS. This abundancy of motor solutions allows the push-up to be an excellent experimental paradigm for the study of motor redundancy in humans. The main upper limb muscle groups utilized in conventional push-ups are the triceps brachii and pectoralis major (Youdas et al., 2010). During downward motion, eccentric contraction of the triceps brachii and pectoralis major flexes the elbow and shoulder, producing joint torques which absorb power and reduce the exerted force at the hands to control the descent toward the floor. Concentric contractions of the pectoralis major and triceps brachii create extension of the elbow and shoulder joints, producing joint torques that generate power to move the body upward. Even though the push-up exercise intrinsically involves fatigue of limbs, the influence of muscular fatigue on this motion, specifically in relation to motor synergy, is unknown.

This research uses the push-up action as an experimental paradigm for the study of adaptations in motor synergies throughout muscular fatigue. Eleven young adults were recruited from the University of Maryland, College Park and were asked to repeatedly perform push-ups at a controlled pace until self-determined failure. The purpose of this research is to determine if motor abundancy is used by the CNS to achieve a motor task solution throughout the challenge of fatigue.

The fatiguing action of a push-up is expected to decrease the power production ability of the elements (joints) available for power production between and within each limb. However, throughout the fatiguing process, the human body system is still able to generate the power necessary to move the body's center of mass. The upper limb system performs negative (power absorption, negative work) and positive (power generation, positive work) work to move the body's center of mass throughout the range of motion. This motion requires that the joints work together to produce or absorb power. Throughout the trial, joint power synergies are expected to be positive, or produce power together to produce the upward and downward motion of the center of mass. Examples of positive joint power synergies are seen in Figure 1, with perfect (a) being the strongest positive synergy that produces the greatest amount of system power (thick black line) and high positive synergy (b) would generate a greater power and work than low positive synergy (c).

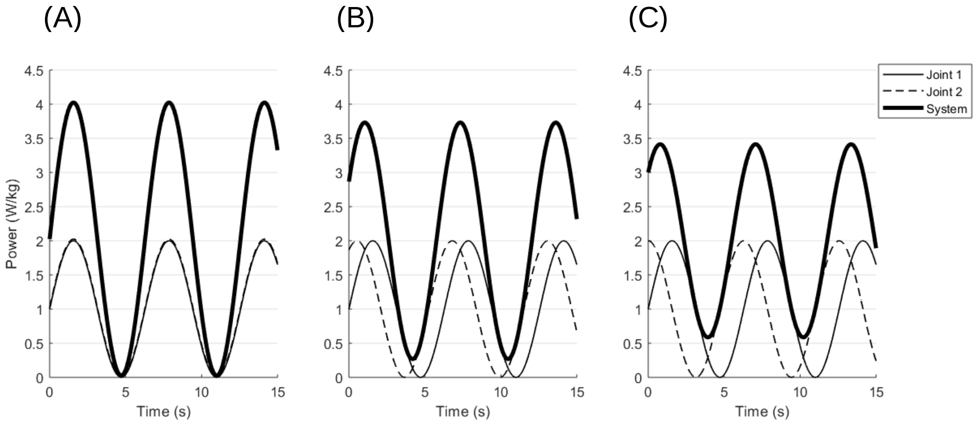


Figure 1. Visual example of joint power synergy two joints. System power is maximized during “Perfect Positive Synergy” when the two joints generate synchronized power signals (A). The magnitudes of the example joint power signals are the same within the perfect, high (B), and low positive synergy (C) examples however the magnitude of the resulting system power

As muscular fatigue reduces the ability of the muscles to produce force, the power generation at each joint will reduce. Muscular fatigue changes the power production of the elemental variables, and to find a solution that moves the body’s center of mass the elemental variables will need to produce power more synchronously. In other words, the challenge of fatigue will necessitate a stronger synergistic sharing pattern between-limbs and within-limbs as the elemental variables are able to produce less power. Consequently, fatigue of the upper limbs during a push-up will **lead to strengthening of motor synergy both between-limbs and within-limbs,** as quantified by an increase in the positive synergy index between upper limbs or within-limb joints (Hypothesis 1: H1). Greater synergies will allow the system to generate maximal limb or system work even as the elemental power production capabilities are affected by fatigue.

Eccentric (active lengthening) and concentric (active shortening) muscle contraction are involved in the downward and upward movement phases of the push-up task, respectively. The upward movement phase will be mechanically difficult as the system is required to overcome gravity while relying on concentric muscle contractions. Concentric muscle contractions have lower force production capabilities than eccentric contractions due to the well-known force-velocity relationship (Hill, 1938; Katz, 1939). The downward movement phase of the push-up is less mechanically challenging than the upward movement phase as greater forces can be produced during eccentric muscle contractions and the system can use the assistance of gravity. Muscular fatigue will reduce the power production ability of the joints used for both upward and downward movement of the COM. Due to reduced power production capability by the joints throughout fatigue, it was hypothesized that greater between and within-limb synergies would be used to produce the required work to move the body’s center of mass. This change in strategy involves an increase in power variability in the joint(s) and an increase in co-variation of joint power production (synergy) to keep total generated power relatively unchanged. Due to the mechanical differences in the movement phases of the push-up that fatigue of the upper limbs during a push-up **will lead to different changes in motor synergies between eccentric and concentric movements** as demonstrated by stronger positive motor synergies in concentric movements as compared to eccentric movements

(Hypothesis 2: H2). This mechanical analysis will produce information that will provide insight on the aspect of this movement that we cannot see, or how the CNS adapts to complete motor tasks throughout challenges such as fatigue.

Literature Review

The purpose of this literature review is to highlight aspects of motor abundancy, clearly define of fatigue as it pertains to this research, and to assess the motor task of the conventional style push-up. This knowledge is essential to understand how this research will advance knowledge within this area of study.

Motor redundancy or motor abundancy?

This research aims to investigate how the abundant human body system performs a push-up throughout the challenge of muscular fatigue. As mentioned, the CNS faces the problem of motor abundancy at many levels of this motor task. At the most external level of a push-up power is generated at the hands by the two upper limbs. These two limbs can contribute different amounts of total linear power summing to the necessary total power, creating infinitely many solutions at this level alone. Then within-limbs, the joint powers within the limb (wrist, elbow, shoulder) can be generated in multiple additive combinations resulting in the overall linear power at the end effector, generating upward motion of the body. Within-each joint the tensile force produced by muscles around the joint act to create the necessary joint torques and therefore power. Required joint torque can be produced in multiple ways, as there are more muscles crossing the joint than are needed to produce the movement. For example, at the elbow there are four muscles (triceps brachii, extensor carpi ulnaris, extensor digiti minimi, and the extensor digitorum communis) which act as the extensors of the forearm (Ramsay, Hunter, & Gonzalez, 2009). For each of these muscles, there exists another level of abundancy through combinations of muscle fibers which are activated to produce the targeted tensile force. When these four levels of abundancy (two limbs, three joints per limb, multiple muscles per joint, and hundreds of muscle fibers per muscle) are combined, the infinite number of solutions and the difficulty in identifying the solution chosen by the CNS is obvious. However, to reduce the complexity to a manageable level, this research focuses on the abundancy of the system at only the between-limb and within-limb levels of power production.

The combinations of between-limb and within-limb joint power used in each repetition will be examined. Analysis of joint kinetics will help define how the whole-body system is continuously changing as push-ups are repeated to volitional fatigue. The term “synergy” will be used to imply co-varied (across repetitions) adjustments of elemental variables that result in lower variability of important performance variables. Between-limb (right and left), within-limb (wrist, elbow, shoulder), and within-limb joint pair (wrist-elbow, wrist-shoulder, and elbow-shoulder) synergies in joint power signals will be quantified by covariance analysis throughout the push-up trial.

Principal Component Analysis or PCA is a comprehensive way to identify correlated changes of motor elements using matrix factorization methods. The PCA model assumes that some underlying factors are responsible for the covariation among the observed variables (Kim & Mueller, 1978). This analysis is suitable for the determination of possible motor synergies as uses statistical techniques to represent a large a set of variables in terms of a smaller number of hypothetical variables (Brown, 2009). Within this research, PCA will be used to identify normal and atypical linear combinations of the six joint power signals obtained throughout the push-up movement. This six-dimensional analysis will yield six principal components (PC1-6), which are new axes of variation defined by the transformation of the six joint power signals. Each principal component axis is selected based on the direction of most variation of the data. If fewer than six of the principal component axes account for most of variation in the data, then the model has identified a reduced number of stable groupings of joint power signals that represent motor synergies. Weightings of the six joint power signals within each principal component will allow for the identification of what elemental variables covary within the identified axes. Systematic changes in the PCA output throughout the push-up trial

Avoiding an ambiguous definition of experimental fatigue

In human performance research, the definition of "fatigue" is often ambiguous. Fatigue is typically used to describe the point where performance aspects, such as power production, perception of task difficulty, or the physiological ability to perform the task, are impaired (Enoka & Stuart, 1992). Within the human body, muscle fatigue has central and peripheral mechanistic causes. Central fatigue is associated with the failure of the nervous system to excite the muscle maximally and can be defined as "a progressive exercise-induced reduction in voluntary activation or neural drive to the muscle (Taylor, Todd, Gandevia, & Taylor, 2006).” Peripheral fatigue is often classified as fatigue of the muscle and is thought to be a result of metabolic inhibition. Distinguishing which aspects of fatigue are limiting the complex human body system is difficult, as central and peripheral causes are frequently intertwined. For the study, muscle fatigue will be considered “the exercise-induced loss of ability to produce force with a muscle or muscle group” (Taylor et al., 2006). This research requires that push-ups are completed at a controlled cadence until self-selected failure, or what will be referred to as volitional fatigue. To establish that volitional fatigue is associated with muscular fatigue, analyses of muscle activation signals, as measured by electromyographic sensors, will be performed. This analysis is necessary to establish that the independent variable of fatigue is changed throughout completion of the push-up trial.

Electromyographic (EMG) data is commonly collected to estimate the action potential signal from a specific set of muscles. EMG signals are normally acquired from surface electrodes placed on the skin, superimposed on the targeted muscle. These sensors measure the summed electrical activity of all muscle fibers in range and the signal is composed of both noise and the summed electrical activity of the muscle fibers. The EMG signal detects changes in the electric potential which is measured in millivolts.

Research investigations which focus on fatigue effects commonly employ max isometric contractions to fatigue a muscle or muscle group between evaluations of a motor task (Huffenus et al., 2006; Kruger et al., 2007; Singh, S K M, et al., 2010; Singh, Varadhan, et al., 2010). This fatiguing procedure allows for the collection of EMG signals from a maximum voluntary isometric contraction (MVIC), a standardized method for measurement of muscle strength. Dynamic analyses, such as EMG associated with motor tasks, are typically standardized to a common reference to allow for the reduction of variance between trials or comparison of subjects. The MVIC is commonly used to normalize the individual EMG signals. However, due to the dependence of muscle parameters on kinematic properties (force/length and force/velocity relationships), MVIC normalization of an EMG signal may complicate data interpretation, as it standardizes a dynamic outcome to a muscle activation recorded from a static task (González-Izal et al., 2010). To avoid this complication, this research uses the motor task of a conventional push-up to fatigue the body system and will normalize the EMG signals to the peak of the first repetition of the trial.

This research is concerned with variations that occur throughout the fatiguing action of repeated push-ups. When muscle fatigue occurs, the EMG signal is altered (De Luca, 1984). Additional motor units are recruited to produce the same amount of muscle tension, resulting in greater magnitudes of peak voltages in the action potential recorded by surface EMG sensors. In the time domain, this change in magnitude can be quantified by integrating the rectified, low-pass filtered, and voltage normalized EMG signal (iEMG). Typically, the iEMG is normalized in time by dividing by the total time of the action recorded (Halaki & Ginn, 2012). Within the frequency domain, fatigue effects in the EMG spectrum can be tracked via mean power frequency (MNF) calculations (Phinyomark, Thongpanja, Hu, Phukpattaranont, & Limsakul, 2012). Mean power frequency is an average frequency calculated as the sum of the product of the EMG power spectrum and the frequency divided by the total sum of the power spectrum, computed as follows:

$$MNF = \sum_{j=1}^{M} f_j P_j \Big/ \sum_{j=1}^{M} P_j, \quad [1]$$

Where f_j is the frequency value of EMG power spectrum at the frequency bin j, P_j is the EMG power spectrum at the frequency bin j, and M is the length of the frequency bin. Decreasing MNF has been shown to correlate with independent measures of fatigue (Öberg, Sandsjö, & Kadefors, 1991; Winter, 2009). Physiologically, this is thought to indicate a resynchronization of the control signal and show a reduction in firing rates of the muscle (De Luca, 1984). This analysis tracked the iEMG and mean frequency in each push-up repetition to verify that muscular fatigue occurred during the push-up trial.

Research which investigates the effect of muscle fatigue on redundant motor tasks suggests that a compensatory strategy is employed by the CNS to overcome the impairment of the motor system. Within a two-finger pressing task, Singh et al. (2010) found that fatigue of the index finger led to an adaptive strategy that increases variance to preserve total force production (Singh, Varadhan, et al., 2010). Fatigue within a multi-finger force production task showed increasing variance within individual digits that preserved the performance variable of overall force production (Singh, Varadhan, et al., 2010). The effect of muscle fatigue on error compensation during a ramped force production task performed by four fingers was investigated by Kruger et al (2007). This research found that when one of four fingers was fatigued, the other digits compensated. However, when all four fingers were fatigued, error compensation decreased, and performance was impaired. Fatigue of elbow or wrist joints as the upper limb performed a 2D throwing motion have been previously investigated (Huffenus et al., 2006). Depending on which joint was fatigued, different compensatory strategies in the relative contribution of joint torques was used to preserve motor performance of the throwing movement. The results of these studies suggest an adaptive increase in variance of elemental variables by the CNS to utilize the abundance of motor solutions available within a redundant motor system. Although these results suggest that motor abundance is used by the CNS to compensate for the effects of fatigue, it is unknown if the CNS strategy changes strategies throughout the process of fatigue.

The push-up as an experimental paradigm for fatigue

The majority of available research on push-up exercises concentrates on defining how muscle excitation patterns, as measured by surface EMG sensors, differ between conventional push-ups and modified strategies such as changes in hand position or use of systems which suspend the body (Lehman, MacMillan, MacIntyre, Chivers, & Fluter, 2006; Youdas et al., 2010). Clinical investigations which aim to determine if the push-up is a viable closed-chain exercise to be used for the rehabilitation of the shoulder muscle groups have been performed. These studies purposely focus on the ability of push-ups to improve scapular rotator strengthening (Lear & Gross, 1998; Lehman et al., 2006; Ludewig, 2004). Of the few studies that have analyzed kinetic data associated with this motor task, one utilizes a cross-bridge bond distributionmoment muscle model to estimate which variation of push-up places most strain on the lower back (Freeman, Karpowicz, Gray, & McGill, 2006). Research into whole body kinetic measures have focused on joint loading in different push-up variations (Dhahbi et al., 2017; Ebben et al., 2011) and report only forces exerted on the ground by the upper body. Gouvali & Boudolos (2005) collected vertical ground reaction force patterns from all four limbs but did not analyze joint kinetics. Whole-body vertical ground reaction force was collected from only three push-up repetitions and reporting focused only on push-up cycle from each participant. All articles that have looked at push-up biomechanics claim to avoid muscular fatigue by only having participants perform a minimal number of push-up repetitions (Dhahbi et al., 2017; Ebben et al., 2011; Freeman et al., 2006; Gouvali & Boudolos, 2005; Lear & Gross, 1998; Lehman et al., 2006; Youdas et al., 2010). There is an obvious lack of research on the effects of fatigue produced by throughout this exercise. This research gap is surprising, considering push-ups are used as a test of muscular endurance, and commonly performed to self-selected failure within exercise regimens.

Chapter 2: Methodology

Subjects/Sampling

An a priori power analysis was performed using G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) and indicated that the z-test with approximately 12 participants, the study would have 80% power to detect statistically significant differences with effect sizes of 0.8 ($\alpha = 0.05$, $\beta = 0.80$).

The participants recruited were comprised of the community at the University of Maryland. All the participants recruited will be between the ages of 19 and 35, with a BMI between 18.5 and 24.9 kg/m^2. No participant recruited had a history of major injury to the upper limbs or back that required medical attention or impaired mobility.

Procedures and data collection

Volunteers participated in a single motion capture data collection after completing informed consent procedures approved by the Institutional Review Board of the University of Maryland, College Park. Self-reported gender was recorded by the researcher. Height was measured using a freestanding mechanical stadiometer. Participants were asked about leg and arm dominance because it has been seen to affect muscle strength (A. M. Brown, Zifchock, & Hillstrom, 2014; Ditroilo, Forte, Benelli, Gambarara, & De Vito, 2010) and could potentially affect synergistic changes. Limb dominance was determined by asking the participants, “Which leg would you kick a soccer ball with?” and “Which hand would you catch a ball with?”

The same researcher fit each participant with a full body retroreflective marker set (Wilken, Rodriguez, Brawner, & Darter, 2012). Four surface EMG sensors (Delsys, Trigno^{TM}; Natick, MA, USA) were placed on the bilateral pectoralis major and lateral head of the triceps brachii. The participants skin which was cleaned with an alcohol wipe and, if excessive hair was present, the placement site was shaved. Electrodes were attached to the skin using a Delsys Adhesive Sensor Interface, which is a precisely cut piece of double-sided tape that fits on the bottom of the surface sensor. The electrodes were placed parallel to the muscular line of action, as recommended by The Surface Electromyography for the Non-Invasive Assessment of Muscles project which is a European concerted action in the Biomedical Health and Research Program of the European Union (Hermens, 1999). The triceps brachii electrode was attached at the midpoint between the posterior aspect of the acromion and the olecranon process and the pectoralis major electrode was positioned at the midpoint of the distance between the sternal notch and the axillary fold.

Audio feedback via metronome (50 bpm) and pre-trial instructions were provided to participants to establish the controlled, three-beat tempo of 24 push-ups per minute. This tempo was similar to push-up cadences used in other research protocols (Lehman et al., 2006). For continuity, researchers instructed each participant by reading instructions which detailed how to perform a conventional style push-up and how they should follow the auditory metronome feedback. These instructions asked participants to as many push-ups as possible to the beat and asked them to stop when they could no longer physically complete the push-up.

After reading a set of verbal instructions explaining the requirements of conventional push-ups, an example push-up was performed by the researcher. The researcher started from a standing position and then moved into plank after the metronome beat was turned on. Then one push-up was performed to the beat. Participants were instructed on how to arrange themselves in a plank position with each limb within the bounds of a force platform (Kistler Instrument Corp., NY, USA; see Figure 1). Researchers then asked for verbal confirmation of methodological understanding from the participant. If a participant did not understand researchers reviewed the instructions or repeated the example push-up.

Before the push-up trial, a static trial was collected for each participant. When directed to, the participants stepped onto two of the force plates and stood in anatomical position. This allowed a defined mathematical model of each participant to be premeditated so that the joint axes could be calculated in the dynamic trial. After the static calibration trial was collected, researchers guided participants to a marked start position between the force platforms. They were reminded of the instructions to wait until they heard the metronome to get into a proper plank position with each limb within the boundaries of one of the four force platforms and then, when ready, start the “down, up, hold plank” motions along with the beat. Dynamic trial collection started when the participants were in the ready position. Motion capture data, including marker positions (200 Hz) and force data from four force plates (1000 Hz) were collected as participants completed one trial where they performed as many push-ups as possible, stopping at self-determined failure.

Data Analysis

Electromyographic data

Electromyographic processing was performed within a custom program written in MATLAB software (MATLAB and Statistics Toolbox Release2017b, The MathWorks, Inc., Natick MA, USA). Mean power frequency of each signal obtained from each push-up repetition was obtained through Fourier transfer of the unfiltered, "raw," EMG signal into the frequency domain. Once signals were in the frequency domain the mean frequency for each push-up repetition was identified using the meanfreq function within MATLAB.

Separately, the integrated linear envelope was calculated within the time domain for every push-up repetition. Electromyographic signals were demeaned, full-wave rectified, and low pass filtered with a 4th order, zero lag Butterworth filter with a cut off frequency of 6 Hz. The linear envelope was normalized to the peak of the signal obtained from the first push-up repetition. Within MATLAB software, the trapezoidal numerical integration (trapz function) of each voltage-normalized linear envelope (iEMG) was performed for each push-up repetition.

Principal Component Analysis

To investigate systematic changes of joint power production, PCA of the six joint power signals was performed. Principal component analysis of the six joint power signals obtained from each repetition was performed using the pca function within MATLAB software. The percentage of the total variance explained by each principal component and the loadings of each joint power signal within the principal components were examined.

System, Limb and Joint Power

Scalar Joint power data were analyzed in Visual3D software (C-Motion, Inc., Germantown, MD, USA). A representation of the upper body segments and joints used for analysis can be seen in Figure 2. Kinetic data were filtered with a 4th order, zero lag Butterworth filter at 50 Hz. Wrist, Elbow, and Shoulder joint power was calculated in Visual3D and exported for analysis in a custom program within MATLAB software. Joint power signals were normalized by body mass (kg) for each participant. Eccentric and concentric phases from each push-up were identified for each push-up repetition based on the energetics of the forearm and upper arm segments (Robertson & Winter, 1980). A push-up cycle was defined by the elbow joint velocity; the cycle started with the initiation of downward movement and continued until the participant moved back into the plank position (Figure 3).

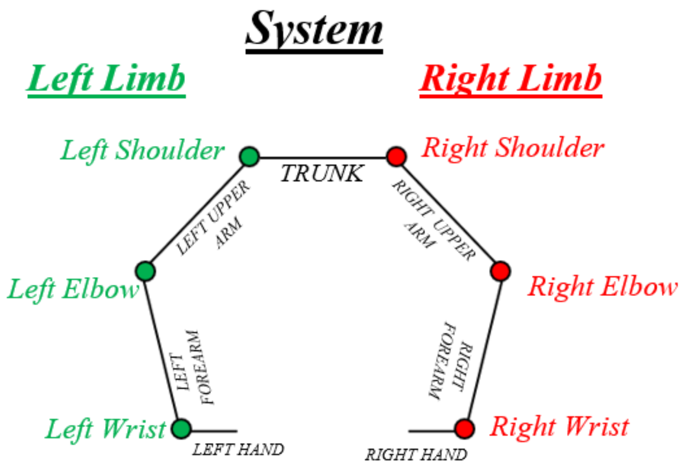


Figure 2. A simplified model of the upper limbs was used in analysis consisting of hand, forearm, upper arm and trunk segments. Joint power was calculated bilaterally at the wrists, elbows and shoulder joints. The left and right limbs consisted of one wrist, elbow and shoulder joint while the system consisted of the two limbs.

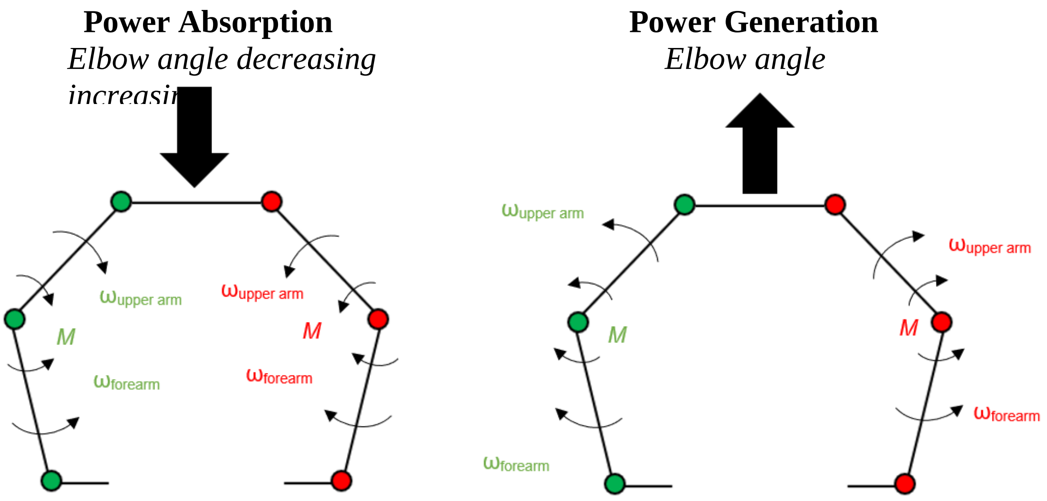


Figure 3. Eccentric and Concentric movement phases were defined based on the angular velocity of the upper arm and forearm segments. Decreasing elbow angles

(A) correspond with power production by the forearm and upper arm. Positive elbow joint angular velocity (B) corresponds with power generation by the two arm segments. The angular velocities (bold arrows) as well as the moment (M; thin arrows) of each segment is indicated.

Shifts in employed motor synergies were quantified by determining how the time profiles of joint power in 3-dimensional joint space shifted over push-up repetitions. The overall power generated by the left (L) and right (R) limbs was calculated by taking the sum of the power produced at the wrist (WRI), elbow (ELB) and shoulder (SHO) joints within the limb:

$$P_R = P_{RSHO} + P_{RELB} + P_{RWRI} \qquad [2a]$$

or

$$P_L = P_{LSHO} + P_{RELB} + P_{RWRI} \qquad [2b]$$

Where P represents the time series of joint power data and P_L / P_R denotes the total linear power generated or absorbed by each limb. Total system power was calculated as the sum of the two limb powers:

$$P_{System} = P_L + P_R \qquad [3]$$

Synergy Calculations

Between-limb and within-limb joint pair synergy (SYN) for each repetition were calculated using the following equation:

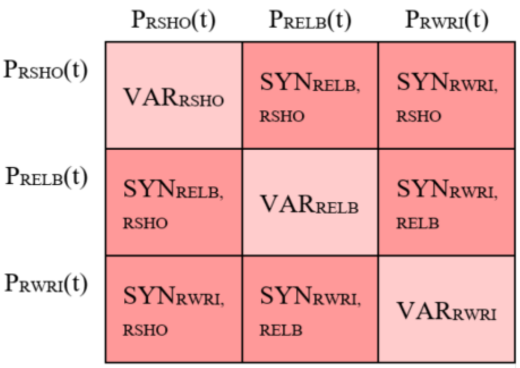
$$SYN_{xy} = \sum_{i=1}^{n} \frac{(x_i - \bar{x}) - (y_i - \bar{y})}{n-1} \qquad [4]$$

Where, for example for the between-limb analysis, x_i = left limb power signal, $\bar{x}$ = mean of left limb power throughout the *i*th repetition, y_i = right limb power signal, $\bar{y}$ = mean of right limb power throughout the i^{th} repetition, and n = number of push-up repetitions performed in the push-up trial. Equation four was used to calculate synergy between-limbs and between the three possible pairs of joints within each limb (Tables 1, and 2). Within-limb synergy was calculated as the sum of the synergies between the three within-limb joint pairs. The variance of each joint power signal was calculated for each push-up repetition (Table 1, and 2).

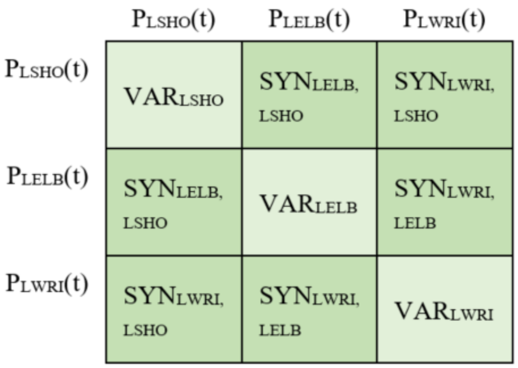
Table 1. Variance and covariance matrices between limbs. Variance is indicated across the diagonal of each matrix and covariance for each pair is shown below and above the diagonal row of variance.

	$P_L(t)$	$P_R(t)$
$P_L(t)$	VAR_L	SYN_{RL}
$P_R(t)$	SYN_{RL}	VAR_R

Table 2. Variance and covariance matrices for signals within the right limb (a; red) and left limb (b; green). Variance is indicated across the diagonal of each matrix and covariance for each pair is shown below and above the diagonal row of variance.



	$P_{RSHO}(t)$	$P_{RELB}(t)$	$P_{RWRI}(t)$
$P_{RSHO}(t)$	VAR_{RSHO}	$SYN_{RELB, RSHO}$	$SYN_{RWRI, RSHO}$
$P_{RELB}(t)$	$SYN_{RELB, RSHO}$	VAR_{RELB}	$SYN_{RWRI, RELB}$
$P_{RWRI}(t)$	$SYN_{RWRI, RSHO}$	$SYN_{RWRI, RELB}$	VAR_{RWRI}



	$P_{LSHO}(t)$	$P_{LELB}(t)$	$P_{LWRI}(t)$
$P_{LSHO}(t)$	VAR_{LSHO}	$SYN_{LELB, LSHO}$	$SYN_{LWRI, LSHO}$
$P_{LELB}(t)$	$SYN_{LELB, LSHO}$	VAR_{LELB}	$SYN_{LWRI, LELB}$
$P_{LWRI}(t)$	$SYN_{LWRI, LSHO}$	$SYN_{LWRI, LELB}$	VAR_{LWRI}

For example, synergy within the left limb was calculated as:

$$SYN_L = SYN_{L_{SHO}\&\, L_{ELB}} + SYN_{L_{ELB}\&\, L_{WRI}} + SYN_{L_{SHO}\&\, L_{WRI}} \qquad [5a]$$

And the synergy within the left limb was calculated as:

$$SYN_R = SYN_{R_{SHO}\&\, R_{ELB}} + SYN_{R_{ELB}\&\, R_{WRI}} + SYN_{R_{SHO}\&\, R_{WRI}} \qquad [5b]$$

Statistics

As participants performed a different number of repetitions ($sample\ size: n_i$) before reaching volitional fatigue, independent correlations (r_i) across participants were transformed into a Fisher's *z* with the following computation:

$$z_i = \tanh^{-1} r_i \qquad [6]$$

Where *i* is a placeholder for each participant. In order to assess the group trend throughout the push-up trial, the mean of the values $\bar{z}$, was computed as being weighted by n - 3 (Alexander, Scozzaro, & Borodkin, 1989):

$$\bar{z} = \frac{\sum(n_i - 3)z_i}{(\sum n_i - 3k)} \qquad [7]$$

Where *k* is equal to the number of participants (*k* = 10 for EMG data, *k* = 11 for all joint power analysis). Mean correlation of all the samples from all the participants was calculated by using the following relationship between r and Fischer's z:

$$\bar{r} = \tanh \bar{z} \qquad [8]$$

The first null hypotheses (H_{01} and H_{02}) that the mean correlations of specific outcome measures were zero, were tested by performing a *z*-test with the following critical value (Kenny, 1987):

$$z_{crit} = \frac{\bar{z}}{\sqrt{\sum n_i - 3}} \qquad [9]$$

The null hypothesis was rejected if z_{crit} > +/-1.96 at α= 0.05 or +/-2.58.

Testing the second null hypothesis (H_{02}) that the synergies between eccentric and concentric movement phases would be equal, required calculation of mean Fischer's *z* values for each movement phase ($\bar{z}_1\ for\ concentric, \bar{z}_2\ for\ eccentric$) as previously described. To test whether the correlation coefficients of were equal a critical value for *z* was computed in the following way (Kenny, 1987):

$$z_{crit} = \frac{\bar{z}_1 - \bar{z}_2}{\sqrt{\frac{1}{n_1 - 3} + \frac{1}{n_2 - 3}}} \qquad [10]$$

Where the null hypothesis was rejected if z_{crit} > +/-1.96 at α = 0.05.

Chapter 3: Results

Participants

Twenty-eight participants were consented and completed the push-up trial. Due to marker sets missing trunk markers, kinetic datasets with complete joint power data were obtained from eleven participants and used for analysis. Demographic information along with the number of completed push-up repetitions that each participant performed in the trial are listed in Table 3.

Table 3. Participant Demographics and count of push-ups performed in trial.

Participant number	Gender	Age (yr.)	Height (m)	Mass (kg)	Dominant Arm
1	Female	22	1.62	52.4	Right
2	Female	21	1.74	70.5	Right
3	Female	22	1.68	76.0	Right
4	Female	20	1.67	58.7	Right
5	Male	20	1.87	93.2	Right
6	Female	20	1.54	48.1	Left
7	Male	23	1.70	81.9	Right
8	Female	19	1.66	60.1	Right
9	Male	21	1.78	74.1	Right
10	Male	25	1.86	95.0	Right
11	Male	25	1.88	94.9	Left

Electromyographic Activity

Complete EMG datasets were collected from 10 of the 11 participants. One sensor placed on the left triceps of Participant 7 was not secured correctly and fell off during collection.

Mean correlations $(\bar{r}_{MNF})$ for the median frequency throughout the push-up trial decreased significantly for all four EMG signals (Figure 4; all $\bar{r}_{MNF} < -0.43$, all $p < 0.01$). Correlation coefficients for MNF over the push-up trial were obtained for each participant are recorded in Appendix A (Table A.1). This alteration in the EMG signal supports our expectation that volitional fatigue would induce muscular fatigue. Decreasing MNF suggests that a resynchronization of control signals and a reduction of firing rates of the muscles is occurring at the muscle level of the movement. Correlation coefficients for MNF over the push-up trial were obtained for each participant are recorded in Appendix A (Table A.1).

Greater magnitudes of voltages in the action potential resulted in greater iEMG over the push-up trial. Individual participant correlation coefficients for the iEMG trend over the push-up trial are recorded in Appendix A (Table A.1). Mean correlation coefficients $(\bar{r}_{iemg})$ obtained from the activation signals indicated that muscle activation was greater throughout the push-up trial (Figure 5, all $p < 0.01$). This suggests that performing push-ups to volitional fatigue is resulting in muscular fatigue at the bilateral triceps brachii and pectoralis major muscle groups. Additional motor units are being recruited resulting in greater magnitudes of peak voltages in the action potential recorded by the EMG sensor. This finding also supports our expectation that repetitions of push-ups would induce muscular fatigue of the main muscle groups used for this motor task.

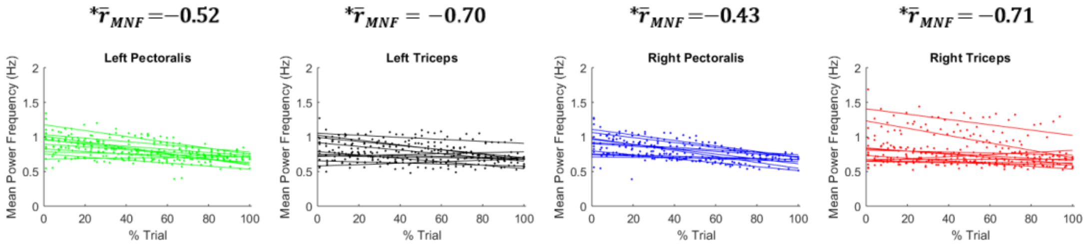


Figure 4. The mean power frequency (MNF) of the four EMG signals over each push-up repetition is displayed (dot). The trendline for each participant is indicated with a thin line. The mean correlations of all four EMG signals indicated significant ($p < 0.01$) decreases in MNF throughout the trial.

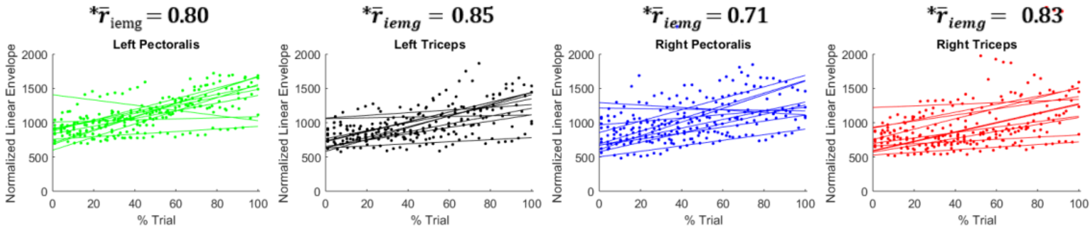


Figure 5. Integrated, normalized linear envelopes for all participants throughout the push-up trial. The integrated linear envelope (iemg) result for each push-up repetition is indicated with a dot. The trendline for each participant is indicated with the thin lines. Mean correlation coefficients for all signals were significantly greater (all $p <$ 0.01) throughout the push-up trial.

Joint Work

The net work performed by the system of two upper limbs decreased ($\bar{r}_{Wnet} = 0.11$, $p < 0.01$) throughout the push-up trials (Figure 6). Similarly, the net work performed by the left limb decreased ($\bar{r}_{Wnet} = 0.11$, $p < 0.01$). However, the net work performed by the right limb did not reduce throughout the trial ($\bar{r}_{Wnet} = 0.00$, $p =$ 0.47). The positive work generated by the system, left limb, and right limb reduced throughout the trial by an average of 27% ($\bar{r}_{Wpos} = -0.54$, $p < 0.01$)., 20% ($\bar{r}_{Wpos} = -0.23$, $p < 0.01$), and 33% ($\bar{r}_{Wpos} = -0.14$, $p < 0.01$), respectively. Likewise, the magnitude of negative work absorbed by the system, left limb and right limb decreased over the push up trial by 27% ($\bar{r}_{Wneg} = 0.36$, $p < 0.01$), 23% ($\bar{r}_{Wneg} = 0.19$, $p < 0.01$), and 32% ($\bar{r}_{Wneg} = 0.11$, $p < 0.01$). Reductions in work of the system and limbs throughout the trial were not expected, though consistent reductions are seen in system and left limb work for all participants. The net power of the right limb was not consistent for all participants. Individual participant correlation coefficients for positive, net, and negative work performed by the system and limbs are included in Appendix A (Table A.2).

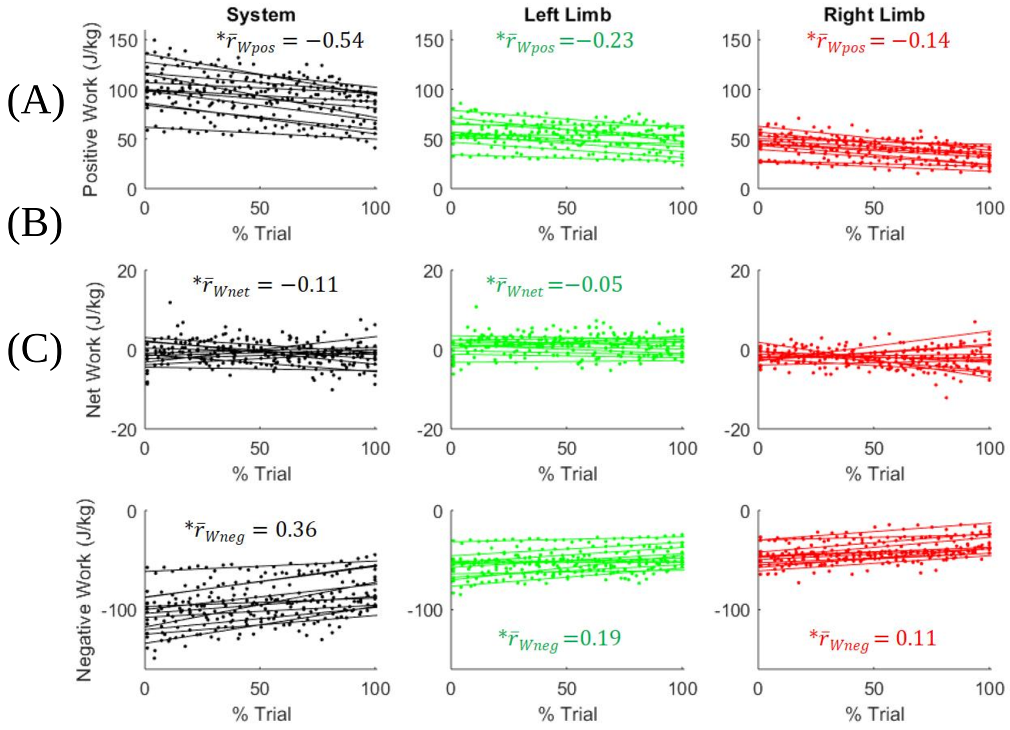


Figure 6. Positive (A), net (B), and negative (C) work performed by the system (black), left limb (green) and right limb (red). Data is shown for each repetition (dot) and data is normalized to the push-up trial. Linear trendlines for each participant are shown.

Joint Power PCA

Principal component analysis of all six joint power signals within each repetition throughout the trial indicated that, on average, the first principal component (PC) accounted for 96.8 (0.8) % of the total variance (Figure 7). The second PC accounted for 2.5 (0.7) % of the variance. All other PCs each accounted for less than 1% of variance in the dataset (Table 4).

Table 4. Joint loadings and variance explained by each principal component.

	PC1		PC2		PC3		PC4		PC5		PC6	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Right Shoulder	0.47	0.12	0.15	0.34	0.42	0.42	0.00	0.08	-0.02	0.03	0.00	0.01
Left Shoulder	0.74	0.09	-0.18	0.21	-0.24	0.28	-0.06	0.08	-0.01	0.03	0.00	0.01
Right Elbow	0.24	0.32	0.21	0.31	-0.03	0.30	0.06	0.41	0.01	0.08	0.01	0.02
Left Elbow	0.31	0.07	0.17	0.29	0.03	0.30	0.13	0.41	0.07	0.06	0.01	0.04
Right Wrist	0.00	0.00	-0.02	0.21	0.00	0.03	0.01	0.04	0.56	0.18	0.44	0.47
Left Wrist	0.00	0.01	-0.02	0.04	0.01	0.03	0.00	0.08	0.72	0.16	-0.06	0.48
% Variance Explained	**96.79**	**0.79**	**2.45**	**0.74**	**0.60**	**0.23**	**0.13**	**0.07**	**0.02**	**0.01**	**0.00**	**0.00**

The first PC was heavily loaded by the contributions of the power signals from the elbows and shoulders (Table 4). These loading scores can range from -1 to 1 and represent what signals are changing to account for the total variance. Loadings within the first PC suggest that the shoulders and elbows contribute to the main control strategy, whereas the loadings of the right and left wrists in PC1 were near zero and did not contribute. Relatively large standard deviations of joint loadings within additional PCs were not consistent for all participants, however these PC accounted for less 5% of the total variance of the dataset. These results support previous findings from muscle activation analysis which determined that the elbows and shoulders contribute most to conventional push-up motor tasks (Youdas et al., 2010). Display of the joint power data along the first two principal components (Figure 8) allows for visualization of the largest variability along the first principal component on the horizontal axis. This is the largest possible variance among all possible choices of the first axis within the data set. The variability along the second principal component axis is the largest among all possible remaining choices and is displayed along the vertical axis.

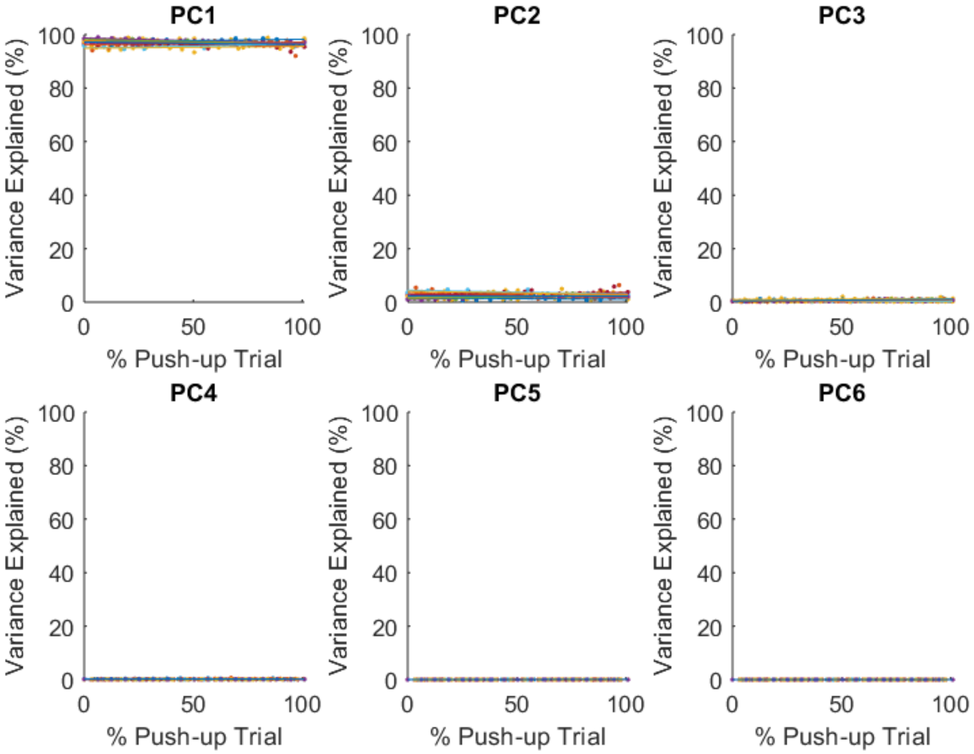


Figure 7. Variance explained by each of the six principal components (PC) for all repetitions from all participants over the normalized push-up trial. Each dot indicates the variance explained for one push-up repetition. Trendlines from each participant's variance throughout the push-up trial are shown (thin lines).

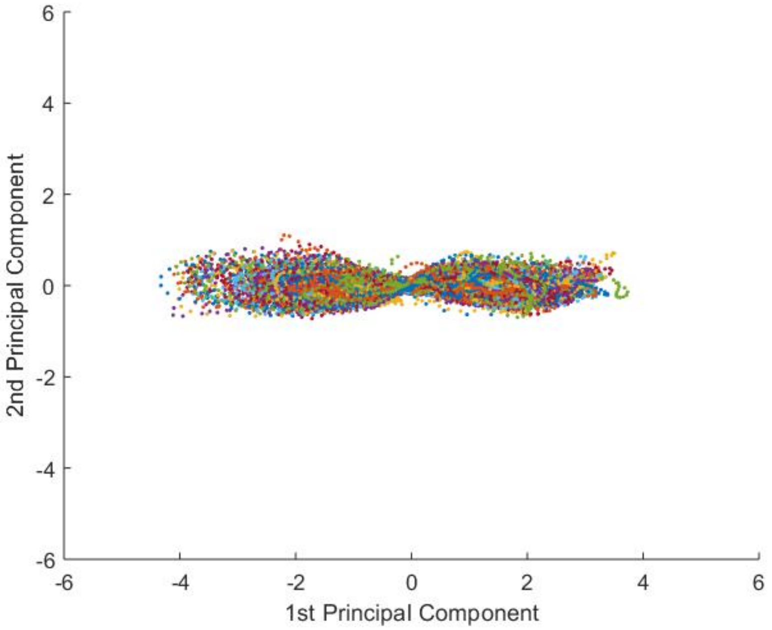


Figure 8. Data from all push-up repetitions (dot) plotted for all participants with respect to the first and second principal component axes. The data shows the largest variability along the first principal component axis on the horizontal. This is the largest possible variance among all possible choices of the first axis. The variability along the second principal component axis is the largest among all possible remaining choices of the second axis and is displayed vertically.

Joint and Limb Power

The wrist, elbow, and shoulder joints all absorbed power (indicated by negative values) during downward, eccentric movement and generated (positive values) power during upward concentric movement (Figure 9). Within left (Figure 9a) and right (Figure 9b) limbs, wrist power was smaller in magnitude than the power produced by the elbow or shoulder joints. Visual inspection of this figure indicates that the peak shoulder power during power absorption and generation was more variable for the left limb. Mean shoulder joint power of the group was comparable between right and left limbs.

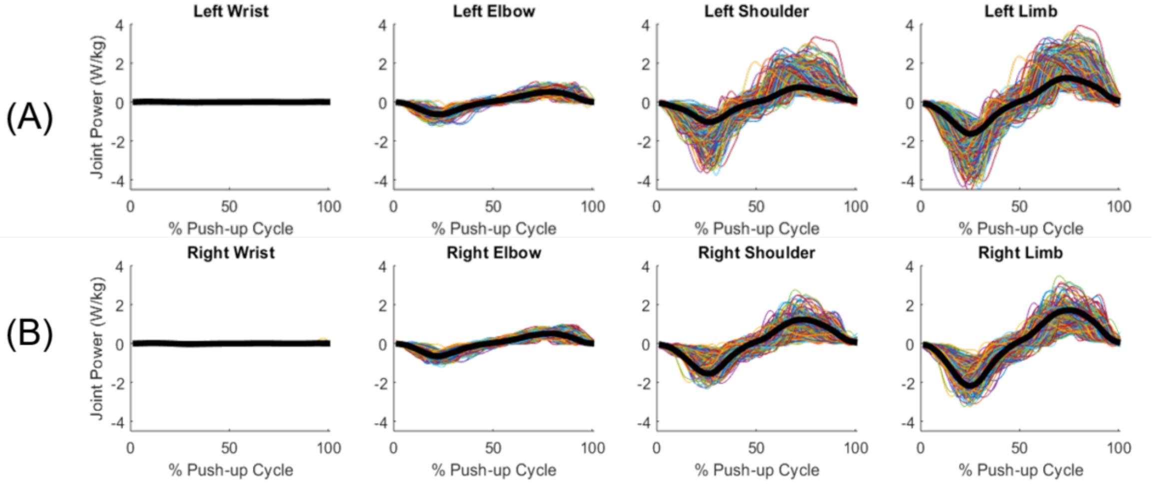


Figure 9. Left (a) and right (b) joint power signals normalized by for the wrists, elbows, shoulders, and limbs. All power signals from every repetition (dot) for all participants are shown in varying colors with the mean of all repetitions in bold black.

Joint Power Variances

Joint power variance over each repetition was expected to increase if the CNS altered the control strategy to utilize motor abundancy to meet power requirements. However, the variance of the joint power signal produced by the system of limbs, the power produced by each limb, as well as the power signal produced at the elbows and shoulder joints all significantly reduced (all $p < 0.01$; Figure 10) throughout the push-up trial. Conversely, the variance at both wrists remained consistent throughout the push-up trial. An overall reduction in variance of power could be associated with the reduced positive and negative work performed by the system and limbs. Variance trends for each participant are included in Appendix B (Table B.1).

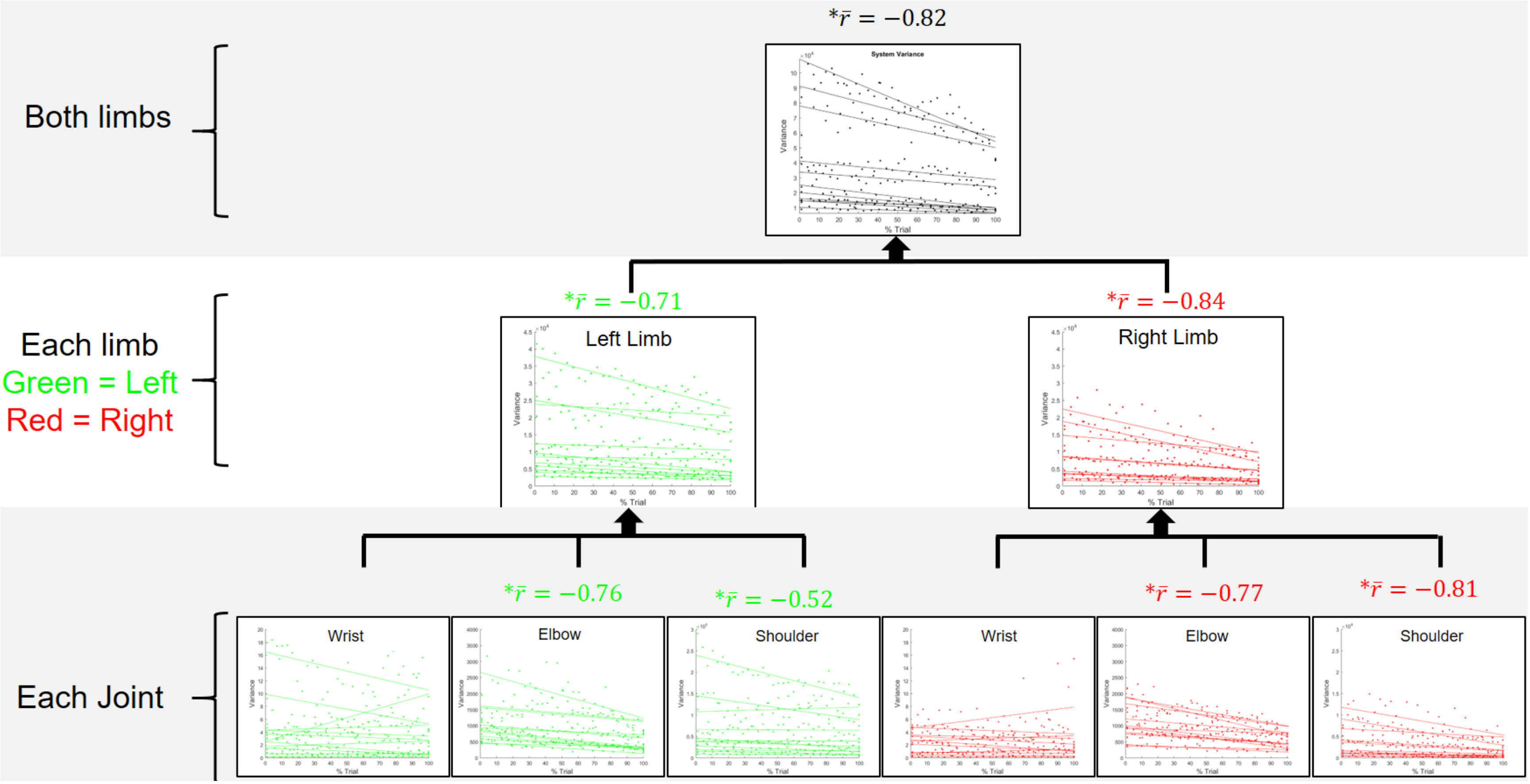


Figure 10. Variance of the system, each limb and each joint throughout the push up trial. Each dot represents the variance between signals for a push-up repetition. Thin lines indicate trends for each participant over the push-up trial (normalized to time). Bold lines represent the group trendline. Asterisks indicate that the slope of the group trendline is statistically different than zero (* $p < 0.05$). The scales of the graphs are the same between- limbs and between joints.

Joint Power Covariances: Synergies

Synergy between limbs, within-limbs and between the within-limb elbow and shoulder power signals were positive however, magnitude significantly (all $p < 0.01$) reduced throughout the trial (Figure 11). The wrist and elbow joint power pairs indicated the opposite relationship, with greater synergy created between the joints throughout the push-up trial. Notably, bilaterally some repetitions indicated negative synergy between the wrist and elbow or wrist and shoulder pairs. These findings are in direct opposition to what was expected under H1, the idea that synergies would increase to overcome the effect of fatigue is not supported. Pearson correlation coefficients for the covariance of joint powers throughout the trial are included in Appendix B for each participant (Table B.2).

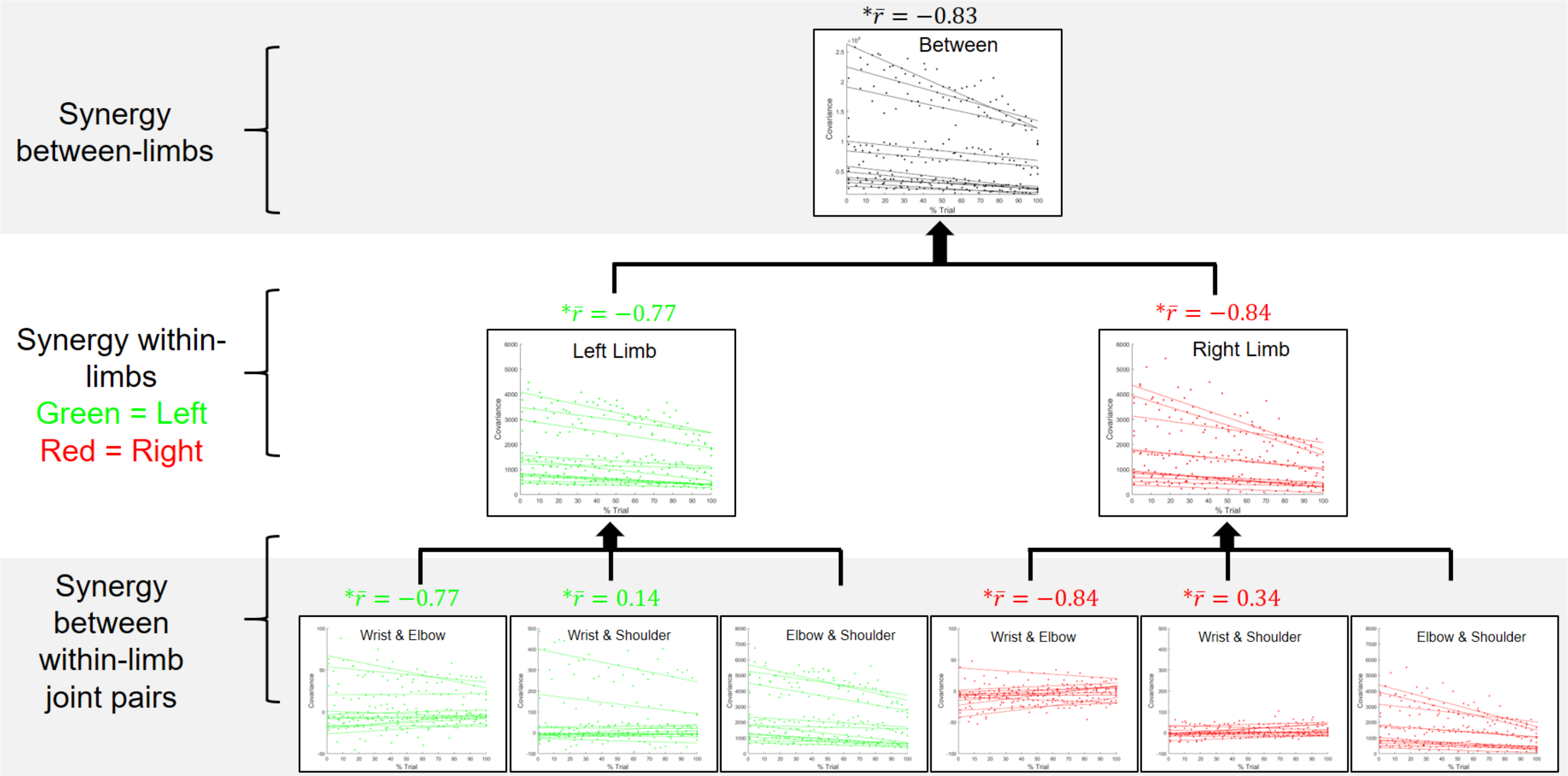


Figure 11. Between-limb, within-limb and between joint pair synergy as computed by covariance between the power signals of each repetition. Each dot represents the covariance between signals for a push-up repetition. Thin lines indicate trends for each participant over the push-up trial (normalized to time). Bold lines represent the group trendline. Asterisks indicate that the slope of the group trendline is statistically different than zero (* $p < 0.05$). The scales of the graphs are the same between limbs and between joint pairs.

Eccentric vs. Concentric Joint Power Synergies

Mean correlation coefficients between-limbs, within the right and left limbs, and between the within right and left elbows and shoulder joint pairs significantly reduced throughout the push-up trial for both eccentric and concentric movements (all $\bar{r}$'s are negative, all $^*p < 0.01$). Additionally, during concentric movement the synergy between the left and right wrist and shoulder joint pair as well as the left wrist and elbow joint pair reduced throughout the push-up trial (all $^*p < 0.01$).

The between-limb synergistic changes between eccentric and concentric movement phases for the system and left limb were not equal throughout the push-up cycle ($^{\S}p < 0.01$), with greater synergy reductions throughout concentric movement analysis. Within-limb comparisons of mean correlation coefficients between eccentric and concentric movement phases at a greater rate during concentric muscle contractions (both $^{\S}p < 0.01$). Similarly, synergy reductions at the bilateral elbow and shoulder joint pairs were greater during concentric analysis ($^{\S}p < 0.01$). The wrist and elbow as well as wrist and shoulder joint pairs within the left limb indicated differential changes in synergy between the movement phases (both $^{\S}p < 0.01$) with only significant reductions in concentric joint pair synergy. Conversely, comparisons of mean correlation coefficients for eccentric and concentric phases within the right limb wrist and elbow as well as wrist and shoulder joint pairs did not suggest any differential changes in synergy between movement phases (all $p \geq 0.11$).

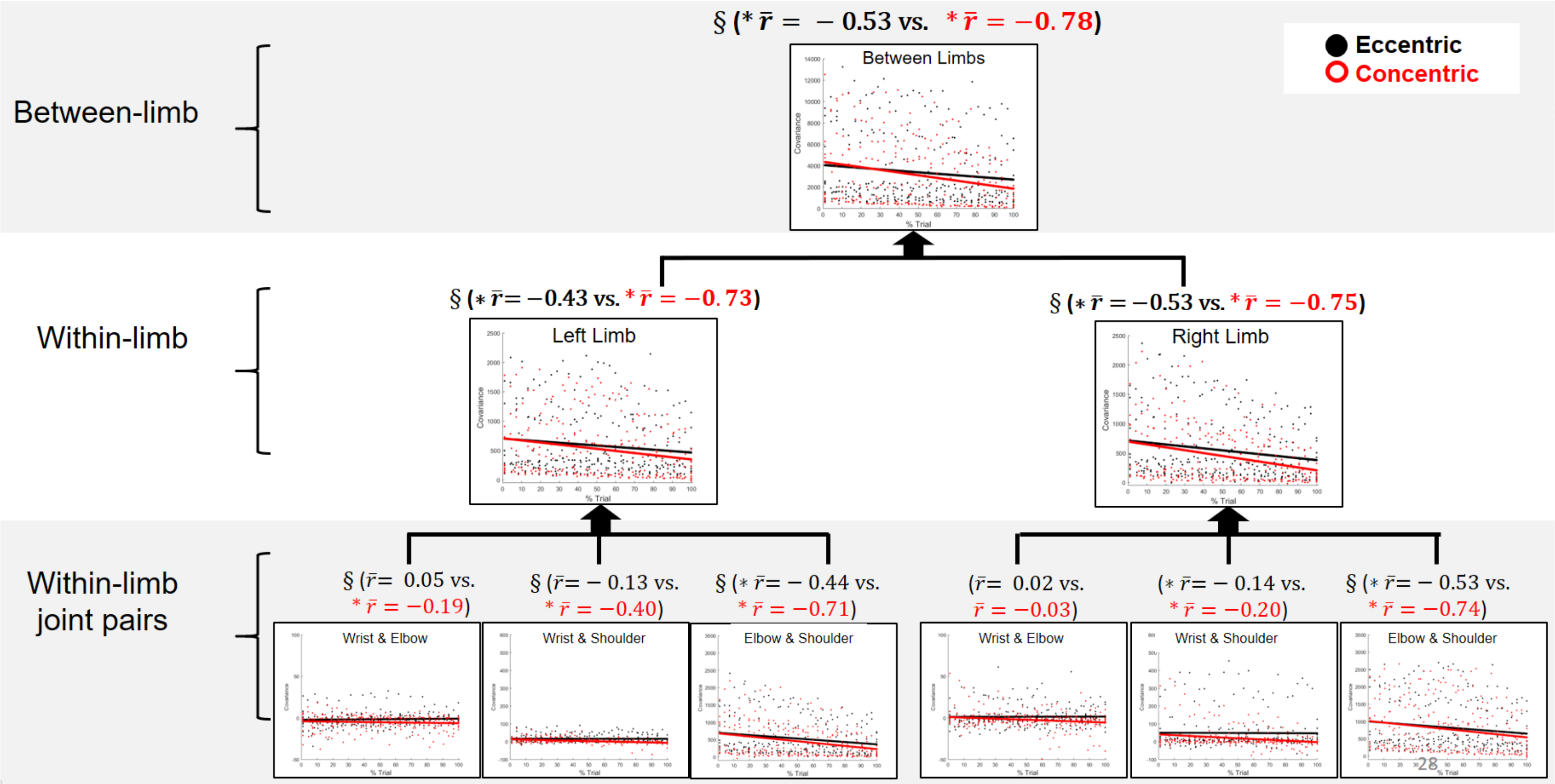


Figure 12. Between-limb, within-limb, and between joint pair covariance among eccentric (black) and concentric movement phases. Each dot represents the covariance calculated for a push-up repetition. Thick lines indicate the line of best fit for data from all participants (normalized to time). Asterisks indicate that mean correlation is statistically different than zero (* $p < 0.05$) and § indicates that the mean correlations are statistically different between eccentric and concentric movement phases (§ $p < 0.05$).

Chapter 4: Title of Chapter 4

This work aimed to determine if abundant motor solutions were used to complete a motor task throughout the challenge of fatigue. The experimental paradigm of conventional push-up repetitions was used. Changes in the elemental variables of joint power production were investigated within and between the limbs. The motor task required a certain amount of work be done to move the body's center of mass up and down. It was expected that as power production capabilities by the elemental variables reduced throughout fatigue, the CNS would adapt strategies and increase synchronization of joint power production, both within-and between the limbs, to meet work requirements of the motor task. The rate of synergy changes throughout the trial were expected to be different for eccentric and concentric movement phases due to the utilization and greater force production capability within downward movement.

General Trends in Data

Volitional Fatigue Induces Muscular Fatigue

This work used the experimental paradigm of repeated push-up movements to investigate how the central nervous system controls a redundant motor system when facing the challenge of fatigue. This paradigm required that participant complete push-ups at a controlled cadence until volitional fatigue was reached. Through analyses of muscle activation signals, as measured by EMG sensors, volitional fatigue was associated with indications of muscular fatigue. Specifically, the computed MNF of the surface EMG signals obtained from the bilateral triceps brachii and pectoralis major muscles during push-up repetitions were found to significantly reduce throughout the push-up trial. This result indicates that the muscle firing frequency reduced, which is thought to indicate a resynchronization of the control signal and show a reduction in firing rates of the muscle (De Luca, 1984). In addition, analysis of the mean trend of iEMG of the four muscles was greater throughout the push-up trial. Greater iEMG of the signals indicated that greater muscle activations were produced by muscles as participants neared volitional fatigue. The reduction of muscle firing frequency and greater muscle activations suggest that volitional fatigue produces muscular fatigue of the triceps brachii and pectoral major muscles.

This interpretation of muscular fatigue is limited to the analysis of the EMG signals obtained bilaterally at the triceps brachii and pectoralis major muscles. These EMG sites were selected as the triceps brachii and pectoralis major muscles are known to be the main muscle groups recruited to perform conventional style push-up movements (Youdas et al., 2010). Fatigue of the main muscle groups used for this motor task indicate that the independent variable of fatigue significantly increased throughout completion of the push-up trial. Although push-ups are commonly used as tests of endurance, this study is the first quantitative report of how muscular fatigue is established at the main muscle groups.

Mechanical Work Decreases Over Push-up Repetitions

It was expected that participants would repeat the same conventional push-up motion to volitional fatigue and the work performed by the system would be similar between all repetitions of the push-up trial. Yet, examination of the net, positive, and negative work produced by the system and individual limbs (Figure 6) indicated a decrease in net work performed by the system, explained by significant reductions in the net work performed by the left limb. Although participants were verbally instructed to keep the same conventional push-up form throughout push-up repetitions, the net work performed by the system significantly reduced throughout the push-up trial. Although the mechanical output of the upper-limb model reduced, the push-up motor task was completed. This may be explained by contributions to the movement from other body segments not modeled.

Muscular fatigue is known to reduce the ability of muscles to produce force, thus reducing the torque generated at the joints, which reduces power production capability. It is not likely that the same motion was performed at a more efficient rate as participants neared volitional fatigue. It is possible that the range of motion of the body or the positioning of arms, while keeping hands in contact with the floor, was gradually altered throughout the trial. Although these findings were not expected, it is advantageous to know that human participants may resort to forms of motor abundancy not investigated in this thesis, such as changing joint configurations when unable to stabilize total, net work production.

CNS Relies on Elbow and Shoulder Joints

Principal component analysis was used to systematically analyze correlations between the six of power signals produced throughout every push-up repetition. Most (96.8%) of the total variance in the joint power signals were explained by one principal component axis. The elemental variables controlled by the first PC included the bilateral elbow and shoulder joint power signals, but not the wrists. This result indicates that throughout the push-up trial, push-up repetitions were performed by a synergy defined by the concurrent power generation or power absorption at the bilateral elbows and shoulders.

Although it is impossible to represent the six-dimensional joint power space used for PCA, the joint power produced by each limb can be visualized in 3D (wrist, elbow, shoulder) joint power space (Figure 13). In line with the results obtained from PCA, most of the joint power is produced by the shoulders or elbows. Power is produced or absorbed in a “figure-eight” shape throughout the push-up cycle. This 3D representation supports the six-dimensional PCA analysis and shows that the CNS is activating the elbow and shoulders at the same time to generate or absorb power while performing the push-up motion.

Within Figure 13, little reliance and variability within the wrist power signal is seen. This could signify that the upper limb system is not as abundant as we expected when constrained to performing conventional style push-up repetitions. If the wrist were to shift strategies and start to contribute to power production, the variability of the signal would have increased. Results indicate that there was little contribution by the wrist joint throughout the push-up trial as compared to the elbows and shoulders. One control method, which relied on the bilateral elbow and shoulder joints was used throughout the trial.

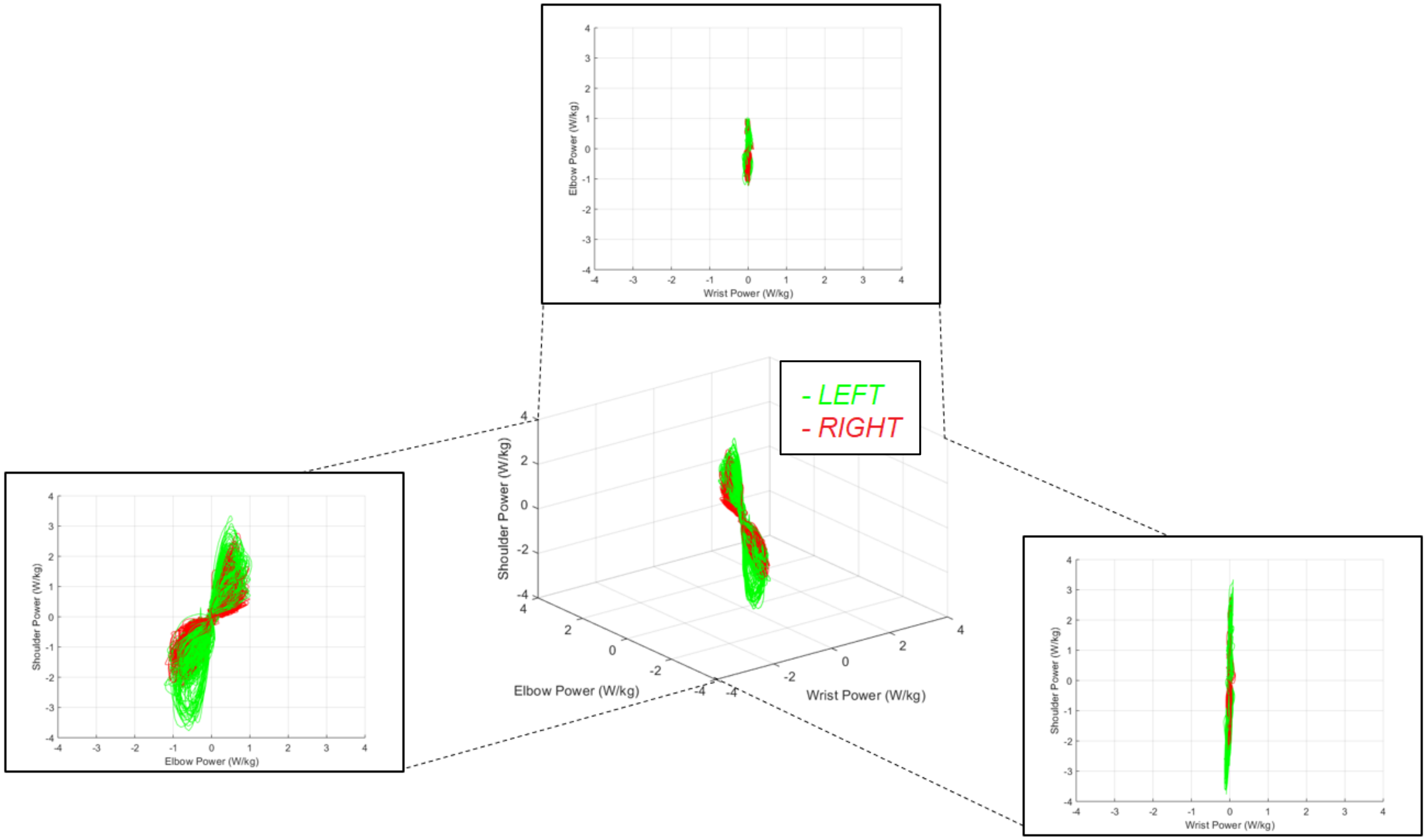


Figure 13. Wrist, elbow and shoulder joint power space for one representative participant (middle, 3D plot). Green lines indicate all the power traces obtained from the left limb and red indicates signals from the right arm. The surrounding 2D plots demonstrate the power between all possible pairs of joint within the left and right limbs.

Joint Power Variance and Synergy

Joint Power Variance

Analysis of joint power variance as well as between-limb, and within-limb covariance was performed to determine if the strategy used by the CNS of joint power production was altered as the system faced the challenge of fatigue. The main results indicated reductions in joint power variance and synergy throughout the push-up trial.

Throughout the push-up trial the magnitude of joint power produced at the elbows and shoulders was consistently greater than the joint power produced at the wrists (Figure 9). This may be due to the limited range of motion at the wrists during the push-up motion. The hand position within a conventional push-up requires that the hand remains positioned with fingers pointed cranially. The wrist joint remains flexed throughout the movement. The wrists small contributions to total system power may also be explained mechanically by the closeness between the line of action between the ground reaction force and wrist joint axis. The limited motion of the wrist joint may also explain why wrist joint variance was not found to significantly increase or decrease throughout the push-up trial (Figure 5).

Under H1, the variance of the joint power signals over a push-up repetition were expected to increase throughout the push-up trial. This increase in joint power variance would indicate a change in strategy in the way that the system power was produced after fatigue. However, the variance of the power signals obtained at each limb as well as at the elbows and shoulder joints decreased throughout the push-up trial. Decreasing joint power variance indicates that the solution identified in the joint power space narrows in range. This decrease in variance could indicate that a more precise motor solution was obtained, but this would be reliant on the verification of consistency of movement. As previously mentioned, the work produced throughout the push-up trial significantly decreased and may indicate a reduction of range of motion or change of arm positioning. The reduction in joint power variance could be associated with the reduction in overall positive and negative work produced by the system and limbs.

Joint Power Synergy

It was expected that between and within-limb synergy would be greater throughout the push-up trial to account for the effects of muscular fatigue. As mentioned, the contribution of the wrist joints to push-up power was limited. Consequently, H2 relied on the resynchronization of the power signals produced at the elbow and shoulder joints throughout progressive push-up repetitions. Greater between-limb and within-limb synergy was expected to gradually maximize the absorbed or generated power necessary within a push-up repetition to compensate for the reduced power generation. Opposite to hypothesis expectations, between-limb synergy decreased throughout the push-up trial. Likewise, the mean correlation coefficients for synergy within-limbs, and within the bilateral elbow and shoulder joint pars decreased significantly throughout the push-up trial (Figure 11). This reduction in synergy between the pair of joints that contribute most to power generation and absorption indicates that power production patterns are less in sync with every push-up repetition. Overall, power is produced in a less efficient way throughout the push-up trial due to the influence of fatigue. As overall within-limb covariance was computed as the summation of the paired joint covariances, clearly the reduction in the elbow and shoulders are responsible for the overall reduction of joint power synergy. Even though between-limb and within-limb synergy reduced, bilaterally, the synergy between the pairs of wrist and elbow joints was significantly greater throughout the push-up trial. As previously mentioned, the wrist range of motion and power production was limited. The increase of synergy between the wrist and elbow joint pairs was in line with H2, however did not contribute enough to overcome fatigue effects at the limb level, due to the small amount of power produced by the wrist joints. Greater power production of the wrist joint does not make intuitive sense as the limited range of motion prevents wrist joint torque or greater wrist joint angular velocity. Thus, this increase in synergy between the elbows and wrists suggest a repositioning of the forearm segment and not greater power production or absorption by the wrist joints which can be investigated in future work.

Fatigue influences the effectiveness of the control strategy used for power production, specifically it reduces the ability of the bilateral elbows and shoulder joints to work together. These joints become less efficient, leading to alterations in the required movement that reduce the mechanical output of the system. As the between-limbs, within-limb and within the shoulder and elbow joint synergy all reduced, fatigue results in the shoulder and elbow joints producing less power in a less synchronized pattern. Instead of an increase in synergy between power signals to optimize power production, the pattern of movement may have been changed. The limited wrist range of motion may limit the abundancy available within this motor task. The push-up is test of endurance and it seems that the large power requirement from both the elbows and shoulders inhibit the CNS from changing joint production strategy or increasing joint pair synergy to overcome fatigue effects.

Synergy Between Eccentric and Concentric Phases

It was hypothesized that the fatigue of the upper limb joints over push-up repetitions would lead to differential changes in motor synergies between eccentric and concentric movements. It was predicted that the changes in strategy by movement phase would be demonstrated by stronger, more positive, motor synergies in concentric movements as compared to eccentric movements after fatigue. Although data indicates that the muscular fatigue led to a differential change in system joint synergy between movement phases, synergy decreased throughout the push-up trial (Figure 10). Diminished synergies throughout the push-up trial indicates the system was unable to compensate for fatigue by increasing synchronization and instead faced increasingly worse synchronization of power signals. The fatigue effects, specifically the decreased force production capability of the muscles, resulted in less synchronous absorption and generation of joint power signals. Other than the direction of synergy throughout the trial, the rate of change of synergy was indeed greater in concentric opposed to eccentric movement phases.

It was expected that motor synergy patterns would not change in the downward movement phase due to the increased available force production within eccentric contractions. Eccentric contractions at a controlled velocity are also assisted by gravity. Even with these advantages significant reductions in synergy between and within-the limbs were noted within the eccentric movement phase. Between-limb and within-limb synergy decreased significantly throughout the push-up trial. Bilaterally there was a significant decrease in eccentric synergy between elbow and shoulder joints, which seems to be the primary contributor to the overall reductions in between and within-limb eccentric synergistics. Likewise, concentric analysis indicated between-limb and within-limb reductions in joint power synergy. Reduction of synergy at the limb and system levels are likely due to significant reductions in synergistics between the bilateral elbow and shoulder pairs. Interestingly, the concentric reductions in between-limbs, within-limbs, and within the bilateral elbow and shoulder pairs were greater than the reductions experienced within the eccentric movement phase. These results support H2’s expectation of differential changes between movement phases. It is likely that eccentric movements indicated greater synergistics due to the assistance of gravity and force production advantages which reduce the effect of muscular fatigue. This differential change between phases is emphasized within the synergy of the bilateral pair of shoulder and wrist joints. At this joint pair the concentric movement indicated that the synergy reduced significantly while eccentric synergy was not significantly different throughout the push-up trial. A similar pattern was seen at the left wrist and elbow, where concentric movement reduced synergistics but eccentric movement indicated no change in synergy. Although joint power synergistics were negatively affected by fatigue, the rate of change in synergy within each movement phase was not equal.

Overall, H2 was supported. Concentric movements, where muscle actions must overcome gravity and a lower force production ability, show greater rates of decreased synergy than eccentric movements. These differential changes in synergy throughout the fatiguing task of push-up repetitions suggests that the synergistic relationship between and within limbs is dependent on the type of muscle contraction performed.

Limitations

The model used in this analysis consisted of upper limb body segments only. Future work should investigate if positions of other body segments could have been used to change the center of mass position, reducing the work required in the push-up motion. The shoulder joint in the model used was modeled as a ball joint between the upper arm and thorax segments. This model is a simplification of the anatomical shoulder joint axes.

Chapter 5: Conclusion

This research was performed to determine if the CNS used motor abundancy throughout the challenge of fatigue. Performing repeated push-ups to volitional fatigue induced muscular fatigue of the main muscle groups used in this motor task as per frequency domain analysis of upper-limb EMG and an evident decrease in the ability of the associated joints to produce muscular power. Principal component analysis of the joint powers obtained from the upper limbs throughout the push-up trial suggested that the CNS utilized one method of control. The control strategy used was reliant on power generation or absorption from the bilateral elbow and shoulder joints. Decreasing mechanical work was revealed throughout repeated reps. Joint power variances decreased throughout the push-up trial, which is related to the overall reduction in mechanical work performed by the limbs and system. It was expected that the CNS would be able to use redundant motor solutions to overcome the effects of fatigue. Although the synergy between and within-limbs at the beginning of the push-up trial was high, the system was not able to adapt strategies to overcome the challenge of fatigue. Fatigue effects decreased the ability of the CNS to produce synergy between and within-limbs. The reduction of between and within-limb synergies appears to be dependent on the type of muscle contraction. Synergies decreased at a greater rate during concentric vs. eccentric movement phases of the push-up. Overall these results suggest that the CNS uses one strategy, bilateral power production from the elbows and shoulders, to control the upper limbs over repeated push-ups. The effectiveness of this strategy decreases as the system faces the challenge of fatigue and the CNS is unable to adapt strategies or utilize abundant solutions within the upper limbs. However, after this reduction in upper extremity power production the motor task is still completed, suggesting that other segments of the body are contributing to the motion.

Appendices

Appendix A

Table A.1: Analysis of electromyographic data for indications of muscular fatigue.

	Mean Frequency (Hz)				Normalized Integrated Linear Envelope (unitless)			
Participant	Left Triceps Brachii	Left Pectoralis Major	Right Triceps Brachii	Right Pectoralis Major	Left Triceps Brachii	Left Pectoralis Major	Right Triceps Brachii	Right Pectoralis Major
1	-0.91 *	-0.94 *	-0.97 *	-0.95 *	0.9 *	0.9 *	0.92 *	0.85 *
2	-0.79 *	-0.48 *	-0.46 *	-0.4 *	0.69 *	0.81 *	0.45 *	0.78 *
3	-0.5 *	0.36	-0.37	0.03	0.12	0.79 *	0.92 *	0.11
4	-0.72 *	-0.23	-0.72 *	-0.59 *	-0.45 *	0.38 *	-0.25	0.37
5	-0.28	-0.23	-0.19	-0.28	0.94 *	0.49 *	0.87 *	0.69 *
6	-0.94 *	-0.86 *	-0.83 *	-0.86 *	0.87 *	0.05	-0.04	0.45 *
8	-0.75 *	-0.82 *	-0.86 *	-0.19	0.95 *	0.9 *	0.92 *	0.79 *
9	-0.68 *	0.18	-0.57 *	0.37 *	0.88 *	0.83 *	0.88 *	0.76 *
10	0.25	-0.82 *	-0.47 *	-0.68 *	0.93 *	0.86 *	0.81 *	0.79 *
11	-0.84 *	-0.41 *	-0.84 *	-0.60 *	0.84 *	0.85 *	0.91 *	0.66 *
$\bar{r}$	**-0.70** Ɨ	**-0.52** Ɨ	**-0.71** Ɨ	**-0.43** Ɨ	**0.85** Ɨ	**0.80** Ɨ	**0.83** Ɨ	**0.71** Ɨ

* $p \leq 0.05$, Pearson correlation test indicates that the participants correlation was significantly different than zero.

Ɨ $p \leq 0.05$ Z test indicates that mean correlation coefficients were significantly different than zero.

Table A.2: Work produced by the System and individual limbs Throughout Push-up Cycles Repeated to Volitional Fatigue

	System			Left Limb			Right Limb		
Participant	Net Work (J/kg)	Positive Work (J/kg)	Negative Work (J/kg)	Net Work (J/kg)	Positive Work (J/kg)	Negative Work (J/kg)	Net Work (J/kg)	Positive Work (J/kg)	Negative Work (J/kg)
1	-0.73 *	-0.90 *	0.89 *	-0.27	-0.90 *	0.91 *	-0.57 *	-0.86 *	0.81 *
2	0.10	-0.84 *	0.82 *	-0.37	-0.84 *	0.84 *	0.25	-0.84 *	0.80 *
3	-0.63 *	-0.85 *	0.82 *	0.20	-0.85 *	0.86 *	-0.59 *	-0.79 *	0.70 *
4	-0.55 *	-0.70 *	0.67 *	0.06 *	-0.73 *	0.70 *	-0.46	-0.63 *	0.57 *
5	0.35 *	-0.90 *	0.89 *	-0.40	-0.90 *	0.90 *	0.47	-0.90 *	0.87 *
6	-0.63 *	-0.81 *	0.77 *	0.38	-0.80 *	0.84 *	-0.67 *	-0.76 *	0.62 *
7	0.35 *	-0.90 *	0.89 *	-0.40 *	-0.90 *	0.90 *	0.47 *	-0.90 *	0.87 *
8	-0.55 *	-0.80 *	0.78 *	0.33	-0.83 *	0.83 *	-0.57 *	-0.70 *	0.59 *
9	0.10	-0.84 *	0.82 *	-0.37	-0.84 *	0.84 *	0.25	-0.84 *	0.80 *
10	0.31	-0.89 *	0.88 *	-0.39 *	-0.89 *	0.89 *	0.44 *	-0.89 *	0.87 *
11	-0.55 *	-0.80 *	0.78 *	0.33	-0.83 *	0.83 *	-0.57 *	-0.70 *	0.59 *
$\bar{r}$	**-0.11 ł**	**-0.54 ł**	**0.36 ł**	**-0.05 ł**	**-0.23 ł**	**0.19 ł**	**0.00**	**-0.14 ł**	**0.11 ł**

* p ≤ 0.05, Pearson correlation test indicates that the participants correlation was significantly different than zero.

ł p ≤ 0.05 Z test indicates that mean correlation coefficients were significantly different than zero.

Appendix B

Table B.1: Variance of the system, limb and individual joints for each participant as well as the mean correlation for the group.

									Variance									
Participant	System		Left Limb		Right Limb		Left Shoulder		Right Shoulder		Left Elbow		Right Elbow		Left Wrist		Right Wrist	
1	-0.93	*	-0.94	*	-0.89	*	-0.86		-0.88	*	-0.96	*	-0.79	*	0.35		-0.18	
2	-0.79	*	-0.79	*	-0.73	*	-0.36		-0.52	*	-0.90	*	-0.76	*	0.38	*	-0.23	
3	-0.88	*	-0.82	*	-0.90	*	-0.84	*	-0.95	*	-0.75	*	-0.79	*	-0.54	*	-0.70	*
4	-0.93	*	-0.89	*	-0.95	*	-0.87	*	-0.92	*	-0.91	*	-0.95	*	-0.57	*	-0.20	
5	-0.93	*	-0.87	*	-0.95	*	-0.82	*	-0.92	*	-0.42	*	-0.85	*	-0.49	*	-0.18	
6	-0.65	*	-0.47		-0.78	*	-0.32	*	-0.79	*	-0.61	*	-0.77	*	-0.61	*	-0.74	
7	-0.70	*	-0.38	*	-0.86	*	-0.06		-0.87	*	-0.73	*	-0.38	*	-0.05		0.61	*
8	-0.92	*	-0.83	*	-0.85	*	-0.59		-0.81	*	-0.87	*	-0.79	*	-0.84	*	-0.35	*
9	-0.57	*	-0.16		-0.68	*	0.04	*	-0.71	*	-0.45	*	-0.64	*	0.70	*	0.28	
10	-0.64	*	-0.26		-0.64	*	0.14		-0.54	*	-0.68	*	-0.83	*	0.21		0.24	
11	-0.80	*	-0.81	*	-0.75	*	-0.79	*	-0.71	*	-0.60	*	-0.74	*	-0.28		-0.50	*
$\bar{r}$	**-0.82**	**Ɨ**	**-0.71**	**Ɨ**	**-0.84**	**Ɨ**	**-0.52**	**Ɨ**	**-0.81**	**Ɨ**	**-0.76**	**Ɨ**	**-0.77**	**Ɨ**	**-0.08**		**-0.07**	

* $p \leq 0.05$, Pearson correlation test indicates that the participants correlation was significantly different than zero.

Ɨ $p \leq 0.05$, Z test indicates that mean correlation coefficients were significantly different than zero.

Table B.2: Between-limb and Within-limb Synergy

					Covariance				
Participant	Between Limb	Left Limb	Right Limb	Left Elbow & Shoulder	Right Elbow & Shoulder	Left Shoulder & Wrist	Right Shoulder & Wrist	Left Elbow & Wrist	Right Elbow & Wrist
1	-0.93 *	-0.95 *	-0.89 *	-0.95 *	-0.90 *	0.28	0.91 *	0.13	0.86 *
2	-0.79 *	-0.84 *	-0.74 *	-0.84 *	-0.73 *	0.11	0.42 *	0.66 *	0.43 *
3	-0.88 *	-0.80 *	-0.88 *	-0.80 *	-0.89 *	0.69 *	0.88 *	0.69 *	0.81 *
4	-0.94 *	-0.90 *	-0.96 *	-0.91 *	-0.96 *	-0.72 *	-0.72 *	-0.79 *	-0.64 *
5	-0.94 *	-0.83 *	-0.95 *	-0.82 *	-0.95 *	-0.59 *	0.26	-0.48 *	0.36 *
6	-0.65 *	-0.58 *	-0.75 *	-0.55 *	-0.75 *	-0.66 *	-0.65 *	-0.22 *	0.02
7	-0.72 *	-0.64 *	-0.85 *	-0.64 *	-0.84 *	-0.21 *	-0.25	0.11 *	-0.69 *
8	-0.89 *	-0.90 *	-0.86 *	-0.91 *	-0.86 *	0.65 *	0.71 *	0.62 *	0.72 *
9	-0.61 *	-0.33	-0.60 *	-0.33	-0.60	-0.01	-0.14	-0.24	0.41 *
10	-0.66 *	-0.52 *	-0.71 *	-0.52 *	-0.72 *	-0.26	0.44 *	0.32	0.65 *
11	-0.80 *	-0.81 *	-0.74 *	-0.83 *	-0.76 *	0.59 *	0.63 *	0.51 *	0.75 *
$\bar{r}$	**-0.83 ł**	**-0.77 ł**	**-0.84 ł**	**-0.77 ł**	**-0.84 ł**	**-0.04**	**0.34 ł**	**0.14 ł**	**0.39 ł**

* p ≤ 0.05, Pearson correlation test indicates that the participants correlation was significantly different than zero.

ł p ≤ 0.05, Z test indicates that mean correlation coefficients were significantly different than zero.

Appendix C

Table C.1 Between-limb and Within-limb Synergy for the Eccentric Movement Phase

	Eccentric Covariance																	
Participant	Between Limb		Left Limb		Right Limb		Left Elbow & Shoulder		Right Elbow & Shoulder		Left Shoulder and Wrist		Right Shoulder & Wrist		Left Elbow and Wrist		Right Elbow & Wrist	
1	-0.20		0.02		-0.02		0.53	*	0.39		-0.22		-0.37		0.71	*	0.51	*
2	-0.48	*	-0.52	*	-0.49	*	-0.56	*	-0.46	*	-0.33		-0.29		-0.12		-0.59	*
3	-0.42		-0.46	*	-0.46	*	0.60	*	-0.14		0.10		0.16		0.40		-0.57	*
4	-0.92	*	-0.81	*	-0.75	*	-0.61	*	-0.61	*	-0.86	*	-0.86	*	-0.78	*	-0.50	
5	-0.50	*	-0.75	*	-0.78	*	-0.10		0.08		-0.40	*	-0.45	*	-0.23		0.00	
6	-0.12		-0.25		-0.17		0.10		-0.70	*	0.07		0.15		-0.61	*	-0.57	
7	-0.54	*	-0.70	*	-0.67	*	-0.34		-0.24		-0.38	*	-0.37	*	-0.03		-0.22	
8	-0.77	*	-0.74	*	-0.74	*	0.53	*	-0.10		-0.52	*	-0.54	*	0.39		0.20	
9	-0.74	*	-0.57	*	-0.57	*	0.42	*	-0.41	*	-0.69	*	-0.70	*	0.06		0.14	
10	-0.66	*	-0.55	*	-0.56	*	0.36	*	0.15		-0.72	*	-0.72	*	0.52	*	-0.15	
11	-0.59	*	-0.62	*	-0.62	*	-0.69	*	-0.02		-0.66	*	-0.67	*	-0.41		0.06	
$\bar{r}$	**-0.53**	**ł**	**-0.43**	**ł**	**-0.53**	**ł**	**-0.44**	**ł**	**-0.53**	**ł**	**-0.13**		**-0.14**		**0.05**		**0.02**	

* $p \leq 0.05$, Pearson correlation test indicates that the participants correlation was significantly different than zero. ł $p \leq 0.05$ Z test indicates that mean correlation coefficients were significantly different than zero.

Table C.2: Between-limb and Within-limb Synergy for the Concentric Movement Phase

	Concentric Covariance								
Participant	Between Limb	Left Limb	Right Limb	Left Elbow & Shoulder	Right Elbow & Shoulder	Left Shoulder and Wrist	Right Shoulder & Wrist	Left Elbow and Wrist	Right Elbow & Wrist
1	-0.95 *	-0.95 *	-0.95 *	-0.04	0.43 *	-0.94 *	-0.94 *	-0.58	-0.82 *
2	-0.95 *	-0.90 *	-0.90 *	0.21	0.16	-0.94 *	-0.94 *	-0.20	-0.23
3	-0.82 *	-0.35	-0.37	0.52 *	-0.58 *	-0.71 *	-0.69 *	0.21	-0.33
4	-0.93 *	-0.87 *	-0.89 *	-0.25	-0.17	-0.95 *	-0.96 *	0.15	-0.34
5	-0.94 *	-0.93 *	-0.92 *	-0.66 *	-0.80 *	-0.84 *	-0.80 *	-0.49	-0.86 *
6	-0.73 *	-0.67 *	-0.62 *	0.09	-0.65 *	-0.87 *	-0.83 *	0.48	-0.26
7	-0.72 *	-0.85 *	-0.85 *	-0.37 *	0.08	-0.71 *	-0.71 *	-0.18	-0.26
8	-0.81 *	-0.75 *	-0.75 *	0.38	0.66 *	-0.83 *	-0.83 *	0.30	0.61 *
9	-0.47 *	-0.14	-0.13	0.47 *	-0.50 *	-0.23	-0.09	-0.67	-0.59 *
10	-0.46 *	-0.66 *	-0.61 *	-0.50 *	-0.56 *	-0.16	-0.10	-0.30	-0.61 *
11	-0.83 *	-0.79 *	-0.82 *	0.76 *	0.44	-0.85 *	-0.86 *	0.47	0.51 *
$\bar{r}$	**-0.78 ƚ**	**-0.73 ƚ**	**-0.75 ƚ**	**-0.71 ƚ**	**-0.74 ƚ**	**-0.40 ƚ**	**-0.20**	**-0.19 ƚ**	**-0.03**

* $p \leq 0.05$, Pearson correlation test indicates that the participants correlation was significantly different than zero.

ƚ $p \leq 0.05$ Z test indicates that mean correlation coefficients were significantly different than zero.

Table C.3 Mean Correlations Between Eccentric and Concentric Movement Phases

	Between Limb	Left Limb	Right Limb	Left Elbow & Shoulder	Right Elbow & Shoulder	Left Shoulder and Wrist	Right Shoulder & Wrist	Left Elbow and Wrist	Right Elbow & Wrist
$\bar{r}_{\text{eccentric}}$	-0.53 Ɨ	-0.43 Ɨ	-0.53 Ɨ	-0.44 Ɨ	-0.53 Ɨ	-0.13	-0.14 Ɨ	0.05	0.02
$\bar{r}_{\text{concentric}}$	-0.78 Ɨ	-0.73 Ɨ	-0.75 Ɨ	-0.71 Ɨ	-0.74 Ɨ	-0.40 Ɨ	-0.20 Ɨ	-0.19 Ɨ	-0.03
$\bar{\bar{z}}_{\text{critical}}$	-5.15 §	-5.19 §	-4.18 §	-4.63 §	-4.14 §	-3.27 §	-0.69	-2.66 §	-0.51

Asterisks indicate that mean correlation is statistically different than zero (* $p < 0.05$) and § indicates that the mean correlations are statistically different between eccentric and concentric movement phases (§ $p < 0.05$)

Bibliography

Alexander, R. A., Scozzaro, M. J., & Borodkin, L. J. (1989). Statistical and empirical examination of the chi-square test for homogenity of correlations in meta-analysis. *Psychological Bulletin*, *106*(2), 329–331.

American College of Sports Medicine. (1991). *Guidelines for exercise testing and prescription* (4th ed.). Philadelphia: Lea & Febiger.

Army, D. of the. (2011). Army Regulation 40-501: Standards of Medical Fitness. Retrieved September 14, 2016, from http://armypubs.army.mil/Search/ePubsSearch/ePubsSearchForm.aspx?x=AR

Brown, A. M., Zifchock, R. A., & Hillstrom, H. J. (2014). Gait & Posture The effects of limb dominance and fatigue on running biomechanics. *Gait & Posture*, *39*(3), 915–919. https://doi.org/10.1016/j.gaitpost.2013.12.007

Brown, J. D. (2009). Principal components analysis and exploratory factor analysis – Definitions, differences and choices. *Shiken: JALT Testing & Evaluation SIG Newsletter*, *13*(1), 26–30.

De Luca, C. J. (1984). Myoelectrical manifestations of localized muscular fatigue in humans. *Critical Reviews in Biomedical Engineering*, *11*(4), 251–279. https://doi.org/10.1017/CBO9781107415324.004

Dhahbi, W., Chaouachi, A., Dhahbi, A. Ben, Cochrane, J., Chèze, L., Burnett, A., & Chamari, K. (2017). The Effect of Variation of Plyometric Push-Ups on Force-Application Kinetics and Perception of Intensity, 190–197.

Ditroilo, M., Forte, R., Benelli, P., Gambarara, D., & De Vito, G. (2010). Effects of age and limb dominance on upper and lower limb muscle function in healthy males and females aged 40-80 years. *Journal of Sports Sciences*, *28*(6), 667–677. https://doi.org/10.1080/02640411003642098

Ebben, W. P., Wurm, B., VandeZanden, T. L., Spadavecchia, M. L., Durocher, J. J., Bickham, C. T., & Petushek, E. J. (2011). Kinetic Analysis of Several Variations of Push-ups. *Journal of Strength & Conditioning Research*, *25*(10), 2891–2894.

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of Physiology*, *586*(1), 11–23. https://doi.org/10.1113/jphysiol.2007.139477

Enoka, R. M., & Stuart, D. G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology*, *72*(5), 1631–1648. https://doi.org/0161-7567/92

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Freeman, S., Karpowicz, A., Gray, J., & McGill, S. (2006). Quantifying muscle patterns and spine load during various forms of the push-up. *Medicine and Science in Sports and Exercise*, *38*(3), 570–577. https://doi.org/10.1249/01.mss.0000189317.08635.1b

González-Izal, M., Malanda, A., Navarro-Amézqueta, I., Gorostiaga, E. M., Mallor, F., Ibañez, J., & Izquierdo, M. (2010). EMG spectral indices and muscle power fatigue during dynamic contractions. *Journal of Electromyography and Kinesiology*, *20*(2), 233–240. https://doi.org/10.1016/j.jelekin.2009.03.011

Gouvali, M. K., & Boudolos, K. (2005). Dynamic and Electromyographical Analysis in Variants of Push-Up Exercise. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *19*(1), 146–151. https://doi.org/10.1519/14733.1

Halaki, M., & Ginn, K. a. (2012). Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to? *Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges*, 175–194. https://doi.org/40113

Hermens, H. J. (1999). *SENIAM : European recommendations for surface electromyography : Results of the SENIAM project* (2nd Editio). Pays-Bas: Roessingh Research and Development.

Hill, A. V. (1938). The Heat of Shortening and the Dynamic Constants of Muscle. *Proceedings of the Royal Society B: Biological Sciences*, *126*(843), 136–195. https://doi.org/10.1098/rspb.1938.0050

Huffenus, A.-F., Amarantini, D., & Forestier, N. (2006). Effects of distal and proximal arm muscles fatigue on multi-joint movement orHuffenus, A.-F., Amarantini, D., & Forestier, N. (2006). Effects of distal and proximal arm muscles fatigue on multi-joint movement organization. Experimental Brain Research, 170. *Experimental Brain Research*, *170*(4), 438–447. https://doi.org/10.1007/s00221-005-0227-3

Katz, B. (1939). The relation between force and speed in muscular contraction. *The Journal of Physiology*, *96*(1), 45–64. https://doi.org/10.1113/jphysiol.1939.sp003756

Kenny, D. A. (1987). Statistics for the Social and Behavioral Sciences. In *Statistica Neerlandica* (p. 434). https://doi.org/10.1111/j.1467-9574.1985.tb01136.x

Kim, J. O., & Mueller, C. W. (1978). *Introduction to factor analysis: What it is and how to do it.* Beverly Hills, CA: SAGE.

Kruger, E. S., Hoopes, J. A., Cordial, R. J., & Li, S. (2007). Error compensation during finger force production after one- and four-finger voluntarily fatiguing exercise. *Experimental Brain Research*, *181*(3), 461–468. https://doi.org/10.1007/s00221-007-0942-z

Latash, M. (2000). There is no motor redundancy in human movements. There is motor abundance. *Motor Control*, *4*, 259–260.

Latash, M. L. (2012). The bliss (not the problem) of motor abundance (not redundancy). *Experimental Brain Research*, *217*(1), 1–5. https://doi.org/10.1007/s00221-012-3000-4

Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor control strategies revealed in the structure of motor variability. *Exercise and Sport Sciences Reviews*, *30*(1), 26–31. https://doi.org/10.1097/00003677-200201000-00006

Lear, L. J., & Gross, M. T. (1998). An electromyographical analysis of the scapular stabilizing synergists during a push-up progression. *J Orthop Sports Phys Ther*, *28*(3), 146–157. https://doi.org/10.2519/jospt.1998.28.3.146

Lehman, G. J., MacMillan, B., MacIntyre, I., Chivers, M., & Fluter, M. (2006). Shoulder muscle EMG activity during push up variations on and off a Swiss ball.

Dynamic Medicine : DM, *5*, 7. https://doi.org/10.1186/1476-5918-5-7

Ludewig, P. M. (2004). Relative Balance of Serratus Anterior and Upper Trapezius Muscle Activity During Push-Up Exercises. *American Journal of Sports Medicine*, *32*(2), 484–493. https://doi.org/10.1177/0363546503258911

Öberg, T., Sandsjö, L., & Kadefors, R. (1991). Variability of the EMG mean power frequency: A study on the trapezius muscle. *Journal of Electromyography and Kinesiology*, *1*(4), 237–243. https://doi.org/10.1016/1050-6411(91)90010-3

Phinyomark, A., Thongpanja, S., Hu, H., Phukpattaranont, P., & Limsakul, C. (2012). The Usefulness of Mean and Median Frequencies in Electromyography Analysis. *Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges*. https://doi.org/10.5772/50639

Ramsay, J. W., Hunter, B. V., & Gonzalez, R. V. (2009). Muscle moment arm and normalized moment contributions as reference data for musculoskeletal elbow and wrist joint models. *Journal of Biomechanics*, *42*(4), 463–473. https://doi.org/10.1016/j.jbiomech.2008.11.035

Robertson, D. G. E., & Winter, D. A. (1980). Mechanical Energy Generation, Absorption and Transfer Amongst Segments During Walking.". *Journal of Biomechanics*, *13*, 845–854.

Singh, T., S K M, V., Zatsiorsky, V. M., & Latash, M. L. (2010). Adaptive increase in force variance during fatigue in tasks with low redundancy. *Neuroscience Letters*, *485*(3), 204–207. https://doi.org/10.1016/j.neulet.2010.09.012

Singh, T., Varadhan, S. K. M., Zatsiorsky, V. M., & Latash, M. L. (2010). Fatigue and motor redundancy: adaptive increase in finger force variance in multi-finger tasks. *Journal of Neurophysiology*, *103*(6), 2990–3000. https://doi.org/10.1152/jn.00077.2010

Taylor, J. L., Todd, G., Gandevia, S. C., & Taylor, J. L. (2006). Evidence for a supraspinal contribution to human muscle fatigue. *Clinical and Experimental Pharmacology & Physiology*, *33*(4), 400–405.

Westerblad, H., Allen, D. G., Bruton, J. D., Andrade, F. H., & Lannergren, J. (1998). Mechanisms underlying the reduction of isometric force in skeletal muscle fatigue. *Acta Physiol Scand*, *162*(3), 253–260. https://doi.org/10.1046/j.1365-201X.1998.0301f.x [doi]

Wilken, J. M., Rodriguez, K. M., Brawner, M., & Darter, B. J. (2012). Gait & Posture Reliability and minimal detectible change values for gait kinematics and kinetics in healthy adults §, *35*, 301–307. https://doi.org/10.1016/j.gaitpost.2011.09.105

Winter, D. a. (2009). *Biomechanics and Motor Control of Human Movement*. Hoboken, NJ, USA: John Wiley & Sons, Inc. https://doi.org/10.1002/9780470549148

Youdas, J. W., Budach, B. D., Ellerbusch, J. V, Stucky, C. M., Wait, K. R., & Hollman, J. H. (2010). Comparison of muscle-activation patterns during the conventional push-up and perfect· pushup^{TM} exercises. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *24*(12), 3352–3362. https://doi.org/10.1519/JSC.0b013e3181cc23b0