A PRINCIPAL COMPONENT ANALYSIS OF LIFTING WAVEFORMS: FATIGUE INFLUENCES ON COORDINATION STRATEGIES

by

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ABSTRACT

Manual materials handling has been examined as it relates to musculoskeletal injury; however, due to the complexity of handling tasks and individual characteristics in technique further analysis is required. Lifting tasks, specifically, show great variability between individuals despite task parameter restrictions and further variability was expected when fatigue or injury alters lifting method. In order to assess the effects of fatigue on lifting technique, individuals underwent several testing sessions which resulted in quantitative generalized fatigue, and localized shoulder and back fatigue which were compared to initial lifting in a non-fatigued condition and then across fatigue states.

The kinematic and relative phase lifting waveform differences between fatigue states were analyzed using Principal Component Analysis (PCA) with further investigation of relative phase through frequency analysis. PCA enabled isolation of variability within the data and therefore provided an indication of area of greatest variability within the lifting waveform. Frequency analysis of relative phase waveforms allowed for a greater understanding of lifting coordination changes.

The results of this study showed significant alterations in kinematic and relative phase lifting waveforms, which varied significantly depending on the fatigue state. The type of fatigue had a significant effect on the corresponding compensations and alterations to lifting technique and coordination even though task parameters remained constant. Altered lifting technique may result in an increased risk of injury particularly in the initiation and placement phases and further variability in coordination during transition of the load could also result in an increased risk of injury with fatigue.

DEDICATION

For my dad who has always believed in me and has shown me the kind of person I aspire to be. Thank you for encouraging me to follow my dreams and make my own path. You are the reason I am not afraid to keep trying, no matter what obstacles I encounter.

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1.0 INTRODUCTION

1.1 Injury Concerns

Through technological advancements and the emergence of alternate methods of biomechanical analysis; the scientific understanding of the human body has improved. Society has witnessed an increase in empirically based occupational health and safety protocols designed to keep workers healthy within their chosen profession. Some implemented safety protocols include team lifting, materials load restrictions, specific training programs in proper lifting technique and handling procedures. As the understanding of biomechanical joint loading and tissue impact increases, the awareness of the mechanisms of injury has improved, leading to better safety protocols. Back in Form (WorkSafeNB, 2000) is an example of a program developed, based on biomechanical studies investigating joint loading during lifting, to improve the safety of nursing staff performing manual patient handling tasks. Occupational health and safety encompasses the areas of physical, psychosocial, intellectual and emotional/mental health. If one of these areas is compromised, issues may arise within the workplace, and other areas may be affected by the initial problem.

Within physically demanding occupations, worker injury has negative implications for not only the individual workers but the employer and company as a whole. Individuals may be required to complete additional work to compensate for the absent worker(s), or productivity or quality of performance may be negatively impacted. Overtime, presents additional financial cost; however, the risk of injury to remaining workers may also increase with mandatory overtime, longer working hours and increased workload (de Castro et al., 2010; Dembe et al., 2007). Also, worker health and safety insurance rates may increase due to injury compensation claims and this leads to direct negative financial consequences, separate from production and quality losses. Maintaining the health and safety of workers is becoming a focus for most employers (Amick et al., 2000). Prevention of injury has always been preferable to treatment for an injury, and as research advances are made, safety protocols are being developed with a greater degree of understanding of the mechanisms of injury.

Physical health and safety includes manual materials handling (MMH) and injury concerns. MMH tasks may be classified as physically demanding according to: load (mass and structure of that which is being handled), frequency (rate of task repetition), duration (time to task completion), and task structure (the physical movement required by the worker to complete the task, the lift envelope and orientation). The ability of an individual to physically complete a MMH task is affected by sex (Albert et al., 2008; Lindbeck & Kjellberg, 2001), age (Ketcham et al., 2004), physical ability (Garner & Shim, 2008), work experience (Plamondon et al., 2004) and history of previous injury (Larivière et al., 2002). Proper design of a workplace has effectively demonstrated that the structuring of a task may decrease the incidence of injury and increase worker satisfaction (Denis et al., 2008; Viikari-Juntura, 1997; Rivillis et al., 2008). Any task redesign requires complete knowledge of the mechanisms of motion and the constraints of the task. Prolonged repetitive tasks may induce fatigue in certain structures, leading to changes in technique that introduce new confounding variables that should be analyzed to provide a comprehensive view of the task. Injury prevention is preferable to injury treatment for several reasons: injuries may not fully heal, subsequent injuries are more likely to occur after the initial injury due to compensation strategies, re-injury is always a concern and treatment may be extensive requiring extended time and resources (Kumar, 2001; Larivière et al., 2002). Understanding injury mechanisms may lead to better injury prevention and therefore better management of finite resources.

Multiple injury mechanisms have been postulated as they relate to injury (Kumar, 2001) including: biomechanical loading due to high or moderate loads (Keyserling, 2000); both peak and cumulative joint loading (Kumar, 1990; Waters et al., 2006); repetitive strain resulting in eventual biological failure (Rempel et al., 1992); technique or style differences which may increase specific joint loading (Straker, 2002); segment coordination and muscular compensations (Boston et al., 1993); and fatigue influences on loading patterns and muscle coordination shifts (Bonato et al., 2003). Fatigue has also been suggested as a major contributor to injury incidence rates because fatigue may affect biomechanical and neuromuscular control (Sparto et al., 1997). Ideally a properly selected and correctly performed lifting technique will effectively protect the individual from injury by minimizing the strain on muscles and joints, allowing for proper overall load distribution, and reducing awkward and extreme postures.

1.2 Lifting Concerns

Research into lifting biomechanics has been conducted to address ergonomic interventions and occupational design. Until recently, biomechanics of the spine during lifting was the primary focus of most researchers with some investigation into lower limb restrictions and even less discussion of shoulder and upper extremity biomechanics. Shoulder pain, however, ranks second in occupational injuries to pain of the back and neck and this has led to an increased interest in the shoulder joint (Sommerich & Hughes, 2007). Lifting technique has been investigated with postural assessments such as the postural index (Burgess-Limerick et al., 1997, Larivière et al., 2002) or simply the position at load initiation (Van Diëen et al., 1999). These postural approaches are limited because lifting requires the coordination of multiple anatomical structures to achieve the desired motion. Due to the complexity of the structures involved, a method of differentiation between different lifting techniques must be developed to allow for classification of technique based on a dynamic understanding of the lift pattern. The manner in which a motion is achieved is as important as the initial, final and extreme positions. As previously stated, lifting places stress on all of the joints involved in this complex task. Injury concerns are primarily associated with the spine and shoulder joints. Spinal injuries associated with lifting range from general pain and discomfort, to biomechanical failure of the intervertebral joints, ligaments and musculature of the back (Granata & Gottipati, 2008; Granata & Rogers, 2007; Keyserling, 2000; Waters et al., 2006). The shoulder joint capsule and rotator cuff tendons and muscles are often negatively affected by the cumulative effects of prolonged lifting. Acute injury may also occur with excessive short term loading. A summary of work-related disorders impacting the shoulder outlined the conditions and suspected causes: heavy work load, high force, and repetitive movement, combined with awkward and static postures presented an increased risk of shoulder pain (Keyserling, 2000; Kumar, 2001; Radwin et al. 2002; Sommerich & Hughes, 2006). Shoulder pain and discomfort may be caused by a variety of disorders: internal impingement of nerves, tendinitis, tendinosis, tenosynovitis, peritendinitis, paratenonitis, joint capsule bursitis, and general muscle, tendon, and ligament irritation or inflammation. To prevent these types of injury, the effects of fatigue on coordinative strategies and subsequent failure of the body to accomplish the desired motion must be understood.

1.2.1 Biomechanical Loading

Previous research in occupational biomechanics has found evidence to support the theories of cumulative loading and repetitive strain as they relate to injury. The theory of cumulative loading is used frequently in the assessment of loading of the spine. It suggests that peak load (maximum load) may not be the only issue in MMH, but that repetitive loading of a lesser load may have the same or greater detrimental effect on the body (Norman et al., 1998). This theory is based on the belief that human tissue is viscoelastic, meaning that constant loading may result in deformation and repetitive loading may decrease overall tolerance of the tissues (Andersson, 1985; Kumar, 1990). Cumulative loading theory suggests that load totals may be added together to a maximum, and each subsequent load application builds onto the previous load to a certain degree and the area under a force application curve may be summed to provide the total cumulative load (Callaghan et al., 2001). Cumulative load theory may be related to fatigue, where low to moderate loads induce fatigue over a prolonged period resulting in eventual failure. The theory of repetitive strain postulates that loading of a body segment places some strain on the muscle and without adequate recovery, repetition of this strain may result in eventual failure of the muscle to maintain required force. The issue of cumulative loading and repetitive strain support the need for research into prolonged MMH tasks such as lifting.

1.2.2 Sex Differences

An issue that remains prevalent within society, as gender equity is commonly cited within occupational settings, is that of gender differences in MMH. It has been suggested that women tend to encounter load and lifting duration restrictions from upper body strength and subsequent fatigue during a prolonged MMH task; whereas, men tend to terminate a task due to back or sometimes lower limb fatigue (Miller et al., 1993). It has been suggested that women and men should be considered separately with respect to lifting technique. Women tend to have a more in-phase lifting pattern indicating a greater level of coordination (Lindbeck et al., 2001). Women, on average, may not produce an equal amount of force; however, many women tend to have a greater capacity for endurance, and men are more suited to power movements requiring greater force. Some studies examining lifting with subjects of both sex, use lesser weights when investigating women (Lindbeck & Kjellberg, 2001), while other studies have used the same weights for both sexes (Marras et al., 2003), and still others have used individual weights according to subject capacity (Albert et al., 2008; Lavender et al., 1999). The issue of comparability is prevalent in many studies where physiological differences seem to lend an advantage to either sex, dependent upon the study design. It was determined in a study conducted by Kumar (1984) that, when adjusted for body mass, women had higher ventilator volumes than men for the same task, suggesting a higher vulnerability to physiological fatigue. It is suspected that the mechanisms of fatigue, or locations/areas of fatigue, will be different between sexes as previous subjective evaluations by subjects indicate different reasons for termination of a lifting task.

1.3 Lifting Technique

There are many different ways to determine correct technique and these may include physiological, neuromuscular, biomechanical, psychophysical, psychological and performance criteria. In determining acceptable lifting technique, all of these criteria have been used to evaluate and strive for an optimal lift pattern (Straker, 2002). Physiological criteria aim to determine the technique that results in the least physiological stress. Some measures of physiological stress are: heart rate, energy expenditure/oxygen consumption, blood pressure, body temperature, pulmonary ventilation volume, respiration rate, lactic acid concentration, perspiration rate, pulse pressure and serum lactate dehydrogrenase. Whole body physiological measures such as heart rate have been previously used to develop supposedly safe lifting techniques. Neuromuscular criteria aim to determine the most efficient pattern of stimulation. Measures of neuromuscular fatigue or failure are often investigated through interpretation of electromyographic activity. The electrical stimulation patterns required to produce and maintain force are good indicators of fatigue; however, in multisegmented systems, which involve multiple joint coordination and employ multiple muscles at each individual joint, these electrical signals must be considered within the entire system. Muscle failure due to biomechanical loading occurs when the muscle itself in unable to maintain force, the muscle fibers themselves fail (Latash, 2008;

Enoka, 2008). Neuromuscular failure may occur when the neural signals can no longer enhance contraction. Biomechanical criteria aim to decrease the amount of mechanical stress placed on the musculoskeletal system during motion. Biomechanical investigations involve determination of peak joint moment, compression and shear, cumulative force and general energy transfer throughout motion.

Psychophysical criteria aim to determine the largest acceptable load through adjustments in the load and frequency. Psychophysical limitations are often affected by metabolic, social environment, experience and personality determinants; however, the benefits to this type of evaluation are seen in its ability to include general health, performance and satisfaction into consideration. The subjectivity of psychophysics presents some issues; fast tasks are often perceived to have greater metabolic demands than the actual, and it is also not very sensitive to bending and twisting (Snook, 1985). Psychological criteria deal with subjective assessments of lifting stress and primarily focus on perceived discomfort and exertion. Psychological issues surrounding lifting technique are often used to gauge subjective assessments of lifting demands. Finally, performance criteria assess time to successful completion of the lifting task, with a technique which results in a shorter lifting time being the desired technique. All of these criteria have been used in the past to investigate and evaluate lifting technique.

Generally, there are three defined lifting techniques: the stoop, squat and freestyle or free-selection lift. Lifting technique may be classified as similar; however, neuromuscular coordination is different between individuals (Scholz & McMillan, 1995). These lifting techniques are classified by starting position and do not assess the lifting trajectory, which is extremely variable between individuals. Lifting technique has previously been suggested as one of the main causes of work-related injuries (Straker, 2003). The idea of a single technique that is most effective in preventing injury is very appealing; however, further investigation has revealed that no single technique may be employed in all situations (Burgess-Limerick, 2003; Straker, 2003). Another interesting finding is that free lifting technique may not always be the safest technique, even though it may be the most comfortable method during initial lifting and compensations may actually lead to more coordination and joint loading issues than they prevent (Burgess-Limerick et al., 1995; Larivière et al., 2002). The changes in loading patterns may result in improper loading of a joint in ways that may compromise the musculature and supporting tissues that maintain stability. Technique selection is task dependant and safe practices must take into consideration other factors such as the degree of repetition, the load being handled, the individual worker characteristics and the range of motion required to complete the task. Guidelines have been developed based generally on static postures: starting and finishing points or the suspected extreme posture expected to present the most risk. These guidelines are usually overly cautious to avoid situations that may compromise a worker's health; however, guidelines that are more task specific and treat the task as a complete dynamic movement would allow for better determination of risky MMH tasks. A task must be considered in its entirety in order to understand the risks associated.

The three main lifting techniques have different biomechanical and physiological impacts on the body. The stoop lift has been identified as the most unsafe technique because biomechanical studies have shown that large degrees of shear force are applied to the spine and a greater torque moment is also produced (Burgess-Limerick, 2003;

Chen, 2000). The stoop technique tends to emerge at the onset of fatigue and is employed for lifting of heavier loads as it allows for greater load acceleration and is less physiologically demanding (Chen, 2000). Even though the stoop technique is less physiologically demanding, it is more mechanically compromising (Burgess-Limerick, 2003; van Diëen et al., 1999). The squat lift has been recommended as a correct technique because the load is kept close to the body for a greater portion of the lift and the back is kept straight as the legs perform the lift; however, this is the most physiologically demanding method of lifting (Burgess-Limerick, 2003; Kumar, 1984; van Diëen et al., 1999). The freestyle technique has a starting posture which falls between the other two lifts. It has been suggested that this type of lift may be easier to perform because the motor control program is familiar and therefore better coordinated; however, there has also been evidence to suggest that self-selected lifting technique may place the body at greater risk due to increased biomechanical loading (Boston, 1993).

The operational definition for lifting technique varies significantly from: the lift posture at the start of the lift, the box trajectory, trunk kinematics, and other more sophisticated assessments of relative phase angles and joint coordination. These methods of classification have previously been investigated to some degree but have been restricted to parameter based discrete determinations. It has been observed that parameter based studies which examine peak loads, cumulative loads, maximum and minimum joint angles, or static capture studies which do not investigate MMH as a dynamic task are ineffective in explaining the resulting issues seen in industry. Work conducted by Wrigley et al. (2006) has shown some promise in the area of waveform analysis of the spine during lifting; however, this type of analysis has not been applied to the shoulder and upper extremities.

1.3.1 Classification of Lifting Technique

The lift technique may be defined by the type of lift used within a specific lift envelope which essentially defines the task. This type of classification does not consider the body posture or trajectory of the load. The lift envelope is defined by the starting position of the load and the final position to be obtained. Lifts may be classified as symmetric or asymmetric dependent upon lateral movement or sagittal lifting parameters such as floor to waist height or floor to shoulder height. Technique classified by style is based on the setup of the lifting task, the objective of the lift and the pattern of motion required to complete it. In order to properly assess the risk involved in a lifting task, the general expected motion must be defined by the degree of asymmetry and the range of motion within the forward plane. Investigations into lifting technique or skill have demonstrated greater levels of axial rotation and shear in asymmetric lifting (Larivière et al., 2002). It has also been found that lifts from floor to knuckle height place less strain on the shoulder than floor to shoulder movements (Chen, 2000).

1.3.2 Postural Assessment of Lifting Technique

This type of assessment focuses primarily on the static posture before and after the performance of the lift. Classification of the type of lift, the lift technique, is usually based on the starting posture adopted by the lifter. The issue with this type of classification is that the lift in classified solely by the posture adopted to begin the lift and there is no indication of the motion pattern itself (Leskinen et al., 1983). Static posture assessment encounters limitations due to the inability to investigate the dynamic moments developed. A dynamic model may be used to investigate the complete motion captured by static frames; however, the most common method of analysis examines the initial, final and extreme postures and this parametric approach to single static frame analysis is ineffective in improving understanding of the dynamic lifting task. The MAC (Manual-handling Assessment Chart) and NIOSH (National Institute of Occupational Safety and Health) Lifting Equation are crude measures that have been developed based on a lifting model. These assessments use the peak posture to determine the safety of a task and the restrictions that should be placed on an activity to prevent injury. Lifting is a dynamic task and postural assessments are inherently static and parameter based. Therefore, classification of technique using postural observations is quick and relatively easy but does not provide the necessary insight into technique, as it disregards lifting as a dynamic motion.

The Postural Stability Assessment (PSA) and the Postural Index (PI) have been previously employed to classify posture and assess risks associated with the adoption of awkward postures. The postural index gives an indication of full body risk, but does not identify risk to specific joints. The PI does not define lifting by the absolute angles of joints and therefore is advantageous as it is independent of task characteristics (Burgess-Limerick, 1997). The PI is determined as the ratio of knee flexion compared to ankle, hip and lumbar vertebral flexion. All flexion angles are determined relative to standing, anatomically neutral postures. A stoop style lift has a lower PI than a squat lift, and this is due to the greater degree of knee flexion seen in a squat lift. The PI has been used to effectively discriminate between lifting protocols which may lead to injury due to a higher degree of risk in adoption of an awkward posture within the sagittal motion plane which places strain on the supporting structures of the body. Postural stability is defined by maintenance of the center of mass (CM) within the base of support or within the functional stability boundary (FSB). The FSB is determined by the maximum degree of CM displacement which may occur before a balance disruption. Stability within a specific joint may be defined by the ability of supporting structures to maintain integrity of the joint and coordinate muscles in an efficient manner to accomplish the desired movement. The PSA is effective in defining stability of the body and supporting structures, as stability has been associated with coordination changes and subsequent injury following a decrease in stability. Postural stability during a task as determined by the shift in center of mass location and three key indices have been indentified to quantify postural stability based on the base of support, instant proximity to center of pressure to the functional stability boundary and stability area ratio (Bagchee et al., 1998). It has been suggested that fatigue leads to a decrease in stability and therefore, fatigue resulting from lifting a load considered to be safe may lead to instability which may cause injury (Bonato, 2003 & Mair et al., 1996). Momentary losses of stability may lead to injury as efforts are made to re-establish stability of a joint.

1.3.3 Load Trajectory

Load trajectory is another method of lift technique classification. Trajectory may be defined as the path of motion observed as a load is lifted. Trajectory path, relative location, velocity and acceleration of a load during a lifting task provide some insight into the mechanisms of lifting. Lifting trajectories may be used to classify technique dependent upon the velocity and acceleration changes throughout the lift, and the location of the load in relation to the body at certain percentages of the lift cycle. There are several techniques which have been defined by load trajectory: the leg lift, load kinetic lift, trunk kinetic lift, forward kinetic lift, two-stage leg lift, and the back lift (Leskinen et al., 1983; Troup et al., 1983). The leg lift, very similar to a squat lift, involves movement from a crouched position with an erect spine to a standing position with no additional forward flexion of the trunk during the lift. The load kinetic lift begins in the same crouched posture; however, the load is located further from the body and it requires that the load first be pulled and then lifted. The trunk kinetic lift begins in a crouched posture similar to the other two; however, straightening of the legs occurs first with an increase in trunk flexion, moving into a slightly more stooped posture before lifting. The forward kinetic lift begins in a crouched position much like the other techniques; however, this time the load is moved away from the body and then lifted. This action is in direct contrast to the load kinetic lift in which the box is moved closer to the body before being lifted. The two stage lift begins in the crouched posture and the box is raised while still crouching, then the second portion of the lift is similar to the leg lift as the box is raised vertically as the subject moves to a standing position. Finally, the back lift involves motion from a stooped posture with knees straight and trunk flexed to an upright posture. These technique descriptions provide a basis for load trajectory analysis. The issue with solely examining load trajectories is found in different body movement patterns that accomplish the same motion; however, load trajectories may be effective indicators of biomechanical loading resulting from load location relative to the body. Both load trajectory and motion waveforms of the body segments should be investigated.

1.4 Discriminating Lifting Technique

1.4.1 Relative Angle, Relative Phase and Coordination

The shoulder joint is complicated with six degrees of motion and numerous muscles which stabilize and create movement. Another issue encountered in shoulder research involves the redundancies noted in the ability to employ different muscles or movement patterns to achieve the final desired position. Human motion is complex; involving multiple muscles, which may fire certain motor units given the degree of fatigue and force production required. Some muscles provide the primary movement while others serve as antagonistic or stabilizing muscles, giving control and support during motion. Muscles acting on and stabilizing the shoulder include but are not limited to: pectoralis major and minor, teres major and minor, rhomboideus major and minor, levator scapulae, subscapularis, supraspinatus, infraspinatus, trapezius, serratus anterior, latissimus dorsi, and the deltoid. All of these muscles are involved in stabilization and motion of the shoulder joint. Due to the high degree of complexity, study of the shoulder joint requires a complete examination of the musculature and stabilizing tissues. Most motion is not isolated at this single joint; therefore, full body coordination provides greater insight into lifting technique and compensation changes in coordination strategies for movement.

Movements that involve multiple body segment joint motion are best understood when all joint angles are considered relative to each other. In a lifting task, complete mapping of joint angles relative to each other gives an understanding of how joints are coordinated during motion. Relative phase is the difference between the calculated phase angles of multiple joints. Phase angles are determined from tangent calculations using velocity and displacement data. The arc tangent calculations remove the requirement for normalization of magnitudes between segments because the phase angle calculation normalizes for these differences while not altering the dynamic data. The advantage of using relative phase instead of examining each angle motion curve individually is seen in the ability to explain situational differences in how angles vary depending on the position of the rest of the body. Relative phase angle determination allows a better understanding of the coordination of the multi-segmented body. Differences in individual joint angles may be better understood in relation to other joints. Relative phase may be displayed by a joint angle displacement and joint angular velocity plot. Coordination during lifting tasks and the adaptations or modifications made to lift trajectories, segment angles, accelerations and velocities as the musculature is fatigued may provide insight into injury mechanisms. Compensations for fatigued muscles differ greatly between individuals with some observed muscle tradeoff to preserve fatigued muscles and presumably prevent injury (Brereton & McGill, 1999). Determination of relative phase angles allows for insight into the coordination patterns developed during prolonged lifting. Changes in angles between upper extremities and the trunk over the course of a lifting task demonstrate coordination shifts that need to be further investigated and understood. A coordination shift may be defined by a change in the proximal-distal motion pattern. A major component of recent interest involving waveform analysis involves coordination patterns. The Dynamic Systems Theory (DST) (Stergiou, 2003) recognizes that human motion is multifactorial and examines the synergies of the neuromuscular system based on task constraints, and morphological, biomechanical and environmental factors. It is understood that coordination of multiple segments and often multiple joints allows for movement and as complexity increases so does the possibility for increased variability within and between individuals. Phase analysis examines and compares the angular velocity and displacement of coordinated segments, and relative phase may be used to quantify coordination during motion. The advantage to examining relative phase is seen in its ability to integrate multiple segments with several degrees of freedom and to allow for examination of variance in patterns.

Relative phase provides a quantification of interjoint coordination. Angle-angle plots of angular position changes of synchronized joints plot a straight line; however, this is often not the case as segments are rarely entirely synchronous. Phase plane analysis plots angular displacement and angular velocity and from this, the phase angle may be determined for a specific joint. The deviation from in-phase or synchronous motion is the difference between the phase angle of the proximal and distal joint. Point estimate of relative phase measures the relationship between segments by determining times to a specific minimum or maximum angle. Positive relative phase angles indicate that the proximal joint leads the distal joint; whereas, negative relative phase angles indicate a lag in the proximal joint behind the distal joint (Burgess-Limerick, 1993). An uncoordinated ending is seen when one joint follows another for the duration of the lift, and a coordinated ending is achieved when the joints finish the lift in phase (Boston, 1993). A greater degree of variability in the relative phase may occur with unstable movement patterns (Kelso, 1995). Discrete relative phase, examining the maximum and minimum relative phase angles, provides information regarding differences of relative phase value and location within motion and changes with different states of control. Some variability is inherent to an individual as no motion will be identical; however, higher levels of variability may be indicative of an underlying pathology (Granata et al., 1999).

Haken's phase transition theory suggests that stable motions will return to the original pattern relatively quickly, with a short relaxation time, and less stable motions will not recover as quickly after a disturbance. The DST identifies relative phase as an order parameter that effectively compresses multiple degrees of freedom into a single variable which defines the dynamic state of a motion pattern. Control parameters result in relative phase relationship shifts as control variables are manipulated. Phase portraits (angular velocity vs. angular displacement) provide insight into the mechanisms of movement and sudden interruptions are clearly represented by spikes in the otherwise cyclic motion. In work conducted by Sterigiou, coordination was investigated in a cyclic gait task; however, work has been done by Scholz to investigate the application of relative phase to a cyclic lifting task. Scholz (1993) states that previous work has focused on lifting as a highly simplistic task and has constrained tasks to further simplify the task of lifting; however, this prevents realistic interpretation of lifting within a working population. In reality, lifting technique is self-selected and constraints in the motion pattern are affected by the task requirements but not dictated by it.

Now that knowledge has been gained with respect to simple constrained lifting, a more complex view of lifting may be pursued. Lifting is a complex full body task, which incorporates multiple joints and body segments, various muscle groups and different coordination patterns to accomplish motion within multiple degrees of freedom. Within a biological system such as the human body, spontaneous transitions between different states have been observed. It has been suggested that a change in established motion patterns may be due to a loss of pattern stability. Stable motion patterns, usually in phase or coordinated patterns are more stable, and recover more quickly when a disturbance is encountered (Scholz & Kelso, 1989). Coordination investigations are not only required to examine the load trajectory, but also the joint trajectory. The organization of lifting supports a movement plan that is focused on spatial trajectory of the load, and joint trajectories change dependent on load and task characteristics. In a multijoint system, it is difficult to discern which variables require attention. Relative phase has been an effective integrator of intralimb, full body coordination; furthermore, it has allowed for determination of seemingly stable patterns, within dynamic movement, which change with control parameter variation (Scholz, 1993, Xu et al., 2008).

Studies conducted in the area of upper extremity and full body coordination have revealed differences in coordination patterns between individuals and in pathological states (Boston et al., 1993; Xu, 2008). A pathological state may be defined by the presence of a disorder, illness, injury or fatigue which changes the normal motion pattern. The lower extremity segments are often out of phase in stoop lifting; whereas, squat lifting patterns tend to be more in phase. Also, spontaneous transitions, when the lifting pattern undergoes an abrupt switch to another technique or style, have been observed during repetitive lifting (Burgess-Limerick et al., 2001).

Motion that is uncoordinated is considered to be inefficient and is defined by over-shooting, under-shooting, or a lack of fluidity in motion. Uncoordinated movements are often erratic and it has been suggested that the probability of injury increases with progressively more uncoordinated movements. Coordinated movements are directed by a lifting strategy implemented through neuromuscular stimulation patterns designed to accomplish the task with minimal energy expenditure and minimal risk. This strategy for lifting is very general and may be modified depending on the specific task. Coordination patterns are affected by physical state and ability, load characteristics, task expectations and may also differ between sexes. Women tend to lift with the legs and back; whereas, men tend to lift with the arms and back. Differences may also be seen as individuals fatigue and change coordinative strategies to a more uncoordinated variable lift. There is strong evidence to suggest lifting strategy changes with prolonged lifting, possibly due to fatigue of the musculoskeletal supporting structures. Coordination is best understood by relative angle phase, which clearly demonstrates the multiple joint angles at specific points within the normalized lifting waveform. Knowing how technique changes with fatigue, how coordination of the musculoskeletal system changes, allows for an understanding of how fatigue may lead to an increased likelihood of injury.

1.4.2 Principal Component Analysis of Lifting Waveforms

Principal component analysis (PCA), a type of factor analysis, is a parametric statistical tool which has been successfully used to extract key components or variables of interest from correlated variables. The advantage of this statistical method is seen in its ability to transform correlated variables to uncorrelated ones to determine underlying factors which have influenced the correlations. It allows determination of linear equations with varying degrees of variability and is useful in data reduction. Data reduction allows for simplification of a seemingly complex data set, where extraction of main loading vectors is helpful in developing a simpler model without redundancies in the ability of variables to explain the waveform structure. Overall, PCA allows extraction of the principal components that explain variance within large data sets with multiple variables, allowing for determination and subsequent elimination of variables that do not contribute significantly to the variance within a data set.

There are several areas of interest within a lifting waveform including the general shape, phase shifts and amplitudes. Waveforms may differ between individuals, and may change as a result of fatigue induced by prolonged lifting. Parameter based studies of kinetic and kinematic variables have been proven ineffective in their ability to identify significant differences in lifting and coordination patterns. Issues are expected to manifest as appreciably different values within a lift and *a priori* selection of the important portions of the lifting cycle often do not allow accurate assessment of the lifting differences and similarities. Studies involving waveform analysis allow for a complete understanding of the lifting activity in its entirety. PCA has successfully been used in waveform analysis of gait cycles in the lower extremities by Deluzio et al.

(1997) and was also used by Wrigley et al. (2006) to investigate the motion of the spine during a repetitive lifting task. PCA has been used to effectively identify, quantify and describe differences in lifting waveforms between different groups (Deluzio et al., 1997). Through extraction of the key variables that characterize waveform structure, much of the functional variability between individual waveforms is explained. PCA has been suggested as a useful tool in the assessment of coordination as it demonstrates important differences in magnitude, phase shifts or general waveform shape and variability which is significant and not random (Daffertshofer et al., 2004). Now this statistical tool may be applied to the shoulder joint and relative phase angle data to effectively extract the principal factors within a lifting cycle observed across general and specific fatigue.

1.5 Muscular Fatigue Mechanisms and Influences on Technique

1.5.1 Muscular Fatigue

Fatigue may be defined as a physical state which may be induced by prolonged repetitive muscle contraction. Fatigue resulting from physical activity is often defined by a reduction in the ability of a muscle to produce force. Fatigue has been related to muscle weakness, coordination changes and injury (Bonato et al., 2003; Chen, 2000; Côté et al., 2008; Côté et al., 2005; Fuller et al., 2008). As previously stated, fatigue may result in a decrease in full body joint coordination which has been suggested as a contributing factor to injury risk. Coordination changes resulting from fatigue are primarily due to a reduction in the ability to produce and maintain force within a muscle which leads to recruitment of other synergistic muscles and eventual muscle failure

(Kumar, 2001). Muscle recruitment patterns adjust depending on the level of fatigue and, due to the ability of the body to accomplish a specific task in several different ways, this recruitment pattern shift manifests as a coordination change. The theory of cumulative loading and repetitive strain may be associated with fatigue as well. As each subsequent lift builds on the strain of the previous lift, the muscles are contracted and stretched with little opportunity for recovery. Fatigued muscles are less capable of maintaining required force and therefore other muscles must be recruited to compensate, changing the motion pattern. If other muscles are also fatigued and have not had the opportunity to recover, muscle failure and injury may ensue. An investigation into the role of fatigue in increasing susceptibility to acute muscle strain injury found that fatigued muscles are not able to absorb the same degree of energy and will sooner reach a degree of stretch that may lead to injury (Maier et al, 1996). An inability to handle loading of the musculoskeletal system and muscle failure, are a direct result of fatigued muscles. Injury prevention in MMH requires a comprehensive understanding of physical limits and what compensations occur when those limits are surpassed.

1.5.2 Mechanisms of Fatigue

Determination of the degree of fatigue within a system has often been difficult to quantify due to difficulty in defining fatigue accurately. Physiological stresses may be determined by heart and respiration rates, and energy expenditure measures such as the oxygen consumption rate. Physiological measures of fatigue are commonly used to determine level of fatigue. Neuromuscular measures often involve use of electromyographical data to determine degree of fatigue (Kallenberg & Hermens, 2008).

As muscles tire, more and more fibres are recruited to maintain force, with movement from small to large motor units, and the frequency of electrical firing decreases as simultaneous stimulation of motor units increases. The strength of the electrical signal increases as well due to the increase in stimulation of the muscle. Subjective scales, such as measures of perceived exertion, pain and discomfort scales have often been used to measure degree of fatigue. The issue with subjective measures is seen in the different perceptions of individuals. Some individuals perceive fatigue sooner or later than the average, so subjective measures are best used with another quantifiable method of gauging fatigue.

The quantifiable measure most commonly used to assess fatigue is the measure of EMG activity. EMG is a measure of electrical activity within a muscle. This measure is a summation of all individual motor unit action potentials (MUAPs) within range of the detection electrode. The advantage of using EMG to determine level of fatigue over a psychophysical measure is in its objectivity. EMG is impacted by sensor placement, skin thickness, hydration, adipose layer depth, cleanliness of the skin and location of the muscle of interest in relation to other muscles. Deep muscles, often stabilizing muscles, give some cross-talk and are not effectively measured using surface EMG. Cross-talk is defined by an inaccurate assessment of muscle activity due to the addition of underlying and adjacent muscle MUAPs. There are limitations as to which muscles may be assessed for fatigue and an awareness of anatomy and underlying musculature is required in order to interpret signals correctly. Fatigue is typically determined by the decrease in the median-frequency of the EMG signal and the increase in the RMS (root-mean-squared) EMG. Overall, EMG readings at specific points within a dynamic task allow for a better understanding of the level of fatigue being experienced within a muscle acting on a joint system.

1.5.3 Coordination and Technique Changes Related to Muscular Fatigue

Fatigued muscles require reprieve and this is accomplished through recruitment of different muscles and changes in neuromuscular electrical stimulation patterns. As a greater number of muscle fibers are recruited within a muscle to maintain force, eventually force cannot be maintained by the initial loading muscles. There are several redundancies, within the shoulder in particular, which allow for use of different muscles to accomplish similar motions. Even with this ability to recruit different muscles to accomplish the same task, technique will change with fatigue. Lift displacements and velocities change according to physical ability. Changes are seen in lift trajectories, dynamic postural patterns and with time, relative phase angles begin to show a less and less coordinated motion (Larivière et al., 2000). Coordination patterns have been previously used to differentiate between the trunk motion patterns of individuals with chronic pain resulting from previous back injury and healthy individuals (Larivière et al., 2000).The advantage to understanding coordination changes, is seen in the ability to differentiate between group, rested and fatigued, motion patterns, based on the degree of coordination.

There have been many investigations into the effects of fatigue on the risk of injury. Fatigued and injured individuals demonstrate different lifting coordination patterns than control subjects (Bonato et al., 2003; Chen, 2000; Côté et al., 2005). Through the duration of a cyclic lifting task, a shift is often seen as a squat lifting strategy moves toward a stoop style of lifting, which is confirmed by an increase in trunk range of motion. Muscle fatigue has been correlated to biomechanical changes and this suggests a compensation strategy, which is often seen in coordination changes (Bonato et al, 2003). A motor control perspective suggests that fatigue leads to inappropriate muscle sequencing, which leads to injury (Brereton & McGill, 1999). Muscle control and performance involves the central and peripheral nervous system as well as local factors of the muscle itself, which may include energy supply and metabolic processes. In a study of extracted muscle tissue it was found that muscle failure comes from an inability of the tissues to absorb energy, a loss of elasticity and a mechanical overload that cannot be met by the overstretched and fatigued tissue (Mair et al., 1996). Muscle fatigue at a cellular level describes failure of the tissue itself to maintain integrity upon application of a load over time. Muscle fatigue at the level of motor control involves the central and peripheral nervous system, and the ability of sensory information about external loading and internal compensations to be relayed to the CNS where motor recruitment of the necessary motor units and synergistic muscles may occur. Central failure due to fatigue suggests that there is an issue in the ability of the body to recruit motor units to maintain force (Enoka, 2008). The ability of the CNS to receive information and issue the appropriate commands to maintain stability and structure is known to be influenced by fatigue.

Biomechanical modeling has been used to classify coordination and determine the level of impairment due to injury or fatigue. Angular velocity and acceleration have been more effective in identifying differences in range of motion throughout the duration of the lift. The pattern of motion changes relative to the control at specific time points within the normalized lift. Though the waveforms are distinctly different between injured and control groups; the changes to the angular displacement, velocity and acceleration are relative to the control waveform (Marras, 1995). Therefore based on the movement waveforms and the pattern established, waveforms may be placed into the respective groups of normal, fatigued and injured. The link between fatigue and injury has been established by several studies. It has been shown that individuals with pain or injury of the low back have different coordination strategies than uninjured individuals and therefore it may be suggested that the discomfort associated with fatigue of a musculoskeletal structure also has an effect on coordination (Larivière et al., 2002). Fatigue may lead to instability, cumulative strain, uncoordinated movement and this may lead to injury. Spontaneous and abrupt transitions within a lifting task have been identified (Burgess-Limerick, 2001), and it is suspected that these perturbations increase with task cycle frequency and fatigue. A loss of stability or muscular integrity due to fatigue increases the risk of injury. Instability may result in uncoordinated reactions and random error in motion. Stability is maintained by passive stabilizing muscle contraction, open-loop recruitment, and active feedback and reflex response systems. When the back muscles are fatigued, stability of the spine decreases and this has been linked to lower back pain and subsequent injury (Granata & Gottipati, 2008). This may be applied to shoulder fatigue mechanisms and suggests that instability due to muscular fatigue may lead to perturbations in motion due to attempts to compensate for poor stability of the joint and subsequent injury.

General fatigue observed in a prolonged lifting task, is a culmination of total fatigue and most akin to reality; however, knowledge of the compensations which occur with specific fatigue may give new insight into how injury of specific structures occurs. General fatigue applies to the fatigue that would typically be experienced in occupational settings and will better approximate real life situations involving a dynamic lifting task; however, specific fatigue of muscle groups provides insight into how compensations occur. Investigations into back, leg and arm specific fatigue give clear views of how the coordination of a task is affected by fatigue of key structures. In a short duration fatiguing exercise, it was found that general fatigue was perceived as more strenuous but coordination patterns were relatively unchanged; however, the back fatiguing protocol which was perceived as less strenuous introduced change into trunk coordination (Gorelick, 2003). Though the back fatiguing protocol was not perceived as very tiring, coordination changed suggesting that inaccurate worker perception of fatigue may increase susceptibility to injury, particularly of the spine. When the arms are fatigued, there is an increase in low back stress, and an increase in load acceleration combined with stiffening of the arms in the later portion of the lift (Chen, 2000). Very little work has been conducted to investigate specific arm fatigue influences on free-lifting technique; however, fatigue of the shoulder joint resulting from repetitive motion has been investigated and the results provide some insight into the compensation patterns adopted when the arms are fatigued.

It has been observed that with fatigue, coordinative strategies will change to accomplish the task (Fuller, 2009; Côté et al., 2008; Côté et al., 2002). Specifically, the trunk motion may change to reduce the loading of the fatigued shoulder joint. Many lifting strategies will change with fatigue to a less coordinated, less in phase motion, and these less coordinated strategies may increase the chance of injury (Scholz, 1993).

Another issue involved in coordination is proprioception and the effects of fatigue on the ability of the body to perceive location and motion. Repetitive motion induced fatigue of the shoulder joint revealed a decrease in grip strength, range of motion, peak acceleration and peak velocity. Fatigue of the shoulder resulted in a greater degree of variability in elbow and wrist motion, and movement trajectory in a hammering task in conjunction with a strategy to maintain relatively constant motion of the shoulder when fatigued or injured (Côté et al., 2005). Research into muscle fatigue induced biomechanical changes during a cyclic, repetitive, lifting task, has given strong evidence that lifting strategies change with prolonged lifting. Kinematic variables of joint range of motion and postural indexes showed an increase in hip and trunk ROM demonstrated in the shift of lifting technique toward a predominantly squat technique (Bonato, 2003). It is believed that the kinematic variations seen in lifting strategy are due to sensory-motor changes with fatigue. It is also possible that peripheral sensory perception decreases with fatigue or as muscles are fatigued (Lee, et al., 2003), muscle response to neural inputs is negatively affected, requiring compensation and motion pattern changes.

1.6 Proposed Research

Despite the advances provided by previous research there remain many questions to answer related to lifting accommodation due to muscular fatigue. The kinematic changes associated with prolonged lifting induced fatigue are not well understood and the coordination strategies even less so. There are many issues involved in the understanding of lifting biomechanics due to the high complexity of the coordination of the body in multiple degrees of freedom. This current investigation will examine the complete lifting waveform and using PCA, will discriminate the key parameters responsible for the variability within subjects and between subjects across the different fatiguing protocols. The PCA waveform analysis will provide greater insight than previous studies, which have be limited by parameter based analyses. This research will provide insight into the coordination changes resulting from prolonged symmetrical lifting and the differences between different fatigued states. The use of PCA to extract key components along a normalized lifting cycle will enable later development of predictive equations and will provide greater understanding of the factors which influence coordination changes with fatigue during lifting. Therefore, the proposed research aims to address the following research questions with respect to fatigue effects on symmetrical lifting coordination patterns through use of PCA:

1. Are there significant differences in kinematic lifting waveforms from the initial, pre-fatigued, lifting profile and the fatigued lifting profile?
2. Are there significant changes in coordination patterns, relative phase, as a result of fatigue?
3. Are there significant differences in kinematic lifting waveforms across the general, shoulder specific and back specific fatigued states?

Hypotheses Statements

1. The pre-fatigued kinematic lifting waveforms will be significantly different from the fatigued lifting profiles.
2. The relative phase will reveal altered coordination strategies in order to compensate for fatigue..

3. The shoulder specific fatigue state will require a greater range of trunk motion as the upper extremities are fatigued; whereas, the back specific fatigued state will require greater arm and shoulder activation while minimizing motion of the fatigued back.

2.0 METHODS

2.1 Participants

Sixteen males and fifteen females, between the ages of 20-40 years (working age), were recruited. Any participant who reported a shoulder or back disorder within the previous year or was currently experiencing shoulder or back discomfort was excluded from the study. Participants' sex, age, height, weight and anthropometric data was collected to be used in analysis. Ethics approval was received from the University of New Brunswick Research Ethics Board prior to commencement of the study.

2.2 Data Collection

2.2.1 Instrumentation

2.2.1.1 Fastrak

Kinematic data was collected using, FASTRAK, an electromagnetic 3D motion tracking system (Polhemus Inc., Vermont, USA). This system provides three-dimensional x,y,z coordinates and the orientation (azimuth, elevation and roll) relative to the stationary source receptor at a collection frequency of 120Hz. This equipment has been verified by the manufacturer to have a static accuracy of 0.1cm position and 0.15^{o} orientation. Motion in six degrees of freedom was investigated through calculations of displacement, velocity and acceleration. Sensors were placed bilaterally on the center of gravity of the hand, forearm and upper arm. Single sensors were placed on the right acromion, spine at the level of C7/T1, T8 and the sacrum. (Appendix A). Sensors were secured using double-sided tape and custom bands. Anatomical landmarks were digitized, using a Fastrak sensor probe, in relation to the sensors to satisfy ISB recommended standards. This digitization allowed for development of a segment embedded coordinate system where each joint angle was then determined relative to the segment of interest.

2.2.1.2 Force Transducers

Force produced in a maximum voluntary capacity for muscle contraction was measured by a force transducer embedded in the laboratory floor. The 500 lb force transducer (Precision Transducers, New South Wales, Australia) transmitted to a Micronmeter signal conditioner (MicronMeter Co., Georgia, United States of America) which then amplified the signal from the load cell. This information was relayed to a LabView program (National Instruments Corp., Texas, United States of America) during data collection.

2.2.1.3 Electronic Triggers

Triggers were used to assess the beginning and end of the lift, from the moment the box left the floor trigger to the moment that the trigger on the shelf was activated. The triggers were standard push button switches and ran through a voltage divider circuit that differentiated between the two switches. The separate voltages gave clear divisions between the beginning and end of the lift in the collecting programs within Labview.

2.2.2 Procedures

2.2.2.1 Lifting Task

The lifting task used in the pre/post fatigue data collection and the general fatiguing protocol consisted of a symmetrical lifting task. Participants were asked to lift a box weighing 10% of the lift specific MVC from floor to shoulder height at a rate of 6 lifts/minute as determined through pilot research. Shoulder height was relative and adjusted according to the height of the hands with the arms raised to 90 degrees of shoulder flexion, horizontal to the floor. Labview and Matlab (Mathworks Inc., Massachusetts, United States of America) programs were used in data collection and analysis. The lifting motion from floor to shoulder height was identified by triggers placed on the floor and on the shelf. Each trigger was identified by a separate voltage, which allowed for accurate determination of the complete lift and synchronization of the different data.

Figure 2.1 Illustration of lifting setup for all lifts.

2.2.2.2 Familiarization Session and Preliminary Testing/Assessment

Prior to the data collection sessions, participants were asked to come to the Laboratory for Occupational Biomechanics and Ergonomics Research to review the study and discuss the different testing sessions. At this time, participants were asked to sign the consent form. Participants were given the opportunity to ask questions and familiarize themselves with the equipment and procedures. This allowed for clarification of the protocols and a more efficient setup at the time of testing. During the familiarization session, anthropometrics were measured and recorded as part of preliminary assessment. A lift specific MVC was also measured at this time (da Silva et al., 2005; Dolan et al., 2005), as part of the preliminary testing, to determine the box weight for the lifting task. The handle, attached to the transducer by a chain, reached to knee height. The participants were instructed to: stand with feet shoulder width apart, centering the load cell between the feet, assume a semi-crouched posture with a straight back, and pull upwards on the handle. As previously determined in pilot work, the box weight for the lifting task was determined as 10% of the lifting MVC.

2.2.2.3 Testing Sessions

Each participant was required to participate in the three separate testing sessions in addition to the familiarization and preliminary assessment session; one for each fatigued state: general, shoulder specific, and back specific. There was a standard protocol that was performed at the beginning and end of each session, with a different fatiguing procedure between the pre-fatigue and fatigued assessments. Fatiguing protocols were randomized between participants.

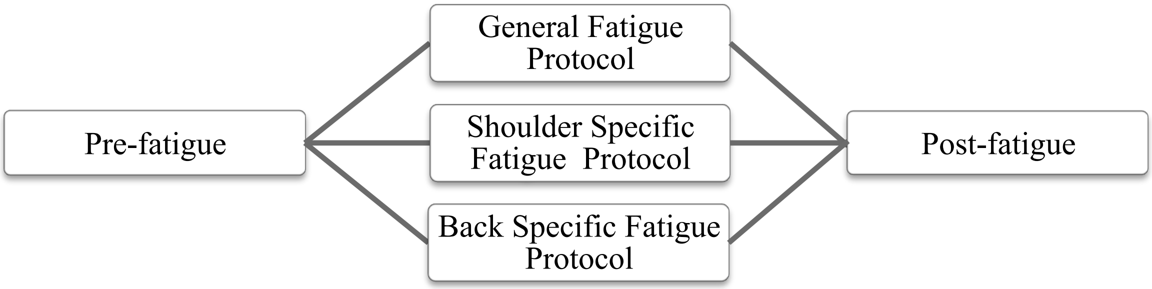


Figure 2.2 Schematic of the experimental design setup.

2.2.2.4 Pre-fatigue assessment

The participants were required to perform three static shoulder and back MVCs for a duration of 15 seconds with 1 minute of rest between MVCs. The order of MVCs, shoulder and back, was randomized between participants. The shoulder MVC was taken from a secured seated position, with the arms raised to the front in a right angle to the trunk, as determined using a goniometer placed at the joint center of the shoulder. Participants were asked to use both pronated hands to pull upward on the bar that had been attached to a force transducer embedded in the floor. The back MVC was determined through a horizontal back extension with the subject secured in a prone position. Participants were asked to perform the back extension from a resting supported slightly flexed position. A full torso harness was attached to the force transducer embedded in the floor to measure the force resulting from the contraction. Upon completion of the MVCs, the electromagnetic sensors were placed on the segments previously outlined and landmarks digitized (Appendix B). At this time, participants were required to perform a 5 second static hold, standing upright with the shoulder at 90 degrees of flexion, holding the box which was to be lifted throughout testing. This was then be followed by five minutes of baseline lifting collection at the rate of 6 lifts per minute from floor to shoulder height. The box weight was determined as 10% of the lift specific MVC, in accordance with previous pilot work conducted. During this time data was collected for 30 second intervals at time 0.5, 2.5 and 4.5 minutes. At this point participants performed the selected fatiguing protocol, the order of fatiguing protocol selected for the session was randomized.

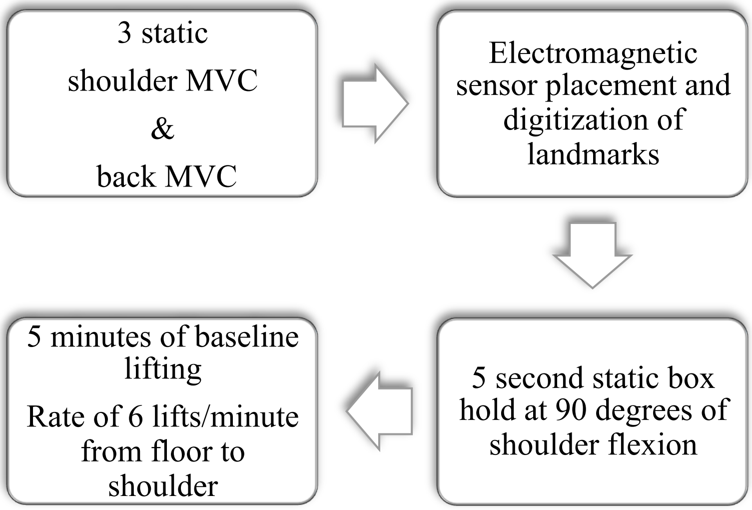


Figure 2.3 Outline of the pre-fatigue collection procedures.

Figure 2.4 Demonstration of shoulder and back MVC procedures: A) shoulder fatiguing protocol; B) low back fatiguing protocol.

2.2.2.5 Fatiguing Protocols

Figure 2.5 outlines the three lifting protocol sessions and each are discussed in detail in this section.

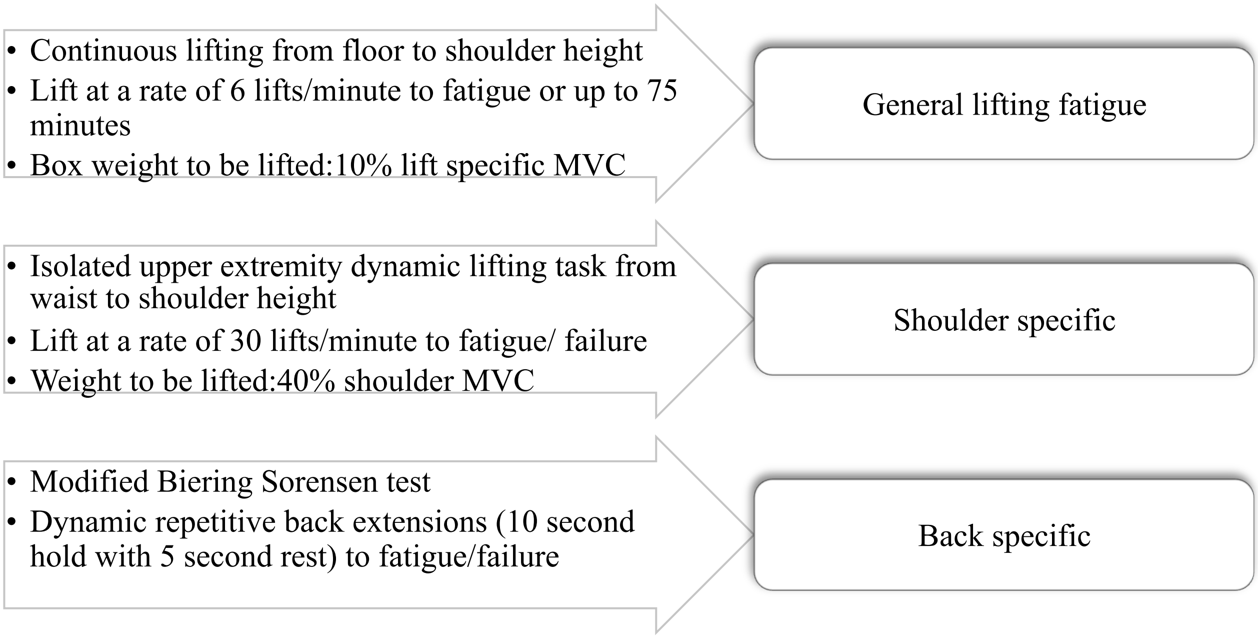


Figure 2.5 Outline of the experimental sessions

General fatiguing protocol. The general fatiguing protocol required participants to continue to lift a box weighing 10% of the pre-determined lift capacity, calculated from the lift specific MVC, from floor to shoulder height at a rate of six lifts per minute to fatigue or up to 75 minutes. Data was collected at five minute intervals for a duration of 0.5 minutes. The box weight, lifting task, and task rate then continued as in the pre-fatigue baseline data collection.

Shoulder specific fatiguing protocol. The shoulder specific fatiguing protocol required participants to lift a weight, 40% of the shoulder MVC as previously determined in pilot work, with both hands in a dynamic motion, mimicking the lifting motion. Participants were required to lift from a constrained seated position, allowing for isolation of the upper extremities with minimal contribution by the spinal musculature. The lifting pattern was from the lap to a target height, set at 110 degrees of shoulder flexion, measured using a standard goniometer. Participants were asked to lift at a rate of thirty lifts per minute until they were unable to reach the target or two consecutive lifts were missed.

Back specific fatiguing protocol. The back specific fatiguing protocol involved a Biering-Sorensen test, which has previously been used to assess isometric endurance of the back muscles (Biering-Sorensen, 1984). To avoid issues of blood occlusion/restriction to the working back extensors, and to more closely approximate the fatigue effects of dynamic lifting, the participant performed a modified, dynamic Biering-Sorensen. Participants were required to perform back extensions with a ratio of 10 seconds of back extension to 5 seconds of rest, repeated to fatigue, when unable to complete the task.

2.2.2.6 Post-assessment: Fatigued state

The post-assessment involved repetition of the pre-assessment procedures. Fatigued participants were required to perform a final five minutes of the general lifting task, at which time data was collected for 30 second intervals at 0.5, 2.5 and 4.5 minutes. Participants were then required to perform a 5 second static hold. MVCs were taken of the shoulder and back at 1, 2 and 5 minutes. This concluded the testing period, sensors were removed and equipment shut down.

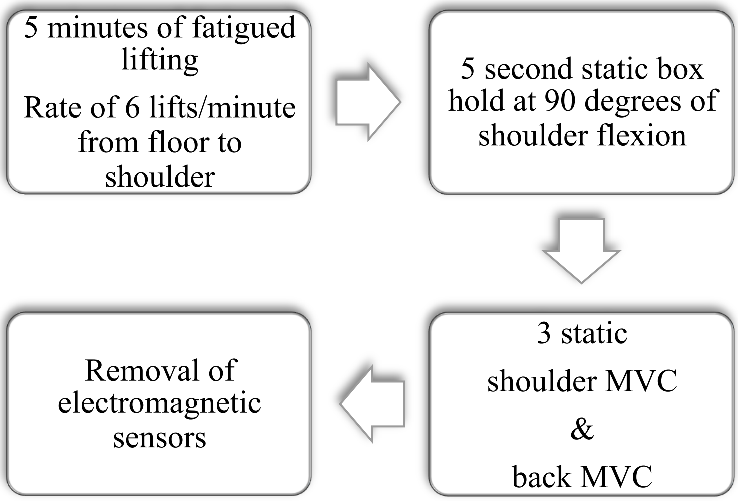


Figure 2.6 Outline of the post fatigue collection procedures.

2.3 Data Analysis

Table 2.1 Waveform and Discrete Variables Analyzed

Waveform Variables	Discrete Variables
Box Trajectory Position	Maximum Lift Capacity
Box Trajectory Velocity	Lift Time
Box Trajectory Acceleration	Shoulder static MVC
Elbow Angular Position	Back static MVC
Shoulder Angular Position	Sex
Shoulder Angular Velocity	Age
Thoracic Angular Position	Height
Thoracic Angular Velocity	Weight
Lumbar Angular Position	
Lumbar Angular Velocity	
Relative phase of the shoulder, thoracic & lumbar spine	

2.3.1 Kinematic Data Analysis

All kinematic data was dual-pass Butterworth filtered at 6 Hz. Data analysis consisted of determination of the joint angles of the elbow, shoulder, pelvis, and trunk (thoracic and lumbar spine). The information collected during Fastrak digitization of landmarks in relation to sensors was then applied to the individual sensor data, throughout the entire collection, using Matlab to determine landmark location throughout the protocol. The angle position and angular velocity was determined throughout the waveform, and from this, coordination was investigated. Coordination was assessed through determination of the relative phase angles of the elbow, shoulder and trunk throughout a lift waveform, normalized to 100%. Lift duration was determined by the triggers at the beginning and end of the lift; whereas, the load trajectory was described by the position of the hands throughout the motion.

The following outlines the data analysis and the research questions that each analysis addressed. Each set of waveforms was analyzed using PCA to allow for better interpretation of differences. The loading vectors were used in curve reconstruction and subsequent repeated measures ANOVAs were conducted to determine significant differences in the principal component scores from the original data set.

1. Lifting kinematics General Fatigue – Are there significant differences in kinematic lifting waveforms from the initial, pre-fatigued lifting profile and the fatigued lifting profile?

Comparisons were made between pre-post lifting patterns observed in the elbow, shoulder, thoracic and lumbar spine angles.

2. Lifting Coordination General Fatigue- Are there significant changes in coordination patterns, relative phase, as a result of fatigue?

Comparisons were made between pre-post lifting patterns observed in the relative phase angles of the shoulder-thoracic spine, shoulder-lumbar spine and the thoracic-lumbar spine.

3. Lifting Kinematics Fatigue States - Are there significant differences in kinematic lifting waveforms across the general, shoulder specific and back specific fatigued states relative to the average un-fatigued state?

In order to compare between the fatigued states, the pre-fatigued states needed to be investigated. PCA was used to assess pre-fatigue lifting profiles of the different testing sessions. If pre-fatigued waveforms were not significantly different, the pre-fatigue waveforms were averaged for each subject to then be used in comparisons between different fatigued states of general, shoulder specific and back specific.

4. Lifting Coordination Fatigue States - Are there significant differences in lifting coordination waveforms across the general, shoulder specific and back specific fatigued states relative to the average un-fatigued state?

Comparisons were made between averaged pre-fatigue waveforms and fatigued conditions.

2.3.2 Relative Phase

Relative phase is used to assess coordination. Phase plane analysis compares the angular displacement and angular velocity and this may be used to quantify joint coordination between joints. Phase angles are determined by the angular velocity -

angular displacement plot where the angle formed by the radius and horizontal axis, the phase angle, is determined through tangent calculations. Relative phase may then be calculated as the difference between the distal segment phase angle and the proximal segment phase angle (Stergiou, 2003). The joints of interest were the: elbow, shoulder, and the thoracic spine. Relative phase was used to investigate the upper extremities and back coordination during prolonged lifting. The coordination of the elbow, shoulder, thoracic trunk segment was investigated.

Phase angle = $\theta_{\text{phase}} = \arctan\left({}^{\text{angular velocity}}/_{\text{angular displacement}}\right)$

Relative phase angle = $\theta_{\text{distal}} - \theta_{\text{proximal}}$

2.3.3 – Relative Phase Frequency Analysis

A relative phase frequency analysis was conducted on the entire data set in order to assess the trends of the lift with respect to coordination of body segments. The relative phase angles were assigned to the respective range and then graphed. Then a repeated measures ANOVA was conducted to assess differences between the different fatigued states for each range. The relative phase angles were set into 30-degree ranges: -180/-150, -150/-120, -120/-90, -90/-60, -60/-30, -30/0, 0/30, 30/60, 60/90, 90/120, 120/150, 150/180. The frequency graphs provided visual information while the statistical analysis provided determination of significance between states of fatigue.

2.3.4 PCA – Principal Component Analysis of Waveforms

Principal Component Analysis was conducted on the kinematic lifting waveforms. Investigations included differences between: individual participants, men and women, pre-fatigued and fatigued states of general lifting, shoulder specific and back specific fatigue across participants. These kinematic investigations included: joint angle, angular velocity and angular acceleration, relative phase/coordination, lifting duration, and load trajectory. The elbow and shoulder joint, and thoracic spine were investigated with respect to the previously stated differences.

PCA begins with development of a covariance matrix (S), which undergoes an orthogonal rotation. Rotation is achieved through manipulation of the S-matrix, identity matrix and a characteristic/normalizing equation. The resulting orthonormal matrix (U) contains the non-correlated variables, eigen-vectors/characteristic vectors. The U-matrix and S-matrix may then be used to determine the variances of the principal components which comprise the diagonal matrix (L). These variances are known as the eigen-values/characteristic roots/latent roots.

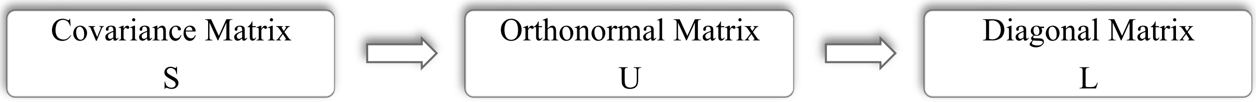


Figure 2.7 Outline of principle component analysis – matrix rotation

Covariance equation $s_{ik} = \frac{1}{n-1}\sum_{j=1}^{n}(x_{ij} - \bar{x}_i)(x_{kj} - \bar{x}_k)$

Orthonormal: eigen-vector equations $[S - lI]_{ti} = 0$ $u_i = \frac{t_i}{\sqrt{t_i' t_i}}$ $ui'ui = 1$

Diagonal: eigen-value equation $U'SU = L$

Essentially, the components with eigen-values (characteristic roots/latent roots) greater than one are selected as the principal components and the variability accounted for by each component is presented as a ratio of the characteristic root to the total.

Depending on the degree of variability accounted for by the extracted components, a correlation may be established between the original waveform and the projected waveform determined by the input values for the determinant components. Usually only a few select components account for much of the variability within and waveform and a screeplot of the eigen-values visually displays the proportion of variability accounted for by the individual components, eventually the higher components offer little to no change in the degree of explained variability and therefore do not benefit the analysis and need not be included in further analysis. There are several ways to assess component significance and determine component retention: the Kaiser criterion requires an eigen-value greater than one, the Cattell Scree test uses visualization of a breakoff point of eigen-value leveling, the trace criterion retains as many components as necessary to account for a specified percentage of variance. The parallel analysis was used in this analysis as it retains only the principle components that explain variance beyond that which would be expected through randomized chance alone (Fischer et al., 2012). By scaling the eigenvalues to percentage of total variation captured, the number of principal components to retain for comparison was determined using parallel analysis (Jackson, 1991; Wrigley et al., 2005, 2006). The experimental data set variance was contrasted against the PCA results of a randomized data set of equal parameters. The PCA allowed for identification of magnitude (size difference) and difference operators (instances of cross-over) within the waveform data. Curves reconstructed from each PC and the accompanying loading curves clearly demonstrated the portion of the lifting waveform in which there was the greatest degree of variability and which PC accounted for this difference.

Upon extraction of the principal components, curves were reconstructed based on the selected components. The PC scores, transformed variables, were compared with the original data using repeated measures ANOVAs. The PCA allowed for interpretation of data and the reconstructed data, PC scores, were used to compare original data with the transformed data providing statistical power to the analysis.

2.4 Significance & Implications

This research gives insight into the effects of fatigue on motion patterns of lifting. The shoulder joint is extremely complex and injury mechanisms are not well understood; therefore, this work will help to develop a deeper understanding of the compensations that occur with fatigue of the shoulder. This study also examined the relationship of multiple body segments through analysis of relative phase, coordination of the arms and back. The investigation of complete waveforms rather than traditional parameter based analysis gives strength to the results of this study. Very little is known about sex differences in lifting technique and compensations that occur as a result of prolonged lifting induced fatigue. This study also improved understanding of compensation as a result of specific fatigue of the shoulder and back in comparison to general fatigue. The PCA of waveforms has previously been used in cyclic activity analyses of gait and lifting. PCA is an effective, data reduction and extraction, statistical tool. This research examined the impacts of fatigue, specific or general, and the resulting compensations and contributes to the overall understanding of lifting coordination patterns and the effects of fatigue. This can aid in understanding of fatigue mechanisms and can help in development of health and safety protocols, designed to minimize injury and re-injury within the workforce.

3.0 RESULTS

There were thirty-one participants recruited who completed the entire study requirements: 15 males/16 females between the ages of 20-32 years (23.9±2.8), with height/weight ranging from 156-198.5cm(171.6±9.8)/53-99.8kg(72.4±11.7) respectively. The box weight ranged from 5.7-22kg (12.4±4.3), dependent on the measured lifting MVC (Appendix C).

The results of this study consist of the participant anthropometrics, pre-fatigue comparisons across testing sessions, maximum voluntary exertion analyses to evaluate fatigue, the principal component analysis of kinematic and relative phase lifting waveforms, and the relative phase frequency analysis.

3.1 Pre-fatigue kinematic and relative phase across testing sessions

In order to evaluate the consistency of the pre-fatigue waveforms between testing sessions, Principal Component Analysis (PCA) was used to investigate differences between the pre-fatigue kinematic waveforms of all sessions in order to determine if the pre-fatigue waveforms could be averaged for comparisons with the fatigued waveforms for each session. There were only significant differences for a few of the comparisons and these occurred in the later PCs which explained less variance (Appendix D). There were significant differences between the following pre-fatigue kinematic waveforms: right elbow flexion/extension PC 3 back and shoulder sessions (19.18% variance explained), right shoulder flexion/extension PC 4 shoulder and general sessions (3.65% variance explained), and trunk flexion/extension PC 2 back and shoulder, shoulder and general sessions (10.63% variance explained). As there was significance found in only a few comparisons and the significance was found in later PCs, which explained less variance, it was acceptable to average the pre-fatigue waveforms across the three testing sessions to allow for direct comparisons between the fatigued states. The relative phase investigations showed some significance in early PCs; however, it was still determined acceptable to average the pre-fatigue waveforms for all testing sessions. There were significant differences in the following pre-fatigue relative phase waveforms: left forearm upper arm PC 1 (49.16% variance explained) and PC 5 (4.40% variance explained) shoulder and general sessions; right forearm upper arm PC 1 (42.88% variance explained) and PC 3 (9.27% variance explained) back and shoulder, shoulder and general sessions; left upper arm trunk PC 1 (24.13% variance explained) shoulder and general sessions, PC 3 (17.43% variance explained) back and shoulder, shoulder and general sessions; right upper arm trunk PC 1 (28.70% variance explained) back and general sessions. As there were minimal differences between the pre-fatigue kinematic and relative phase waveforms of all three sessions, the pre-waveforms were averaged for later comparisons to the fatigued waveforms. All waveforms analyzed can be seen in Appendix E.

3.2 Maximum Voluntary Exertion/Contraction Fatigue

Maximum voluntary exertion forces were measured in the pre-assessment and post fatigue assessments for all testing sessions (Appendix F). The average percent decrease in contraction strength were as follows: general fatiguing protocol, back 18% ($p<0.001$) and shoulder 14% ($p<0.001$); shoulder specific fatigue protocol, back 11% ($p=0.003$) and shoulder 24% ($p<0.001$); back specific fatigue protocol, back 17%

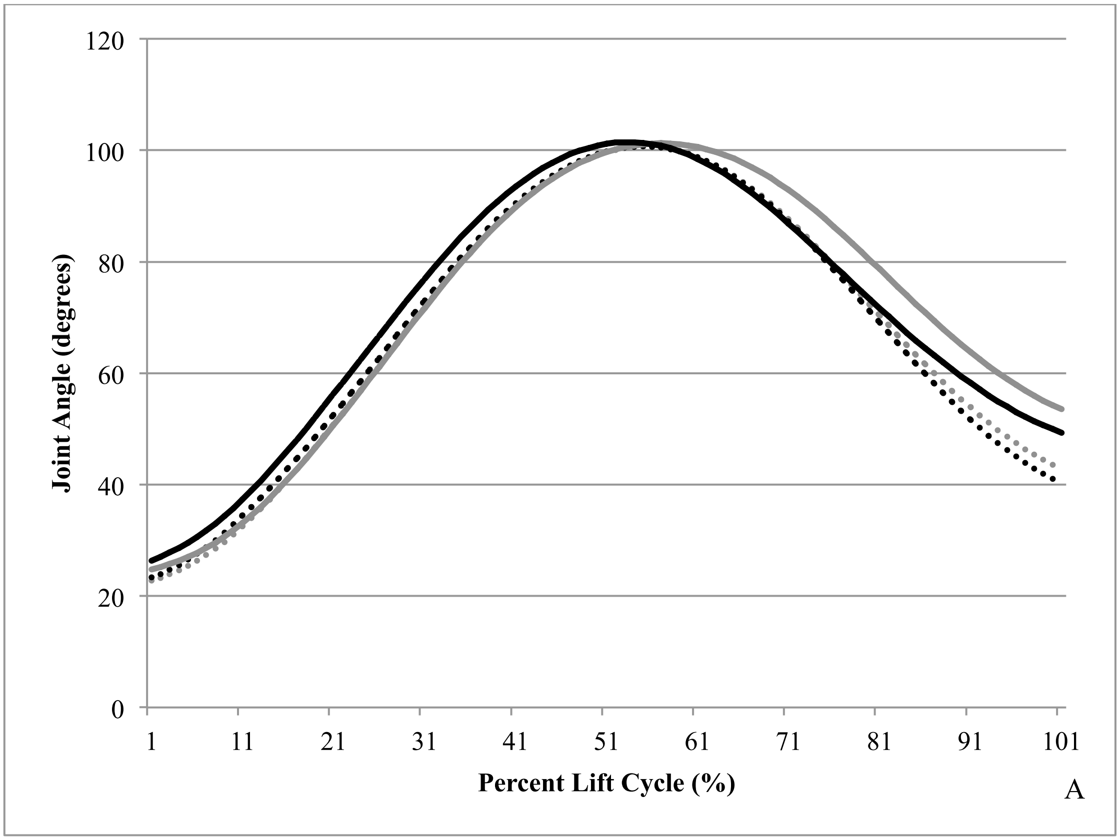
($p<0.001$) and shoulder 10% ($p<0.001$) (Table 3.2). There was an observed degree of fatigue in most cases and a few individuals appeared to experience a warm up effect despite verbal confirmation of perceived exertion and fatigue. Although efforts were made to minimize the effect of recovery on fatigue measures by conducting data collection efficiently, some recovery may have been experienced. In the general fatigue protocol the back MVC suggested significant fatigue of the postural muscles of the spine. The shoulder specific fatigue protocol showed evidence of significant fatigue of shoulder musculature and in the back specific fatigue protocol there was evidence of fatigue but this was not significant. Statistically significant fatigue of the back musculature is sometimes difficult to achieve due to the constant postural requirements and demands; however, decreases in the ability of these muscles to generate force may still raise significantly the risk of injury.

Table 3.1: Pre-post fatigue percent changes in MVE measures for the shoulder and back musculature across testing sessions.

% Change pre – post						
	General		**Shoulder**		**Back**	
	Back	**Shoulder**	**Back**	**Shoulder**	**Back**	**Shoulder**
Average%	-18	-14	-12	-24	-17	-10
minimum	31%	0%	47%	-12%	35%	11%
maximum	-54%	-32%	-39%	-41%	-70%	-21%

3.3 Results of kinematics and relative phase of pre-fatigue, general fatigue, shoulder specific and back specific fatigue conditions

Investigation of the kinematic waveforms showed significant differences between specific conditions for all PCs. Interpretation of the loading curves involves a focus on the areas of greatest and least variance explained by the PC. Loading curves give an indication of the areas within the lift that require further analysis and interpretation. If significance is determined between conditions, the loading curve indicates where these significant differences are located. Magnitude differences are associated with high variability, and difference operators are associated with low variability, which often occurs with a reversal between conditions. Magnitude differences, as implied, are differences in the magnitude of the variable under examination. Difference operators occur when there is a crossover between variable measures for the different conditions. An example of kinematic waveform and relative phase waveform interpretation will be provided to help in later understanding of the reconstructed curves and loading curves. It is also important to note that the reconstructed curves are based on variance explained by the specific PC and the mean curves are required to clarify the areas of interest identified by the individual PCs. For ease of understanding, load initiation involves initial contact with the box, essentially the starting position and beginning of the lift, load transition is the majority of the movement of the box from initiation to load placement, which is the final phase, involving placement of the box on the shelf. Kinematic graphs show the joint angle over a normalized lift. Relative phase graphs are more complex as relative phase is used to compress the joint angles and velocities of a distal and proximal segment into a single variable. Firstly, relative phase angles close to zero suggest that the segments are in phase; whereas, relative phase angles approaching 180 degrees are considered out of phase. In relative phase graphs, a positive slope indicates that the distal segment is moving faster, and conversely a negative slope indicates that the proximal segment is moving faster in phase space. Maximums and minimums provide information about reversals in coordination dynamics as the coordination between the two segments shifts. Angular positioning information is interpreted through observation of the positive and negative relative phase angles in phase space. Positive relative phase angles indicate that the distal segment is leading the proximal, and negative relative phase angles indicate that the proximal segment is ahead of the distal segment in phase space. Information provided by relative phase provides a greater insight into the overall coordination of major segments.



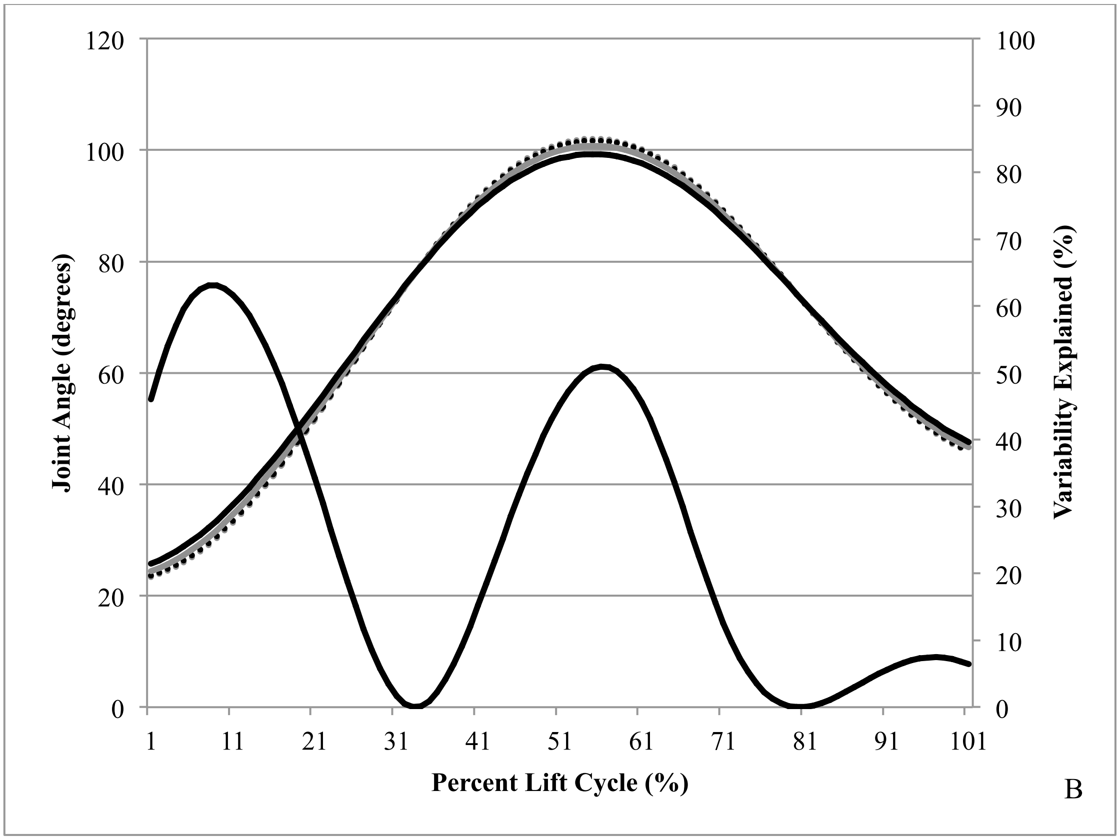
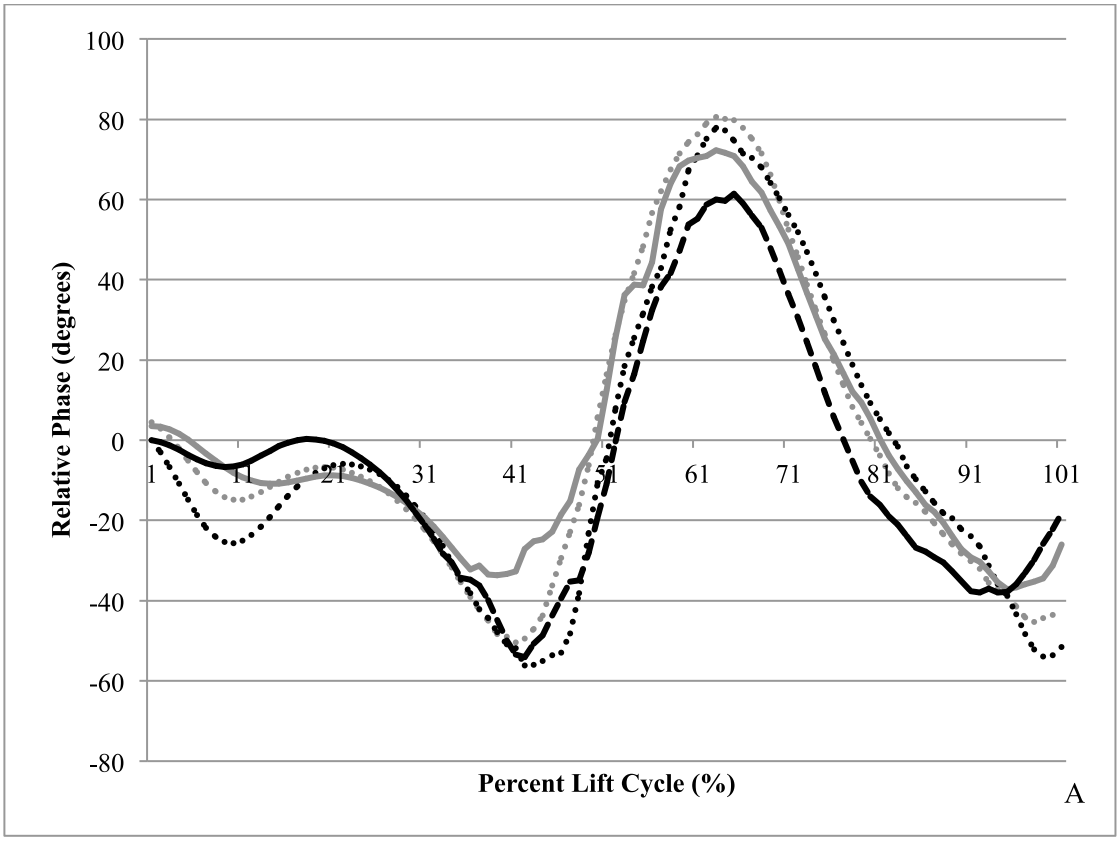


Figure 3.1: Left elbow flexion/extension angle pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 3 Reconstructed Curves.

As can be seen in figure 3.1, a kinematic graph of PC3 (18.96% variance explained) left elbow pre-fatigue, back-fatigued, shoulder-fatigued, general-fatigued conditions, there is a magnitude difference around 10% and 55% of the cycle, and there are difference operators around 30% and 80%. In this example the general-fatigue waveform is found between the pre-fatigue waveform, which follows closely with the back-fatigued waveform, and the shoulder-fatigued waveform. In the lift initiation phase there is a magnitude difference where the shoulder-fatigued waveform shows greater flexion than the general-fatigued waveform, and even greater than the back-fatigued and pre-fatigued waveforms. The difference operator which occurs around 30% of the lift shows a shift as the shoulder-fatigued condition does not go into as much flexion as the general-fatigue, with the pre-fatigue and back-fatigue sessions showing the greatest degree of flexion during the load transition. Another difference operator occurs at 80% when the joint moves into a greater degree of flexion once again in the shoulder-fatigued condition compared to the general-fatigued, and to a greater degree compared to the pre-fatigued and back-fatigued conditions.



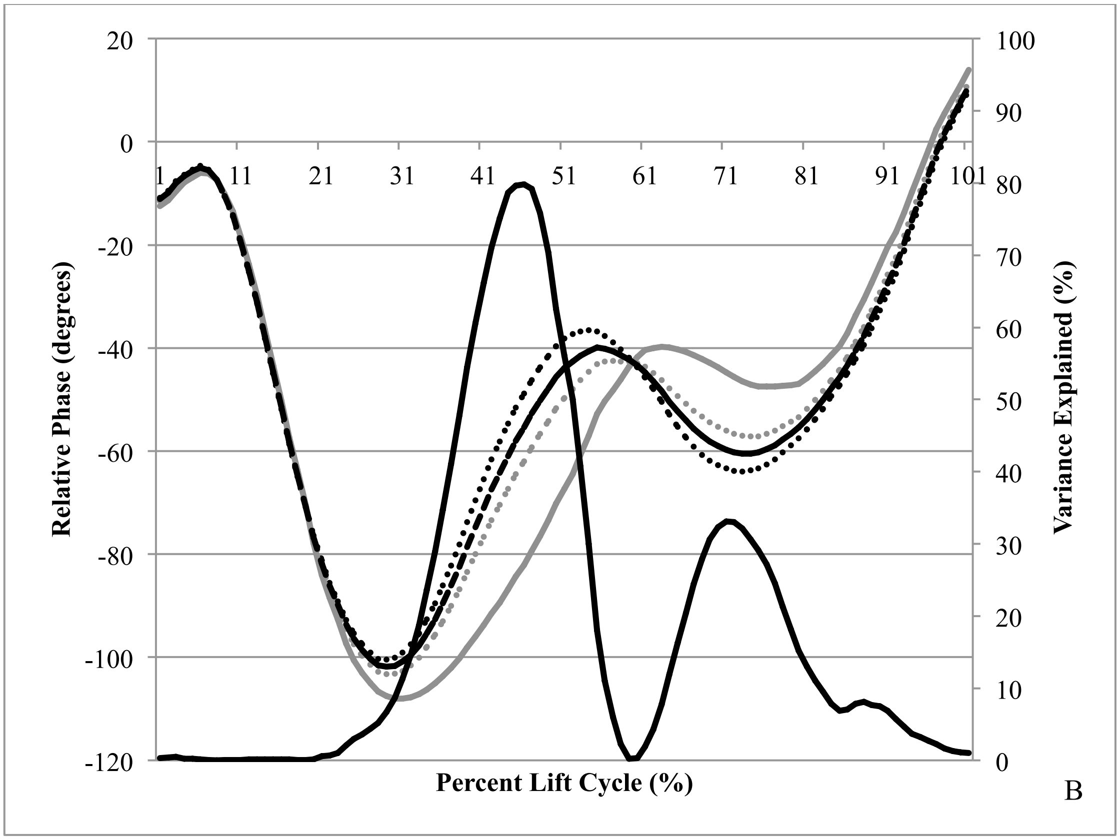


Figure 3.2: Right forearm and right arm relative phase pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 3 Reconstructed Curves.

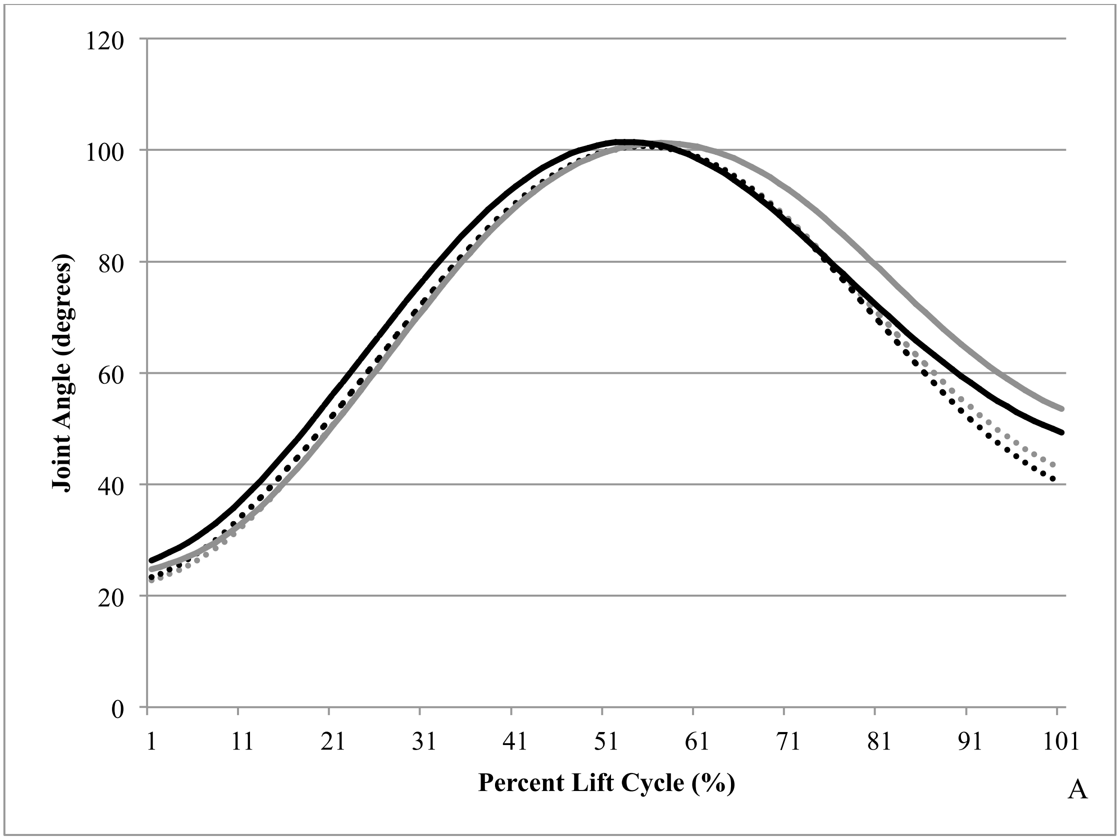
As can be seen in figure 3.2, a relative phase graph of PC3 (8.69%) right forearm and right upper arm relative phase pre-fatigue, back fatigued, shoulder fatigued, general fatigued conditions, there is a magnitude difference at 45% and 70% of the cycle, and there is a difference operator at 60%. In this example, the initiation and early transition phase is fairly similar until a magnitude difference was isolated at around 45% where all conditions had a negative relative phase value with a positive slope but the phase angles were closest to zero for the back fatigued condition, then the shoulder-fatigued, then the pre-fatigue and general fatigued conditions. The slope suggests that the distal joint, the forearm, is moving at a greater velocity than the proximal joint, the shoulder. The negative phase angle indicates that the shoulder joint angle is greater than the elbow joint angle in phase space. Finally, the back fatigued condition had a more in-phase motion of the right forearm and upper arm than the other conditions, shoulder-fatigued, pre-fatigued, and general-fatigued being the least in phase, and this is seen in the magnitude differences identified by the PC. At 60% of the lift cycle, there is a difference operator where a phase reversal occurs. The magnitude difference at 70% shows that the back fatigued condition is less in phase than the other conditions, shoulder-fatigued, pre-fatigue, and general-fatigued being the most in phase, respectively. The negative phase angle again indicates that the upper arm is ahead of the forearm in phase space. The local minimum shows a velocity reversal as the upper arm, which was moving at a greater velocity than the forearm, switches and the forearm continues at a greater velocity than the upper arm in the late transitional phase of the lift. It is interesting to note that averaged curves do not show these differences. After variance explained by PC1 and PC2 is removed, the variance explained by PC3 is easily visible in the reconstructed curves. Although it is not seen in the averaged curves, PC3 isolated variance around 45% of the lift cycle and the differences between conditions at this point in the cycle are more readily seen with the removal of other degrees of variance.

3.4 Kinematic comparisons of pre-fatigue, general fatigue, shoulder specific and back specific fatigue conditions

This section includes the averaged curves and principal component reconstructed curves for all investigated kinematic measures across fatigue conditions with the associated table of principal component values and statistical significance (table 3.2).

Table 3.2: Statistical significance ($p<0.05$) between fatigue conditions of principal components for kinematic variables.

Variable	PC	Variance Explained	pre-fatigue / general fatigue	pre-fatigue / back fatigue	pre-fatigue / shoulder fatigue	general fatigue / back fatigue	general fatigue / shoulder fatigue	back fatigue / shoulder fatigue
Left Elbow Flexion/Extension	1	52.54	<0.000*	0.311	0.306	<0.000*	0.012*	0.181
	2	22.88	0.726	0.400	0.001*	0.753	0.075	0.102
	3	18.96	0.150	0.552	<0.000*	0.330	0.219	0.018*
	4	4.02	0.737	0.186	0.017*	0.310	0.062	0.023*
Right Elbow Flexion/Extension	1	44.12	0.002*	0.624	0.052	0.003*	0.350	0.096
	2	34.17	0.072	0.112	<0.000*	0.036*	0.001*	0.124
	3	15.89	0.684	0.354	0.009*	0.584	0.205	0.020*
	4	4.34	0.161	0.184	0.008*	0.092	0.255	0.015*
Left Shoulder Flexion/Extension	1	60.86	0.721	0.018*	0.575	0.254	0.959	0.211
	2	19.26	<0.000*	0.298	<0.000*	0.006*	0.508	0.058
	3	14.32	0.007*	0.062	0.248	0.001*	0.022*	0.019*
	4	3.77	0.573	0.252	0.014*	0.732	0.024*	0.031*
Right Shoulder Flexion/Extension	1	69.60	0.044*	0.006*	0.454	0.002*	0.017*	0.165
	2	14.18	0.131	0.238	0.008*	0.433	0.482	0.157
	3	11.89	<0.000*	0.725	0.004*	0.001*	0.171	0.021*
Trunk Flexion/Extension	1	87.97	0.019*	0.070	0.479	0.269	0.032*	0.116
	2	10.43	0.883	0.657	<0.000*	0.582	0.001*	<0.000*



120
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Joint Angle (degrees)
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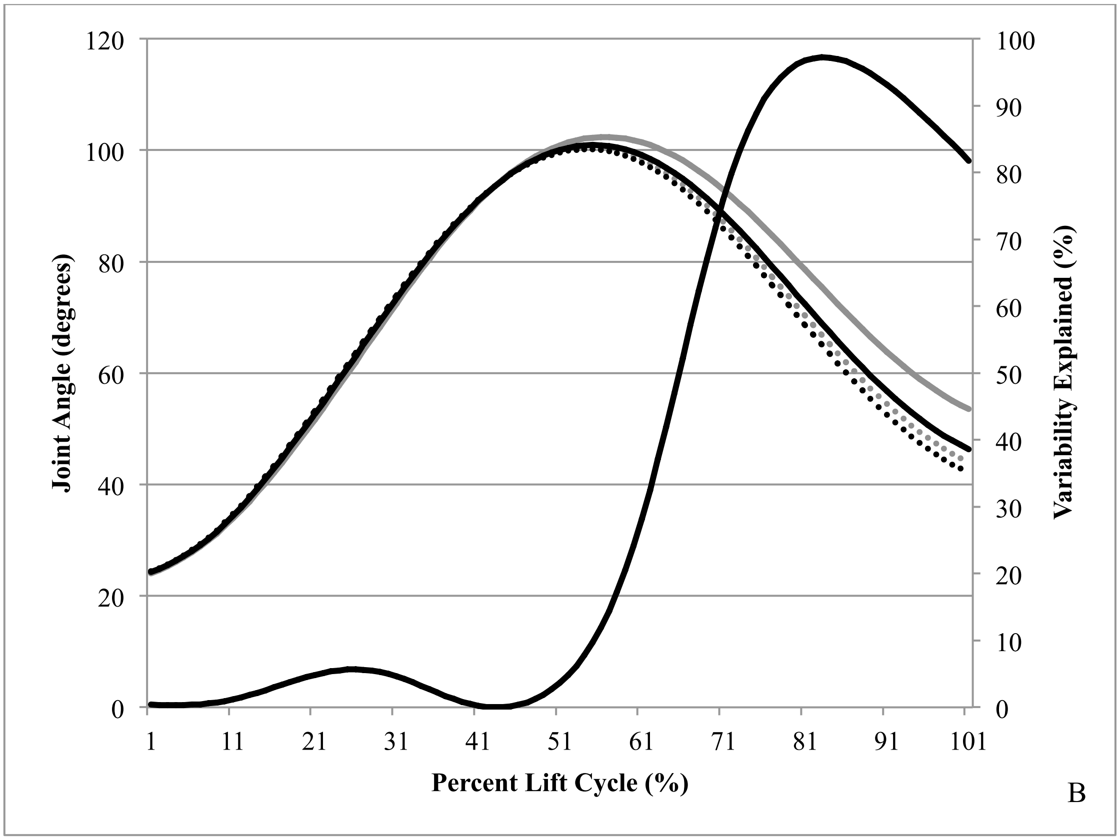
Percent Lift Cycle (%)
A



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Joint Angle (degrees)
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Variability Explained (%)
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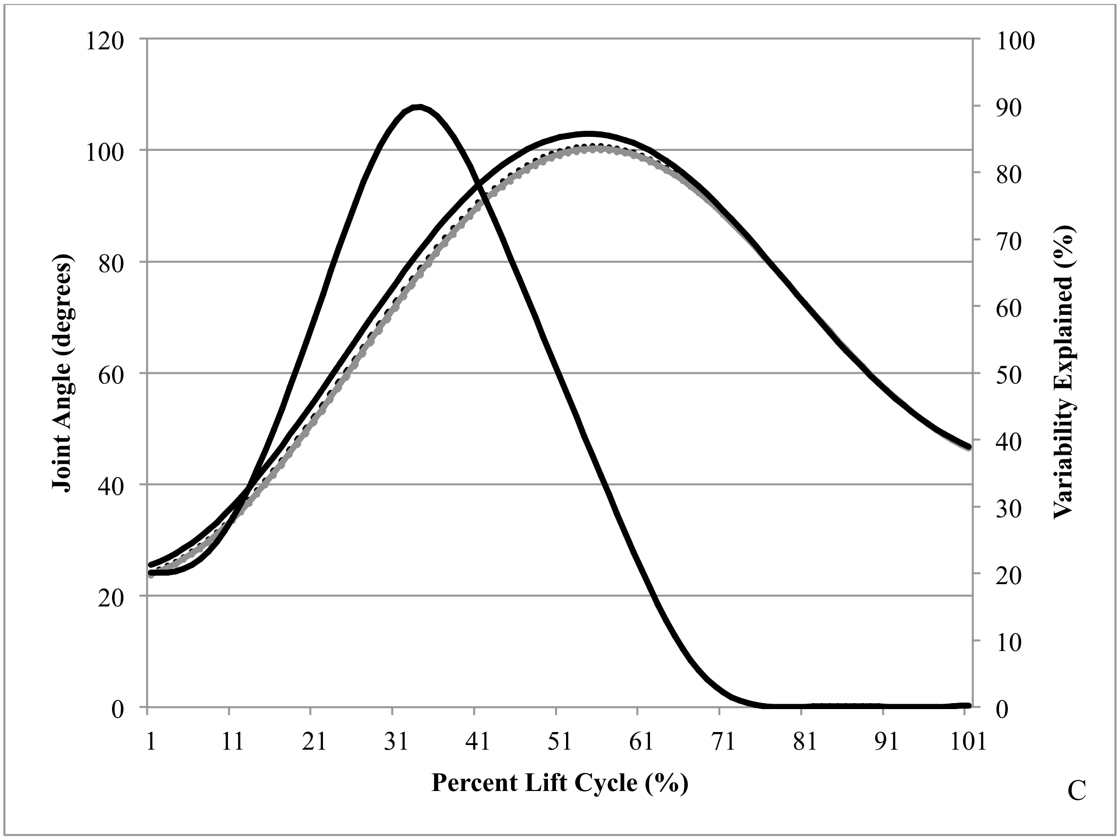
Percent Lift Cycle (%)
B



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Joint Angle (degrees)
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Variability Explained (%)
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Percent Lift Cycle (%)
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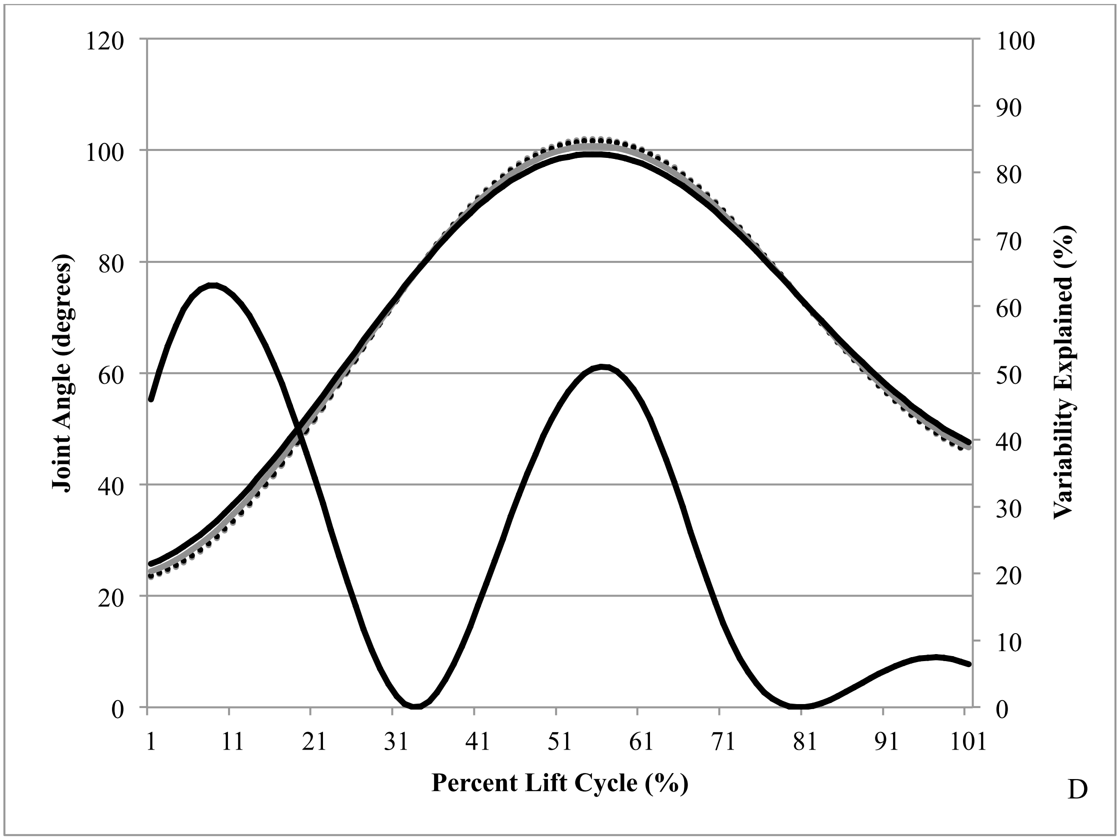

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Joint Angle (degrees)
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Variability Explained (%)
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101
Percent Lift Cycle (%)
D

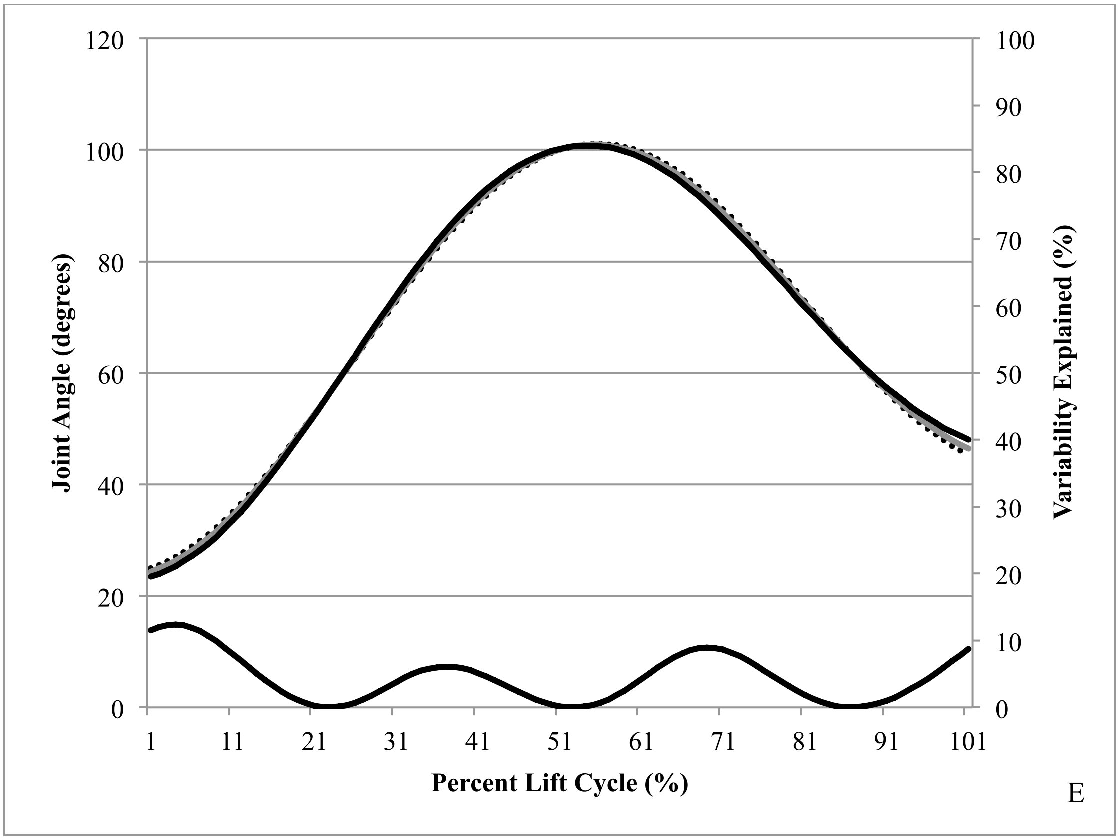
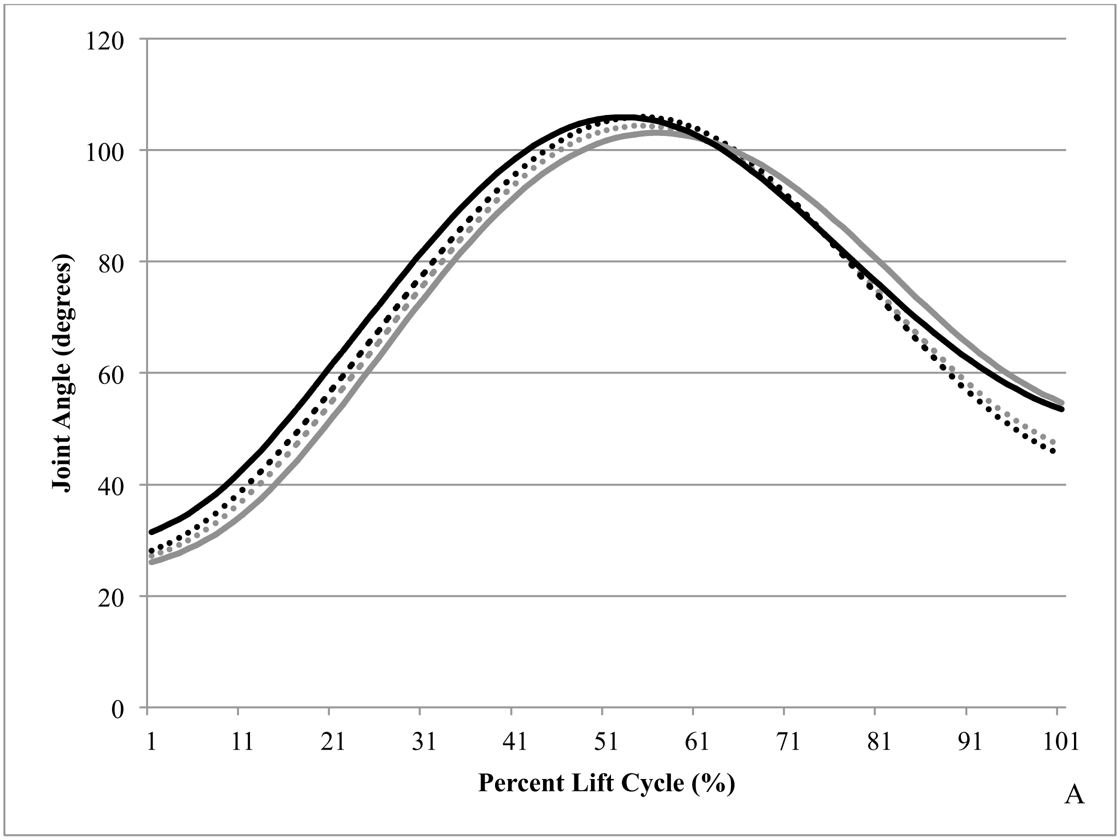
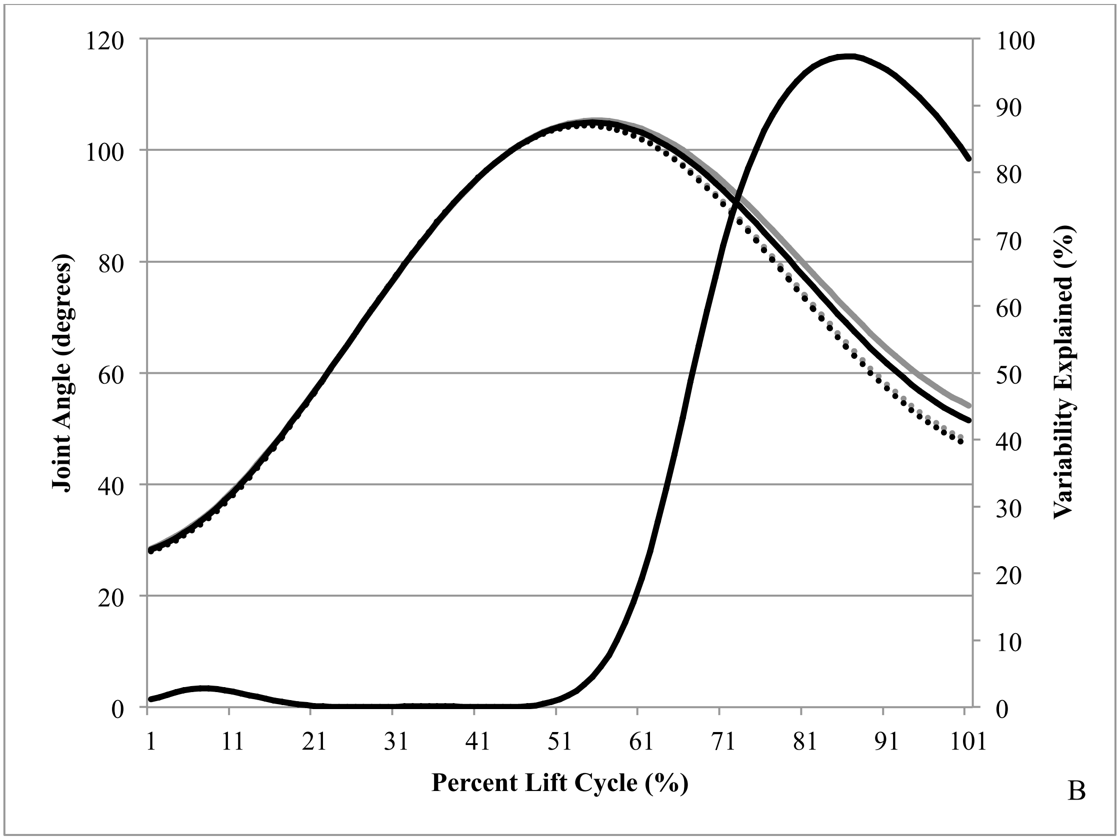


Figure 3.3: Left elbow flexion/extension angle pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3. E. Principal Component 4.

The parallel retention analysis retained four PCs from the principal component analysis of the left elbow flexion/extension pre-fatigue and fatigued conditions kinematic waveforms (table 3.2). PC1 (52.54 % variance explained) highlighted a magnitude difference in the load placement phase at 80% of the lift cycle. Significant differences were found between the pre-fatigued condition (PF) and the general-fatigued (GF) condition, back fatigued (BF) and shoulder-fatigued (SF), and the GF and SF. The elbow remained more flexed for the general condition compared to the SF, PF and BF conditions respectively. PC2 (22.88% variance explained) highlighted magnitude differences in the early transition phase of the lift at 30% of the lift cycle. Significant differences were found between PF and SF, as the elbow was more flexed in the SF condition. PC3 (18.96% variance explained) highlighted two magnitude differences in the initiation and in the mid-transition phase of the lift, with a difference operator in the early transition phase. Significant differences were found between the PF and SF, and the BF and GF conditions. PC4 (4.02% variance explained) highlighted magnitude differences around 5%, 35%, 70%, and 95% of the lift cycle; while difference operators were detected at 20%, 50%, and 85%. Significant differences were found between the PF and SF, and the BF and GF conditions. These differences detected by PC3 and PC4, although significant, were not visually relevant.





Joint Angle (degrees)
Variability Explained (%)
Percent Lift Cycle (%)
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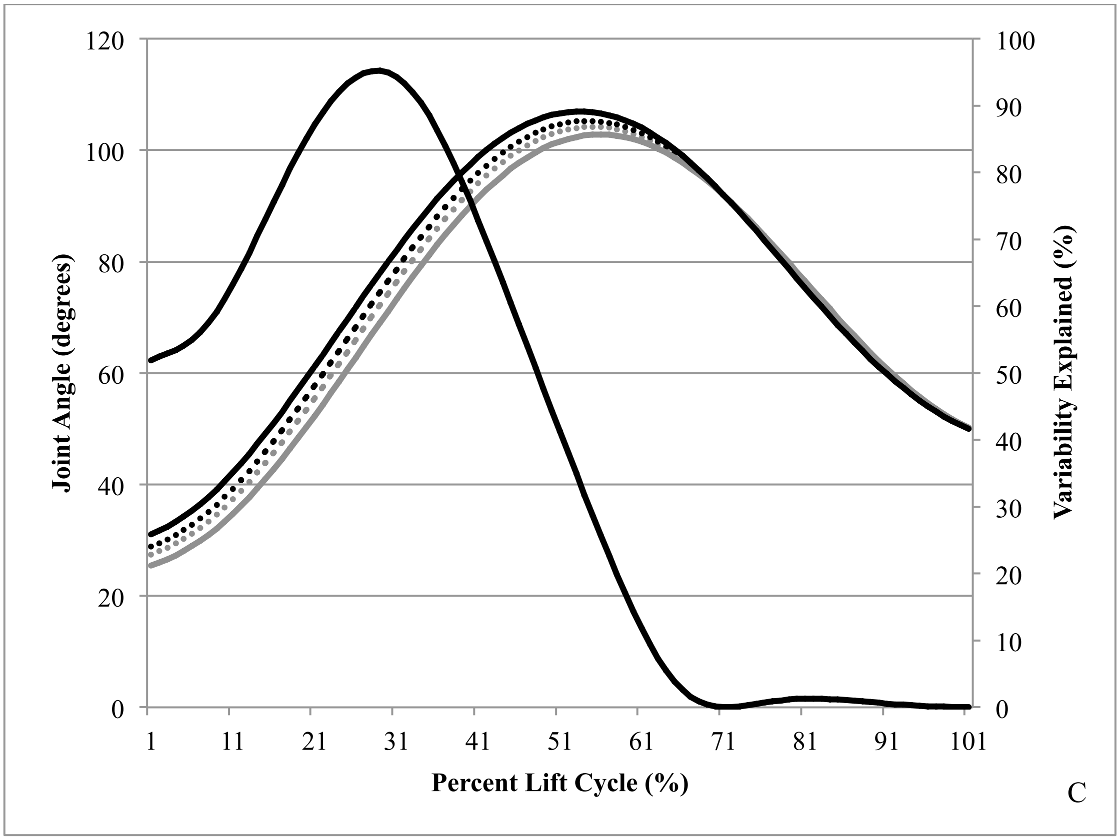

Joint Angle (degrees)
Variability Explained (%)
Percent Lift Cycle (%)
0
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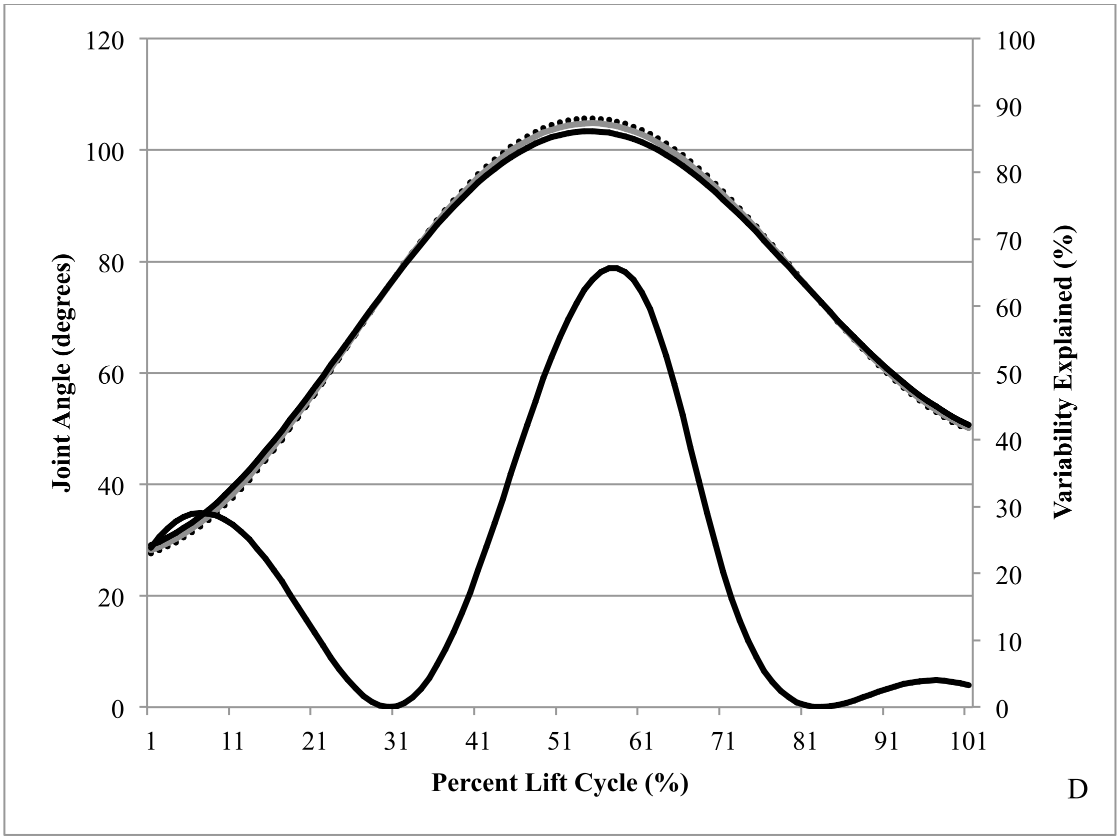

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Joint Angle (degrees)
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Variability Explained (%)
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Percent Lift Cycle (%)
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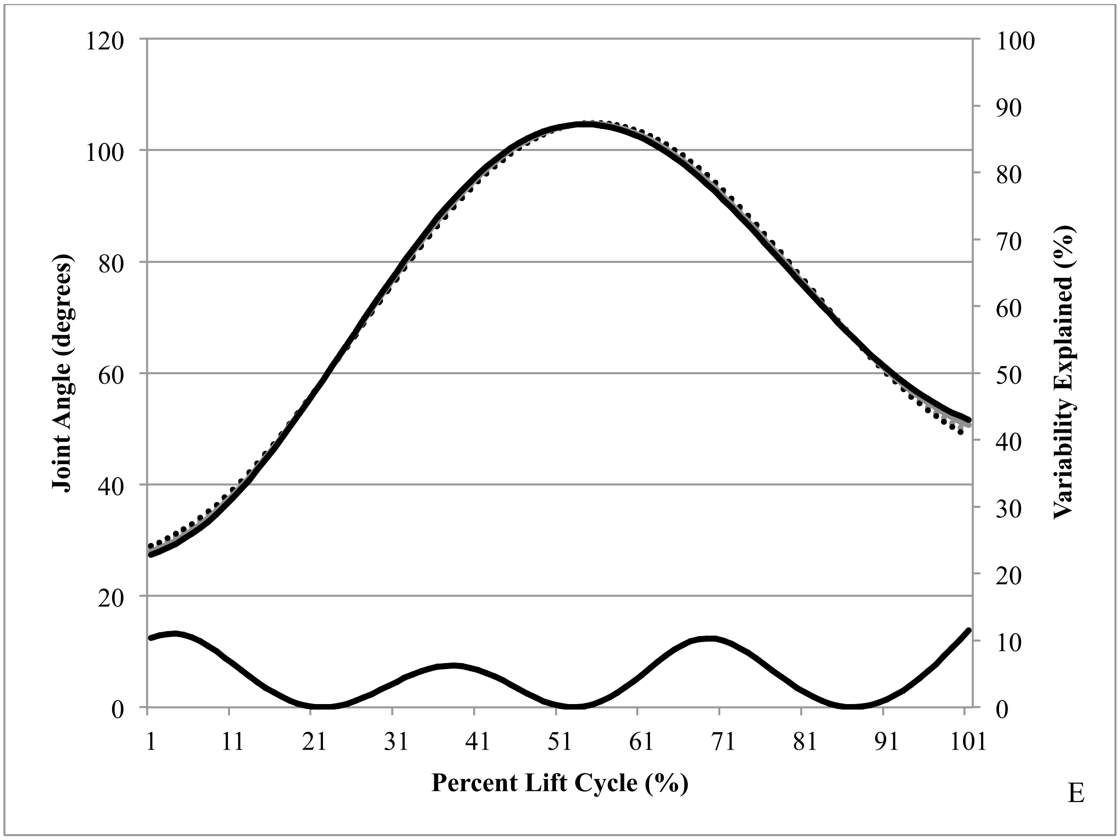

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Joint Angle (degrees)
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Variability Explained (%)
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Percent Lift Cycle (%)
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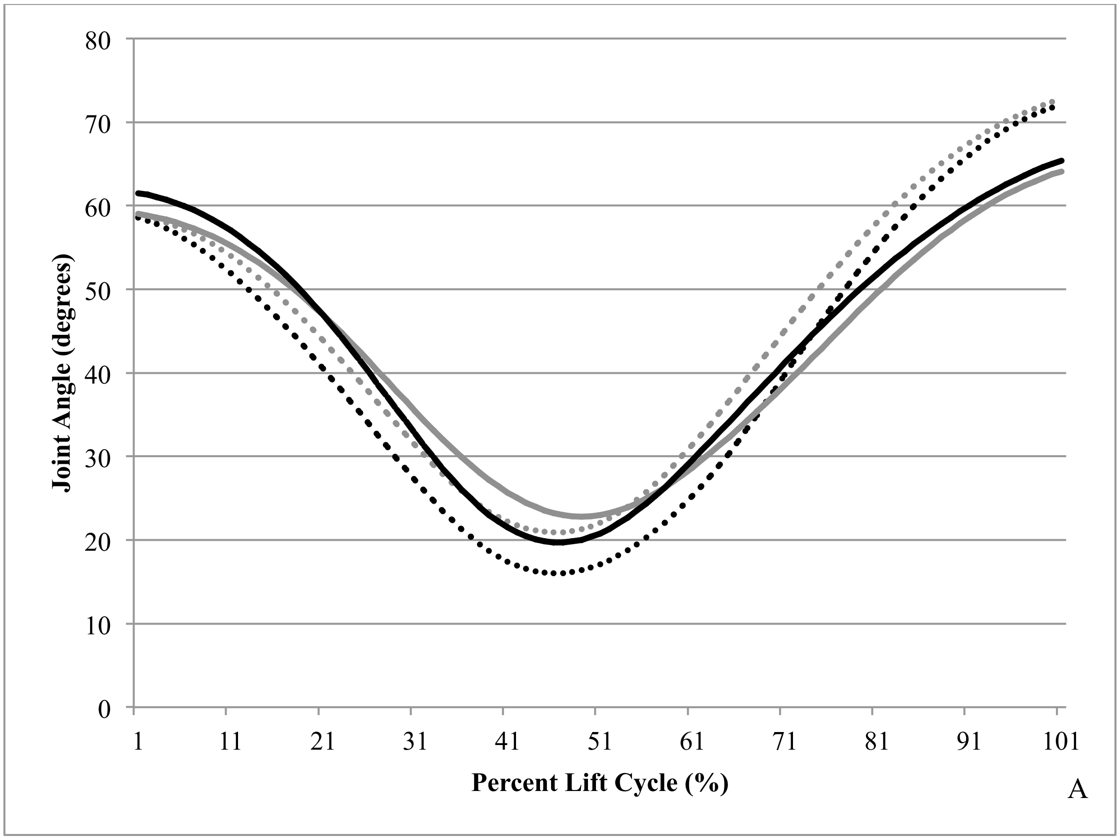
Figure 3.4: Right elbow flexion/extension angle pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3. E. Principal Component 4.

The parallel retention analysis retained four PCs from the principal component analysis of the right elbow flexion/extension pre-fatigue and fatigued conditions kinematic waveforms (table 3.2). PC1 (44.12 % variance explained) highlighted a magnitude at 85% of the lift cycle. Significant differences were found between the PF and GF, and the BF and GF conditions. The elbow remained more flexed for the general condition compared to the SF, PF and BF conditions respectively. PC2 (34.17% variance explained) highlighted magnitude differences at 30% of the lift cycle. Significant differences were found between PF and SF, BF and GF, and GF and SF conditions. The elbow was more flexed for the SF condition compared to the BF, PF and GF conditions, respectively. PC3 (15.89% variance explained) highlighted two magnitude differences at 10% and 60%, with difference operators at 30% and 60%. Significant differences were found between the PF and SF, and BF and SF conditions. PC4 (4.34% variance explained) highlighted magnitude differences around 5%, 35%, 70%, and 95% of the lift cycle; while difference operators were detected at 20%, 50%, and 85%. Significant differences were found between the PF and SF, and the BF and GF conditions. These differences detected by PC3 and PC4, although significant, were not visually relevant.



Joint Angle (degrees)
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Percent Lift Cycle (%)
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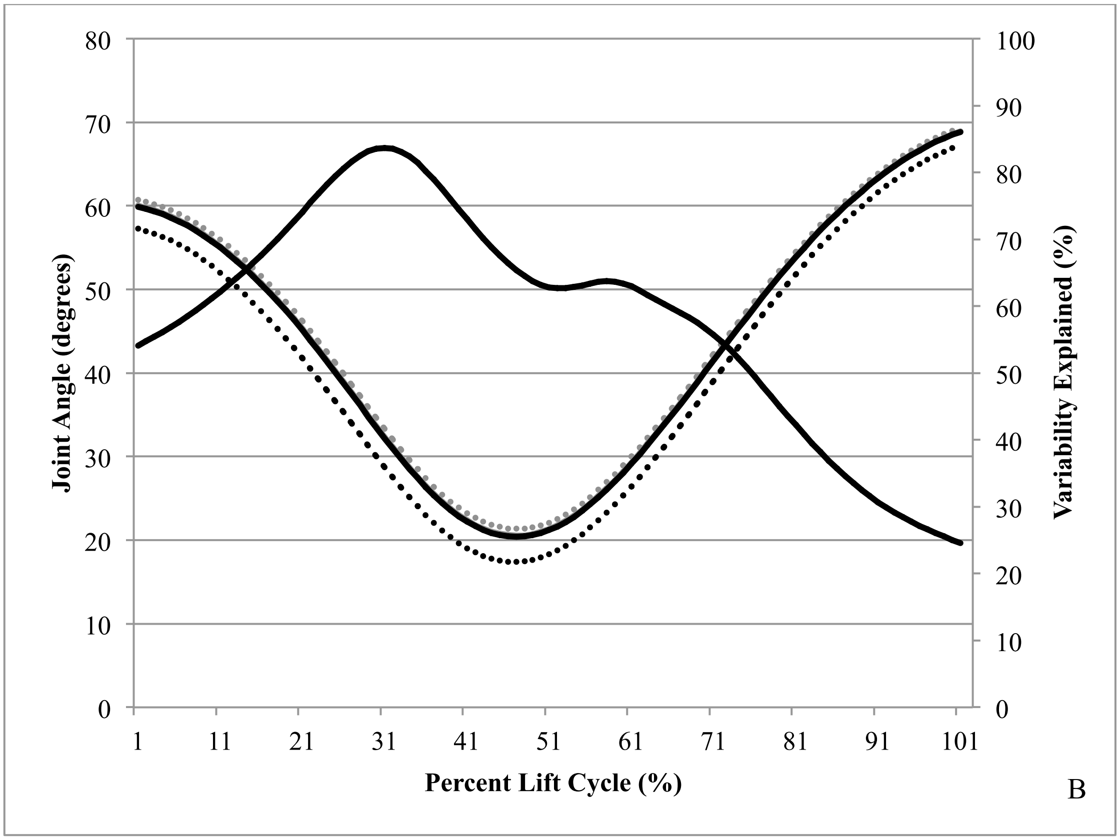

Joint Angle (degrees)
Variability Explained (%)
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Percent Lift Cycle (%)
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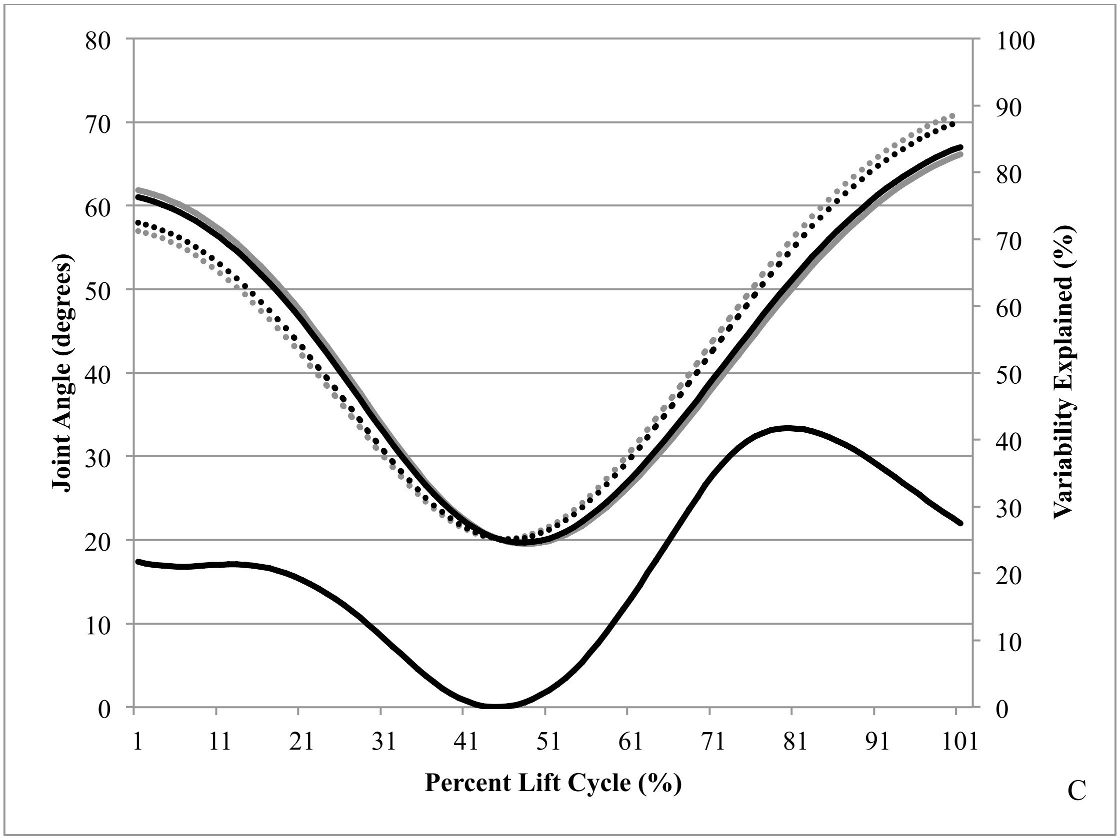

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Joint Angle (degrees)
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Variability Explained (%)
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Percent Lift Cycle (%)
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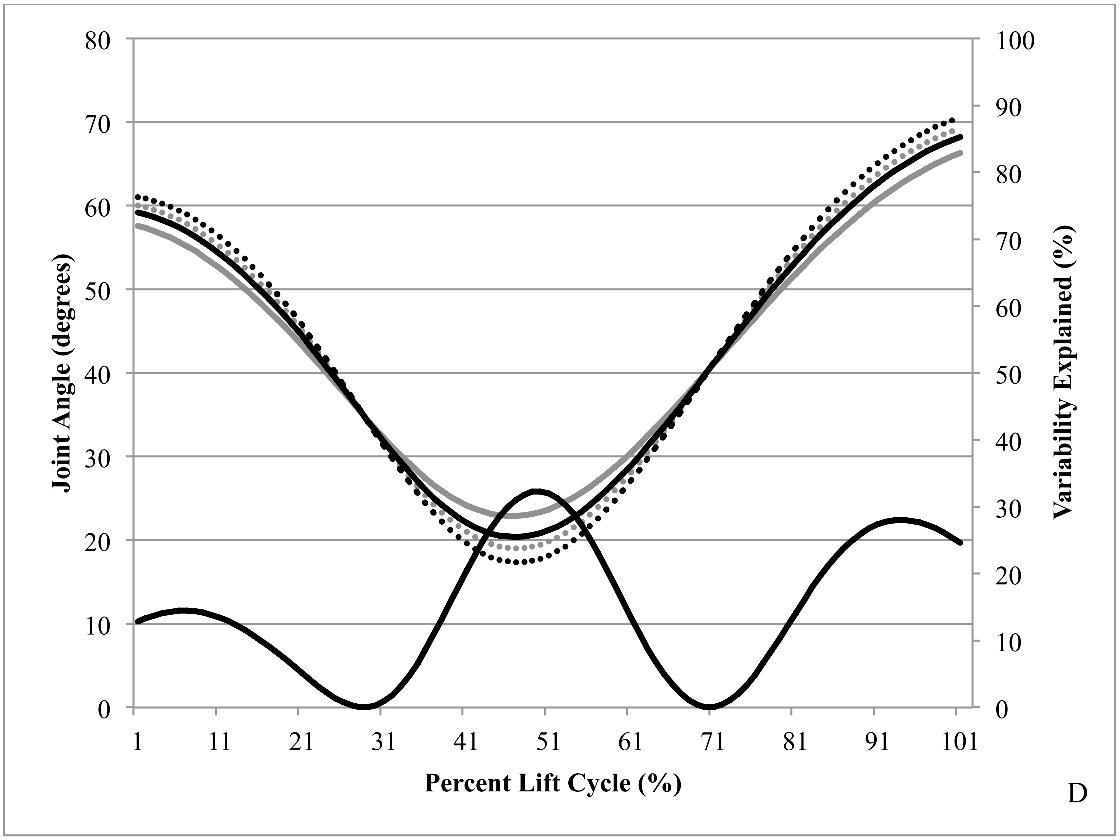

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Joint Angle (degrees)
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Variability Explained (%)
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Percent Lift Cycle (%)
D

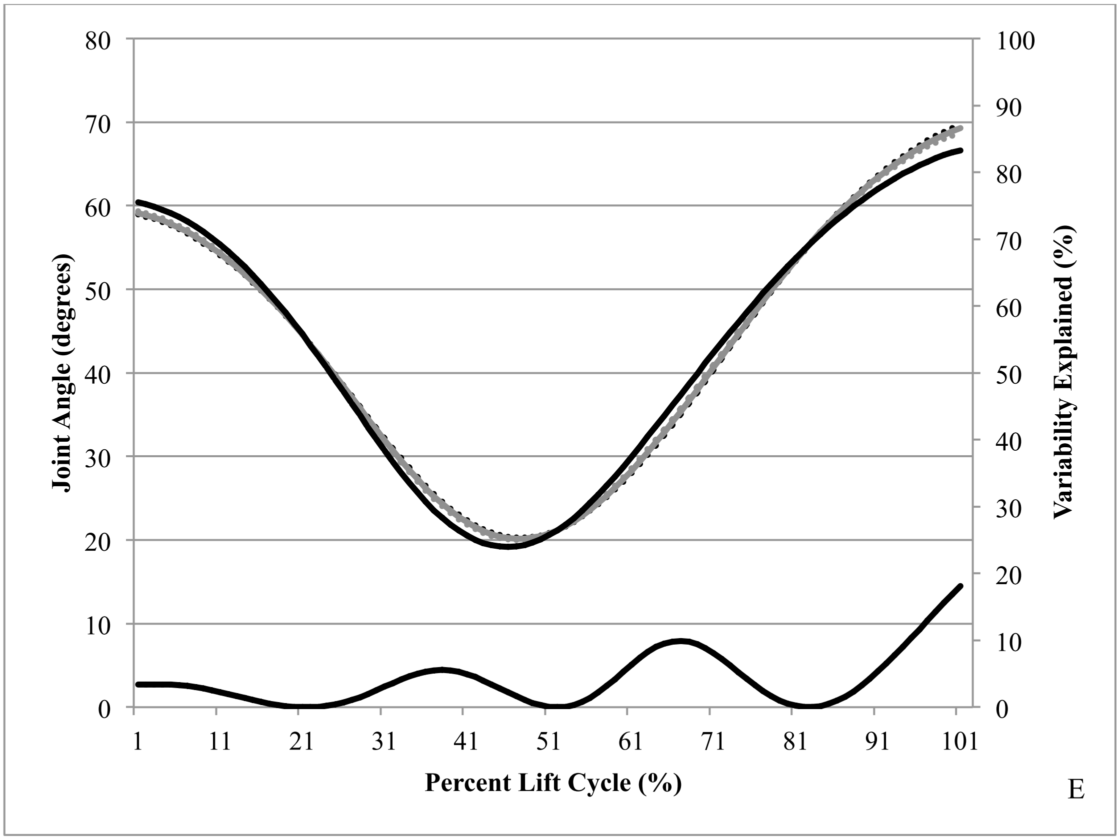
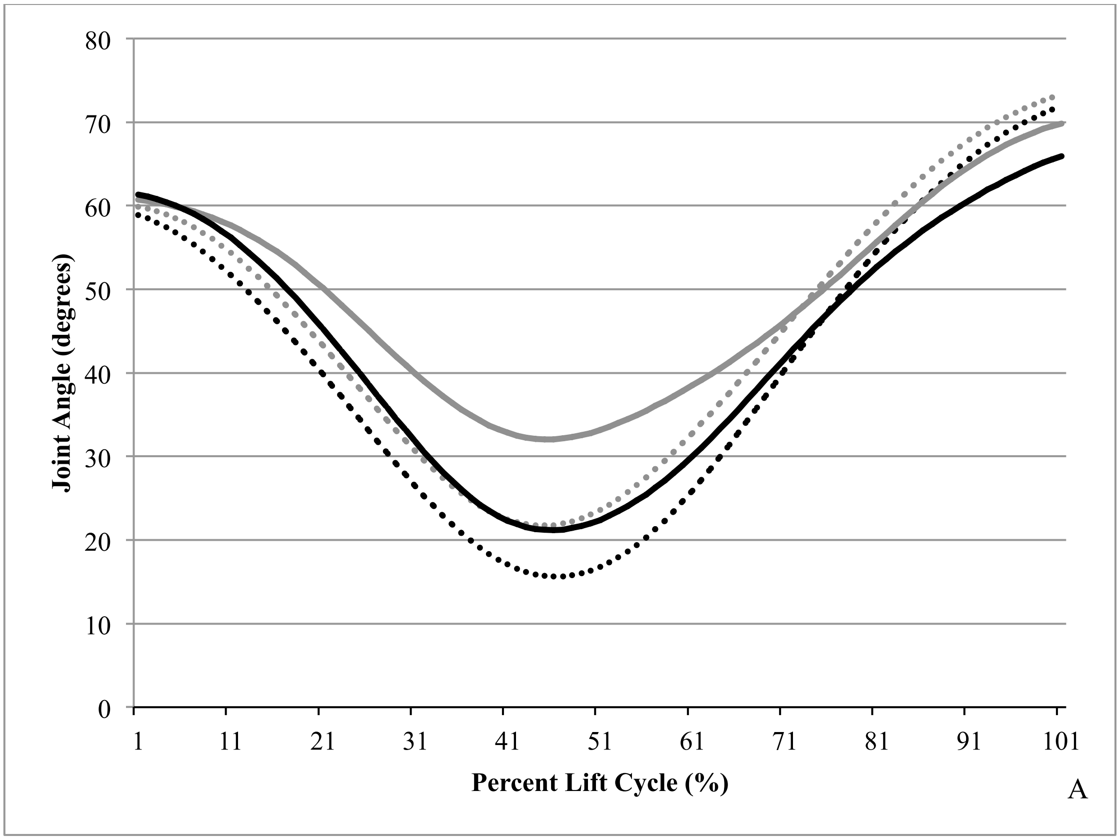


Figure 3.5: Left shoulder flexion/extension angle pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3. E. Principal Component 4.

The parallel retention analysis retained four PCs from the principal component analysis of the left shoulder flexion/extension pre-fatigue and fatigued conditions kinematic waveforms (table 3.2). PC1 (60.86% variance explained) highlighted a magnitude difference from 30-60% of the lift cycle. Significant differences were found between the PF and BF conditions where the shoulder was more flexed in the PF compared to the BF condition. PC2 (19.26% variance explained) highlighted two magnitude differences at 20% and 80% of the lift cycle, with a difference operator at

45%. Significant differences were found between PF and GF, PF and SF, and BF and GF conditions. The shoulder was less flexed between the BF and GF at 20%, then at 80% the shoulder was more flexed in the PF condition compared to the SF and GF fatigue conditions, respectively. PC3 (14.32% variance explained) highlighted magnitude differences at 5%, 50% and 95%, with difference operators at 30% and 70%. Significant differences were found between the PF and GF, BF and GF, BF and SF, and GF SF conditions. The shoulder was more flexed for the PF than the BF condition. The BF curve indicated that the left shoulder was more flexed than the GF and SF conditions until 70% at which point the BF condition has a more flexed shoulder for the remainder of the lift. Finally the shoulder was more flexed for the SF compared to the GF until 20% at which time the shoulder was less flexed in the SF condition until 60% when the SF condition once again was in a greater degree of flexion. PC4 (3.77% variance explained) highlighted magnitude differences around 5%, 35%, 65%, and 95% of the lift cycle; while difference operators were detected at 20%, 50% and 80%. Significant differences were found between PF and SF, BF and SF, and GF and SF conditions. These differences detected, agreed with the other PCs and the differences observed between the SF condition and the other conditions.


80
70
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0
Joint Angle (degrees)
1
11
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Percent Lift Cycle (%)
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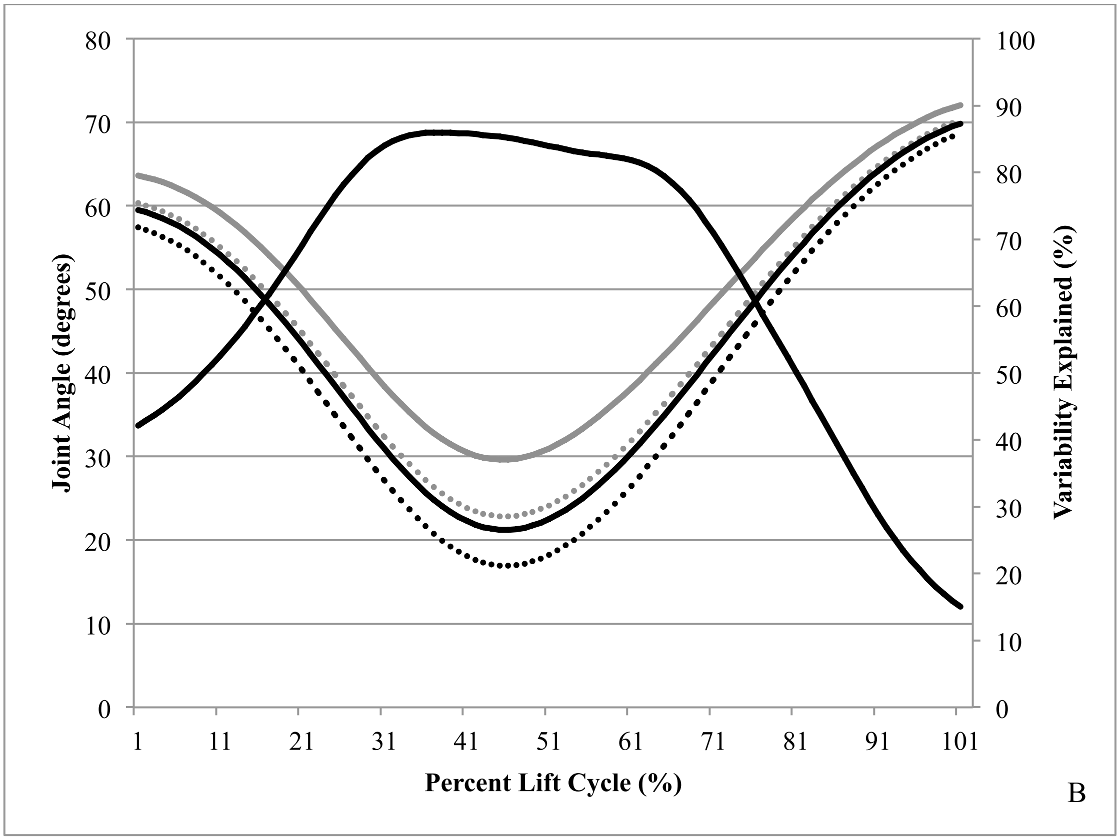
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Percent Lift Cycle (%)
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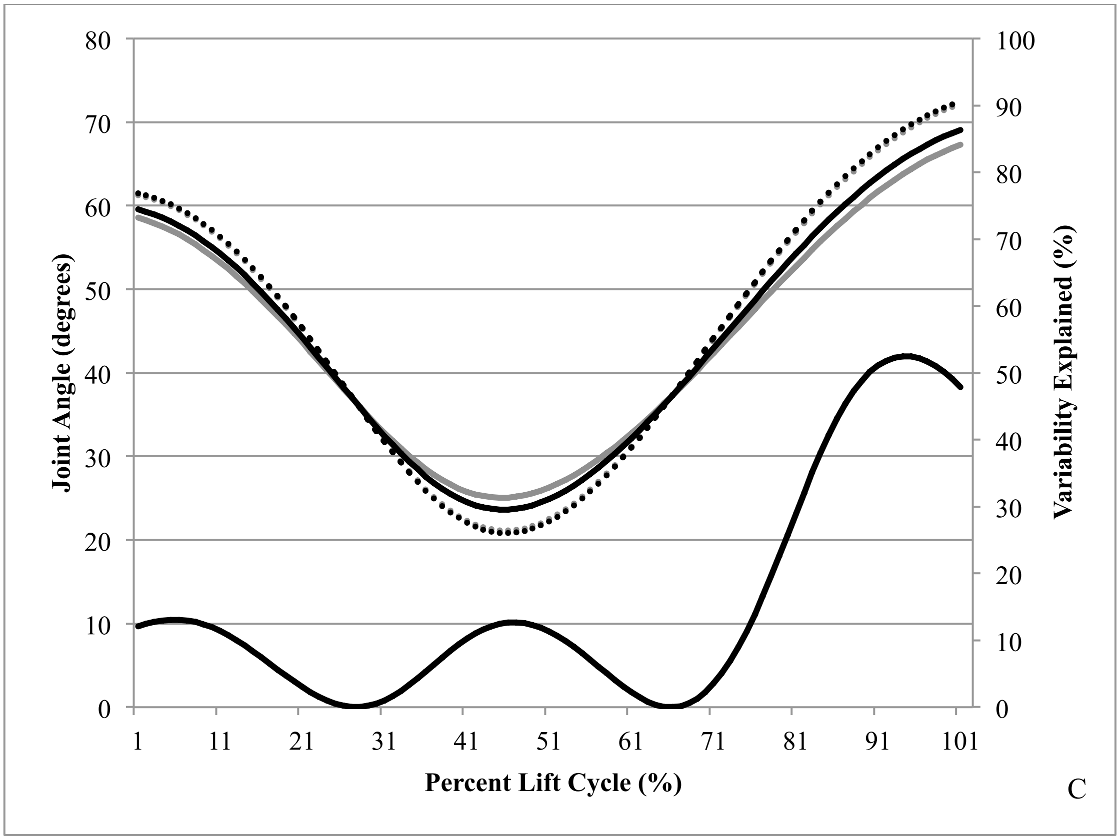
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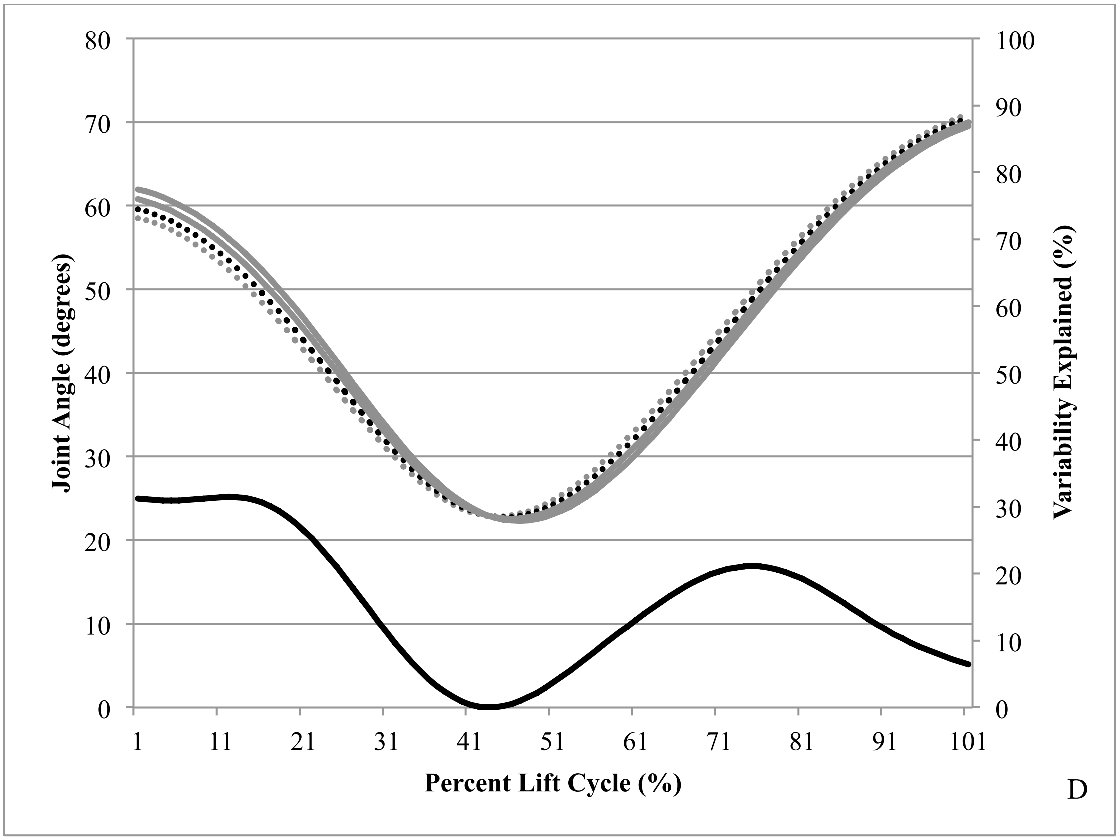
Joint Angle (degrees)
Variability Explained (%)
Percent Lift Cycle (%)
C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Joint Angle (degrees)
Variability Explained (%)
Percent Lift Cycle (%)
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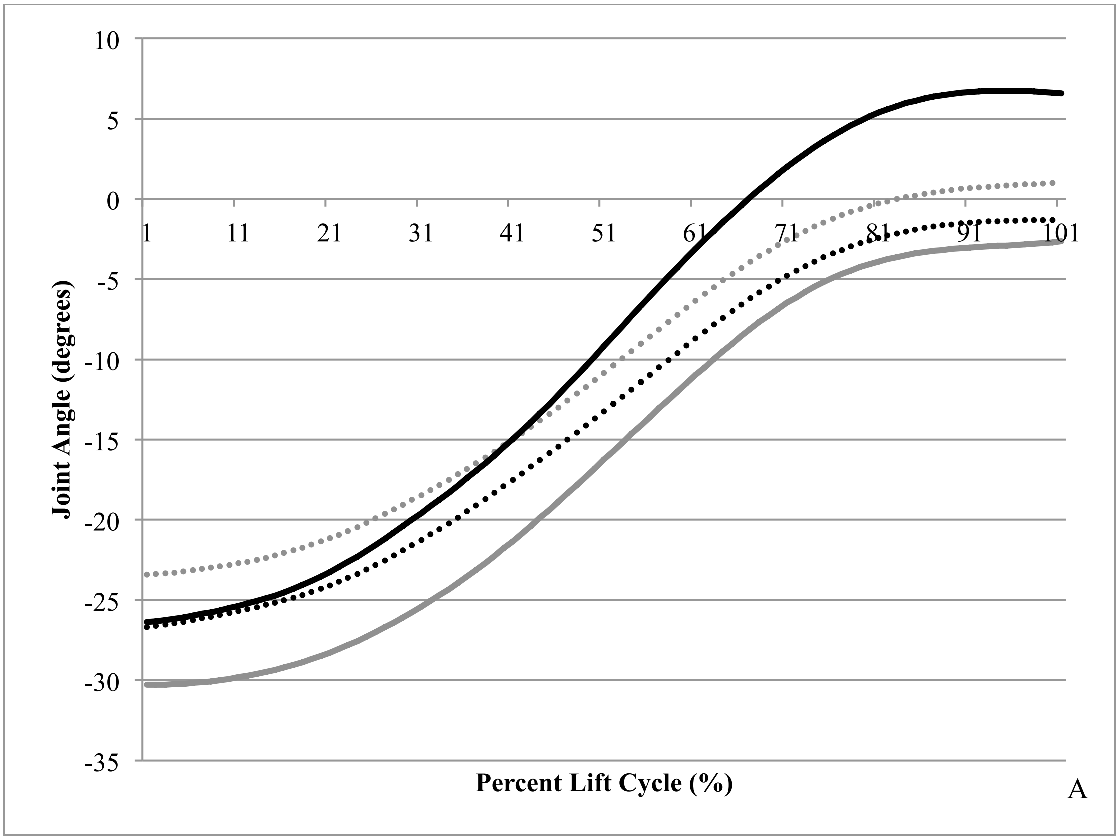
Figure 3.6: Right shoulder flexion/extension angle pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3.

The parallel retention analysis retained three PCs from the principal component analysis of the right shoulder flexion/extension pre-fatigue and fatigued conditions kinematic waveforms (table 3.2). PC1 (69.60% variance explained) highlighted a magnitude difference between 30-70% of the lift cycle. Significant differences were found between the PF and BF, PF and GF, BF and GF, and GF and SF conditions. The PF and SF condition were similar in degrees of shoulder flexion, with the GF condition showing greater levels of flexion and the BF condition having less flexion. PC2 (14.18% variance explained) highlighted magnitude differences at 10%, 45% and 90% of the lift cycle, with difference operators at 25% and 65%. The loading curve suggested that although there were magnitude differences early in the lift, PC2 primarily loaded at 90%. Significant differences were found between PF and SF conditions as the shoulder was in a lesser degree of flexion later in the lift for the SF compared to the PF condition. PC3 (11.89% variance explained) highlighted two magnitude differences at 15% and 75%, with difference operators at 45%. Significant differences were found between the PF and GF, PF and GF, BF and GF, and the BF and SF conditions. These differences agreed with the other PCs and captured the remaining variance explained between the different conditions.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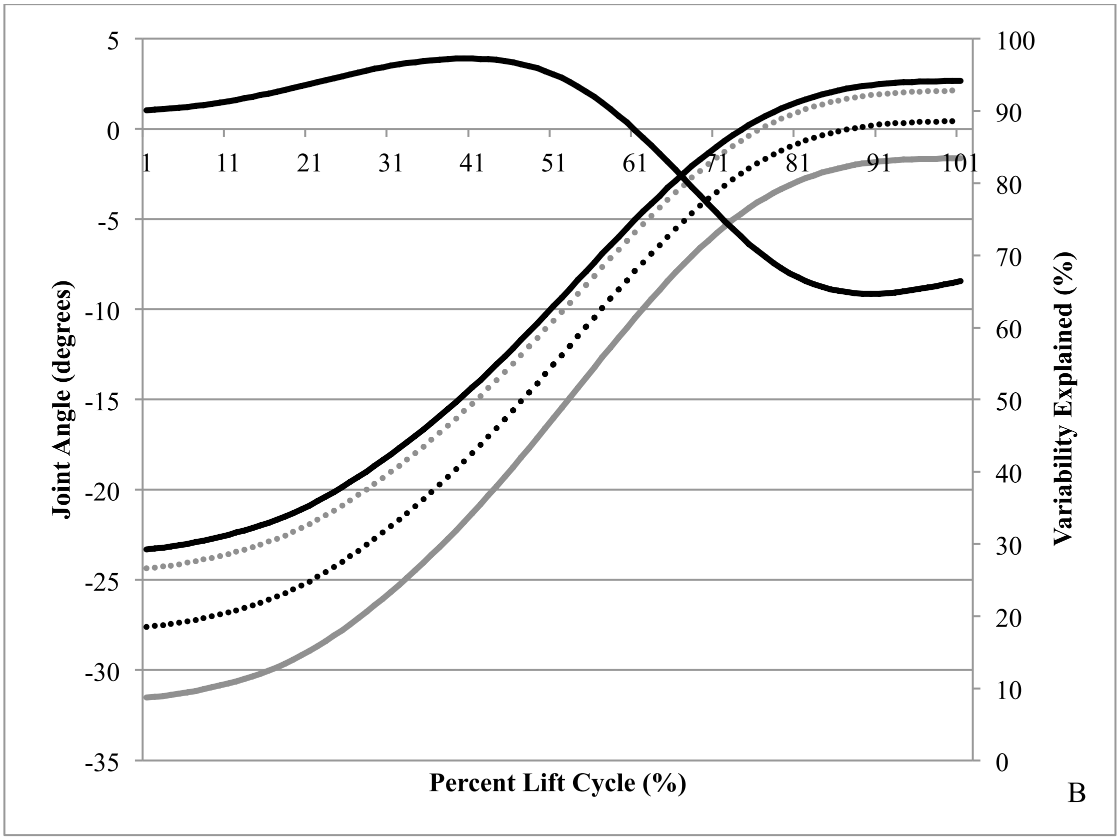
Joint Angle (degrees)
Percent Lift Cycle (%)
A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Joint Angle (degrees)
Variability Explained (%)
Percent Lift Cycle (%)
B

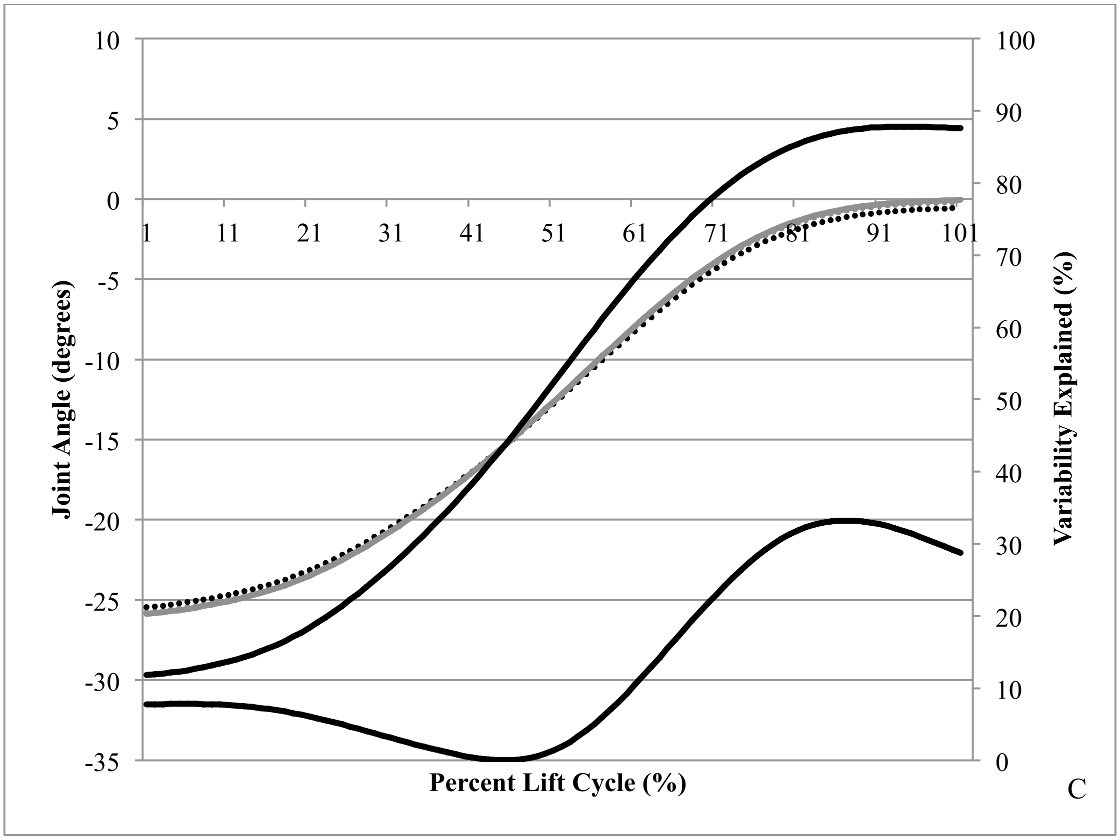


Figure 3.7: Trunk flexion/extension angle pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2.

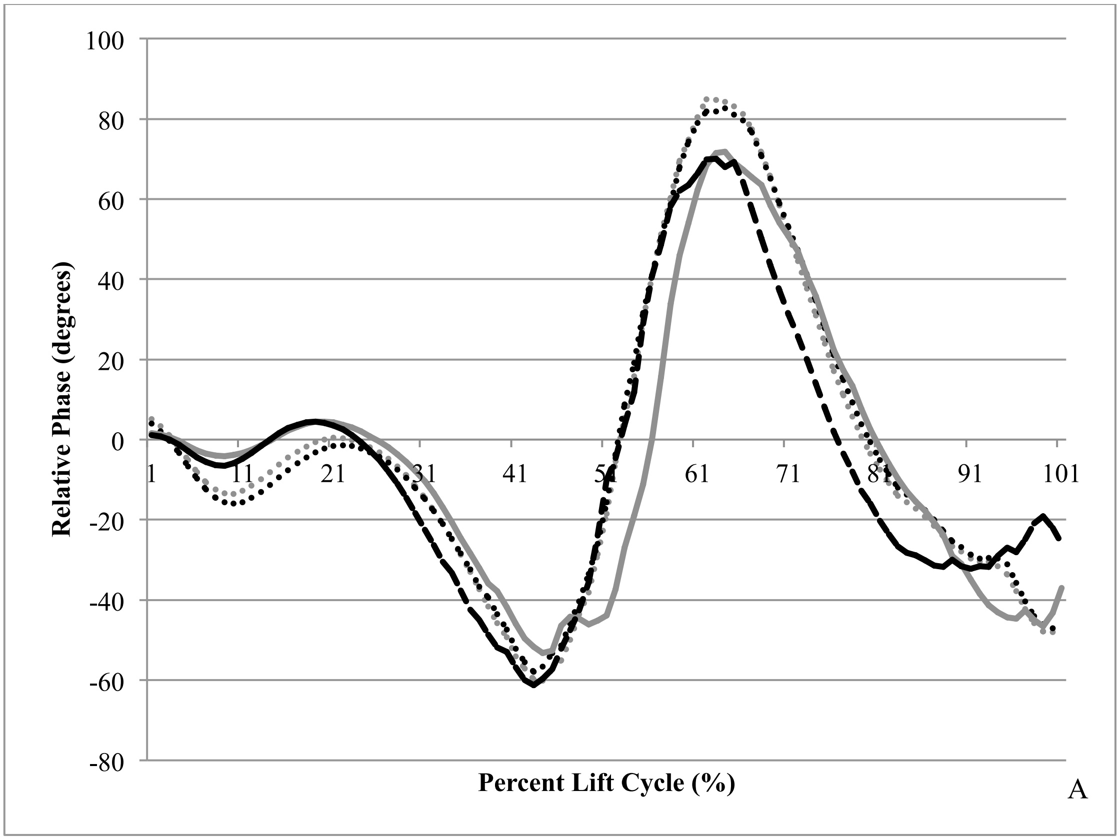
The parallel retention analysis retained two PCs from the principal component analysis of the right elbow flexion/extension pre-fatigue and fatigued conditions kinematic waveforms (table 3.2). PC1 (87.97% variance explained) highlighted a magnitude difference throughout the lift with an emphasis on the earlier portion of the lift, from 0-70% of the lift cycle. Significant differences were found between the PF and GF, and GF and SF conditions. The trunk angle showed greater flexion for the GF condition compared to the PF and SF conditions. PC2 (10.43% variance explained) highlighted magnitude differences at 10% and, to a greater extent, 85% of the lift cycle, with a difference operator at 45%. Significant differences were found between the PF and SF, and the BF and SF conditions. The reconstructed and averaged curves showed a cross-over as the SF trunk angle went from being greater than the other conditions to a more extended angle later in the lift.

3.5 Relative phase comparisons of pre-fatigue, general fatigue, shoulder specific and back specific fatigue conditions

This section includes the averaged curves and principal component reconstructed curves for all investigated relative phase measures across fatigue conditions with the associated tables of principal component values and statistical significance.

Table 3.3: Statistical significance ($p<0.05$) between fatigue conditions of principal components for relative phase variables.

Variable	PC	Variance Explained	pre-fatigue / general fatigue	pre-fatigue / back fatigue	pre-fatigue / shoulder fatigue	general fatigue / back fatigue	general fatigue / shoulder fatigue	back fatigue / shoulder fatigue
Left Forearm Upper Arm	1	47.05	0.008*	0.083	0.742	0.397	0.020*	0.242
	2	17.72	0.317	0.527	0.163	0.159	0.836	0.171
	3	9.03	0.974	0.758	0.003*	0.808	0.006*	0.032*
	4	6.75	0.094	0.041*	0.352	0.005*	0.500	0.026*
	5	4.04	0.851	0.233	0.374	0.125	0.522	0.099
Right Forearm Upper Arm	1	41.69	0.584	0.019*	0.020*	0.336	0.127	0.765
	2	22.13	0.193	0.225	0.118	0.080	0.974	0.065
	3	8.69	0.342	0.129	<0.000*	0.953	0.001*	<0.000*
	4	8.58	0.651	0.268	0.399	0.267	0.193	0.990
	5	3.77	0.203	0.067	0.245	0.013*	0.911	0.056
Left Upper Arm Trunk	1	25.01	0.023*	<0.000*	<0.000*	<0.000*	0.312	<0.000*
	2	22.49	0.004*	0.865	0.366	0.024*	0.004*	0.478
	3	17.10	0.302	0.012*	0.377	0.047*	0.071	0.567
	4	11.48	0.652	0.379	0.769	0.979	0.524	0.420
	5	7.97	0.323	0.623	0.119	0.696	0.914	0.572
	6	5.88	0.635	0.431	0.682	0.285	0.520	0.806
	7	3.32	0.354	0.706	0.062	0.655	0.489	0.252
Right Upper Arm Trunk	1	24.97	0.768	<0.000*	<0.000*	0.019*	0.010*	<0.000*
	2	21.40	0.523	0.626	0.063	0.466	0.385	0.067
	3	18.47	0.010*	<0.000*	0.118	<0.000*	0.001*	0.152
	4	11.99	0.511	0.800	0.512	0.501	0.888	0.518
	5	8.91	0.504	0.388	0.036*	0.214	0.064	0.244
	6	5.00	0.252	0.185	0.138	0.077	0.048*	0.921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Relative Phase (degrees)
Percent Lift Cycle (%)
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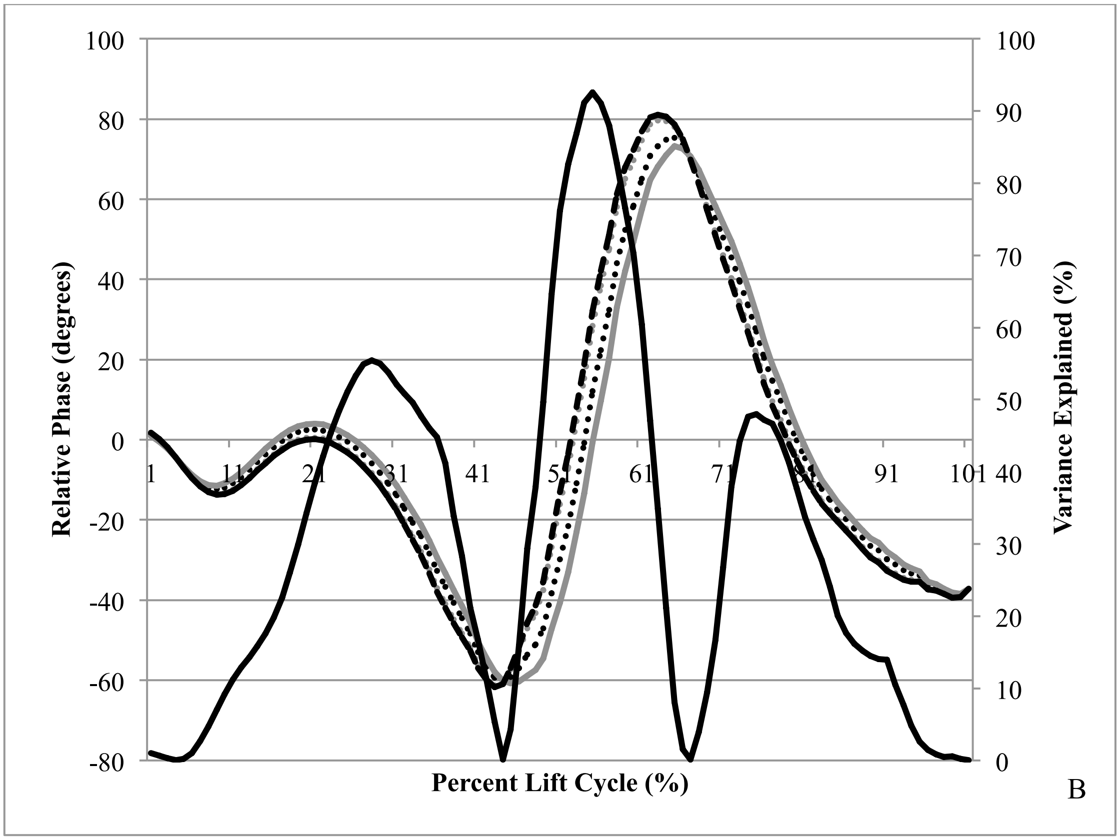
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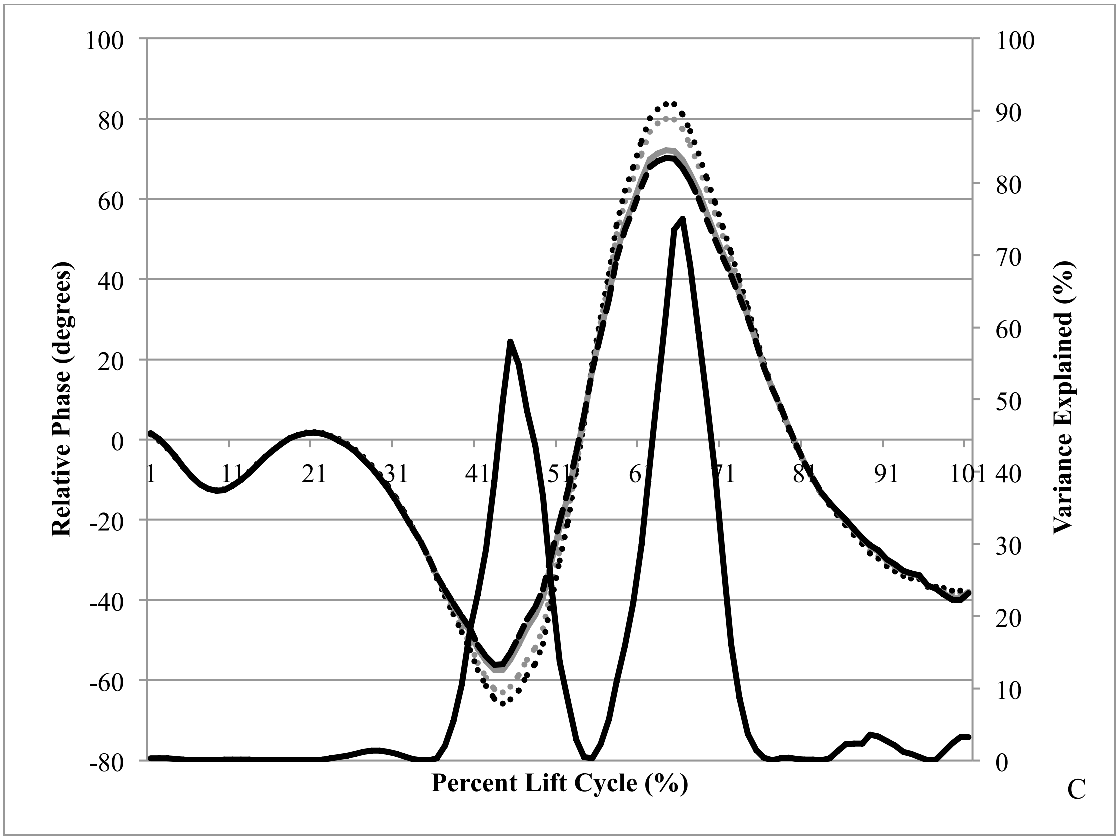
Relative Phase (degrees)
Variance Explained (%)
Percent Lift Cycle (%)
B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Percent Lift Cycle (%)
Variance Explained (%)
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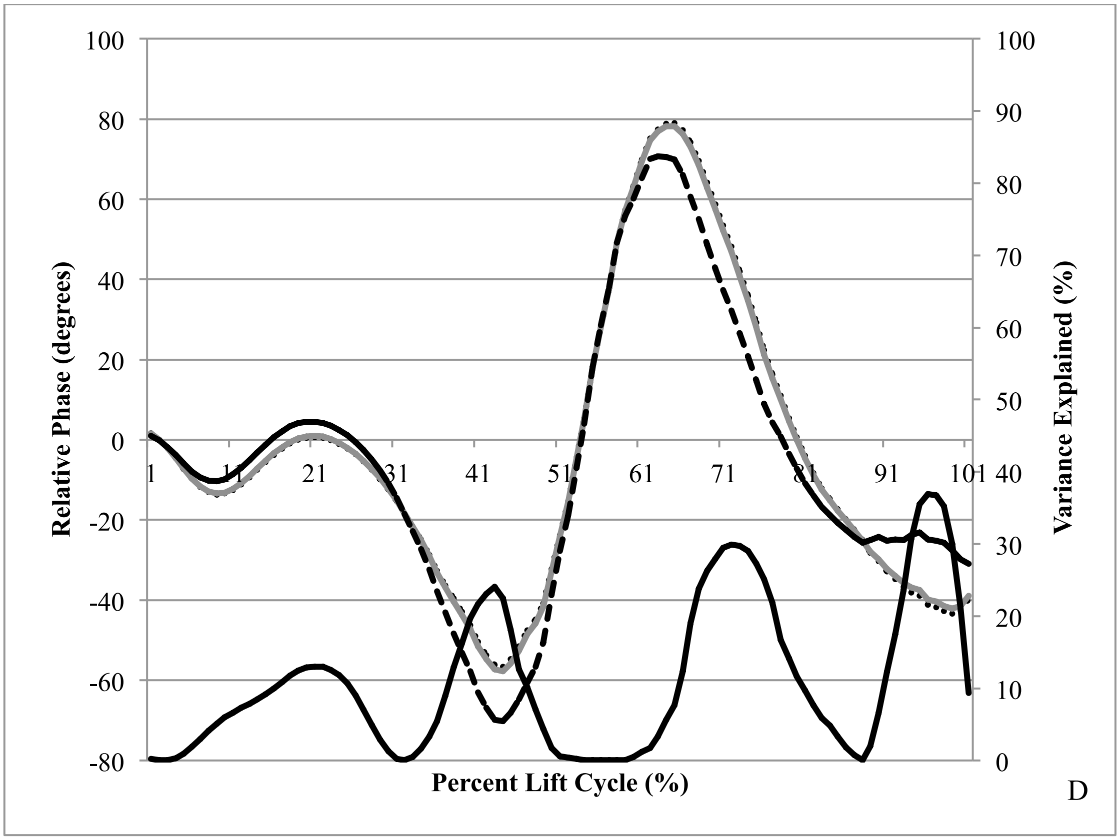
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Percent Lift Cycle (%)
Variance Explained (%)
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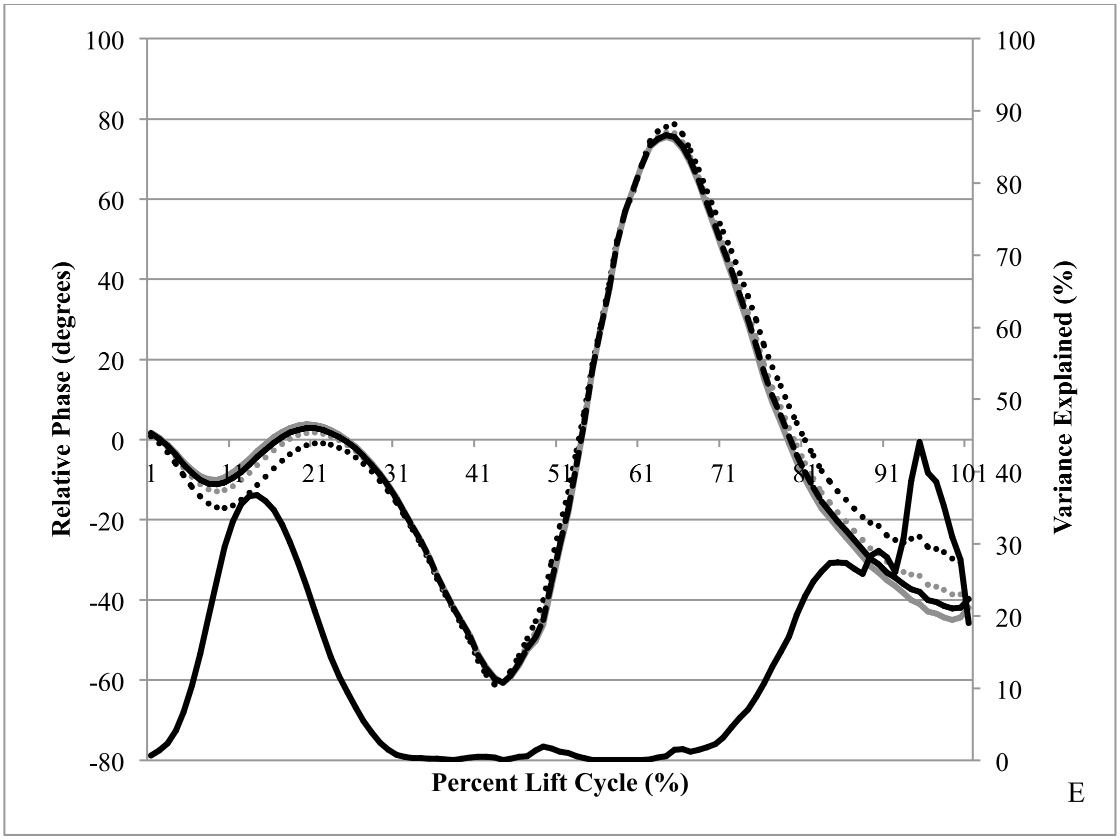

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Relative Phase (degrees)
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Variance Explained (%)
Percent Lift Cycle (%)
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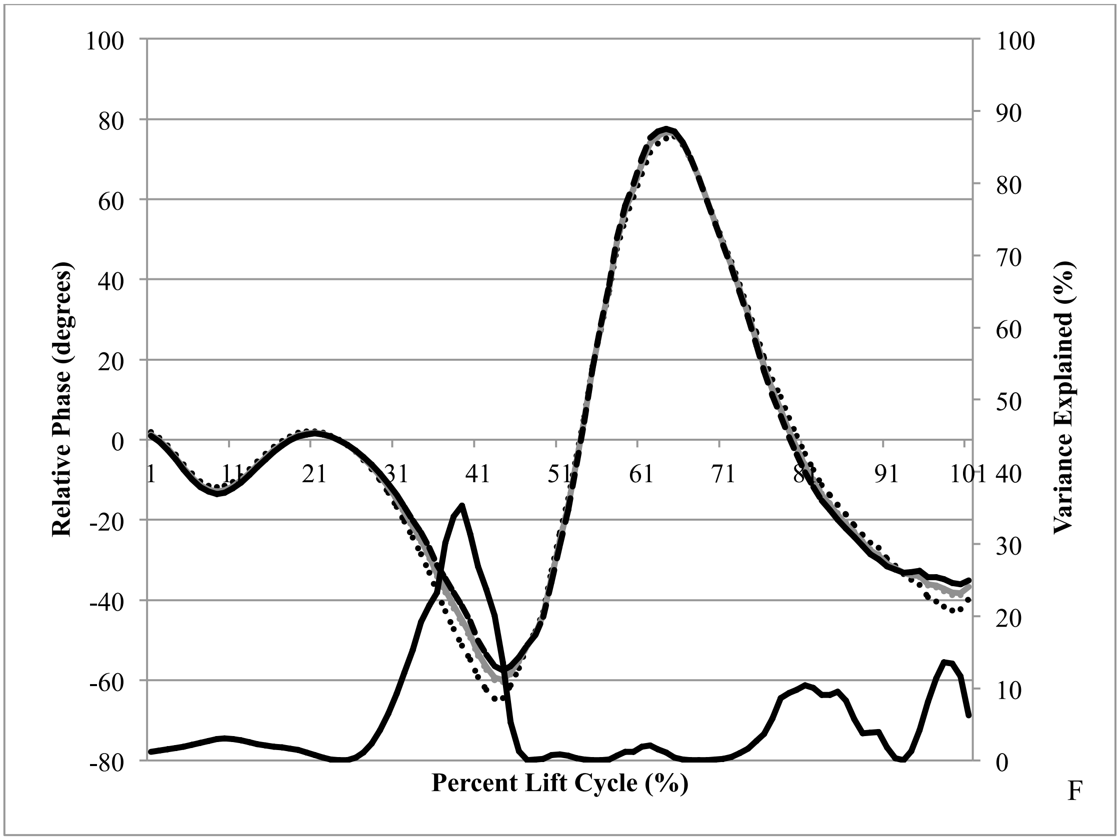

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Relative Phase (degrees)
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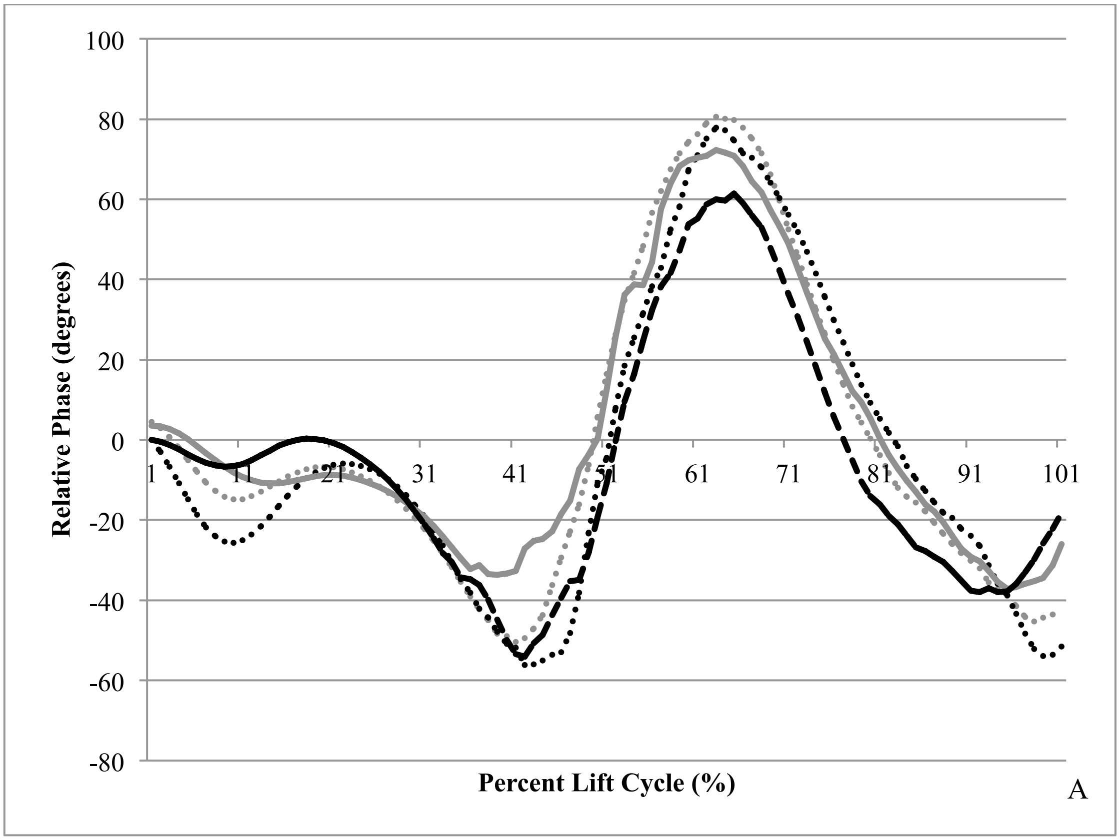
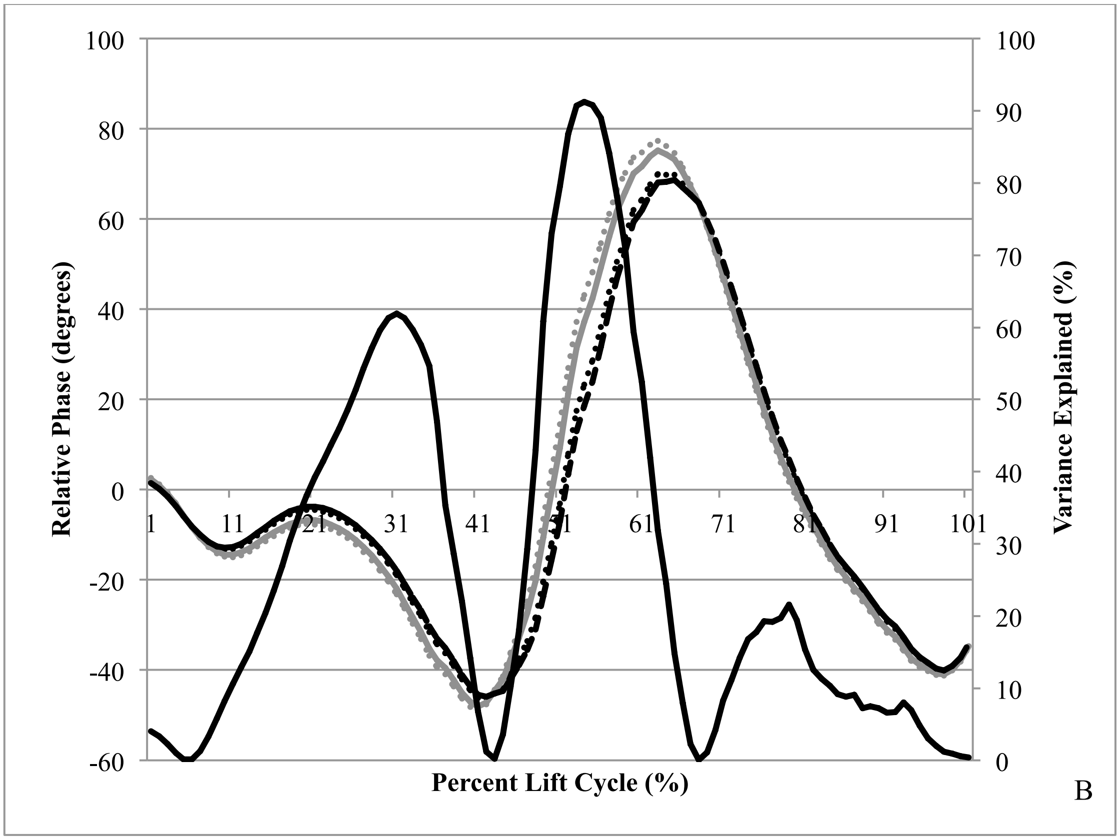
Variance Explained (%)
Percent Lift Cycle (%)
F

Figure 3.8: Left forearm and left arm relative phase pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3. E. Principal Component 4. F. Principal Component 5.

The parallel retention analysis retained five PCs from the principal component analysis of the left forearm and upper arm, pre-fatigue and fatigued conditions, relative phase waveforms (table 3.3). PC1 (47.05% variance explained) highlighted magnitude differences at 30%, 50% and 75% of the lift cycle, with the greatest amount of variance around 50%. Difference operators were also identified at 45% and 65%. Significant differences were found between the PF and SF, PF and GF, and GF and SF conditions. At 30% of the lift the PF and SF conditions were similar, then the BF and GF conditions drew closer to zero, with the GF condition being closest to zero, suggesting an a more in phase motion for the left forearm and upper arm. The negative value and negative slope suggest that the upper arm is moving more quickly and at is at a greater angle than the forearm. At 50% the SF condition was closest to zero with, the GF, PF and BF conditions following further from zero. A positive slope suggests that the forearm was moving at a greater rate than the upper arm, and the shift from negative values to positive values demonstrates a shift as the forearm stops following the upper arm in phase space and moves away from being in phase. Finally, at 75% of the lift, the SF condition is again greater than the PF and GF state, and the BF. A negative slope with positive values indicates that the upper arm was moving faster than the lower, as the segments became more in phase and approached zero. PC2 (17.72% variance explained) identified magnitude differences at 45% and 65% of the lift, with more variance explained around 65%, and a difference operator at 55%. There were no significant differences between the different conditions. This may have occurred because though there was high variability within each condition, the differences between each condition were not significant. PC3 (9.03% variance explained) detected magnitude differences at 45%, 70% and 95%, with difference operators at 30% and 85%. There were significant differences between the PF and SF, BF and SF, and GF and SF conditions. At 45% of the lift the relative phase angles for the PF, BF and GF conditions were similar while the SF condition had a more negative value suggesting a more out of phase motion. The coordination change occurs at the local minimum as the upper arm, which had been moving faster than the forearm, slows and the forearm begins to move faster than the upper arm. At all times, the upper arm led the forearm in phase space. At 70% of the lift, a time shift was detected as the SF condition relative phase pattern occurred earlier than the other conditions. At this point in the lift cycle, the forearm was leading the upper arm in phase space, as the upper arm moved at a greater velocity and the two segments moved to a more in phase motion. Finally, at 95% the upper arm had resumed leading of the forearm, with the SF condition having a more in phase pattern than the other conditions during load placement. PC4 (6.75% variance explained) indicated that there were magnitude differences at 15% and 95% of the lift. Significant differences were seen between the PF and BF, BF and GF, and BF and SF conditions. At 15%, the BF condition was less in phase than the other conditions as the upper arm led the forearm in phase space, with the forearm moving at a greater velocity as the two segments became more in phase. Later in the lift at 95%, the BF condition showed a more in phase motion than the other conditions with the upper arm moving slightly faster than the forearm as the upper arm led the motion. PC5 (4.04% variance explained) detected a magnitude difference at 40% of the lift cycle. There were no significant differences between the different conditions. This may have occurred because though there was high variability within each condition, the differences between each condition were not significant.

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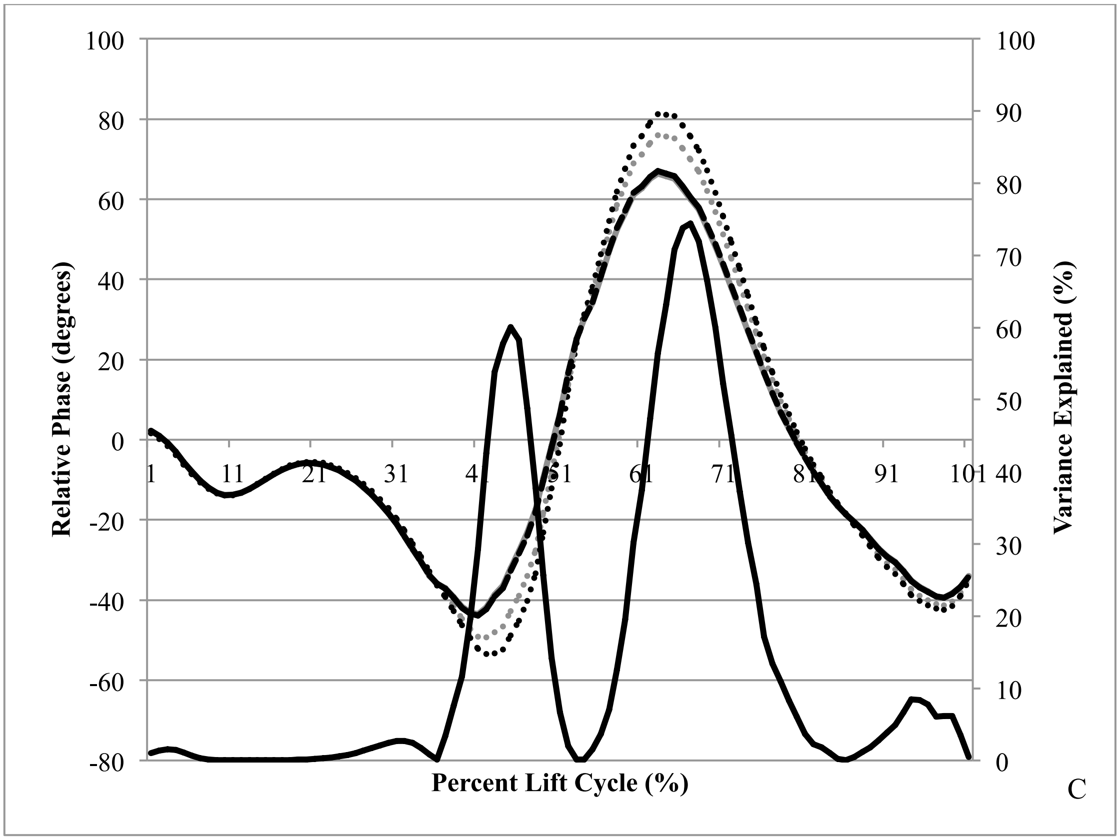
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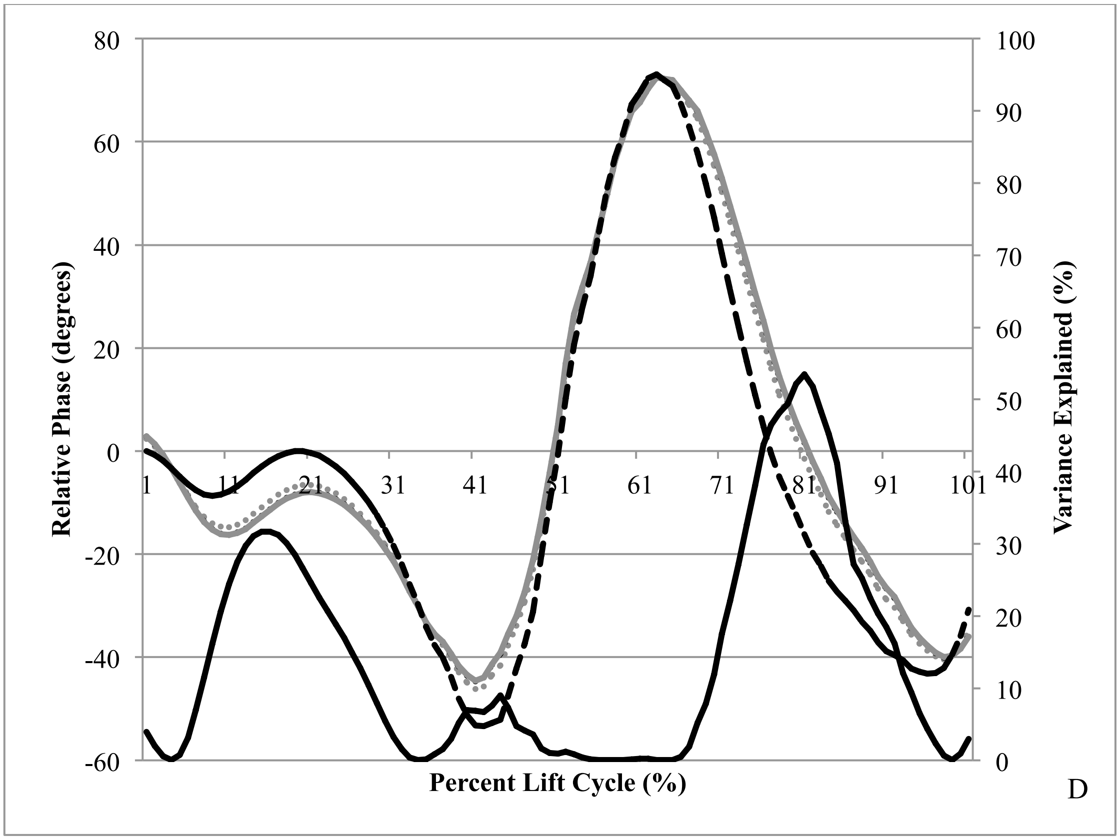
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Relative Phase (degrees)
Variance Explained (%)
Percent Lift Cycle (%)
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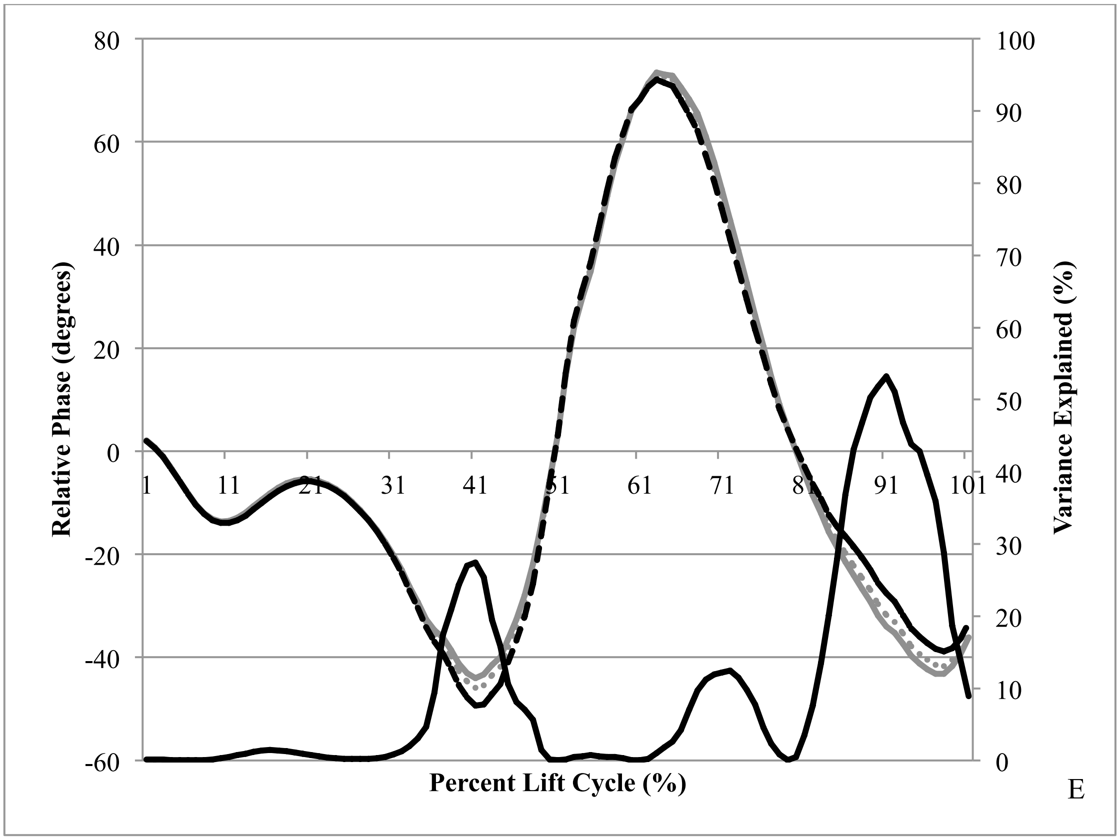
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Relative Phase (degrees)
Variance Explained (%)
Percent Lift Cycle (%)
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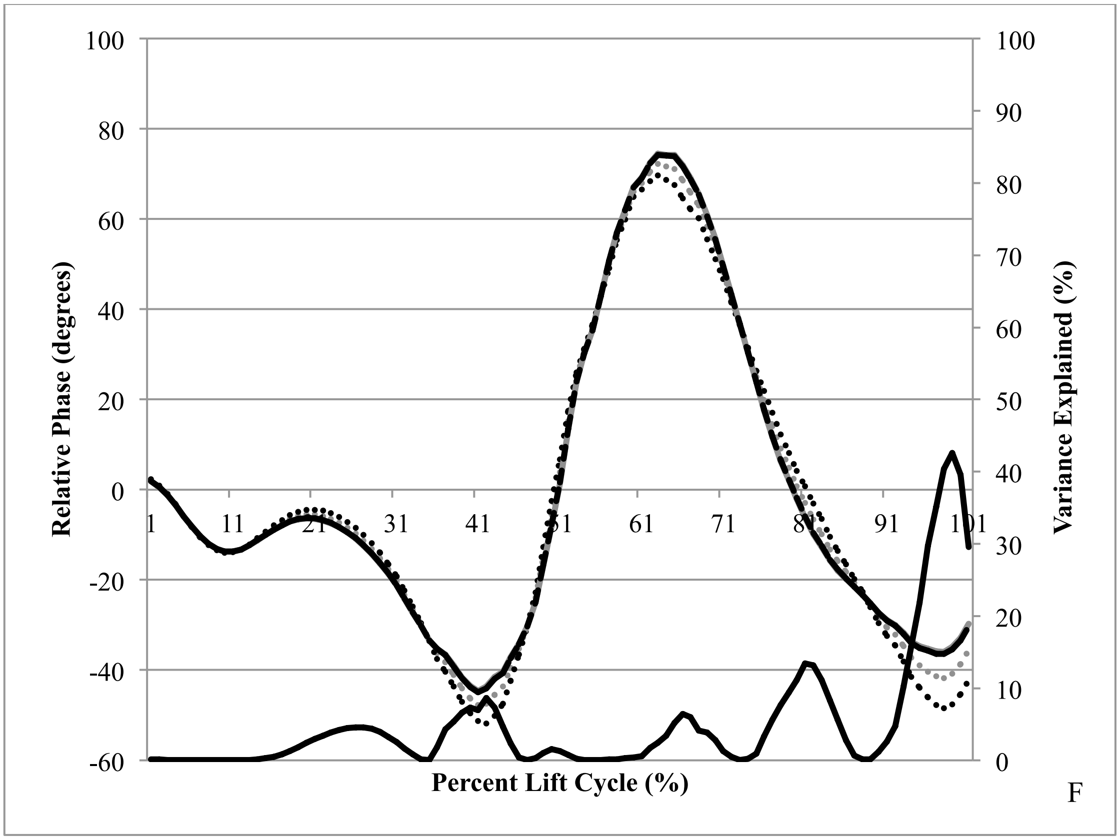
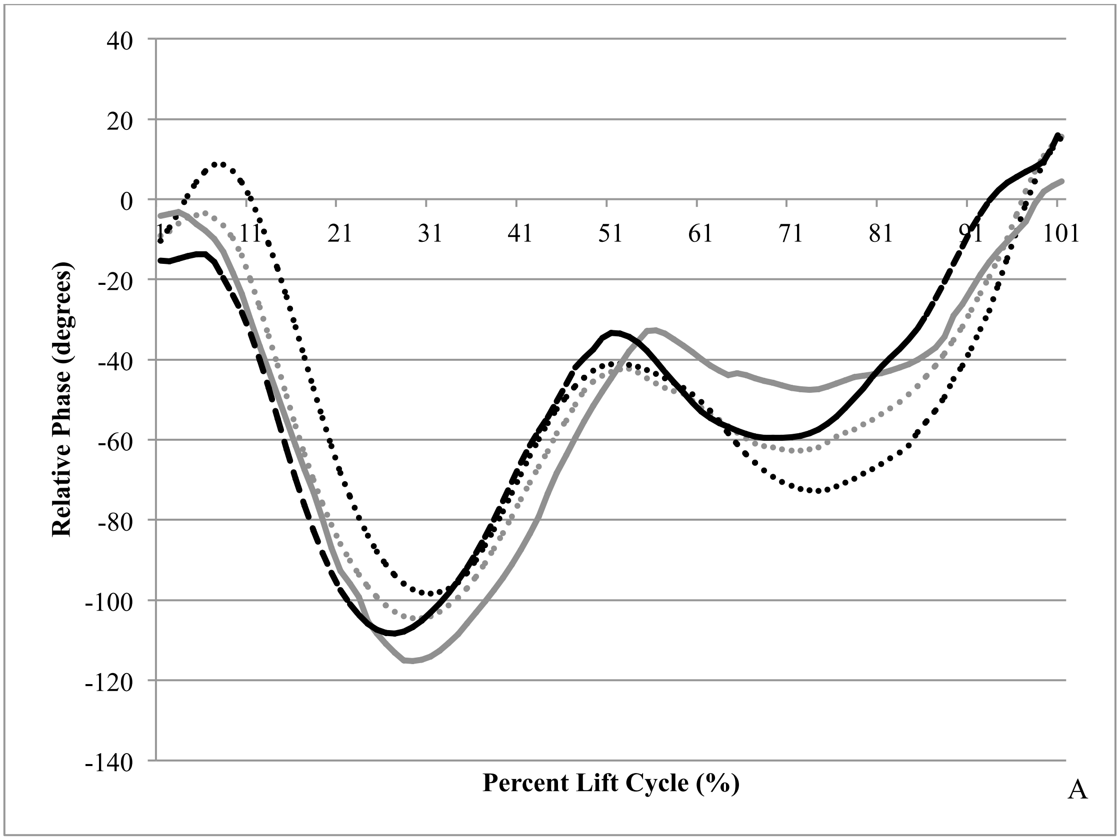
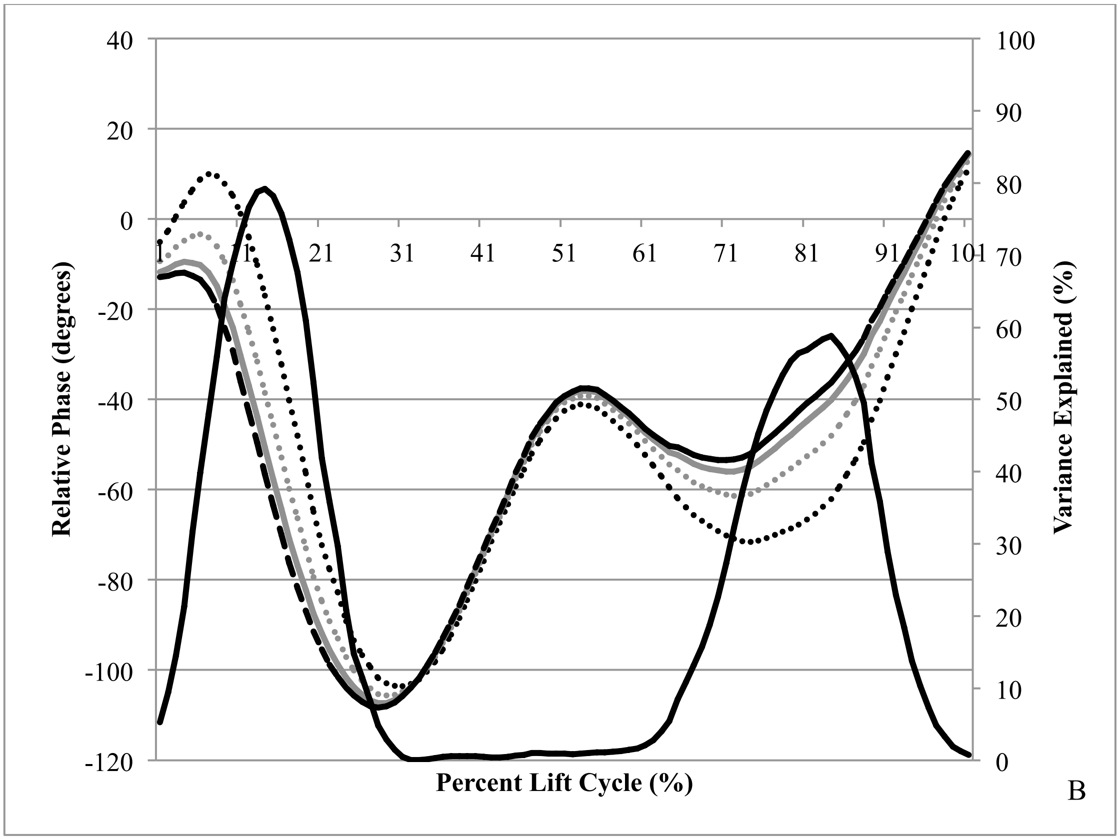


Figure 3.9: Right forearm and right arm relative phase pre-fatigue condition (·····) compared to general (——); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (——). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3. E. Principal Component 4. F. Principal Component 5.

The parallel retention analysis retained five PCs from the principal component analysis of the right forearm and upper arm, pre-fatigue and fatigued conditions, relative phase waveforms (table 3.3). PC1 (41.69% variance explained) highlighted magnitude differences at 30% and to a greater extent at 50% of the lift cycle, with a difference operator at 45%. Significant differences were found between PF and BF, and PF and SF conditions. At 30%, the SF and BF conditions occurred slightly later than the PF condition. The slope and phase angles were similar, simply shifted as the upper arm led the lower arm in phase space and at a greater velocity, as the two segments became less in phase. At 50% of the lift, the waveforms were once again shifted to later in the lift cycle and the slope was positive but slightly less than the PF condition indicating the forearm is moving faster relative to the upper arm in both instances; however, there is less of a difference in the SF and BF velocities compared to the PF. The forearm was moving ahead of the upper arm and the segments were becoming progressively less in phase. PC2 (22.13% variance explained) highlighted magnitude differences at 45% and 65%, with a difference operator at 55%. There were no significant differences between the different conditions. PC3 (8.69% variance explained) highlighted magnitude differences at 15%, 40% and 80%, with difference operators at 5%, 35% and 95%. Significant differences were found between the PF and SF, BF and SF, and GF and SF conditions. In this instance, the SF condition followed a similar waveform pattern with more exaggerated values. At 15%, the SF condition was more in phase with the upper arm ahead of the lower arm in phase space, and the lower arm was moving slightly faster in phase space. Then at 40% the SF condition was significantly more out of phase with the upper arm ahead of the lower arm in phase space. At this point in the lift, there was a reversal as the forearm switched and was moving at a faster relative phase than the upper arm. Finally at 80% of the lift the motion occurred earlier with the segments becoming less in phase, with the upper arm moving faster and ahead of the lower arm in phase space. PC4 (8.58% variance explained) detected magnitude differences at 40%, 70% and 90% of the lift, with a difference operator at 80%. There were no significant differences between the different conditions. PC5 (3.77% variance explained) highlighted magnitude differences at 40%, 65%, 80% and to a greater extent at 95% of the lift cycle. There were two difference operators detected at 75% and 90% of the cycle. There were significant differences between the BF and GF conditions. At 95% of the lift cycle the upper arm was ahead of the lower arm in phase space as the velocity difference reversed, the BF condition showed a more out of phase pattern between the upper arm and lower arm segments.

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Variance Explained (%)
Percent Lift Cycle (%)
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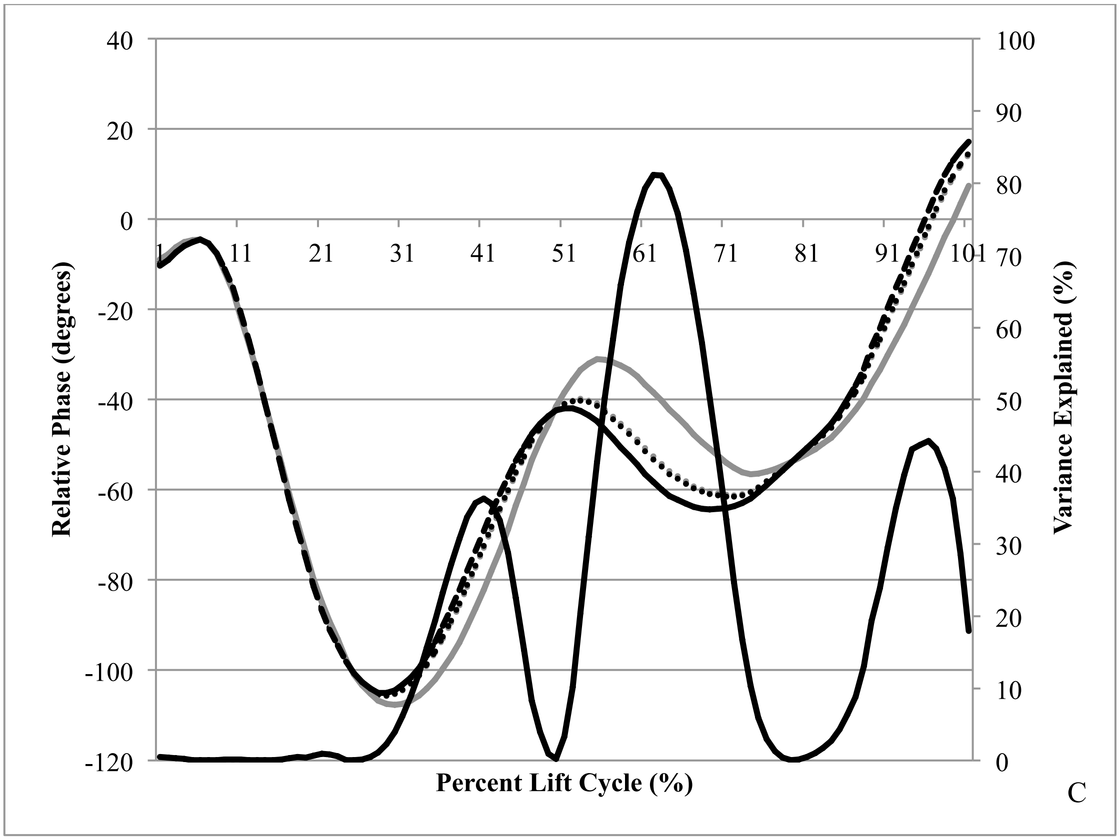
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Relative Phase (degrees)
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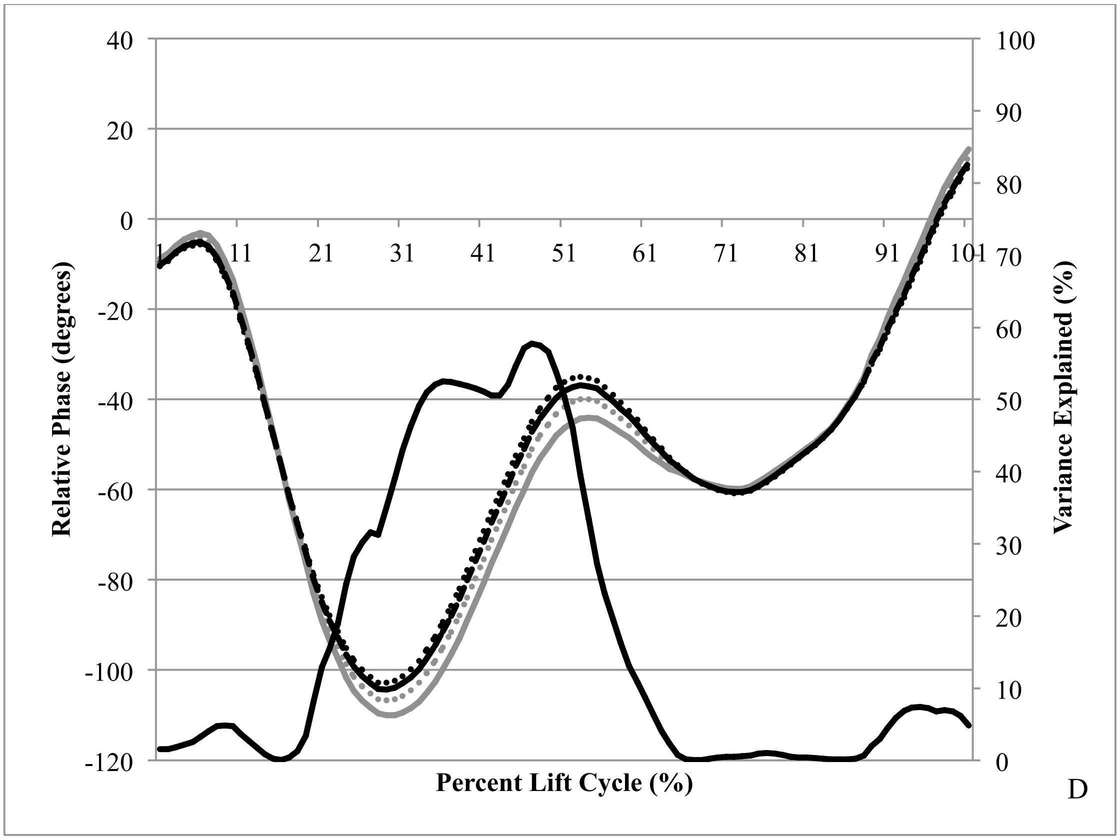
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Relative Phase (degrees)
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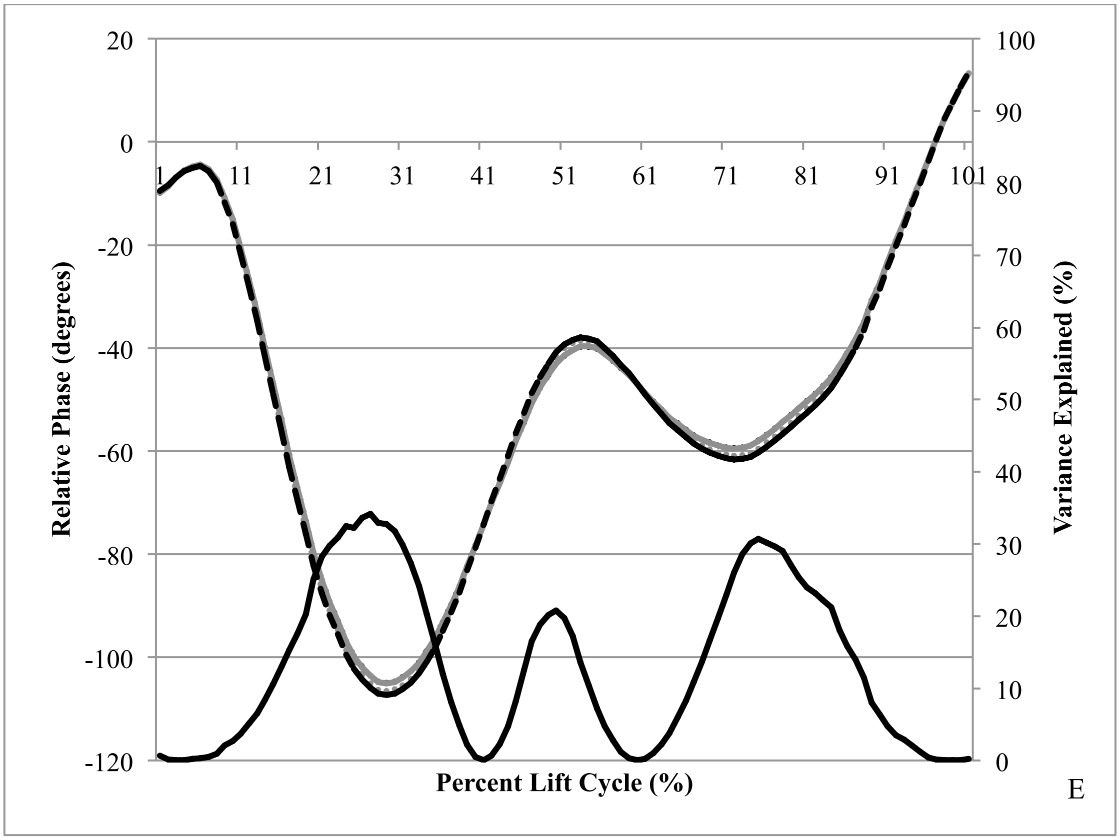
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Variance Explained (%)
Percent Lift Cycle (%)
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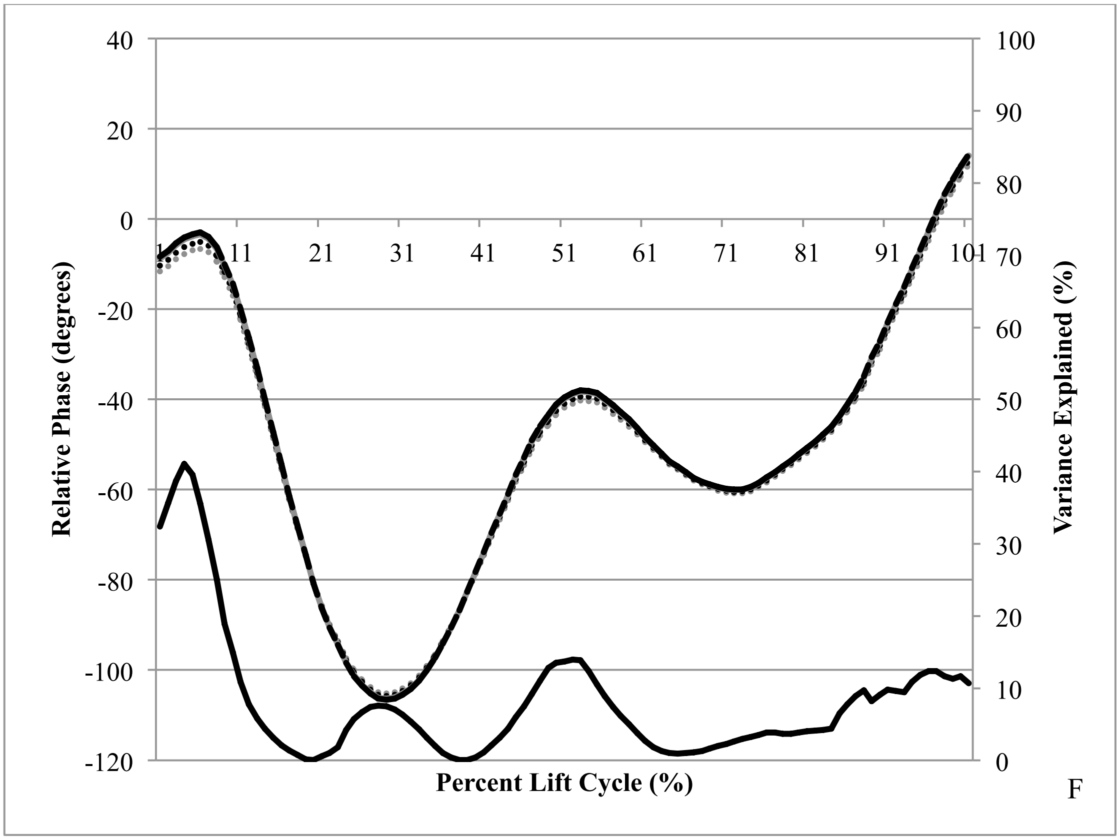
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Variance Explained (%)
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Percent Lift Cycle (%)
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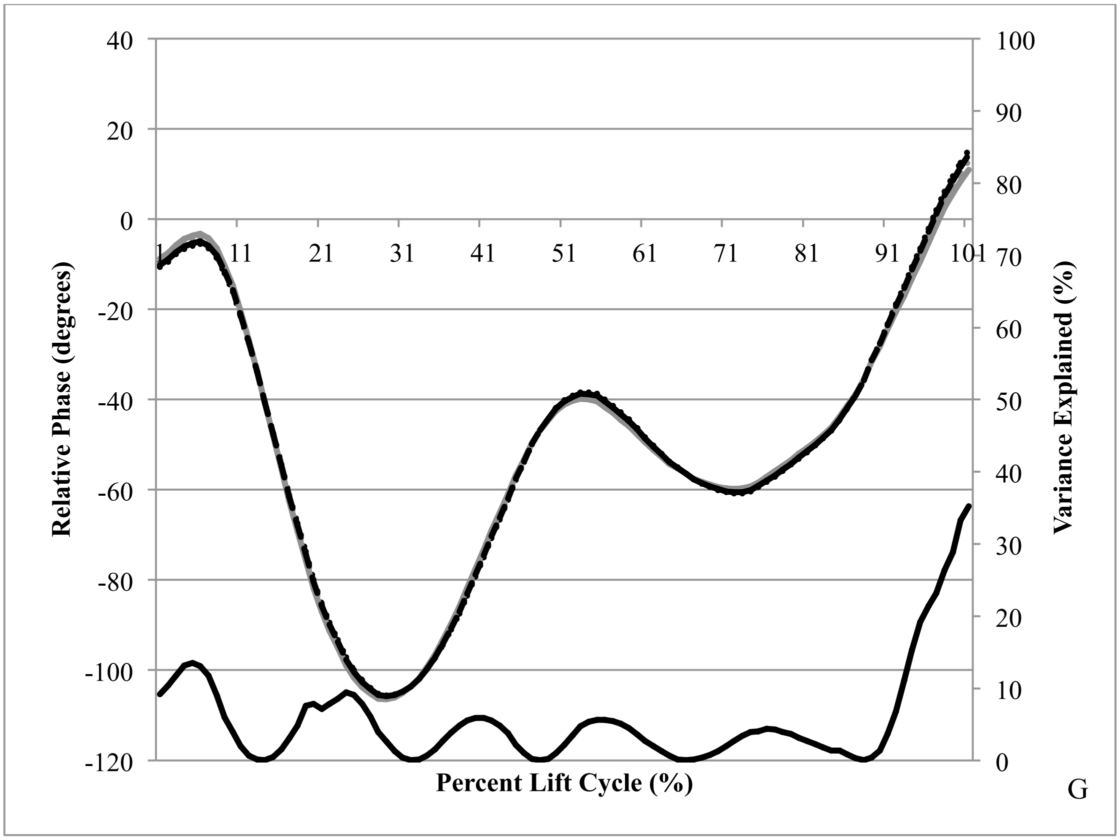
40
20
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-20
-40
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-100
-120
Relative Phase (degrees)
100
90
80
70
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50
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Variance Explained (%)
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101
Percent Lift Cycle (%)
G

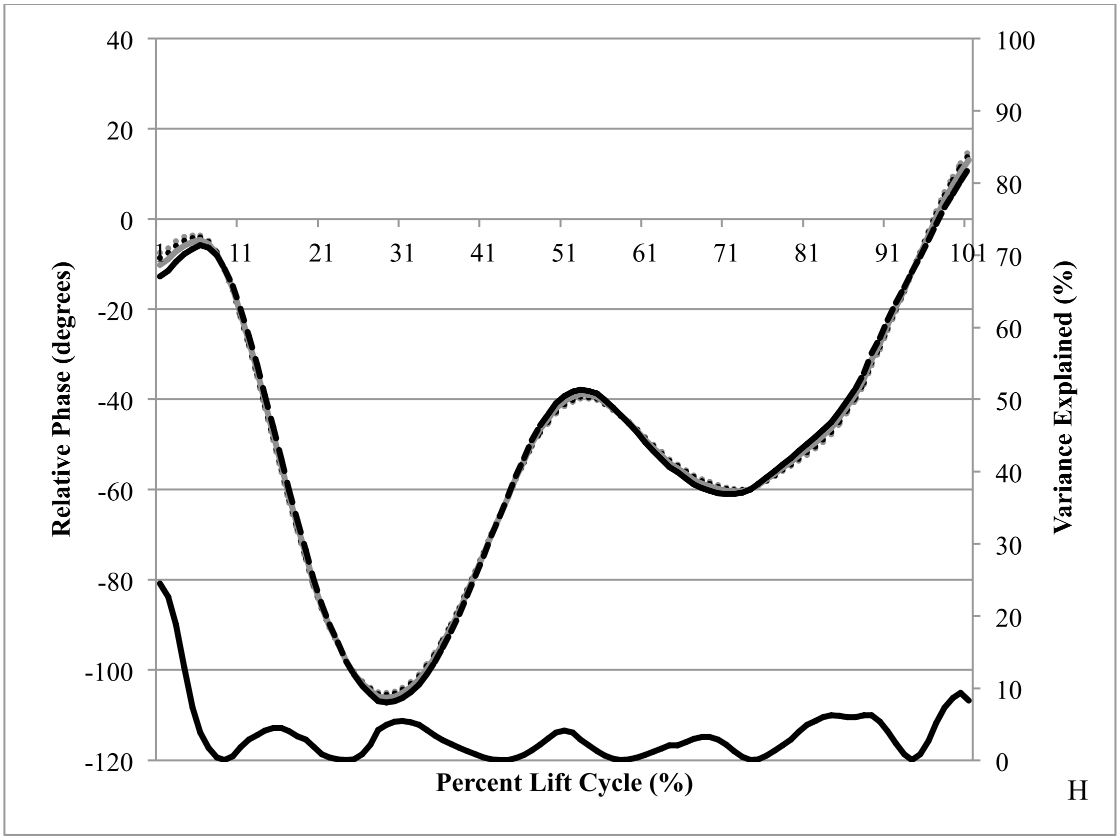
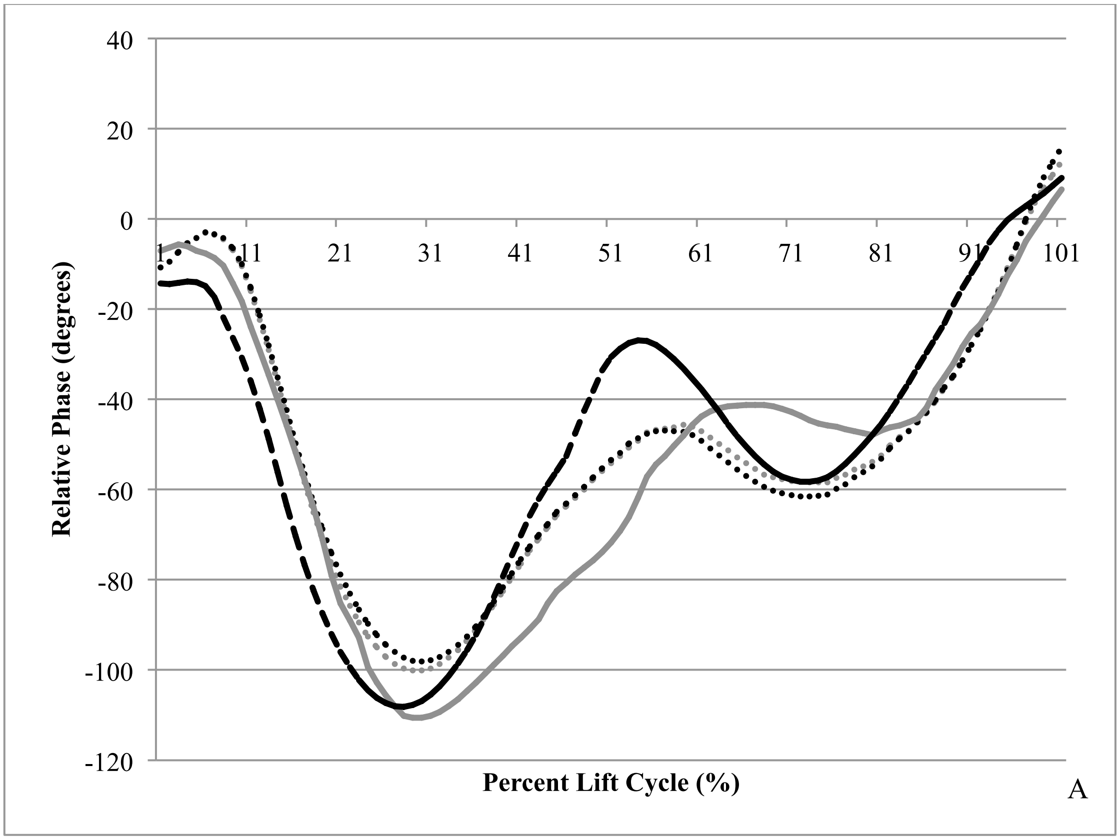
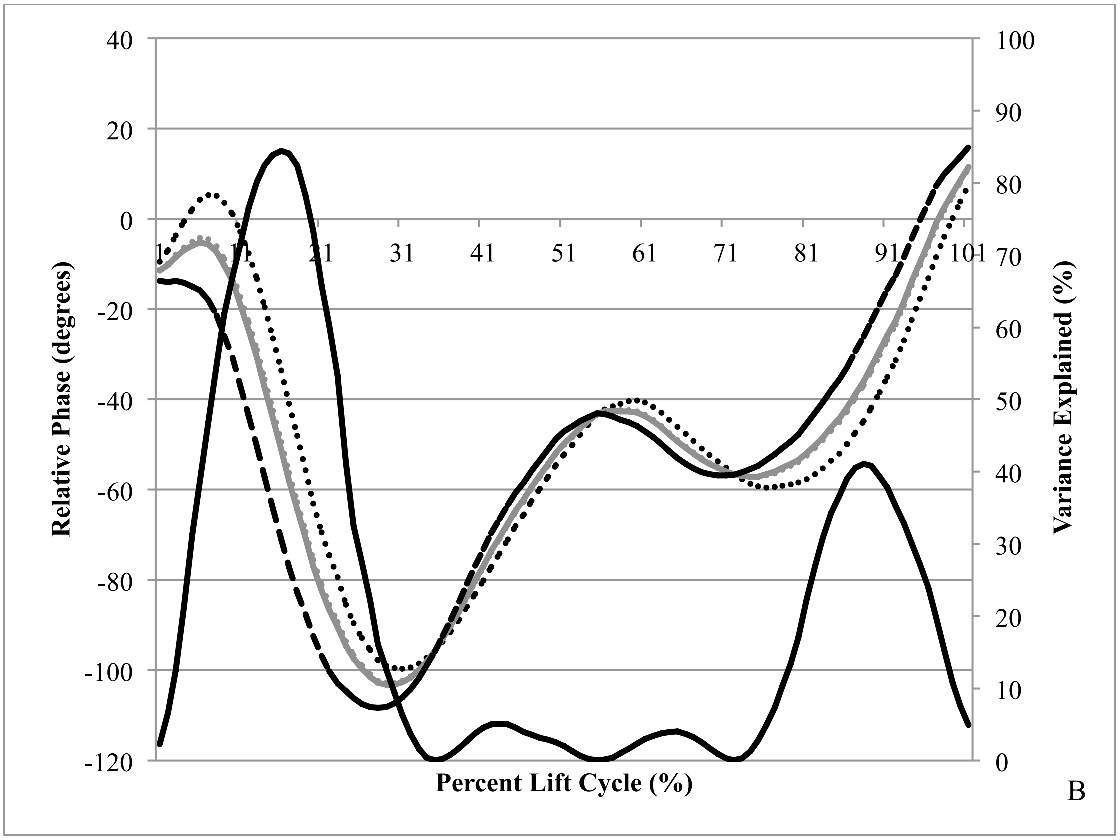


Figure 3.10: Left arm and trunk relative phase pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3. E. Principal Component 4. F. Principal Component 5. G. Principal Component 6. H. Principal Component 7.

The parallel retention analysis retained seven PCs from the principal component analysis of the left upper arm and trunk, pre-fatigue and fatigued conditions, relative phase waveforms (table 3.3). PC1 (25.01% variance explained) highlighted a magnitude difference at 15% and 80% of the lift cycle. Significant differences were found between the PF and BF, PF and GF, PF and SF, BF and GF, and BF and SF. At 15%, there was a time shift as the BF curve occurred later than the PF condition, and the SF and GF occurred earlier. The trunk was leading the motion in phase space and was moving faster than the upper arm as the segments became less in phase. At 80% of the lift cycle, the slight positive slope indicated that the upper arm was moving faster than the trunk as the segments became more in phase, while the trunk continued to lead the upper arm in phase space. The SF, GF and PF conditions, respectively, showed a more in phase motion than the BF condition. PC2 (22.49% variance explained) highlighted magnitude differences at 40%, 60% and 95% of the lift, with difference operators at 50% and 80%. Significant differences were found between PF and GF, BF and GF, and GF and SF conditions. At 40%, there was a shift as the SF, BF and PF condition curves occurred earlier than the GF. The trunk led the motion in phase space; however, the upper arm moved at a greater velocity relative to the trunk as the segments became more in phase. At 60%, the GF condition was more in phase than the other conditions, with the trunk still leading and also moving slightly faster than the upper arm. Finally, at 95% of the lift, the upper arm began to lead the motion as the upper arm was moving faster than the trunk, the segments became more in phase before once again moving more out of phase. The GF condition curve occurred a bit later but similarly the segments became more in phase as the upper arm moved at a greater velocity before beginning to lead the motion in phase space. PC3 (17.10% variance explained) highlighted a magnitude difference from 20-55% of the lift. Significant differences were found between PF and BF, and BF and GF conditions. There was a local minimum around 30% of the lift, indicating a coordination shift as the upper arm began to move faster than the leading trunk, and the segments moved toward a more in phase pattern. The timing shift was seen as the BF and SF condition curves occurred earlier than the PF and GF conditions, respectively.

PC4 (11.48% variance explained) highlighted magnitude differences at 25%, 50% and 75%, with difference operators at 40% and 60% of the lift cycle. PC5 (7.97% variance explained) had a multi-mode loading curve which highlighted magnitude differences at 5% and 50% with multiple areas of additional loading and cross-overs. PC6 (5.88% variance explained) also had a multi-mode loading curve which highlighted magnitude differences from 90-100% of the lift. PC7 (3.32% variance explained) had a multi-mode loading curve which highlighted magnitude differences from 0-5% of the lift. Analysis of the PC coefficients for the final four PCs did not show significant differences between the conditions.




40
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-100
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Relative Phase (degrees)
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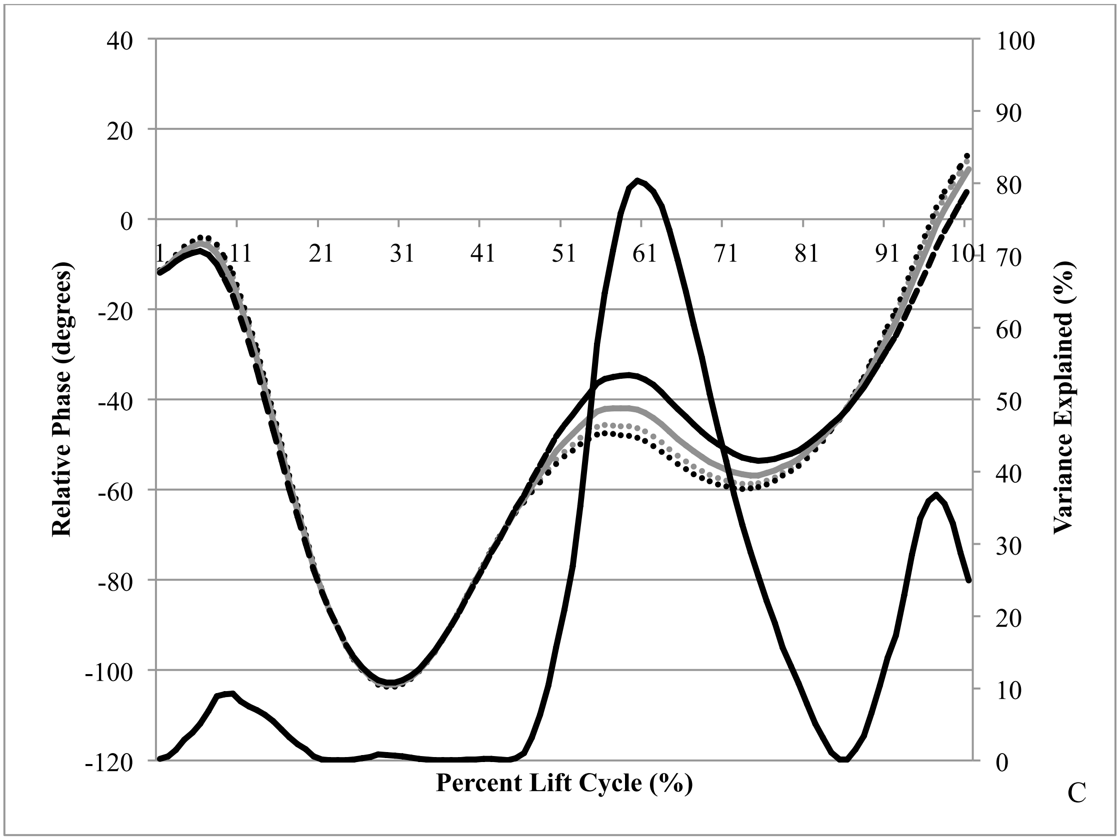
Variance Explained (%)
Percent Lift Cycle (%)
B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Relative Phase (degrees)
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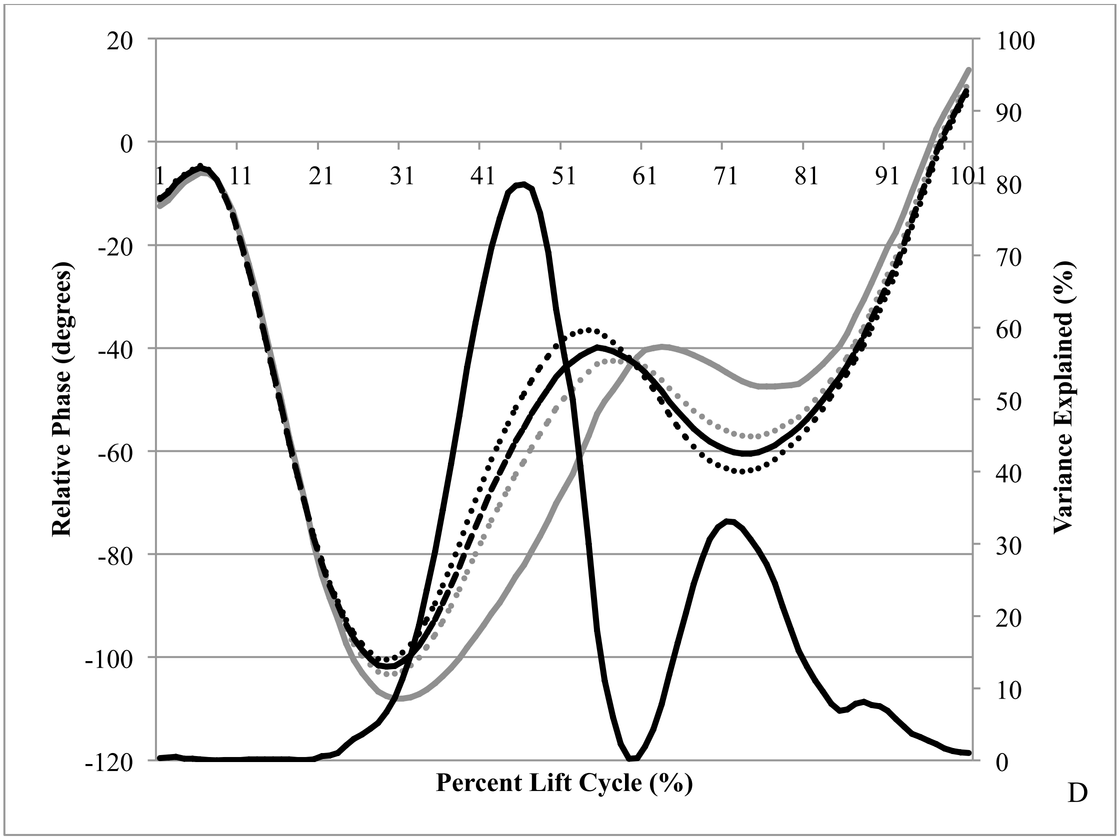
Variance Explained (%)
Percent Lift Cycle (%)
C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Relative Phase (degrees)
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Percent Lift Cycle (%)
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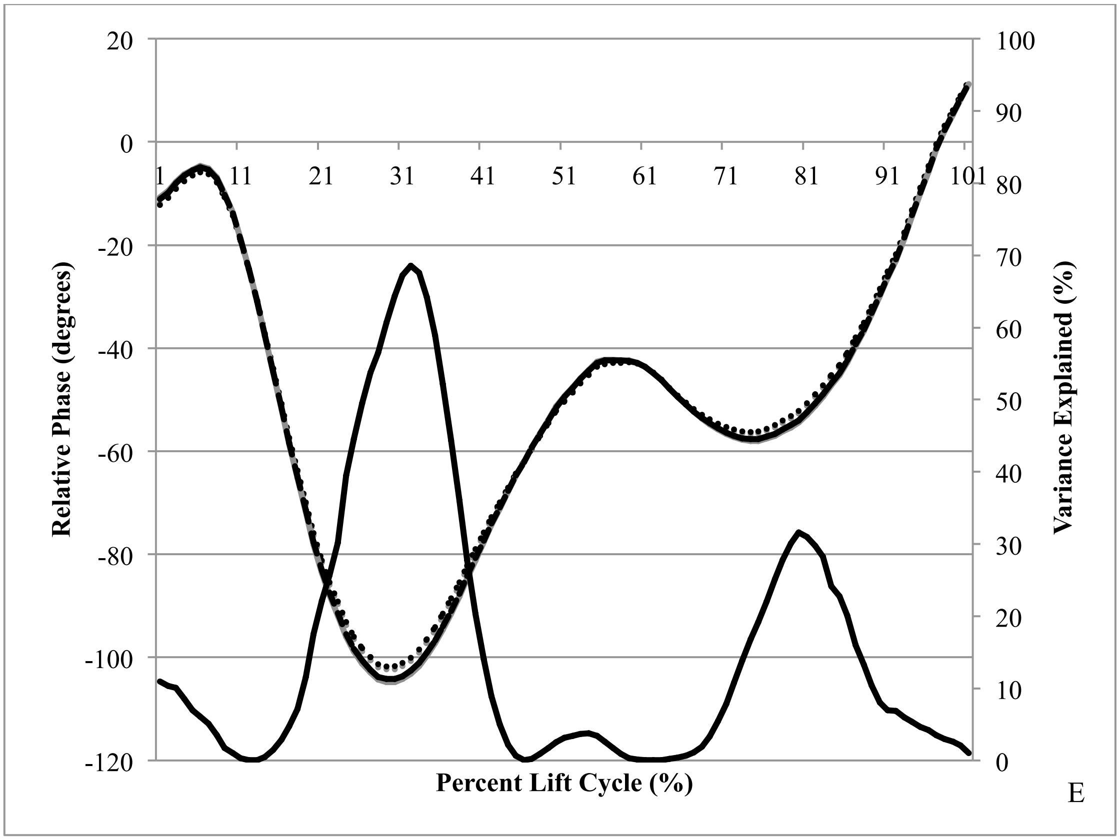
0
Variance Explained (%)

D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Relative Phase (degrees)
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Percent Lift Cycle (%)
100
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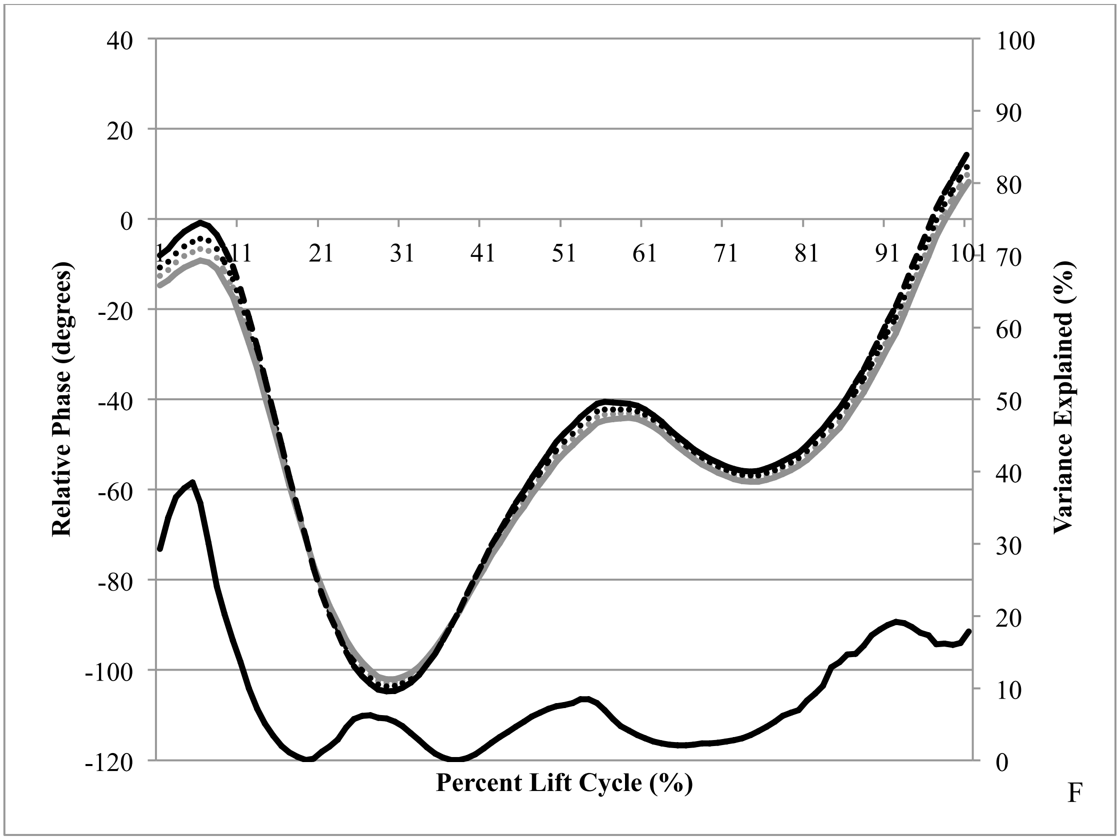
0
Variance Explained (%)

E



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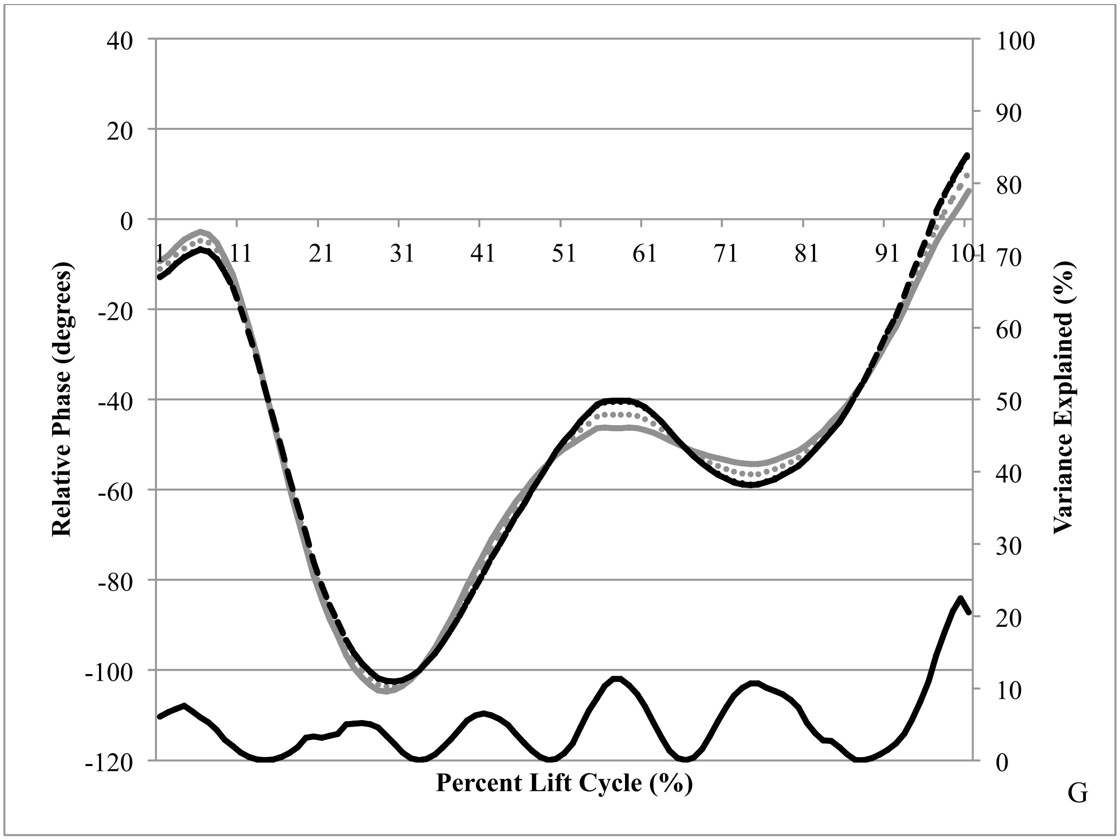
Relative Phase (degrees)
Variance Explained (%)
Percent Lift Cycle (%)
F



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71
81
91
101
Relative Phase (degrees)
Variance Explained (%)
Percent Lift Cycle (%)
G

Figure 3.11: Right arm and trunk relative phase pre-fatigue condition (·····) compared to general (—); back (·····); shoulder (- - -) fatigue conditions respectively. Principal component loading curve (—). A. Averaged Curves. B. Principal Component 1. C. Principal Component 2. D. Principal Component 3. E. Principal Component 4. F. Principal Component 5. G. Principal Component 6.

The parallel retention analysis retained six PCs from the principal component analysis of the right upper arm and trunk, pre-fatigue and fatigued conditions, relative phase waveforms (table 3.3). PC1 (24.97% variance explained) highlighted magnitude differences at 15% and 85% of the lift cycle. Significant differences were found between the PF and BF, PF and SF, BF and GF, BF and SF, and GF and SF conditions. At 15%, there was a time shift as the BF curve occurred later than the PF and GF conditions, while the SF curve occurred earlier. The trunk was leading the motion in phase space and was moving faster than the upper arm as the segments became less in phase. At 80% of the lift cycle, the slight positive slope indicated that the upper arm was moving faster than the trunk as the segments became more in phase, while the trunk continued to led the upper arm in phase space. The SF condition, showed a more in phase motion than the GF and PF conditions and the BF condition was even less in phase. PC2 (21.40% variance explained) highlighted magnitude differences at 60% and 95%, with a difference operator at 85%. There were no significant differences between the different conditions. PC3 (18.47% variance explained) highlighted magnitude differences at 45% and 70%, with a difference operator at 60%. Significant differences were found between PF and BF, PF and GF, BF and GF, and GF and SF conditions. At

45%, the trunk led the motion as the upper arm moved at a greater velocity bringing the segments to be more in phase. The BF and SF conditions occurred earlier than the PF and GF conditions respectively. At 70%, the GF condition was more in phase than the PF, SF and BF conditions respectively. A local minimum occurred around this point in the lift suggesting a coordination shift as the trunk was no longer moving at a faster rate than the upper arm. At this time the segments began moving to a more in phase motion. PC4 (11.99% variance explained) highlighted magnitude differences at 30% and 80% of the lift cycle. There were no significant differences between the different conditions. PC5 (8.91% variance explained) had a multi-mode loading curve that highlighted magnitude differences at 5% and from 80-100% of the lift. Significant differences were found between the PF and SF conditions. At 5%, the SF was more in phase than the BF, PF and GF respectively. A local maximum occurred as the leading trunk increased velocity and began moving faster than the upper arm in phase space. Later in the lift, 80-100%, the SF curve occurred earlier than the BF, PF and GF curves. The trunk still led the motion in phase space but the upper arm was moving at a greater velocity that brought the segments closer to being in phase. PC6 (5.00% variance explained) also had a multi-mode loading curve that highlighted magnitude differences from 95-100% of the lift. There were significant differences between the GF and SF conditions. There were several areas along the lift cycle that showed variation between the SF and GF conditions but the major influence was late in the lift during load placement as the SF condition showed a greater upper arm velocity relative to the trunk as the upper arm led the motion in phase space. The SF and BF conditions were less in phase than the PF and GF conditions respectively.

3.6 Relative Phase Frequency Analysis Results

The frequency analysis of the relative phase angles throughout the entire lift cycle gave a better understanding of the relative phase angle distribution during a lift both in an non-fatigued state and a generally fatigued state, as well as the differences in frequency across fatigue conditions. Some significance can be accounted for by frequency extremes as the relative phase angles were focused fairly centrally. The frequency plot and analysis of significance showed a difference in the tendency toward specific relative phase angles depending on the state of fatigue. The relative phase angles were set into 30 degree ranges: -180/-150, -150/-120, -120/-90, -90/-60, -60/-30, -30/0, 0/30, 30/60, 60/90, 90/120, 120/150, 150/180. Generally the frequency of relative phase of the forearm and upper arm was most concentrated between -30 and 60 degrees; while the upper arm and trunk relative phase was most frequently within the range of -60 and 0 degrees. The overall motion is most within phase when near 0 relative phase. The negative values indicate that the shoulder was at a greater angle than the elbow/the trunk was at a greater angle than the shoulder in phase space while positive values indicate that the elbow was at a greater angle than the shoulder/the shoulder was at a greater angle than the trunk. Knowing the general frequency of relative phase angles clearly shows a tendency toward a slightly out of phase shoulder and elbow with high frequencies for both a positive and negative phase one can see a fairly even distribution between shoulder and elbow joint motion. It is also apparent that the trunk trends toward a greater angle than the shoulder joint. Differences between fatigue conditions were statistically significant. The areas of greater interest were the areas of high frequency and significance between conditions. Significance between low frequencies at the edges of the frequency plot was ignored as areas of highest frequency indicate where the greatest time is spent during the lift in a specific relative position. Areas of significance identify areas of greatest difference between the different conditions for the multiple relative phase measures of the arms and trunk. Unlike traditional interpretations of relative phase the frequency analysis gives additional information about the degree of the lift spent in specific levels of relative phase.

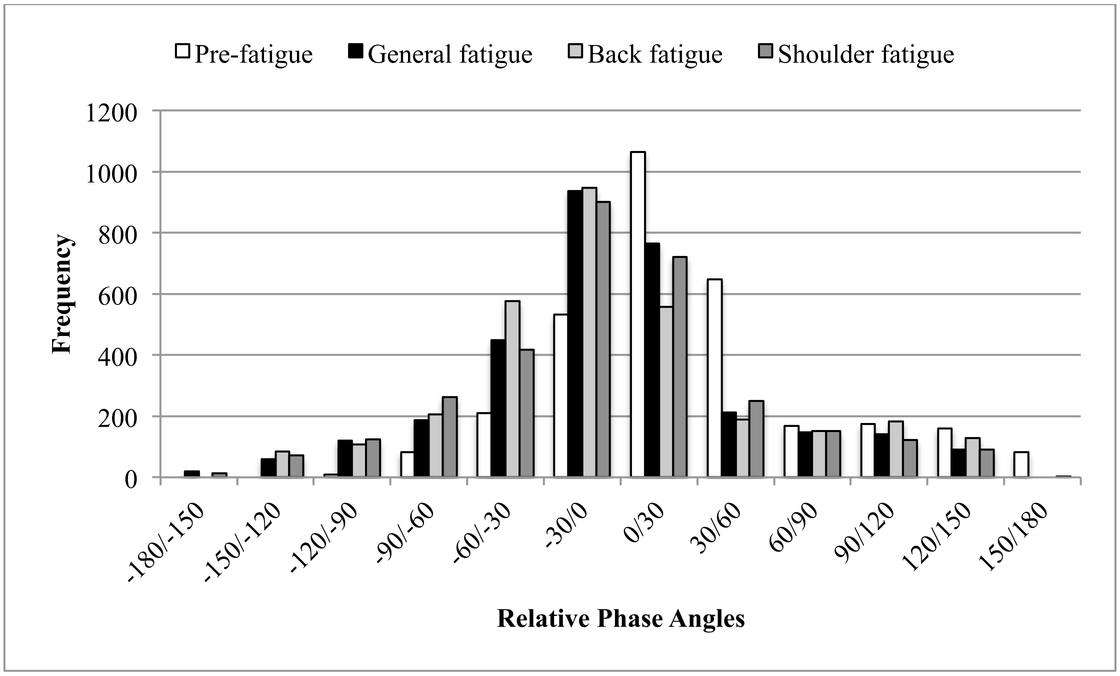

Figure 3.12: Frequency plots of left forearm upper arm for pre-fatigue, general fatigue, back specific fatigue and shoulder specific fatigue conditions.

Table 3.4: Significance ($p<0.05$*) of left forearm/upper arm relative phase angle frequency distribution across conditions (pre-fatigue/general fatigue, pre-fatigue/back fatigue, pre-fatigue/shoulder-fatigue, general-fatigue/back-fatigue, general-fatigue/shoulder-fatigue, back-fatigue/shoulder-fatigue).

Relative Phase Angle Frequencies	pre-fatigue / general fatigue	pre-fatigue / back fatigue	pre-fatigue / shoulder fatigue	general fatigue / back fatigue	general fatigue / shoulder fatigue	back fatigue / shoulder fatigue
-180/-150	0.106	---	0.256	0.106	0.735	0.256
-150/-120	0.002*	0.001*	0.001*	0.249	0.619	0.645
-120/-90	0.052	0.161	0.038*	0.475	0.859	0.403
-90/-60	0.417	0.894	0.201	0.655	0.050	0.284
-60/-30	0.041*	0.465	0.024*	0.068	0.547	0.053
-30/0	0.029*	0.121	0.006*	0.894	0.616	0.583
0/30	0.077	0.178	0.212	0.008*	0.573	0.018*
30/60	0.229	0.383	0.003*	0.576	0.307	0.072
60/90	0.230	0.251	0.451	0.832	0.894	1.000
90/120	0.468	0.360	0.141	0.158	0.457	0.011*
120/150	0.773	0.051	0.688	0.222	0.968	0.178
150/180	---	---	0.325	---	0.325	0.325

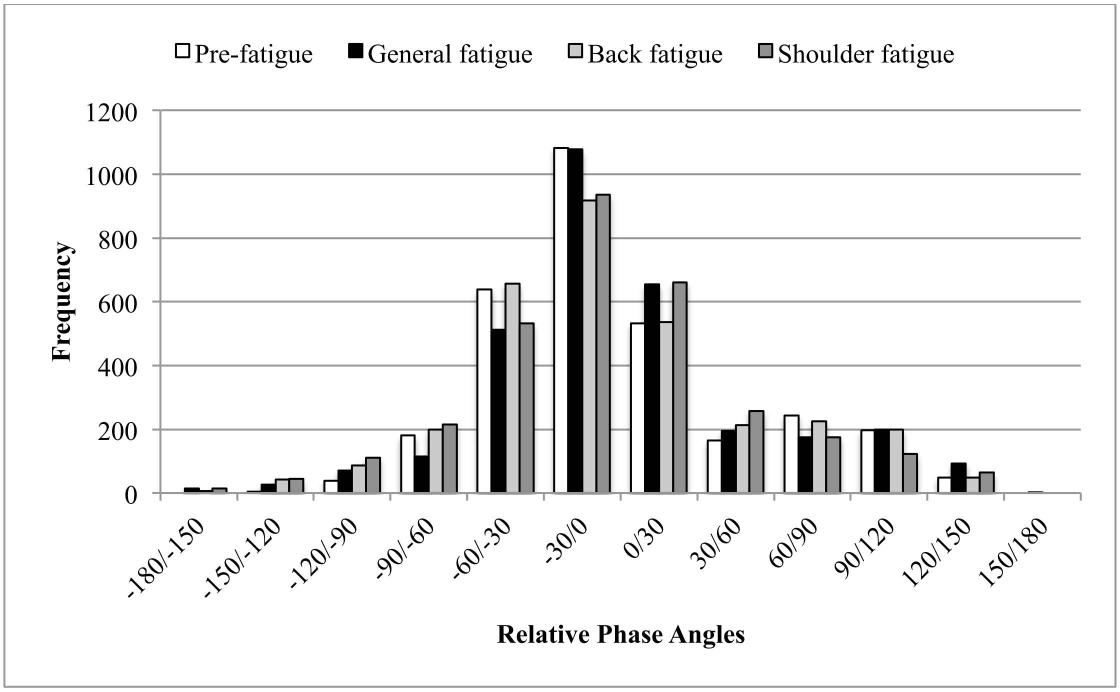

Figure 3.13: Frequency plots of right forearm upper arm for pre-fatigue, general fatigue, back specific fatigue and shoulder specific fatigue conditions

Table 3.5: Significance (p<0.05*) of right forearm upper arm relative phase angle frequency distribution across conditions (pre-fatigue/general fatigue, pre-fatigue/back fatigue, pre-fatigue/shoulder-fatigue, general-fatigue/back-fatigue, general-fatigue/shoulder-fatigue, back-fatigue/shoulder-fatigue)

Relative Phase Angle Frequencies	pre-fatigue / general fatigue	pre-fatigue / back fatigue	pre-fatigue / shoulder fatigue	general fatigue / back fatigue	general fatigue / shoulder fatigue	back fatigue / shoulder fatigue
-180/-150	0.129	0.325	0.184	0.354	0.946	0.487
-150/-120	0.050	0.002*	0.015*	0.316	0.339	0.869
-120/-90	0.090	0.027*	0.004*	0.471	0.156	0.281
-90/-60	0.041*	0.550	0.327	0.011*	0.003*	0.658
-60/-30	0.064	0.722	0.089	0.043*	0.793	0.093
-30/0	0.945	0.018*	0.026*	0.034*	0.077	0.799
0/30	0.034*	0.919	0.009*	0.044*	0.909	0.022*
30/60	0.274	0.088	0.011*	0.637	0.103	0.333
60/90	0.035*	0.488	0.041*	0.169	0.972	0.164
90/120	0.979	0.974	0.028*	1.000	0.061	0.02*
120/150	0.052	0.948	0.553	0.058	0.370	0.503
150/180	0.325	---	---	0.325	0.325	---

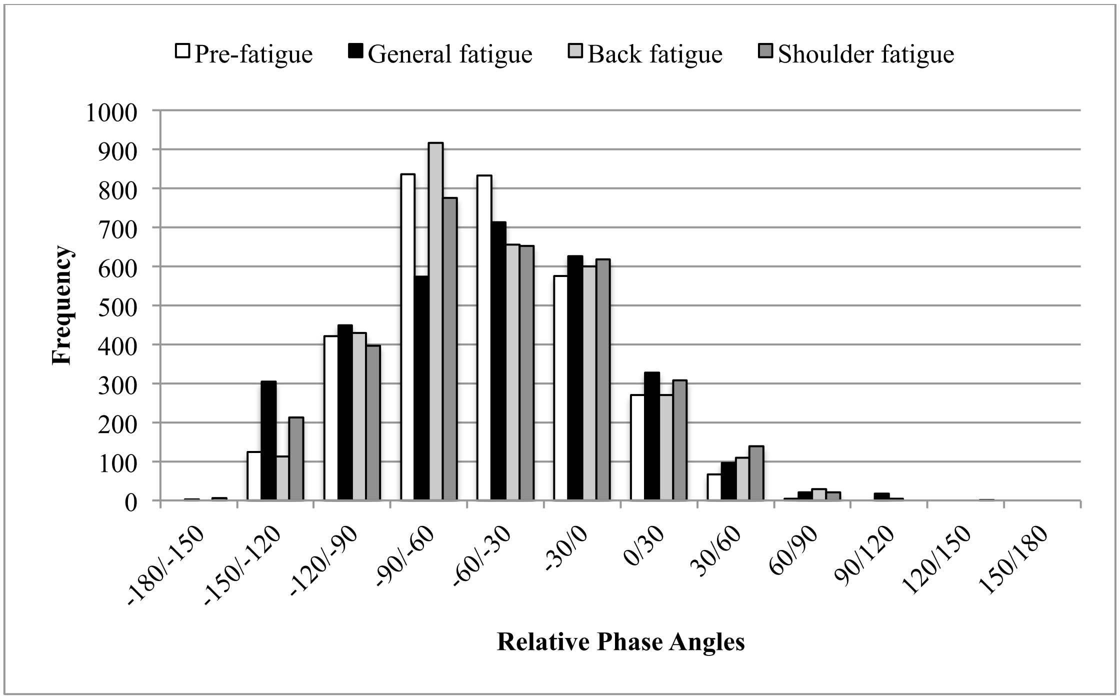

Figure 3.14: Frequency plots of left upper arm trunk for pre-fatigue, general fatigue, back specific fatigue and shoulder specific fatigue conditions.

Table 3.6: Significance ($p<0.05$*) of left upper arm trunk relative phase angle frequency distribution across conditions (pre-fatigue/general fatigue, pre-fatigue/back fatigue, pre-fatigue/shoulder-fatigue, general-fatigue/back-fatigue, general-fatigue/shoulder-fatigue, back-fatigue/shoulder-fatigue)

Relative Phase Angle Frequencies	pre-fatigue / general fatigue	pre-fatigue / back fatigue	pre-fatigue / shoulder fatigue	general fatigue / back fatigue	general fatigue / shoulder fatigue	back fatigue / shoulder fatigue
-180/-150	0.325	---	0.325	0.325	0.536	0.325
-150/-120	<0.000*	0.705	0.005*	<0.000*	0.036*	0.016*
-120/-90	0.583	0.900	0.536	0.742	0.292	0.552
-90/-60	<0.000*	0.228	0.391	<0.000*	0.004*	0.029*
-60/-30	0.121	0.012*	0.004*	0.551	0.484	0.945
-30/0	0.326	0.608	0.438	0.664	0.909	0.790
0/30	0.281	0.975	0.361	0.319	0.750	0.422
30/60	0.260	0.121	0.009*	0.684	0.163	0.452
60/90	0.157	0.044*	0.054	0.354	1.000	0.569
90/120	0.179	0.325	---	0.382	0.179	0.325
120/150	---	---	0.325	---	0.325	0.325
150/180	---	---	---	---	---	---

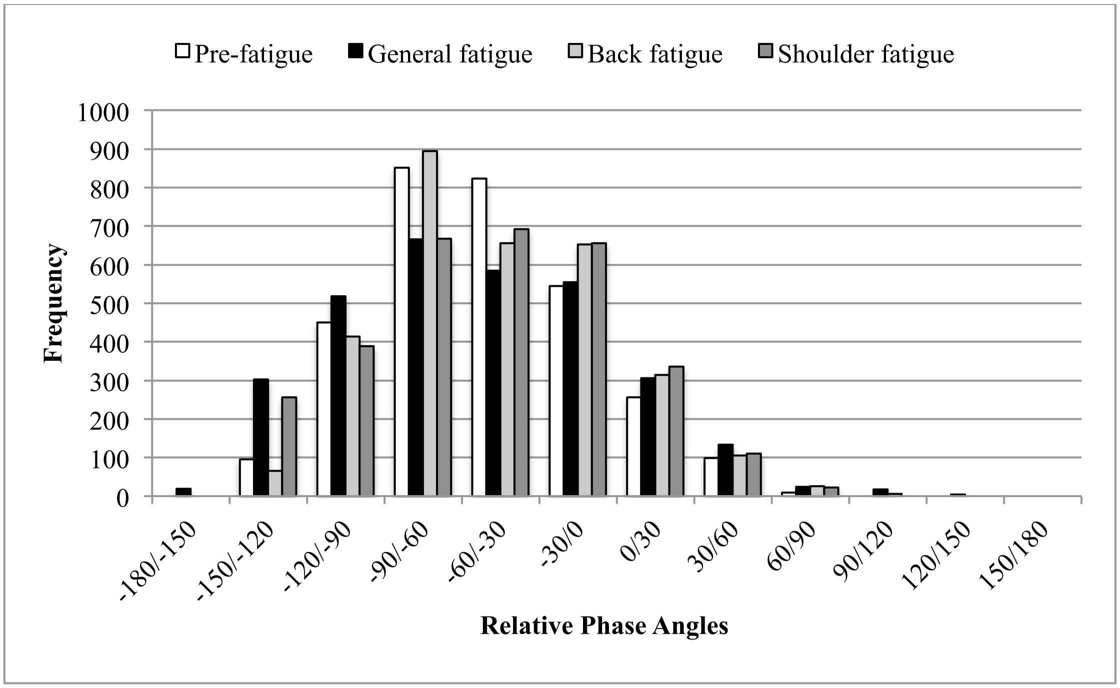

Figure 3.15: Frequency plots of right upper arm trunk for pre-fatigue, general fatigue, back specific fatigue and shoulder specific fatigue conditions.

Table 3.7: Significance ($p<0.05^*$) of right upper arm trunk relative phase angle frequency distribution across conditions (pre-fatigue/general fatigue, pre-fatigue/back fatigue, pre-fatigue/shoulder-fatigue, general-fatigue/back-fatigue, general-fatigue/shoulder-fatigue, back-fatigue/shoulder-fatigue)

Relative Phase Angle Frequencies	pre-fatigue / general fatigue	pre-fatigue / back fatigue	pre-fatigue / shoulder fatigue	general fatigue / back fatigue	general fatigue / shoulder fatigue	back fatigue / shoulder fatigue
-180/-150	0.325	---	---	0.325	0.325	---
-150/-120	<0.000*	0.438	<0.000*	<0.000*	0.356	<0.000*
-120/-90	0.219	0.656	0.311	0.194	0.069	0.537
-90/-60	0.013*	0.311	0.004*	0.005*	0.990	<0.000*
-60/-30	0.002*	0.004*	0.062	0.389	0.198	0.774
-30/0	0.945	0.018*	0.026*	0.034*	0.077	0.799
0/30	0.265	0.262	0.053	0.925	0.571	0.538
30/60	0.252	0.738	0.616	0.478	0.548	0.837
60/90	0.340	0.037*	0.362	0.945	0.951	0.897
90/120	0.114	0.325	---	0.318	0.114	0.325
120/150	0.325	---	---	0.325	0.325	---
150/180	---	---	---	---	---	---

4.0 Discussion

Lifting technique has been suggested as one of the main causes of work-related injury (Straker, 2002). Further, fatigue associated with prolonged lifting has been suggested as a possible risk factor for musculoskeletal injury as it may affect biomechanical and neuromuscular control (Sparto et al., 1997). This study examined how fatigue leads to changes in technique and coordination.

There are many methods of defining lifting technique and assessing changes in technique observed over time. This study defined technique using kinematic and relative phase variables. Kinematics of trunk, shoulder and elbow angle, and relative phase between lower arm and upper arm segments, and arm and trunk segments were assessed throughout the entire lift waveform. Principal component analysis has been previously used to reduce the variability within data sets into uncorrelated components, which are then analyzed. The benefit of applying PCA to a waveform data set is that it allows analysis of the entire waveform rather than reducing the waveform into parameter measures. PCA has been used to determine clinical group differences (Deluzio et al., 1997) and control for confounding factors (Wrigley et al., 2005, 2006). This study was able to assess differences between the lifting waveform profiles of individuals experiencing general fatigue due prolonged lifting, specific localized fatigue of the shoulder and of the back, and individuals in a healthy rested state.

The pre-fatigue waveforms were compared to the fatigued states and then the fatigued states were compared. Overall, there was inherent variability between participants as lift technique was self-selected and further variability was observed in the fatigued states. Variability is expected due to the multiple coordination patterns that may be employed to achieve the lifting task despite some general task constraints and this agrees with previous studies examining lifting motion strategies (Chen, 2000, Sparto et al., 1997 & Radwin, 2002). Interestingly, variability increased with fatigue. The PCA was able to isolate significant variability within the observed waveforms. Reduction of the waveforms into factor coefficients allowed for better determination of issues throughout the lift cycle.

4.1 Principal Component Analysis of Lifting Waveforms

4.1.1 General Fatigue

Generalized fatigue had the greatest influence on technique later in the lifting waveform, during load placement. Increased variability during load placement may be due to the increased effort to coordinate fatigued muscles in an action that requires greater control and accuracy than the initiation or transition of the load. While the target area for load placement remained constant, fatigue profiles were highly variable as motion patterns were altered by fatigue. The pre fatigue lifting profiles across testing sessions were not significantly variable; however, fatigued lifting profiles showed an increased variability. Overall, general fatigue due to prolonged lifting resulted in a decrease in overall trunk motion as the trunk remained more flexed, possibly leading to greater shear forces on the spine (Dolan et al., 1994). There was an increase in elbow flexion to compensate for decreased shoulder flexion, which agrees with previous studies focused on shoulder fatigue and injury during an upper extremity task (Côté et al., 2005). The generalized fatigue protocol resulted in changes to the trunk, shoulder and elbow motion but most notable was the decreased trunk motion as it remained more flexed and the increased elbow flexion to compensate for the decreased motion of the fatigued shoulders. The greatest variability in lifting profiles seen later in the lift cycle suggests that with fatigue load placement near the end of the lift is of greatest concern. Placement of the load requires accuracy and control; therefore, despite consistency of load placement location, this was the area of greatest variability.

4.1.2 Shoulder Specific Fatigue

The difference between pre-fatigued and shoulder specific fatigued lifts showed the greatest variability in lifting waveforms. In the late phase of the lift, load placement, there was an even greater increase in elbow flexion, with decreased shoulder flexion and a greater degree of trunk extension as well. It has been determined previously that when the shoulder musculature is fatigued or injured that efforts will be made to reduce shoulder motion by increasing motion in other joints to compensate and complete the task (Côté et al., 2002). Chen (2000), saw an increase in trunk motion and stiffening of the arms during lifting after localized arm fatigue.

4.1.3 Back Specific Fatigue

Localized back fatigue resulted in an overall decrease in trunk motion as the trunk remained more flexed throughout the lift which may have resulted in increased shear of the spine. The trunk was more flexed in late phase load placement, and the arms are extended with greater shoulder flexion and decreased elbow flexion. The reduction in trunk motion may be an attempt to decrease the possibility of pain and injury, and the motion is achieved through compensation by the upper extremities. This is different than a previous study of lifting fatigue that found musculature was able to compensate and maintain similar lifting patterns despite fatigue (van Dieën et al., 1996); however, this may be due to a less intensive and isolated fatigue protocol.

4.2 Relative Phase Analysis

4.2.1 Principal Component Analysis of Relative Phase

The principal component analysis of relative phase variance was extremely complex. The greatest degree of variance in relative phase measures between the lower and upper arm segments was detected during the transition phase of the lift; whereas, the greatest variance in relative phase measures of the arm and trunk were detected in the early and late phases of the lift, load initiation and placement. There was a large degree of variance in the angular displacement and motion of the arm segments, the coordination of the arms, during transition of the load. There was a large degree of variance in the coordination of the trunk and arms during load initiation and load placement. The differences between conditions were statistically significant in some areas; however, reconstructed curves were not easily interpreted due to the overall complexity of relative phase analysis that became even more complex when assessed further by principal component analysis. The principal component analysis and reconstructions were most useful in determining areas of great variance within the relative phase data and revealed important variance between the arm segments relative phase during load transition, while the variance between the arm and trunk was greatest during load initiation and load placement.

4.2.2 Frequency Analysis of Relative Phase

Relative phase was also assessed through frequency analysis, which examined the tendency of motion toward specific relative phase angle ranges. Each range of relative phase angles was compared between the fatigue conditions and significant differences were found between conditions within specific bins. The frequency analysis revealed general trends in relative phase angle distribution across conditions. Generally, the frequency of relative phase of the forearm and upper arm was most concentrated between -30 and 60 degrees; while the upper arm and trunk relative phase was most frequently within the range of -60 and 0 degrees. There were significant differences between the fatigue conditions despite a central tendency toward a more in phase motion pattern. The analysis of relative phase frequency showed a shift from the lower arm moving ahead of the upper arm in phase space to the upper arm leading the lower arm during the fatigued conditions; however, in all conditions the greatest frequency was near 0, indicating a trend toward a more in phase motion. The analysis of the trunk and upper arm relative phase showed an increase in negative relative phase suggesting that the trunk was moving ahead of the upper arm. Generally, relative phase frequency in back specific and shoulder specific fatigued individuals showed a shift toward a more negative relative phase between the arm segments. General fatigue also resulted in a greater distribution of frequency to negative relative phase of the trunk and arm than in the pre-fatigued state as the trunk was ahead of the arm in phase space and there was a more even distribution with a greater amount of time spent further out of phase. The back fatigue and shoulder fatigue showed similar shifts toward a more in phase pattern, with the trunk most often moving ahead of the arm in phase space. The frequency analysis results confirm coordination of motion changes significantly with fatigue.

4.3 Limitations

This study provided insight into lifting technique across the entire lift waveform through investigation of the kinematics and relative phase using principal component analysis. As previously stated throughout this document, lifting is a complex multisegment coordinated task and there are many variables that require further investigation. Additional data was collected for later analysis and further comparisons could be made with respect to traditional biomechanical evaluation of parameters and gender comparisons. This particular study examined inexperienced/novice lifters, young healthy adults, both male and female. Experienced lifters (professional lifters/workers) may fatigue differently and may have a different method of compensating for fatigue (Plamondon et al., 2010). Although there was no direct lifting technique instruction given to the participants, the lift was somewhat constrained with respect to object weight and shape, lift height and lift direction (symmetrical). In a workplace situation, these variables may change and necessitate a modified lifting technique. Another approach was used to determine individual lifting capacity, rather than using a standard load. This approach was not entirely translatable to manual materials handling because in industry most loads will be set regardless of the worker capacity. The analysis only observed the first few lifts and the final few lifts, therefore changes occurring during the fatiguing process were not investigated; however, lifts were recorded every 5 minutes for future analysis. The data collection window was one hour and fifteen minutes where a longer collection period closer to an actual work shift would be more beneficial in understanding the effects of generalized fatigue on technique throughout a work shift

4.4 Future Research

Future research could investigate gender, age and experience differences, and the effects of previous injury on development of fatigue and subsequent technique changes. The task itself may be modified, using a standard load regardless of determined lifting capacity of the individual, using a different lift orientation examining asymmetrical lifting rather than symmetrical, adjusting lifting rate and duration of lifting protocol, investigating the effects of lift parameters from floor to waist, floor to shoulder, and waist to shoulder the main focus of this study was fatigue differences between a generally fatigued lift pattern and a specifically fatigued lifting pattern. There are many variables which may be investigated: kinematics, kinetics and neural control mechanisms. The data from this study was used to first investigate the kinematic waveforms of individual joints and then the interjoint coordination was assessed using relative phase analysis. Additional data was collected and analyzed with respect to kinetic joint loading with respect to a known load and body positioning throughout the lift, psychophysical data was recorded as a rate of perceived exertion, and neural control through the use of electromyographic analyses, in order to provide a clearer picture of the technique changes observed with fatigue.

Ideally, once an understanding of technique changes resulting from fatigue is achieved from laboratory investigation, further research may be conducted in a workplace setting where experienced and possibly injured individuals may work for prolonged periods in manual materials handling. Laboratory work allows for more controlled observations while field work will allow for a more realistic view of workplace constraints on the individual worker.

4.5 Discussion of Significance

The purpose of this investigation was to increase the understanding of the effects of general and specific fatigue on lifting technique and coordination. Previous literature has revealed the need for examinations into prolonged fatigued lifting. This study revealed significant differences between the non-fatigued and fatigued lifting profiles with further differences seen between the different fatigued states.

Manual materials handling has been associated with severe musculoskeletal injury and research has been conducted to assess and develop proper lifting technique/parameter recommendations. Many assessment tools track extreme awkward postures, duration and frequency of task, relative load initiation and placement measures load dimensions and contact points, anticipated trajectory, load weight and lift symmetry. Assessment tools such as the NIOSH lifting tables (Waters), the Psychophysical tables (Snook & Ciriello) and Mital tables have been used as guidelines for work design but have been criticized for being too restrictive and no longer current with the literature. The major issue with these types of assessment is that load initiation and placement are assessed but load trajectory may not be determined. Although frequency and duration of task are usually considered, the effects of fatigue and altered lifting technique is missed by these assessments. The specificity of these assessments is quite high for correctly identifying low risk tasks; however, the sensitivity for moderate to high risk tasks was not as good. As research has provided further insight into risk factors and injury mechanisms associated with manual materials handling these assessment tools have undergone revisions. These revisions have improved assessment accuracy and correct identification of task risk; however, many of these tools still oversimplify the underlying biomechanics of a task. This research highlights areas of concern with respect to kinematics and coordination along the entire lifting waveform, suggesting that initiation and load placement is of kinematic concern, and coordination is most variable during load transition. The mechanisms of accomplishing a complete lifting task are complex and our assessment tools are only able to assess risk to a certain level. Coordination and technique across the entire lifting task is affected by fatigue. A more comprehensive assessment tool that considers fatigue and injury effects on coordination of a lifting task would improve the quality of risk assessment tools.

Previous observations have determined that there are some similarities in the motion patterns of fatigued and injured individuals (Côté et al., 2005). While there are still some differences, one may infer that similar changes in lifting coordination may occur in injured individuals as in fatigued individuals. Changes in lifting coordination could lead to further damage to the compensating joints and associated structures. During assessment of a task, the complete task with load trajectory should be considered with consideration of the effects of fatigue or previous injury. Injured individuals may elect a compensatory motion pattern initially or with fatigue may be required to alter their lifting pattern. Similarly, fatigued individuals may self modify a lifting task in an attempt to avoid injury.

5.0 Conclusion

This study investigated the effects of fatigue on lifting motion patterns. General fatigue induced through prolonged repetitive lifting significantly alters lifting patterns, both kinematic waveform variables and coordination measures (relative phase), relative to the rested state. These compensations may lead to an increased risk for injury as the ability to react to perturbations in the task is reduced by fatigue. Additionally, the overall coordination of the lift changed with fatigue as the body compensated to limit the burden on fatigued parts of the body. These changes in coordination were significant but further research will need to be done to investigate the possible risks of these changes in coordination. Finally, the effects of general fatigue and localized specific shoulder or back fatigue have significant but different effects on the lifting motion pattern. Through thorough investigation of the entire lift waveform there were significant differences between the different fatigue conditions at different stages of the lift. These findings suggest that the location of fatigue has an impact on certain points of the lift trajectory. As previously suggested, fatigue and injury motion patterns have some similarities and further investigation could be done to assess the effects of injury; however, for the purposes of this investigation the alterations seen in fatigued lifters could be cautiously extended to injured workers. If injured individuals continue to lift regularly, the altered motion could lead to further injury in the compensating structures. As seen in the waveform analysis, individuals significantly alter the lifting motion pattern when fatigued, and the alterations are significantly different depending on the specifically fatigued structures. Some of these differences were seen in the load transition phase, suggesting that traditional investigations of postures at load initiation and placement may not accurately detect issues in lifting.

Summary of Significance

- the greatest variability in lifting kinematics was seen during load placement
- general fatigue resulted in: decreased trunk motion with the trunk remaining more flexed, increased elbow flexion and decreased shoulder flexion
- shoulder specific fatigue resulted in: increased trunk extension, increased elbow flexion and decreased shoulder flexion
- back specific fatigue resulted in: decreased trunk extension with the trunk remaining more flexed, decreased elbow flexion and increased shoulder flexion
- arm and trunk relative phase angles were most variable during early load transition and late load placement
- lower arm and upper arm relative phase angles were most variable during load transition
- the frequency analysis of relative phase revealed a general trend toward in phase motion with proximal segments leading distal segments more frequently
- pre-fatigued lifting patterns were significantly different than general fatigue lifting motion
- general fatigue and localized fatigue of the shoulder and back resulted in significant variance in lifting motion

In conclusion, the pre-fatigued kinematic lifting waveforms had less variance than the fatigued lifting profiles. There were significant changes in the relative phase lifting waveforms, indicating a change in coordination as a result of fatigue. The shoulder joint motion was restricted when generally fatigued and specifically shoulder fatigued while the trunk compensated. When the trunk musculature was fatigued, the upper arms compensated for decreased trunk motion in order to complete the task. Finally, there were greater compensations in shoulder joint motion than trunk motion as a result of general fatigue, suggesting that when generally fatigued the shoulder joint may be limiting.

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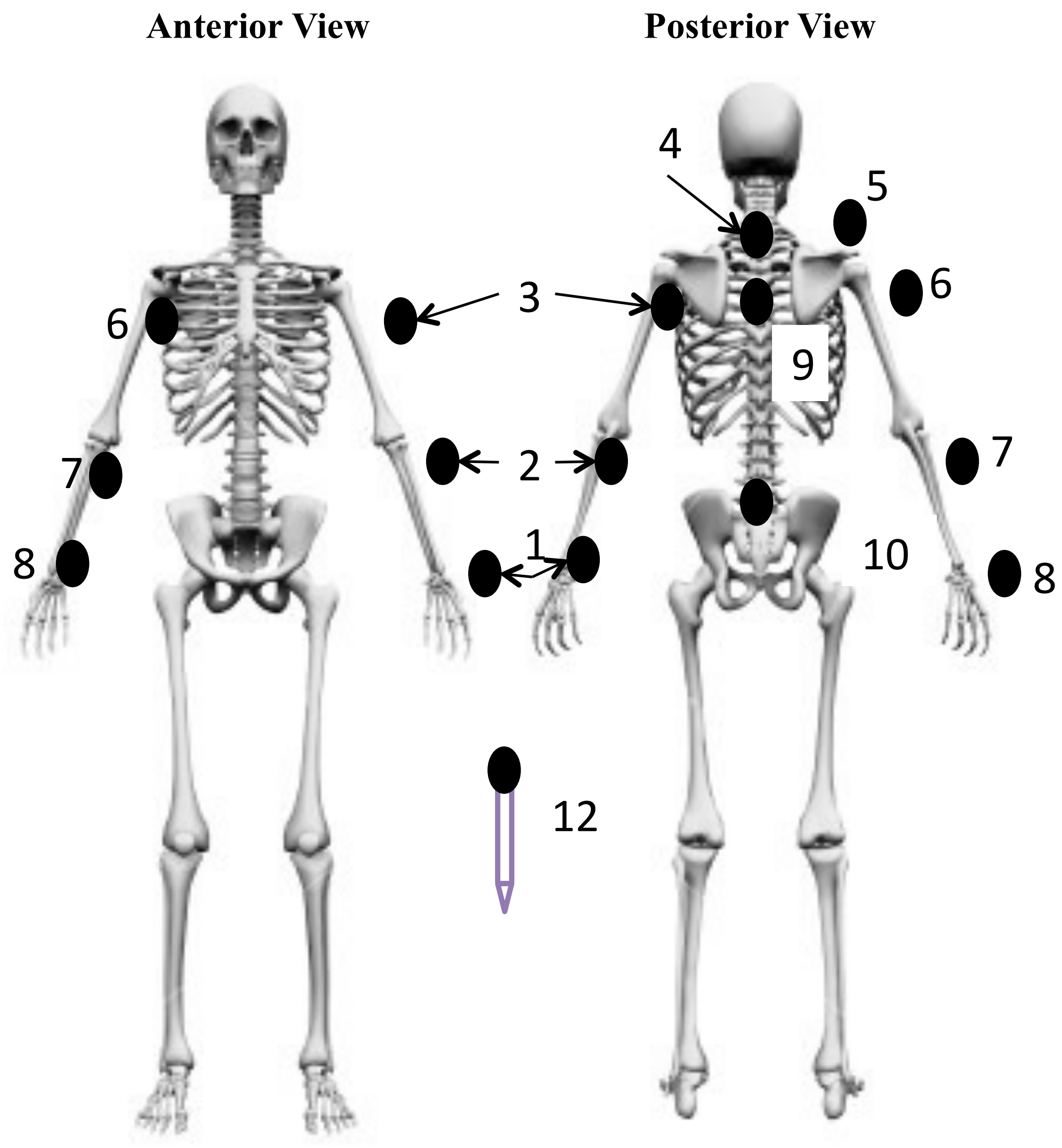
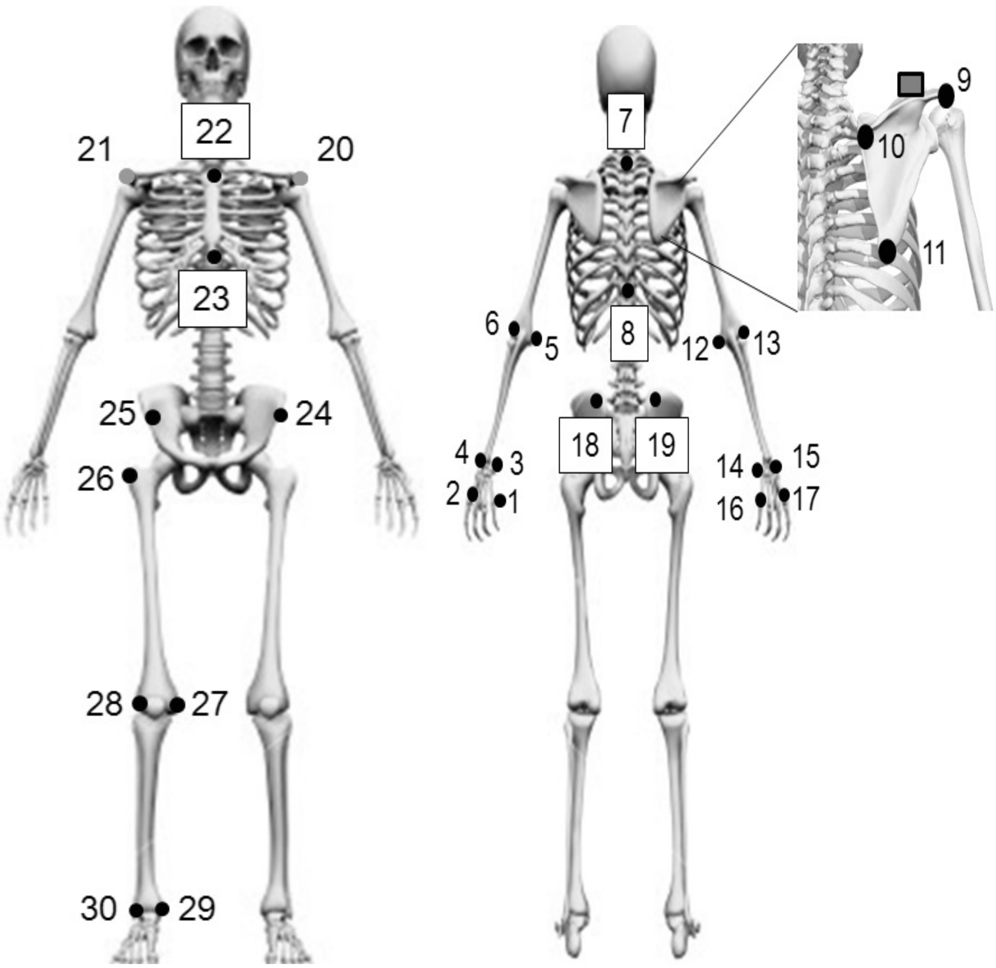
APPENDIX A

Electromagnetic Sensor Placement



APPENDIX B

Digitization Points



APPENDIX C

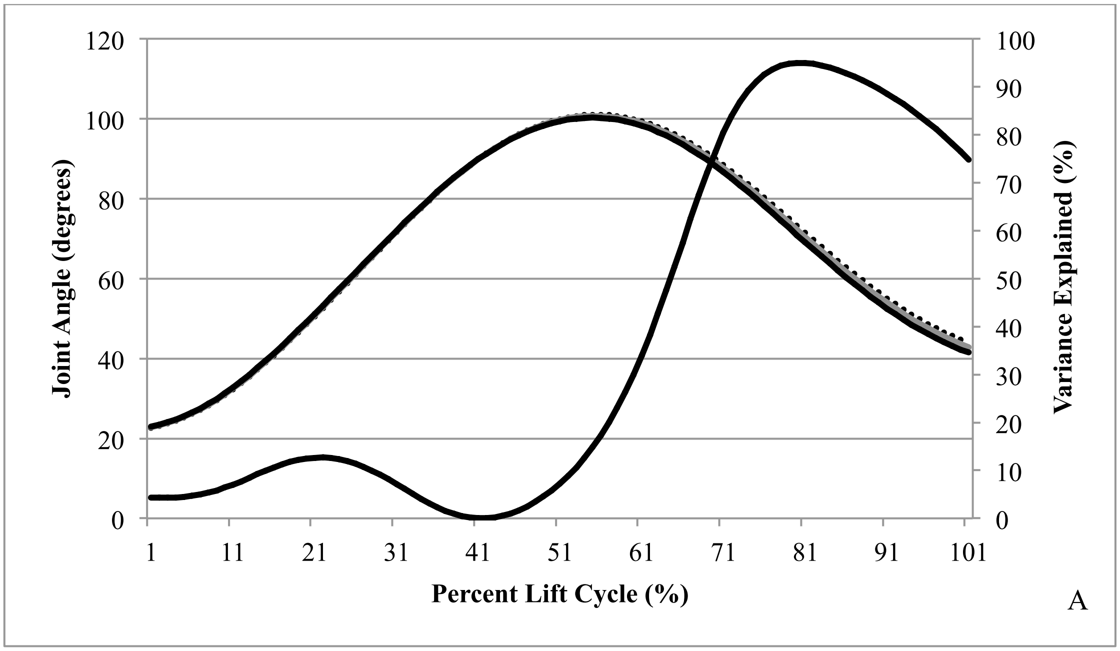
Participant Anthropometrics

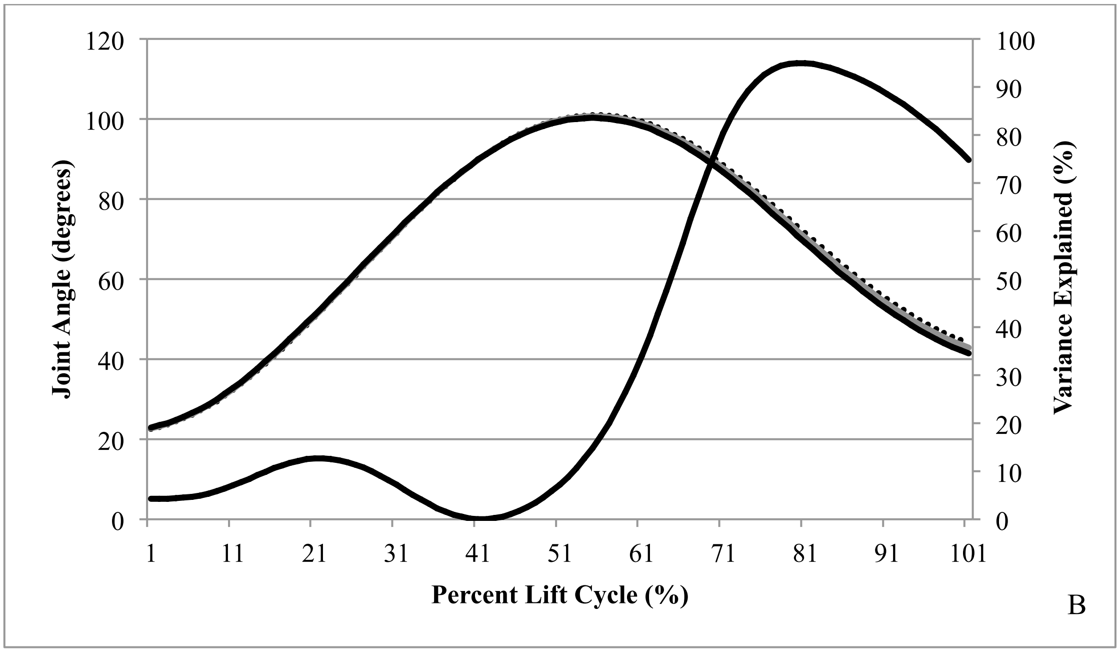
Participant	**Age**	**Height**	**Weight**	**Box(kg)**	**Sex**
1	24	169	57.3	8.4	female
2	22	171	74.5	11	female
3	25	182	76.1	15.2	male
4	28	174	78.6	15.6	male
5	32	178	80	18.8	male
6	26	180	75.5	16	male
7	23	166	63	10.3	female
8	22	163	53	8	female
9	23	168	72	7.8	female
10	28	188	99.8	17.8	male
11	22	175	71.4	15.5	male
12	23	178.8	87.7	18.2	male
13	25	184	72.2	16.3	male
14	23	165	60.2	10.9	female
15	25	176	81.4	11	male
16	25	166.3	59.5	8.3	female
17	23	160	63.4	5.7	female
18	22	165	77.5	8.8	female
19	22	162.5	71.1	13.5	male
20	31	160.9	73.6	10.5	female
21	22	179.5	80.7	14.4	male
22	24	163	66.4	10.9	female

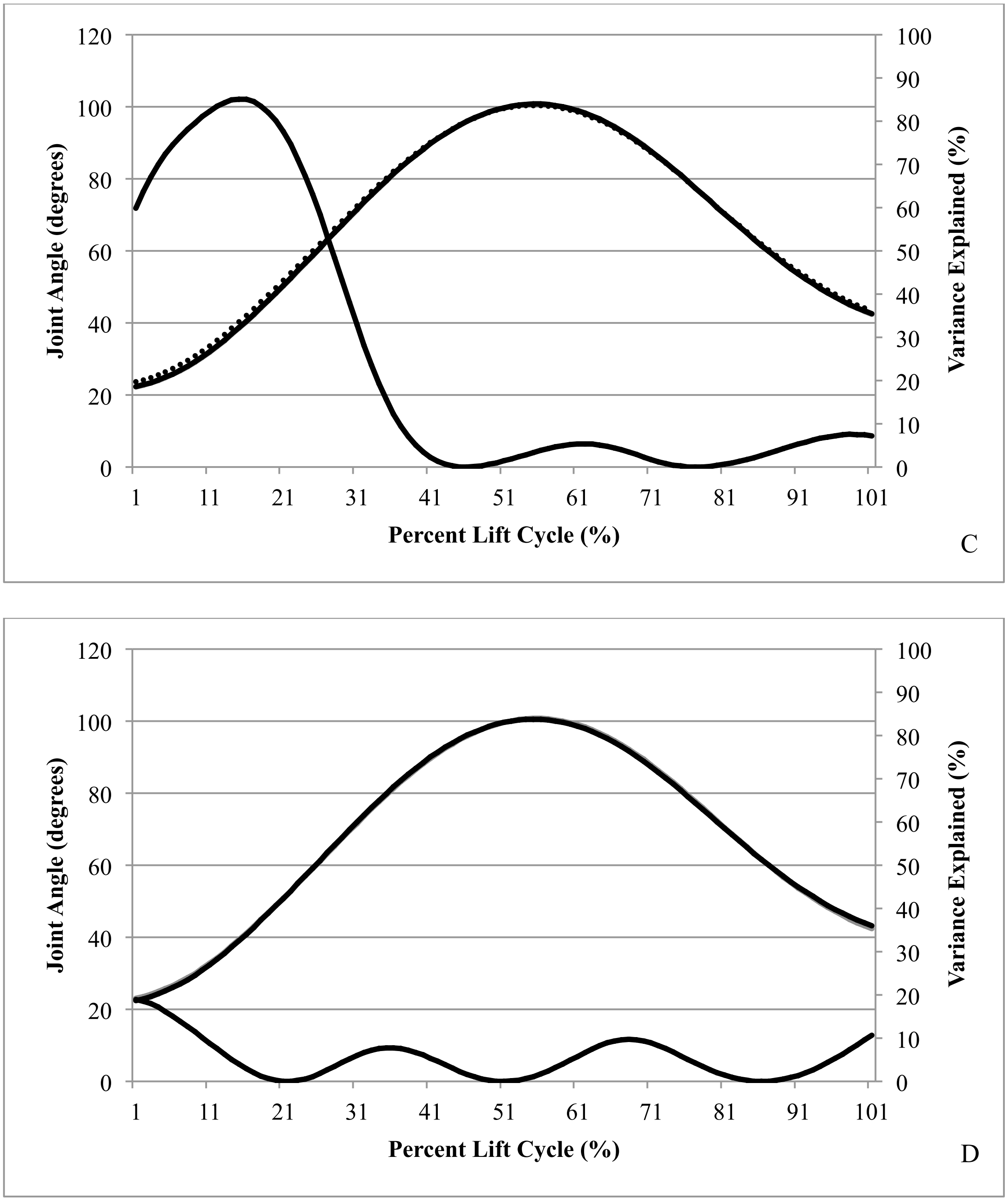
23	22	179	84.1	22	male
24	24	174	63.1	6	female
25	21	176	87.3	15.1	male
26	25	156	55.9	7.3	female
27	24	168	71.6	7.5	female
28	22	198.5	86.4	13.7	male
29	20	176.5	89.2	15.1	male
30	22	158.8	53.2	7.9	female
31	21	158.5	60.1	16.9	male
AVERAGE	23.9	171.6	72.4	12.4	15 FEMALES 16 MALES
minimum	20	156	53	5.7	
maximum	32	198.5	99.8	22	
±	2.76	9.76	11.73	4.29	

APPENDIX D

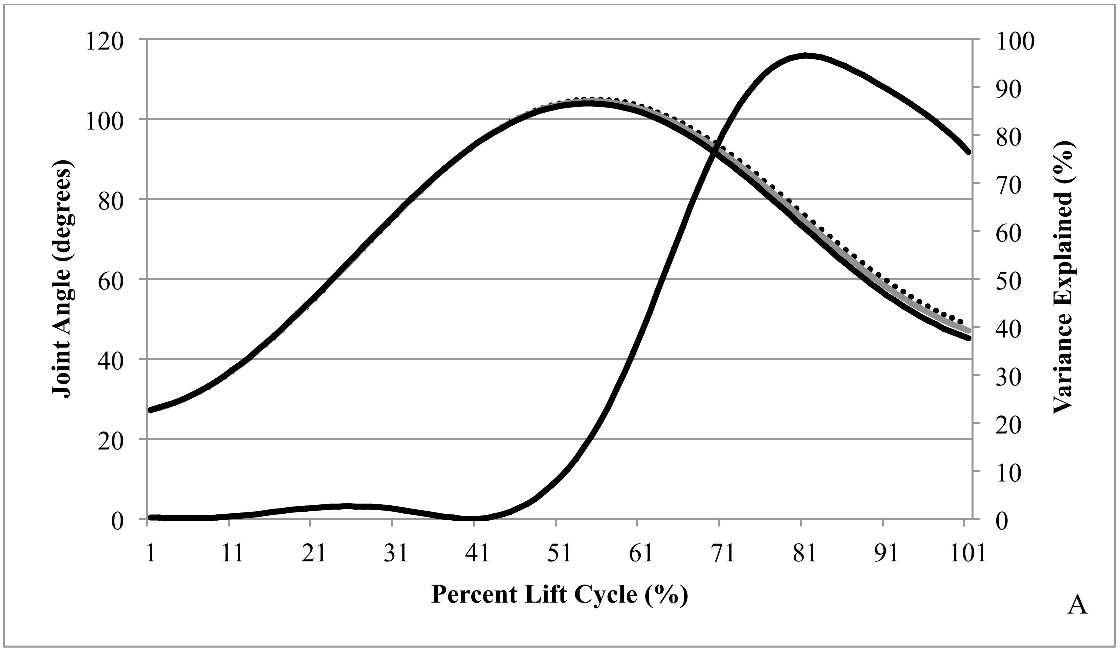
Pre-fatigue waveforms across sessions: Kinematic and Relative Phase Waveforms



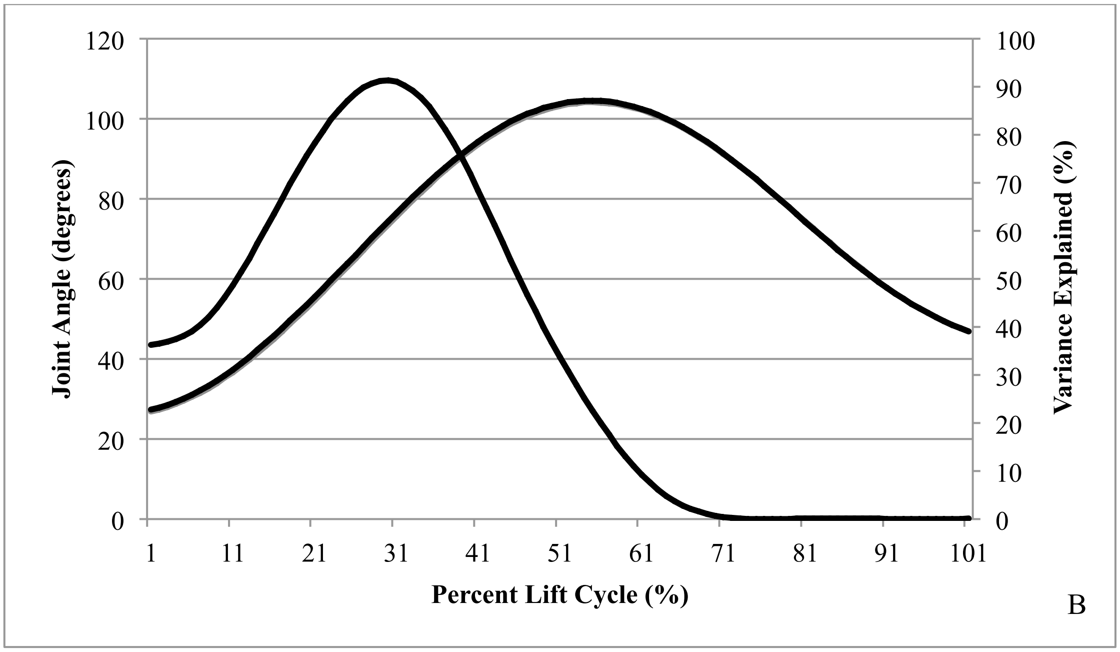




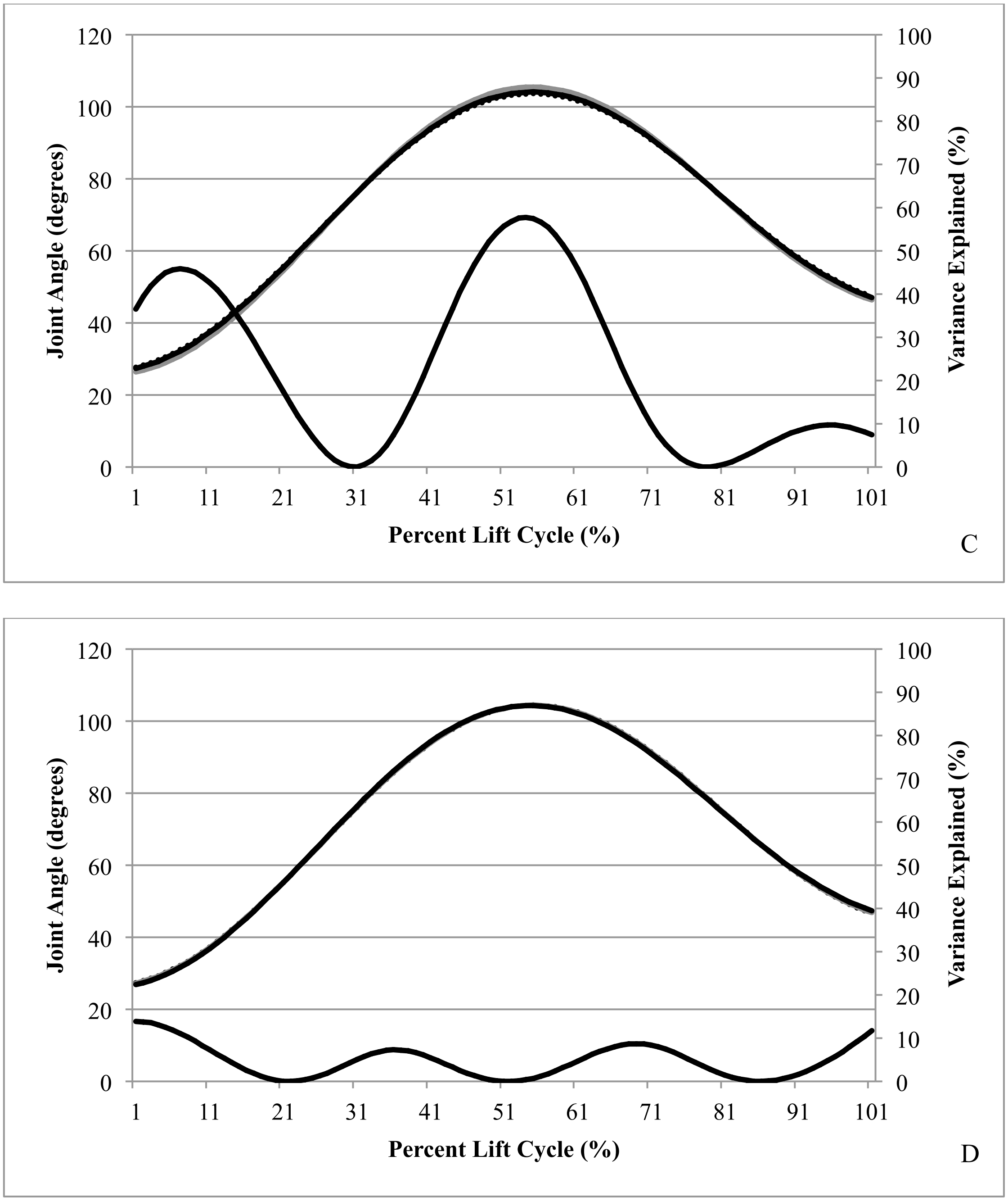
Left elbow flexion/extension angle pre-fatigue conditions compared between general (—); back (·····); shoulder (- - -) testing sessions respectively. Principal component loading curve (—). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3. D. Principal Component 4.



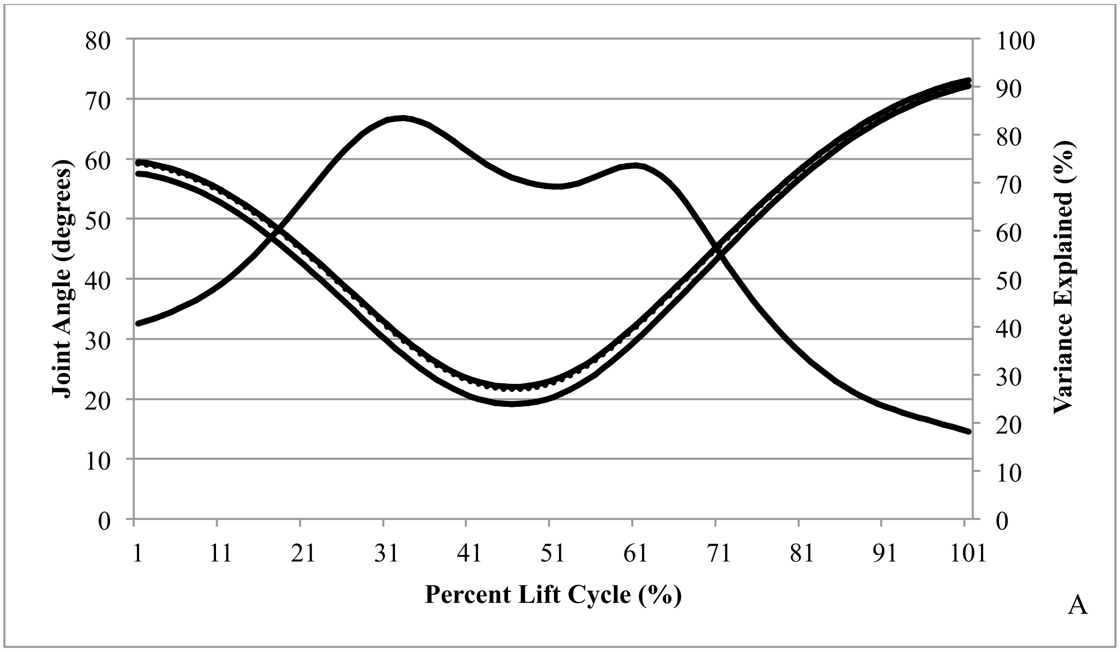
Joint Angle (degrees)
120
100
80
60
40
20
0
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
A



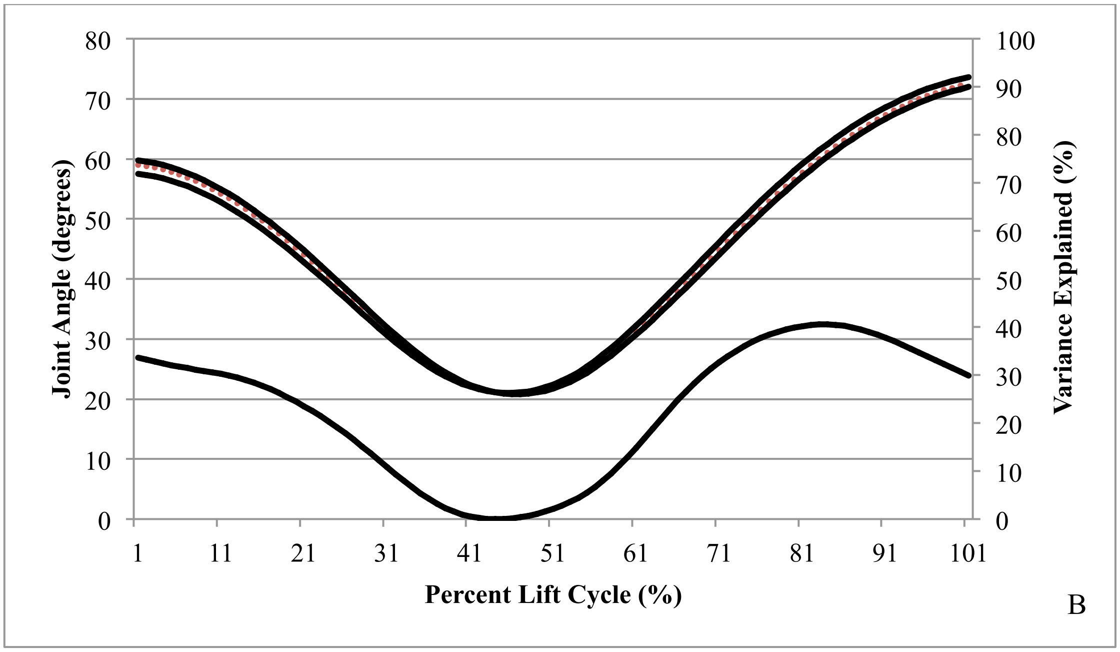
Joint Angle (degrees)
120
100
80
60
40
20
0
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
B



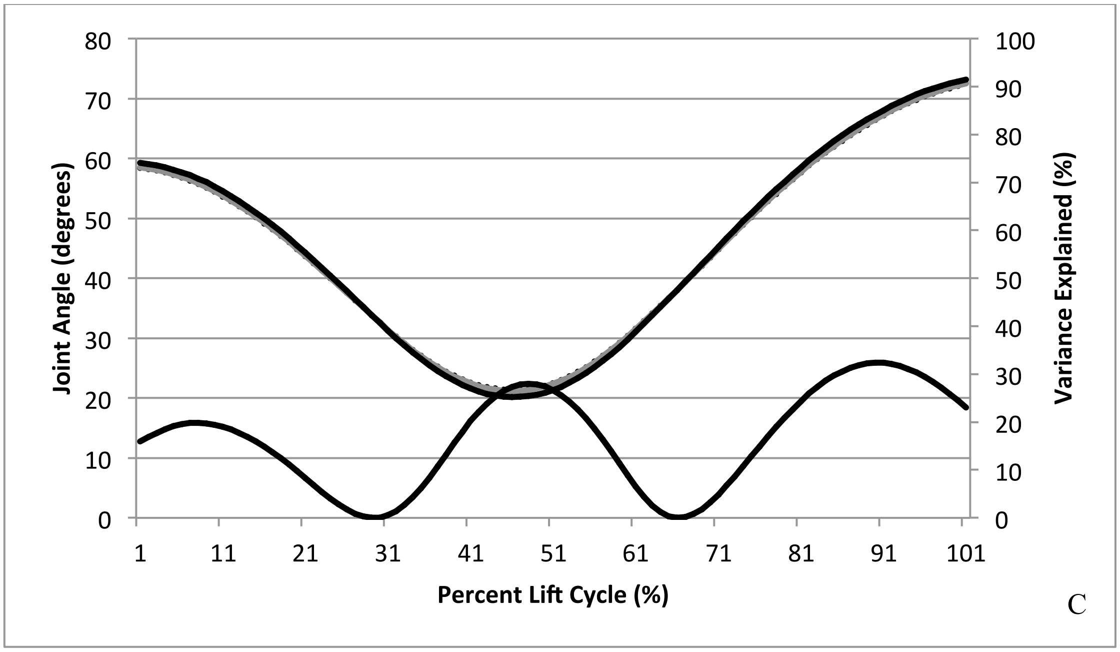
Right elbow flexion/extension angle pre-fatigue conditions compared between general (——); back (·····); shoulder (- - -) testing sessions respectively. Principal component loading curve (——). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3. D. Principal Component 4.



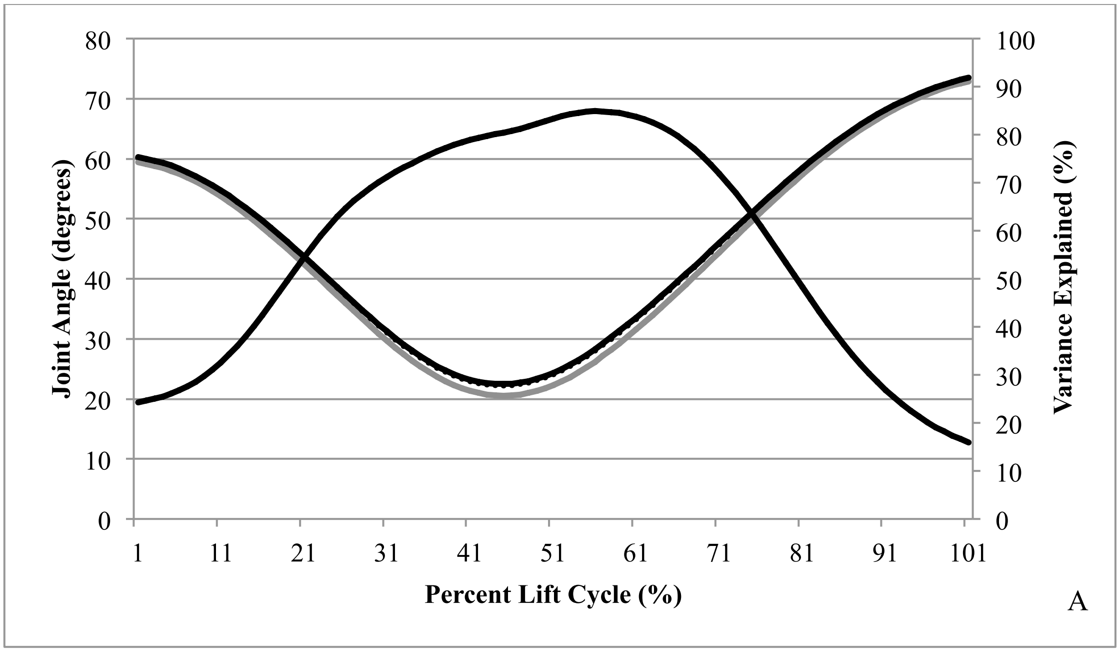
Joint Angle (degrees)
0
10
20
30
40
50
60
70
80
Variance Explained (%)
0
10
20
30
40
50
60
70
80
90
100
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
A

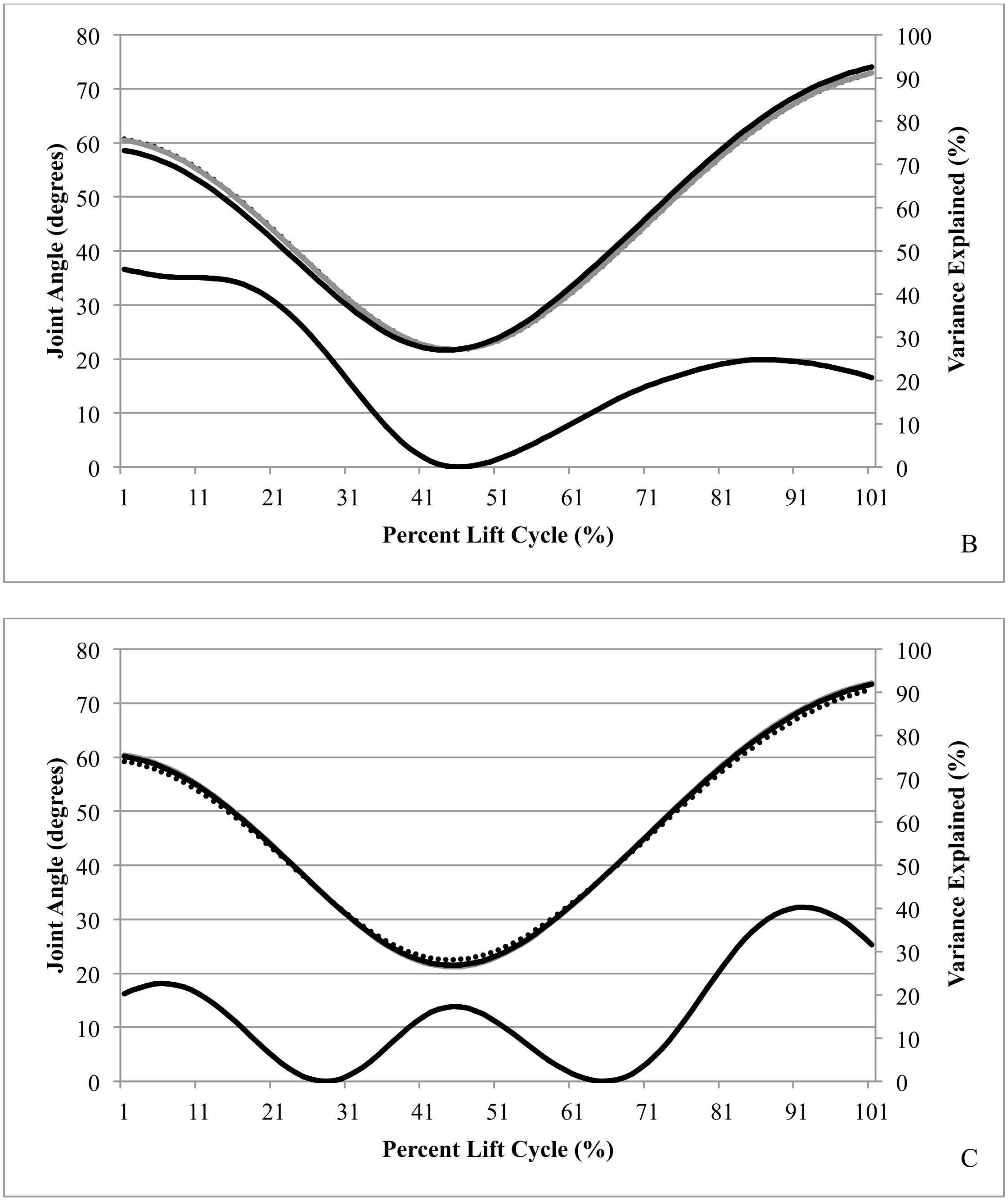


Joint Angle (degrees)
0
10
20
30
40
50
60
70
80
Variance Explained (%)
0
10
20
30
40
50
60
70
80
90
100
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
B

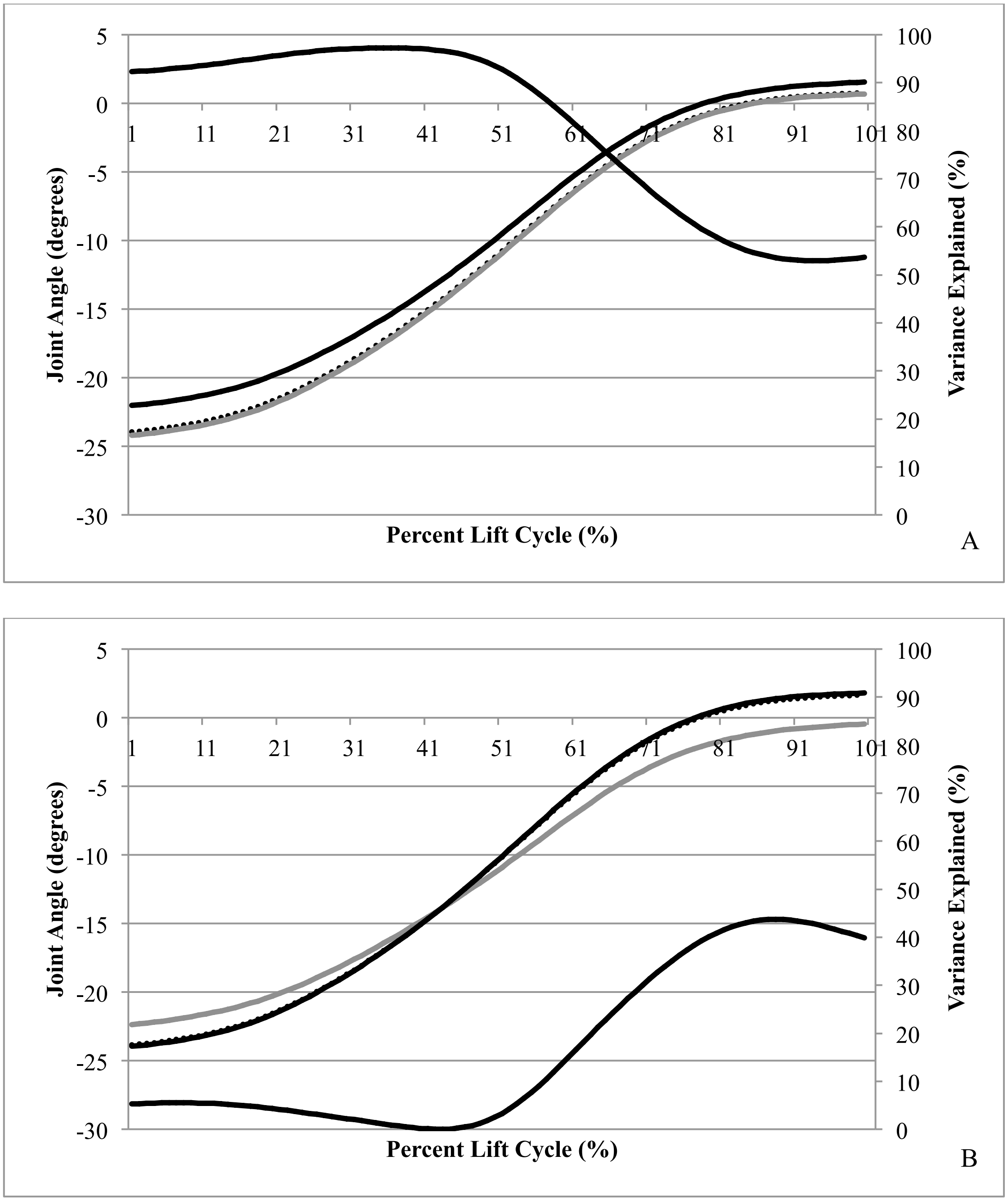


Left shoulder flexion/extension angle pre-fatigue conditions compared between general (—); back (.....); shoulder (- - -) testing sessions respectively. Principal component loading curve (—). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3.

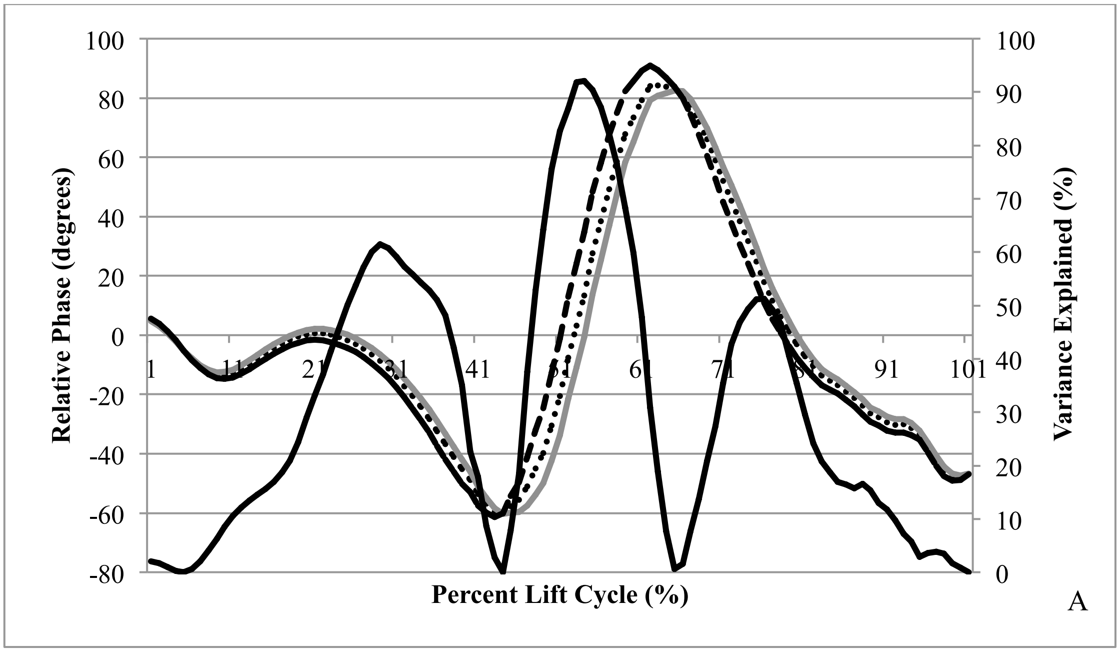




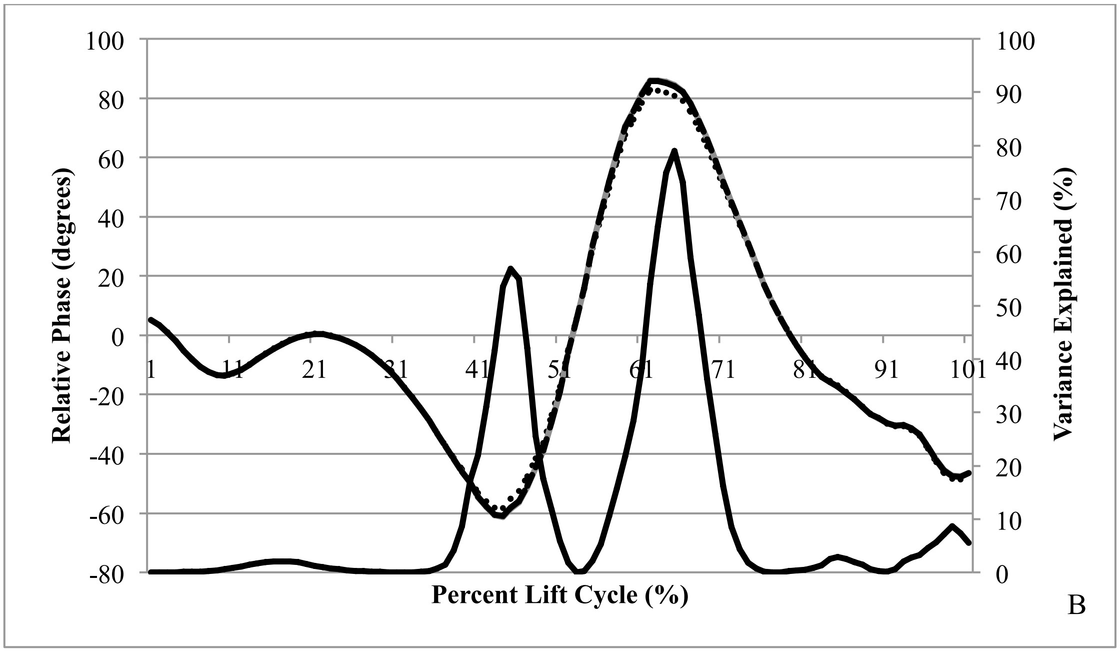
Right shoulder flexion/extension angle pre-fatigue conditions compared between general (—); back (·····); shoulder (- - -) testing sessions respectively. Principal component loading curve (—). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3.



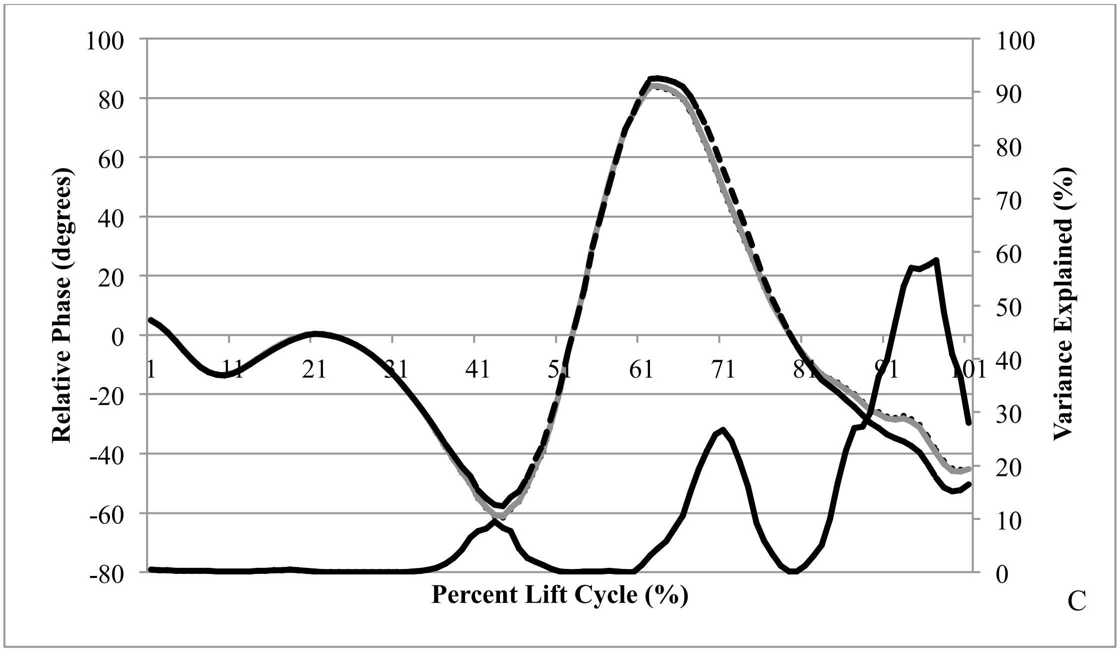
Trunk flexion/extension angle pre-fatigue conditions compared between general (—); back (·····); shoulder (- - -) testing sessions respectively. Principal component loading curve (—). A. Principal Component 1. B. Principal Component 2.

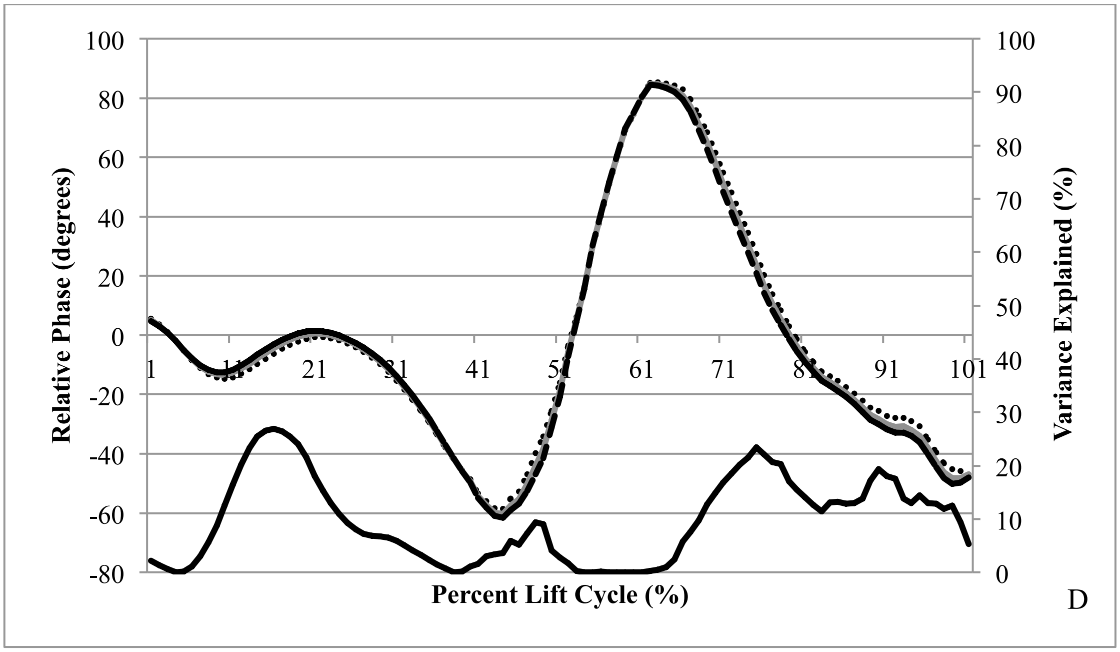


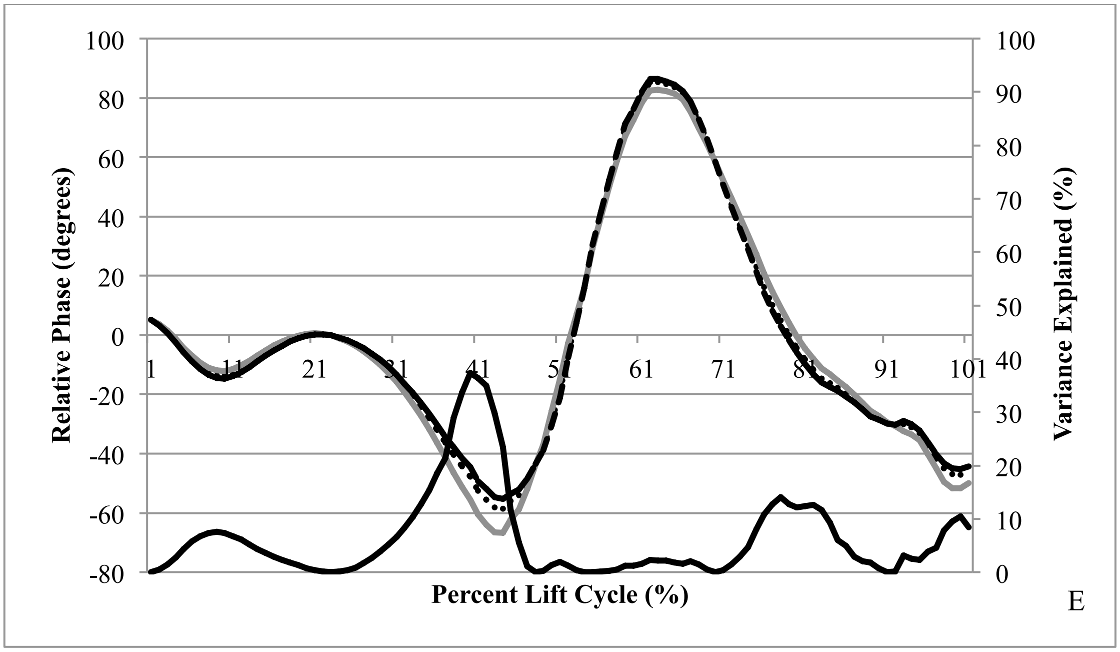
Relative Phase (degrees)
100
80
60
40
20
0
-20
-40
-60
-80
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
A



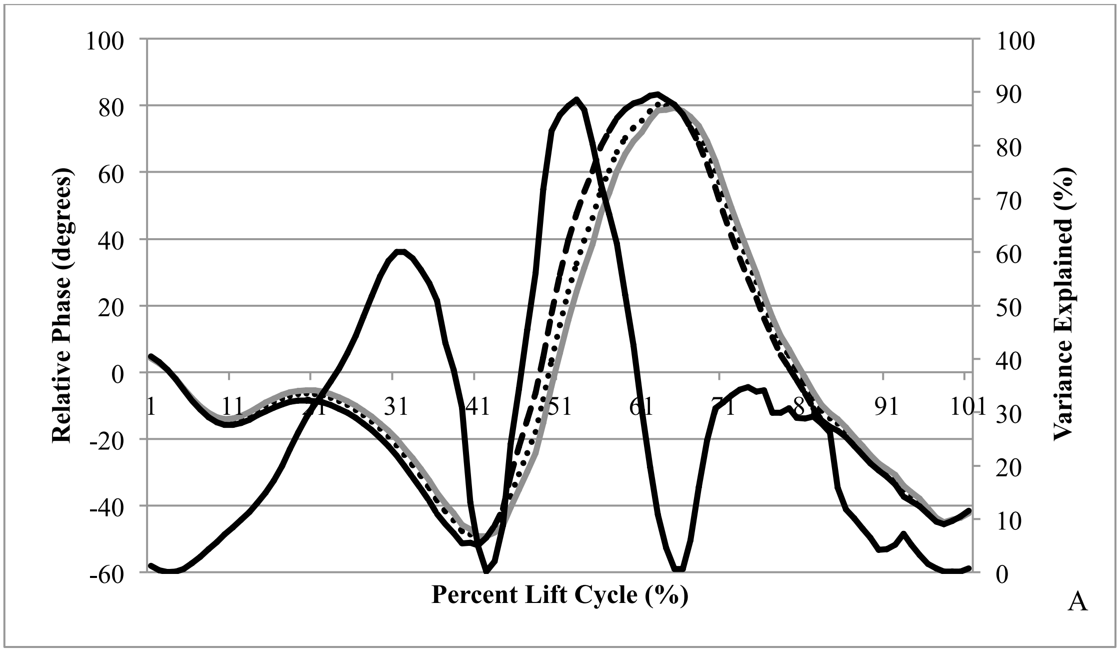
Relative Phase (degrees)
100
80
60
40
20
0
-20
-40
-60
-80
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
B

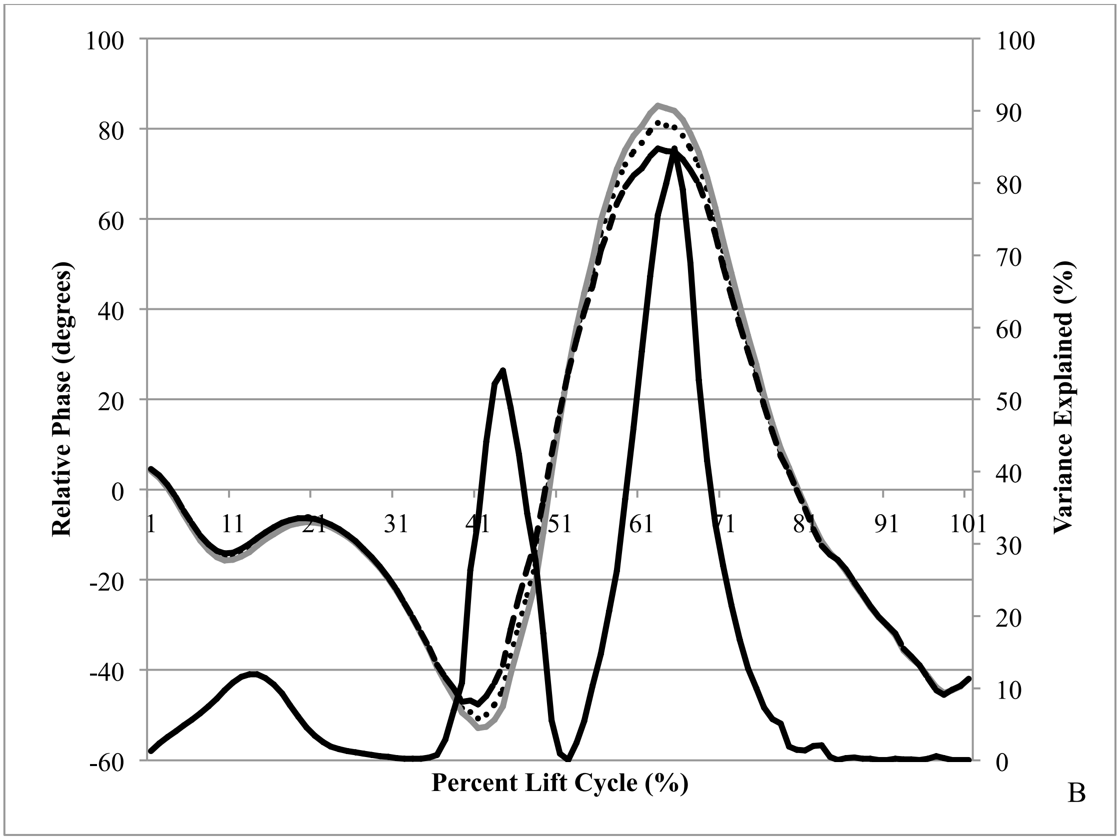

Relative Phase (degrees)
100
80
60
40
20
0
-20
-40
-60
-80
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
C

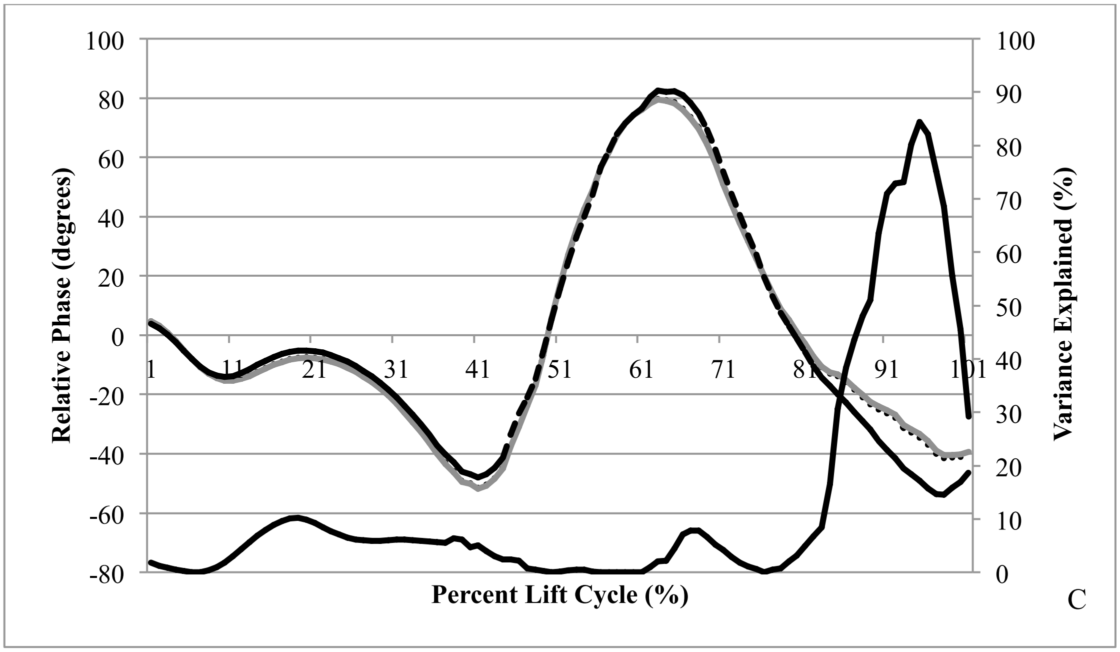

Relative Phase (degrees)
100
80
60
40
20
0
-20
-40
-60
-80
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
D

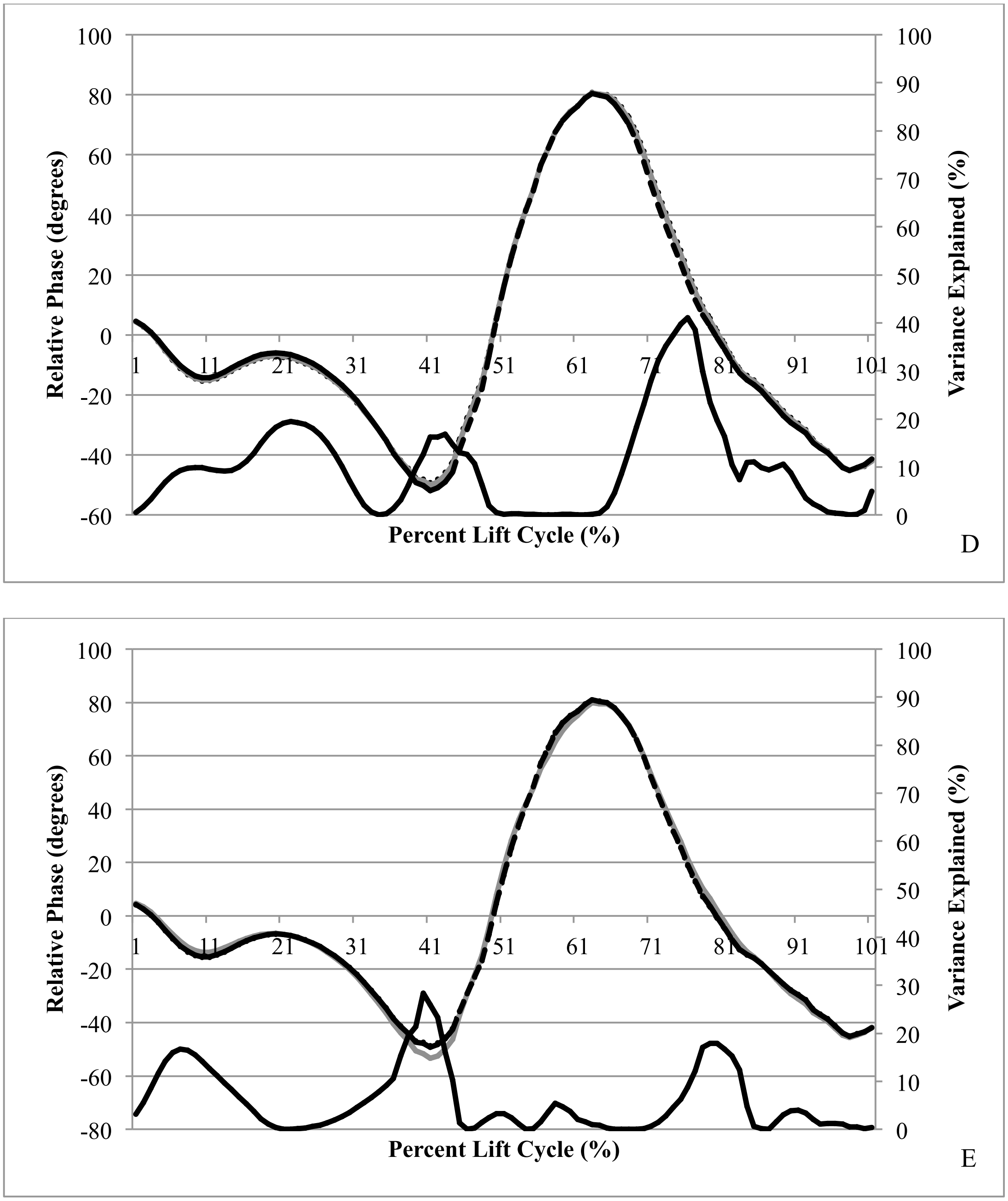


Left forearm and left arm relative phase pre-fatigue conditions compared between general (—); back (·····); shoulder (- - -) testing sessions respectively. Principal component loading curve (—). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3. D. Principal Component 4. E. Principal Component 5.

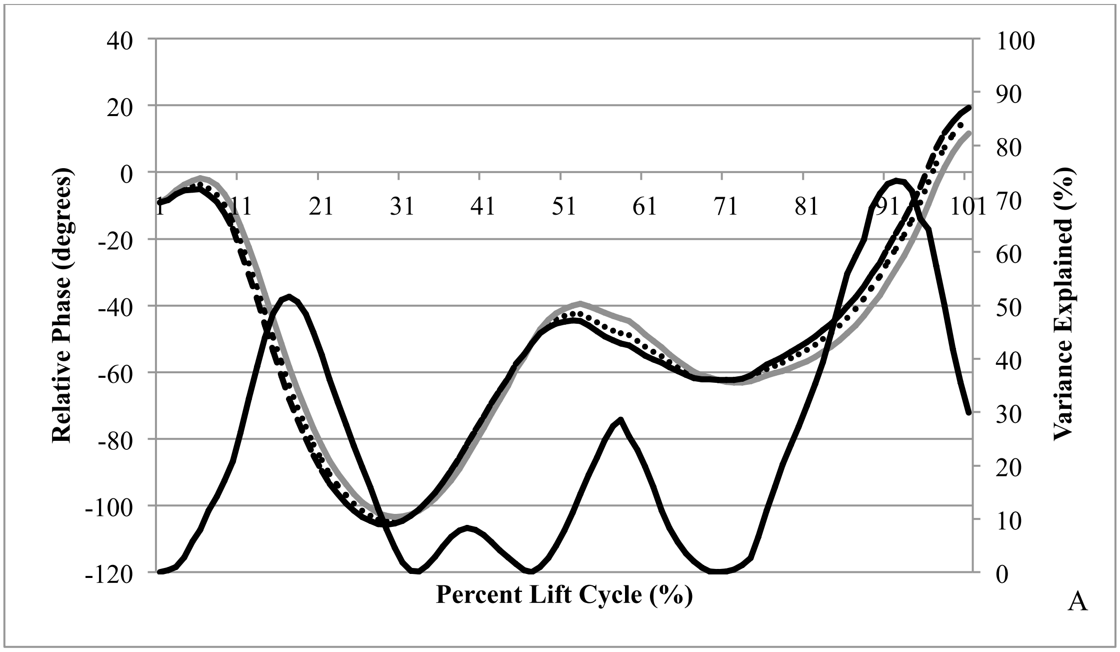


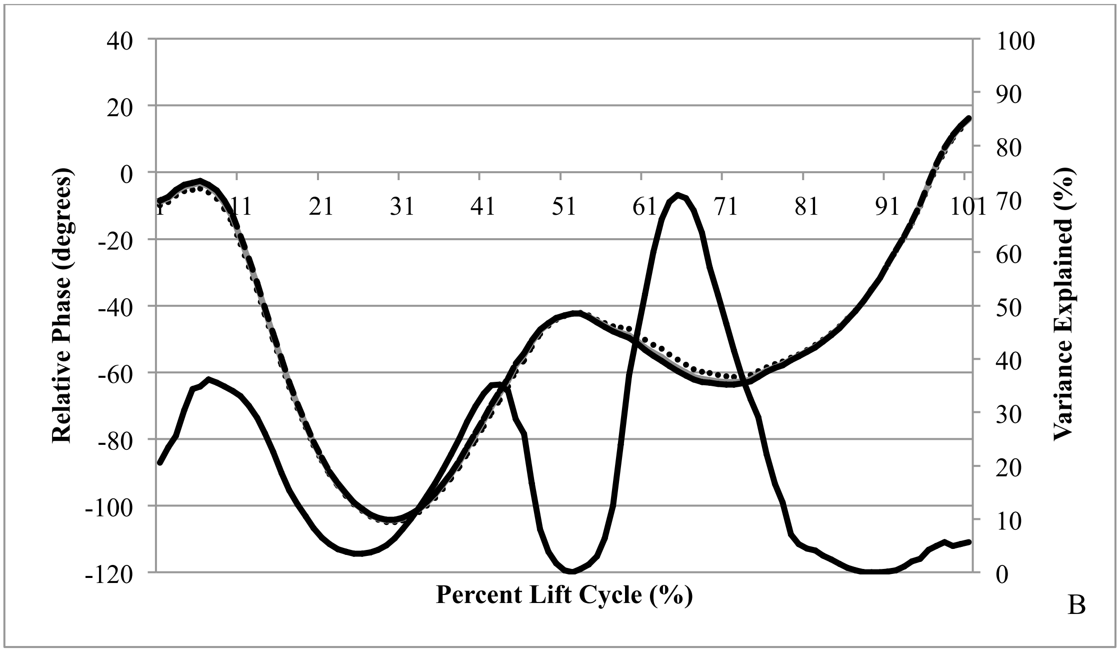

Relative Phase (degrees)
100
80
60
40
20
0
-20
-40
-60
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
B

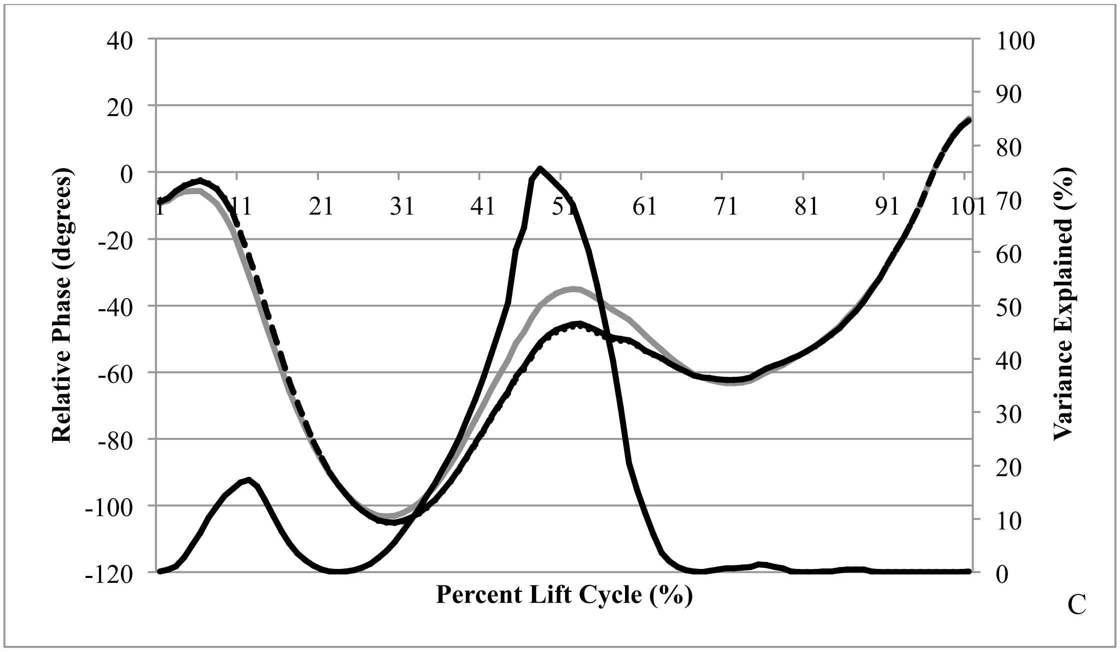

Relative Phase (degrees)
100
80
60
40
20
0
-20
-40
-60
-80
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
C

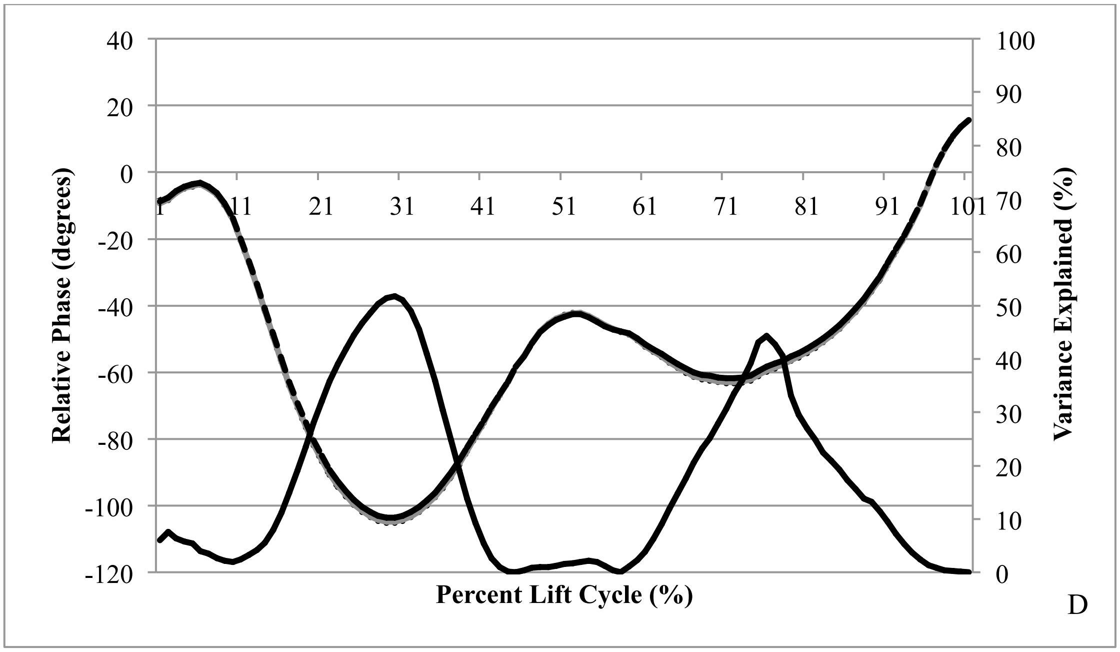


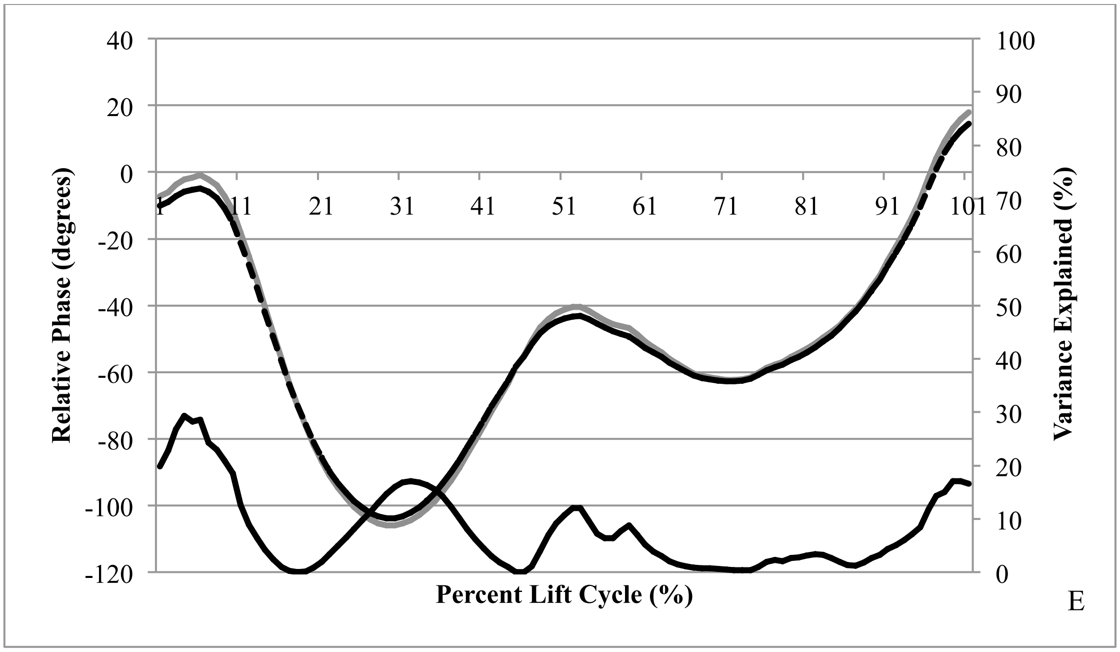
Right forearm and right arm relative phase pre-fatigue conditions compared between general (—); back (·····); shoulder (- - -) testing sessions respectively. Principal component loading curve (—). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3. D. Principal Component 4. E. Principal Component 5.

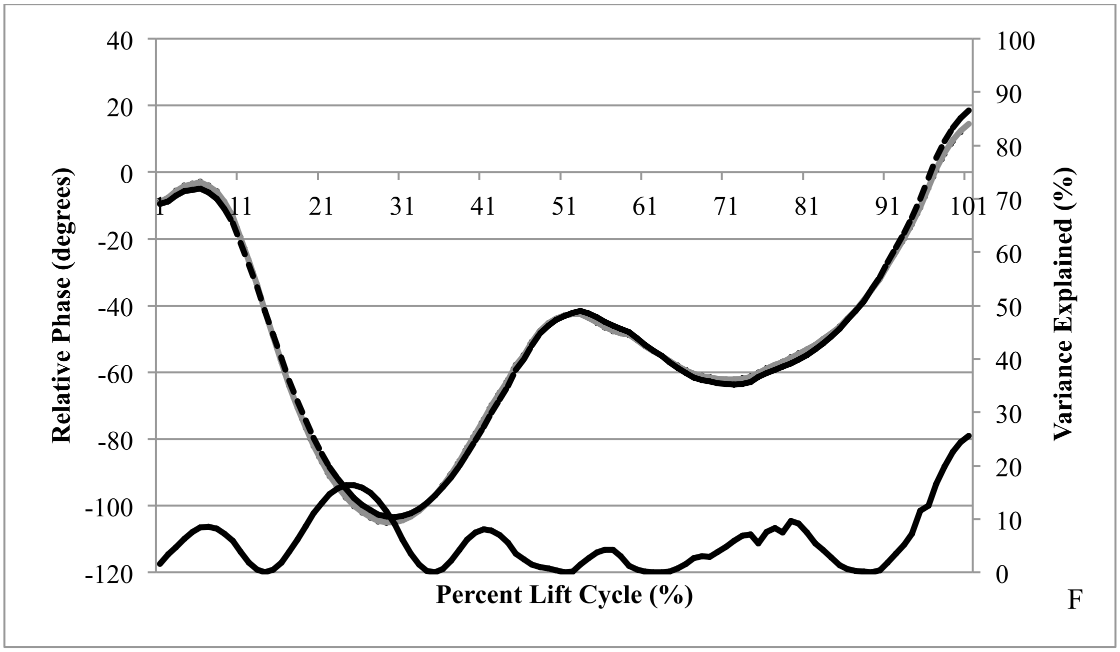

Relative Phase (degrees)
40
20
0
-20
-40
-60
-80
-100
-120
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
A

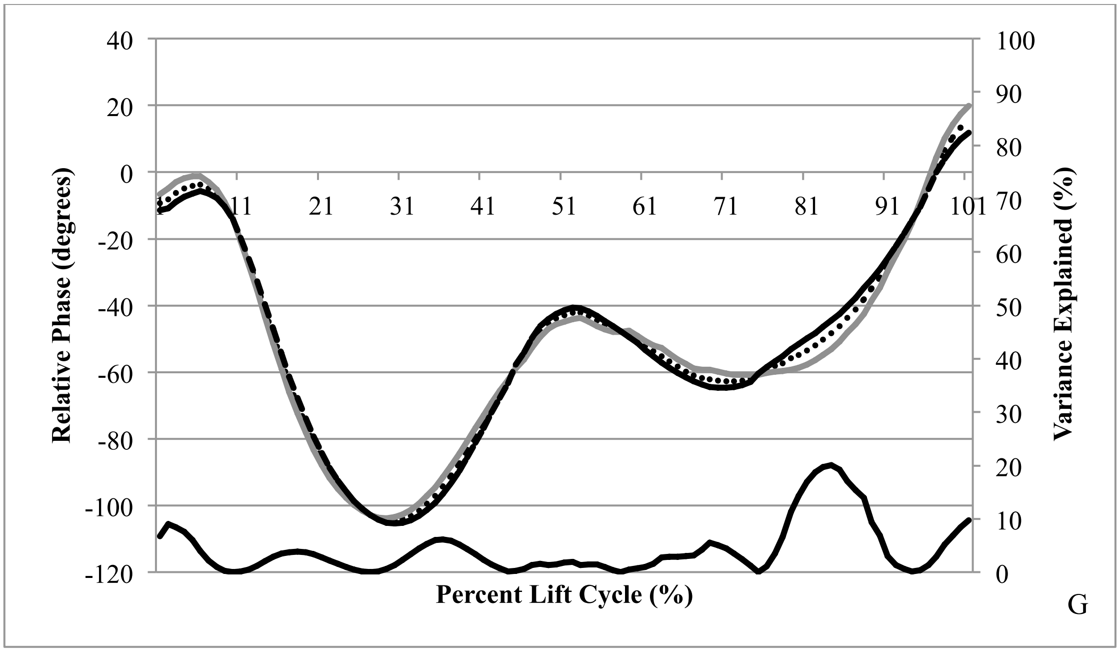

Relative Phase (degrees)
40
20
0
-20
-40
-60
-80
-100
-120
Variance Explained (%)
100
90
80
70
60
50
40
30
20
10
0
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
B


40
20
0
-20
-40
-60
-80
-100
-120
Relative Phase (degrees)
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
100
90
80
70
60
50
40
30
20
10
0
Variance Explained (%)
C

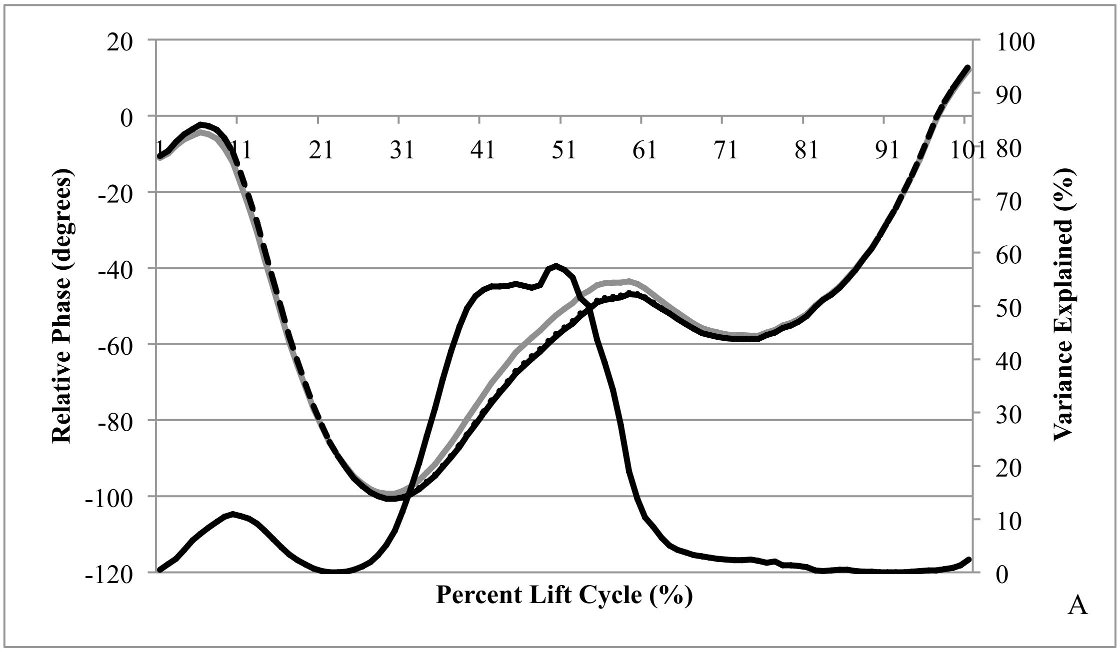

40
20
0
-20
-40
-60
-80
-100
-120
Relative Phase (degrees)
1
11
21
31
41
51
61
71
81
91
101
Percent Lift Cycle (%)
100
90
80
70
60
50
40
30
20
10
0
Variance Explained (%)
D

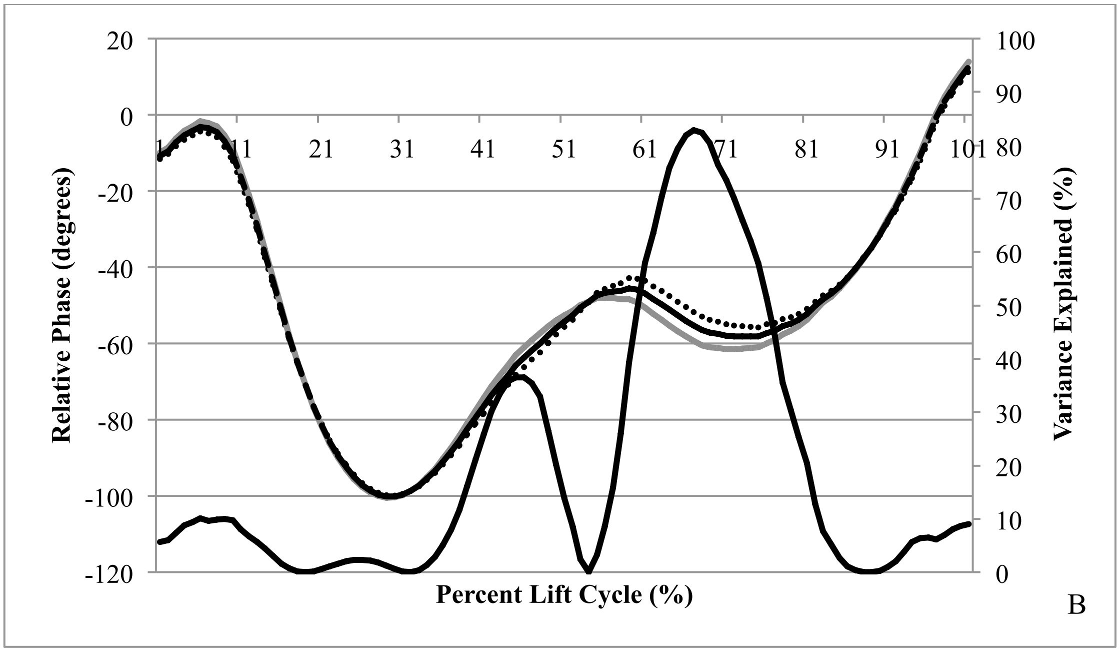

40
20
0
-20
-40
-60
-80
-100
-120
Relative Phase (degrees)
1
11
21
31
41
51
61
71
81
91
101
100
90
80
70
60
50
40
30
20
10
0
Variance Explained (%)
Percent Lift Cycle (%)
E

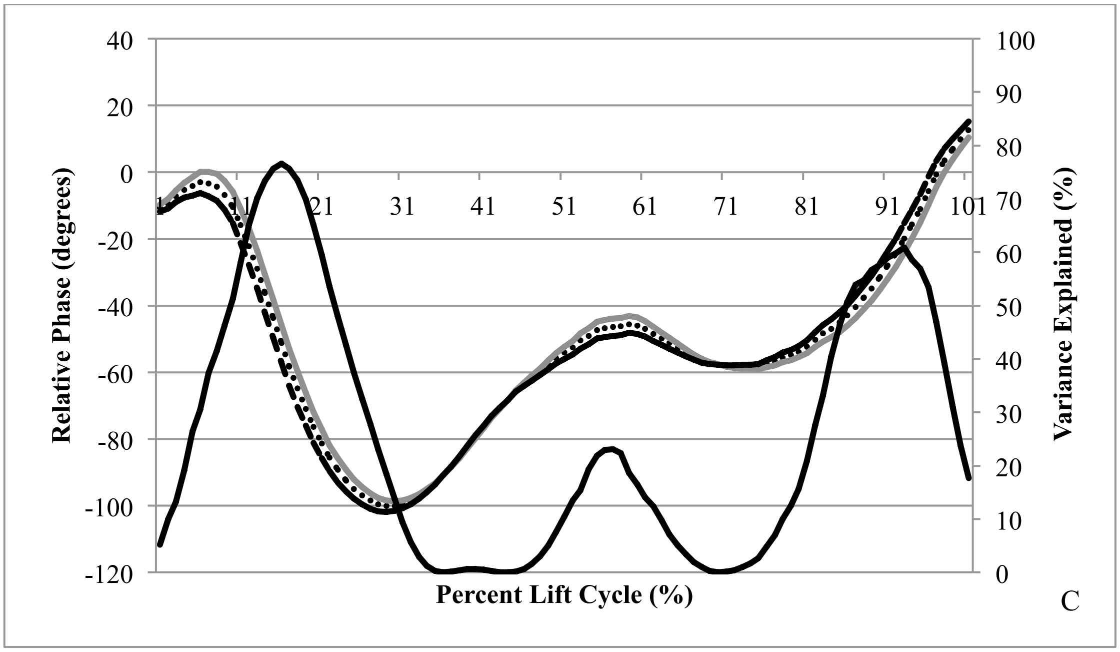

40
20
0
-20
-40
-60
-80
-100
-120
Relative Phase (degrees)
1
11
21
31
41
51
61
71
81
91
101
100
90
80
70
60
50
40
30
20
10
0
Variance Explained (%)
Percent Lift Cycle (%)
F



Left arm and trunk relative phase pre-fatigue conditions compared between general (——); back (.....); shoulder (- - -) testing sessions respectively. Principal component loading curve (——). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3. D. Principal Component 4. E. Principal Component 5. F. Principal Component 6. G. Principal Component 7.




20
0
-20
-40
-60
-80
-100
-120
1
11
21
31
41
51
61
71
81
91
101
100
90
80
70
60
50
40
30
20
10
0
Relative Phase (degrees)
Variance Explained (%)
Percent Lift Cycle (%)
B


40
20
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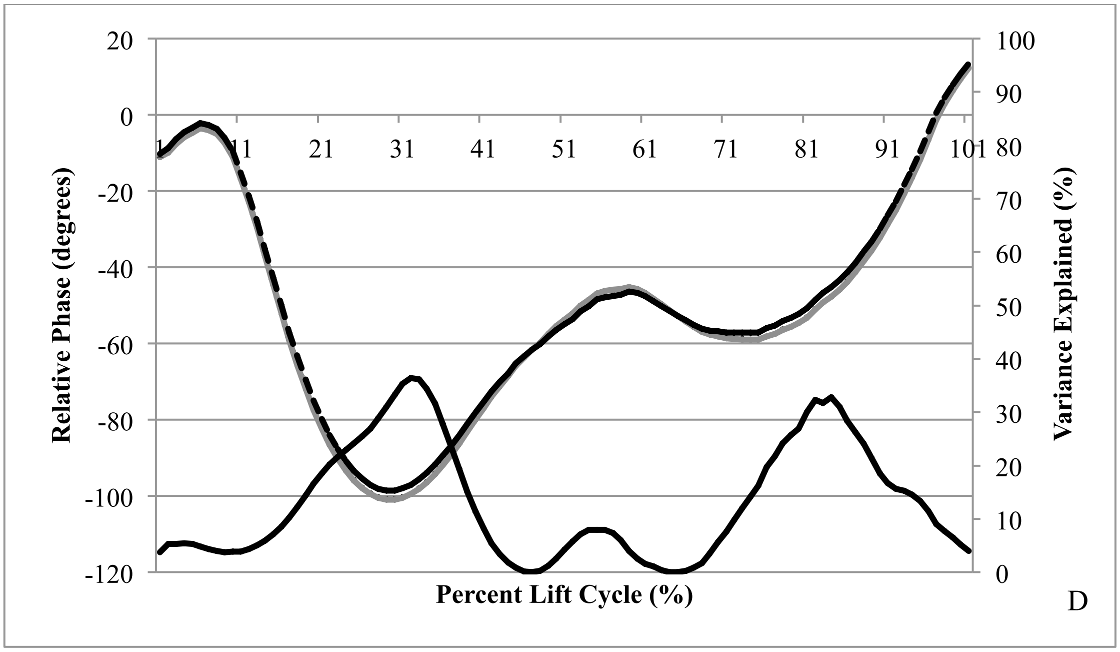
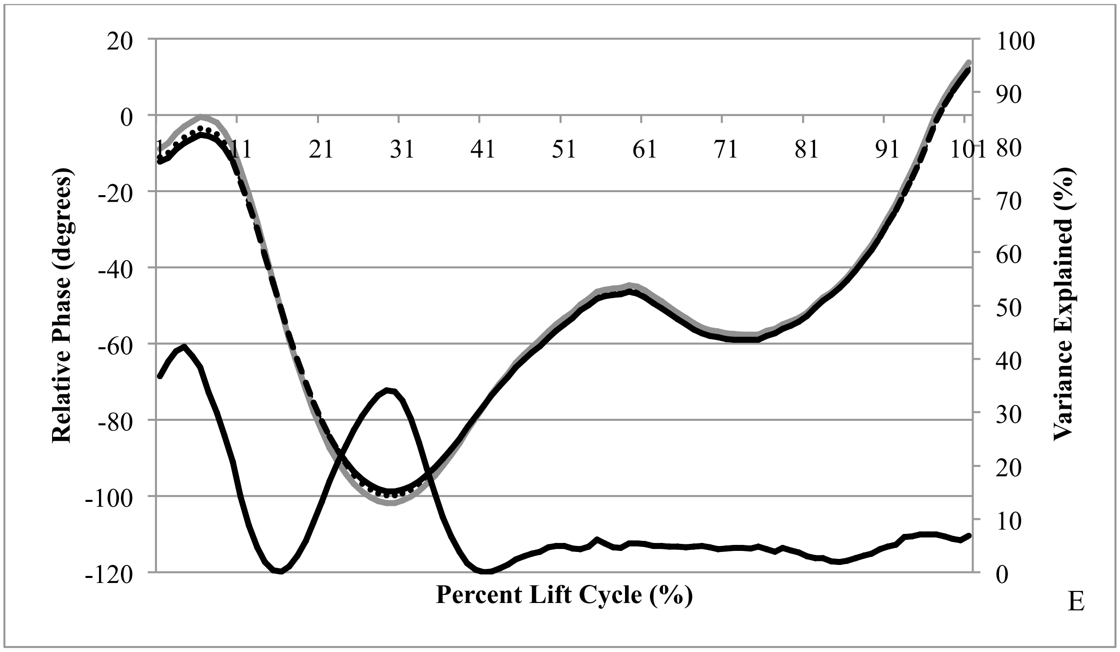
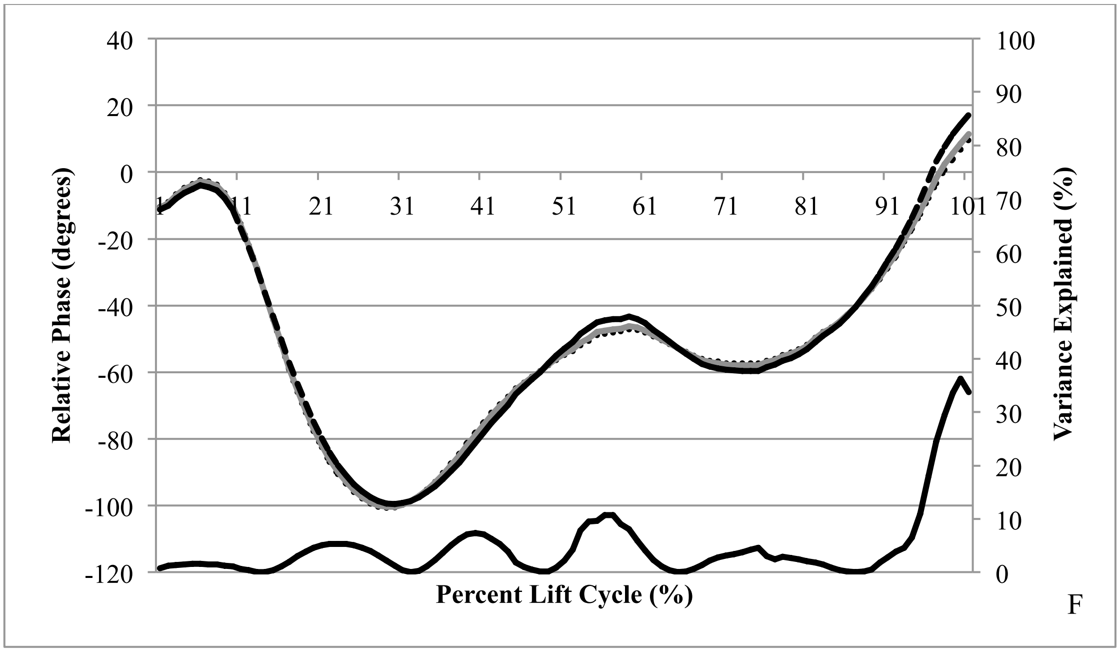
-20
-40
-60
-80
-100
-120
1
11
21
31
41
51
61
71
81
91
101
100
90
80
70
60
50
40
30
20
10
0
Relative Phase (degrees)
Variance Explained (%)
Percent Lift Cycle (%)
C



20
0
-20
-40
-60
-80
-100
-120
Relative Phase (degrees)
1
11
21
31
41
51
61
71
81
91
101
100
90
80
70
60
50
40
30
20
10
0
Variance Explained (%)
Percent Lift Cycle (%)
D



20
0
-20
-40
-60
-80
-100
-120
Relative Phase (degrees)
1
11
21
31
41
51
61
71
81
91
101
100
90
80
70
60
50
40
30
20
10
0
Variance Explained (%)
Percent Lift Cycle (%)
E



Right arm and trunk relative phase pre-fatigue conditions compared between general (——); back (·····); shoulder (- - -) testing sessions respectively. Principal component loading curve (——). A. Principal Component 1. B. Principal Component 2. C. Principal Component 3. D. Principal Component 4. E. Principal Component 5. F. Principal Component 6.

APPENDIX E

Participant	General				Shoulder				Back				% Change pre - post					
	Back		Shoulder		Back		Shoulder		Back		Shoulder		General		Shoulder		Back	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Back	Shoulder	Back	Shoulder	Back	Shoulder
1	359.9	253.0	92.5	70.3	302.4	348.2	94.5	58.3	375.2	260.1	95.6	83.8	-30%	-24%	15%	-38%	-31%	-12%
2	557.7	462.4	117.3	109.4	696.0	566.0	122.0	96.0	471.7	524.0	119.3	109.5	-17%	-7%	-19%	-21%	11%	-8%
3	612.6	401.7	241.3	223.5	659.8	512.9	235.6	182.2	589.0	537.0	246.0	228.0	-34%	-7%	-22%	-23%	-9%	-7%
4	352.4	434.6	226.8	208.8	404.7	395.5	223.3	194.7	675.6	425.4	221.3	182.9	23%	-8%	-2%	-13%	-37%	-17%
5	282.5	353.7	198.9	199.8	595.1	513.2	209.9	179.8	494.8	432.2	198.7	213.2	25%	0%	-14%	-14%	-13%	7%
6	712.0	494.2	199.8	142.0	825.4	683.8	190.7	168.0	782.7	533.3	191.9	173.5	-31%	-29%	-17%	-12%	-32%	-10%
7	446.8	329.6	135.1	118.7	454.2	352.0	126.1	93.3	437.3	337.8	123.2	113.8	-26%	-12%	-23%	-26%	-23%	-8%
8	369.4	210.7	107.8	105.3	402.2	305.0	120.4	97.9	437.2	240.8	115.7	128.8	-43%	-2%	-24%	-19%	-45%	11%
9	269.5	354.2	90.2	78.6	431.3	373.9	83.3	61.4	453.9	419.3	85.3	82.1	31%	-13%	-13%	-26%	-8%	-4%
10	674.8	444.5	248.5	214.0	633.6	548.6	236.8	187.7	681.6	539.9	277.1	231.4	-34%	-14%	-13%	-21%	-21%	-16%
11	887.8	708.1	243.5	176.1	886.9	771.2	221.1	167.1	661.2	532.6	244.5	227.0	-20%	-28%	-13%	-24%	-19%	-7%
12	749.8	767.2	191.6	170.6	632.2	929.2	189.6	155.8	717.3	969.5	196.6	159.2	2%	-11%	47%	-18%	35%	-19%
13	567.0	379.0	234.0	204.0	566.7	482.1	215.1	182.8	625.6	567.6	213.6	203.2	-33%	-13%	-15%	-15%	-9%	-5%
14	408.7	351.9	103.5	87.4	471.2	485.5	108.8	80.0	460.9	290.7	94.2	76.6	-14%	-16%	3%	-26%	-37%	-19%
15	369.4	226.7	176.3	120.4	315.2	222.6	176.8	133.9	386.5	116.0	163.5	135.0	-39%	-32%	-29%	-24%	-70%	-17%
16	364.7	315.3	125.5	109.4	379.3	404.1	133.5	104.2	312.6	312.8	124.7	113.1	-14%	-13%	7%	-22%	0%	-9%
17	304.7	210.5	121.4	105.5	244.8	164.3	115.1	95.8	355.0	286.2	116.0	108.7	-31%	-13%	-33%	-17%	-19%	-6%
18	387.0	352.0	128.0	103.0	329.0	298.0	99.0	67.0	270.0	321.0	121.0	108.0	-9%	-20%	-9%	-32%	19%	-11%
19	574.1	456.1	166.8	149.7	588.0	512.0	162.0	125.0	555.0	375.0	174.4	148.1	-21%	-10%	-13%	-23%	-32%	-15%
20	701.8	680.0	172.1	165.2	661.0	465.0	178.0	154.0	780.3	748.0	175.0	138.8	-3%	-4%	-30%	-13%	-4%	-21%
21	443.9	347.0	187.2	160.8	590.0	358.3	205.0	164.7	580.8	460.6	202.3	176.9	-22%	-14%	-39%	-20%	-21%	-13%
22	522.5	442.3	164.3	148.5	469.7	462.7	147.0	124.4	507.5	496.9	147.0	124.4	-15%	-10%	-1%	-15%	-2%	-15%
23	1247.3	696.3	359.8	303.1	1160.6	785.2	365.2	245.4	1188.9	1022.8	358.6	328.7	-44%	-16%	-32%	-33%	-14%	-8%
24	453.6	392.2	98.8	85.6	354.9	310.6	71.7	53.1	424.7	284.0	76.0	65.9	-14%	-13%	-12%	-26%	-33%	-13%
25	550.8	493.6	309.0	232.3	452.6	349.4	220.0	170.2	372.2	361.7	214.2	181.2	-10%	-25%	-23%	-23%	-3%	-15%
26	532.7	550.8	145.2	128.0	420.7	446.8	116.2	83.0	406.6	321.9	106.1	102.1	3%	-12%	6%	-29%	-21%	-4%
27	520.4	390.3	104.9	89.8	544.4	511.6	115.0	73.0	418.8	439.0	83.2	79.0	-25%	-14%	-6%	-37%	5%	-5%
28	725.0	334.3	246.4	221.8	569.6	649.3	228.9	166.9	441.4	498.7	205.9	190.3	-54%	-10%	14%	-27%	13%	-8%
29	573.3	504.4	163.5	128.8	599.0	550.0	157.0	103.5	674.4	434.0	148.9	131.7	-12%	-21%	-8%	-34%	-36%	-12%
30	604.4	522.0	219.0	173.0	620.7	598.1	209.0	124.3	614.0	431.1	212.5	190.6	-14%	-21%	-4%	-41%	-30%	-10%
31	428.8	211.2	88.7	79.0	314.4	205.9	99.5	64.6	326.6	201.8	99.5	81.3	-51%	-11%	-35%	-35%	-38%	-18%
average	534.0	421.6	174.4	148.8	534.7	469.7	167.0	127.7	531.6	442.6	166.2	148.9	-18%	-14%	-12%	-24%	-17%	-10%
standard deviation	201.3	146.9	67.5	56.6	192.7	173.9	63.2	50.0	185.9	195.9	66.0	59.8	0.015*	0.110	0.168	0.009*	0.072	0.285
minimum	269.5	210.5	88.7	70.3	244.8	164.3	71.7	53.1	270.0	116.0	76.0	65.9	31%	0%	47%	-12%	35%	11%
maximum	1247.3	767.2	359.8	303.1	1160.6	929.2	365.2	245.4	1188.9	1022.8	358.6	328.7	-54%	-32%	-39%	-41%	-70%	-21%

APPENDIX F

PCA tables of pre-fatigue values across testing sessions for kinematic and relative phase variables.

Kinematic Variables	PC	Variance Explained	pre-general/ pre-back	pre-general/ pre-shoulder	pre-back/ pre-shoulder
Left Elbow Flexion/Extension	1	50.97	0.594	0.549	0.267
	2	24.62	0.459	0.496	0.989
	3	17.60	0.297	0.929	0.279
	4	4.82	0.515	0.283	0.636
Right Elbow Flexion/Extension	1	47.56	0.523	0.435	0.109
	2	27.23	0.678	0.694	0.951
	3	19.18	0.036*	0.069	0.574
	4	4.47	0.736	0.475	0.273
Left Shoulder Flexion/Extension	1	59.28	0.258	0.125	0.808
	2	20.14	0.558	0.124	0.248
	3	16.00	0.905	0.503	0.307
Right Shoulder Flexion/Extension	1	62.50	0.436	0.430	0.917
	2	19.01	0.920	0.199	0.167
	3	13.56	0.207	0.804	0.231
	4	3.65	0.426	0.029*	0.391
Trunk Flexion/Extension	1	87.64	0.906	0.379	0.427
	2	10.63	0.018*	0.007*	0.842

Relative Phase Variables	PC	Variance Explained	pre-general/ pre-back	pre-general/ pre-shoulder	pre-back/ pre-shoulder
Left Forearm Upper Arm	1	49.16	0.215	0.011*	0.168
	2	16.53	0.619	0.965	0.723
	3	8.99	0.874	0.330	0.238
	4	6.35	0.202	0.515	0.117
	5	4.40	0.072	0.015*	0.422
Right Forearm Upper Arm	1	42.88	0.294	0.047*	0.193
	2	21.28	0.634	0.156	0.491
	3	9.27	0.857	0.019*	0.012*
	4	7.55	0.763	0.452	0.352
	5	4.13	0.323	0.273	0.903
Left Upper Arm Trunk	1	24.13	0.059	0.027*	0.330
	2	21.32	0.539	0.834	0.439
	3	17.43	0.022*	0.022*	0.873
	4	13.11	0.895	0.579	0.604
	5	7.85	0.191	0.166	0.993
	6	5.74	0.933	0.240	0.225
	7	3.70	0.071	0.001*	0.229
Right Upper Arm Trunk	1	28.70	0.144	0.054	0.002*
	2	21.33	0.054	0.415	0.433
	3	15.20	0.299	0.288	0.898
	4	10.84	0.963	0.330	0.356
	5	9.75	0.311	0.237	0.618
	6	4.80	0.631	0.063	0.073

APPENDIX G

PCA scores across all analyses of pre-fatigue across sessions and between defined specified fatigue states.

Variable	PC	Back	General	Shoulder
Left Elbow Flexion/Extension	1	6.92 ± 13.83	0.67 ± 11.41	-7.59 ± 14.44
	2	2.21 ± 9.93	-4.31 ± 8.35	2.09 ± 9.40
	3	6.28 ± 8.55	-3.48 ± 7.56	-2.80 ± 7.22
	4	-0.11 ± 3.70	2.10 ± 4.02	-1.99 ± 4.51
Right Elbow Flexion/Extension	1	9.40 ± 13.97	0.91 ± 10.96	-10.31 ± 14.41
	2	1.35 ± 8.76	-3.20 ± 11.26	1.85 ± 9.95
	3	5.24 ± 8.99	-7.22 ± 7.17	1.98 ± 8.86
	4	1.76 ± 3.67	0.48 ± 4.08	-2.24 ± 4.40
Left Shoulder Flexion/Extension	1	5.59 ± 19.47	-14.14 ± 19.57	8.55 ± 19.16
	2	-1.81 ± 11.38	-7.74 ± 10.54	9.56 ± 11.89
	3	-3.07 ± 11.29	-1.84 ± 8.78	4.91 ± 10.09
Right Shoulder Flexion/Extension	1	3.74 ± 20.81	-9.15 ± 20.02	5.41 ± 19.92
	2	-5.15 ± 11.98	-4.05 ± 9.41	9.19 ± 11.81
	3	-5.90 ± 9.69	3.97 ± 9.60	1.93 ± 8.95
	4	0.00 ± 4.78	-3.45 ± 4.64	3.45 ± 5.19
Trunk Flexion/Extension	1	-4.01 ± 15.84	-5.82 ± 17.23	9.82 ± 21.27
	2	-4.80 ± 6.89	10.61 ± 5.19	-5.81 ± 6.47

Variable	PC	Back	General	Shoulder
Left Forearm Upper Arm	1	8.19 ± 54.48	58.15 ± 56.46	-66.33 ± 47.85
	2	9.87 ± 34.31	-5.70 ± 31.81	-4.17 ± 27.10
	3	13.60 ± 20.47	9.94 ± 22.15	-23.54 ± 25.59
	4	18.96 ± 18.85	-2.37 ± 19.83	-16.59 ± 18.85
	5	6.24 ± 14.95	-25.96 ± 14.65	19.72 ± 17.43
Right Forearm Upper Arm	1	-8.09 ± 47.91	-38.62 ± 44.99	46.71 ± 48.28
	2	-2.83 ± 34.12	-20.65 ± 37.21	23.48 ± 27.95
	3	15.43 ± 25.37	19.88 ± 21.49	-35.31 ± 17.21
	4	-8.08 ± 20.52	-2.68 ± 19.99	10.76 ± 19.12
	5	-7.42 ± 16.10	12.44 ± 13.42	-5.02 ± 14.35
Left Upper Arm Trunk	1	3.42 ± 27.33	-32.07 ± 24.86	28.66 ± 29.47
	2	-10.18 ± 25.40	2.51 ± 28.53	7.66 ± 23.73
	3	-18.31 ± 26.03	33.33 ± 19.41	-15.03 ± 23.41
	4	4.32 ± 23.13	2.04 ± 16.57	-6.36 ± 20.87
	5	-6.98 ± 16.65	13.84 ± 15.03	-6.86 ± 15.32
	6	6.43 ± 14.46	5.09 ± 11.39	-11.51 ± 14.18
	7	-1.48 ± 10.63	22.55 ± 10.43	-21.07 ± 9.94
Right Upper Arm Trunk	1	-0.64 ± 32.95	-28.51 ± 27.75	29.15 ± 33.45
	2	-18.06 ± 27.91	18.90 ± 32.06	-0.85 ± 20.54
	3	7.08 ± 22.30	-17.08 ± 24.42	10.00 ± 22.27
	4	5.67 ± 23.27	6.51 ± 16.28	-12.18 ± 18.17
	5	-2.18 ± 17.63	12.17 ± 18.95	-9.99 ± 18.74
	6	10.93 ± 14.49	4.73 ± 10.71	-15.65 ± 13.00

Variable	PC	Pre-fatigue	Back fatigue	General fatigue	Shoulder fatigue
Left Elbow Flexion/Extension	1	-13.13 ± 11.03	-23.38 ± 15.13	37.19 ± 13.35	-0.68 ± 17.37
	2	-9.86 ± 6.03	-2.24 ± 11.06	-6.46 ± 10.87	18.56 ± 9.94
	3	-8.04 ± 7.79	-5.67 ± 7.47	1.19 ± 10.08	12.51 ± 9.93
	4	1.27 ± 3.47	5.48 ± 4.31	0.29 ± 3.98	-7.03 ± 4.44
Right Elbow Flexion/Extension	1	-12.08 ± 10.80	-16.18 ± 14.09	21.05 ± 13.31	7.20 ± 15.11
	2	7.75 ± 7.91	-6.68 ± 11.39	27.63 ± 12.67	-28.70 ± 13.13
	3	-2.70 ± 7.75	-5.89 ± 7.45	-0.28 ± 8.47	8.86 ± 8.91
	4	2.69 ± 3.48	6.30 ± 4.16	-2.29 ± 4.81	-6.69 ± 4.26
Left Shoulder Flexion/Extension	1	13.18 ± 17.49	-23.22 ± 21.09	5.59 ± 22.56	4.46 ± 20.61
	2	23.13 ± 9.55	13.96 ± 9.42	-22.62 ± 11.63	-14.47 ± 13.32
	3	5.81 ± 8.46	16.63 ± 9.91	-19.44 ± 10.21	-3.01 ± 10.26
	4	-0.93 ± 3.71	-5.55 ± 5.03	-3.36 ± 5.75	9.83 ± 5.39
Right Shoulder Flexion/Extension	1	1.34 ± 17.65	-42.94 ± 21.61	52.38 ± 25.92	-10.78 ± 25.26
	2	-13.46 ± 9.32	-5.09 ± 9.46	4.56 ± 11.40	13.98 ± 11.71
	3	-12.50 ± 8.28	-14.69 ± 10.58	19.38 ± 8.00	7.81 ± 10.58
Trunk Flexion/Extension	1	18.35 ± 15.43	-7.08 ± 20.41	-37.88 ± 27.99	26.62 ± 20.54
	2	8.50 ± 5.55	11.36 ± 7.92	7.63 ± 7.38	-27.49 ± 6.98

Variable	PC	Pre-fatigue	Back fatigue	General fatigue	Shoulder fatigue
Left Forearm Upper Arm	1	-37.07 ± 45.54	20.83 ± 57.75	66.36 ± 55.21	-50.12 ± 49.37
	2	-14.96 ± 23.61	-31.46 ± 26.06	18.79 ± 35.12	27.64 ± 40.81
	3	-18.62 ± 16.39	-25.14 ± 26.92	-18.03 ± 22.15	61.79 ± 22.19
	4	1.25 ± 14.58	42.78 ± 20.73	-28.42 ± 19.16	-15.61 ± 22.35
	5	0.48 ± 11.98	-20.99 ± 14.71	3.67 ± 15.10	16.84 ± 18.63
Right Forearm Upper Arm	1	-43.89 ± 41.22	25.53 ± 49.33	-23.37 ± 47.84	41.73 ± 48.32
	2	-16.61 ± 26.18	-43.71 ± 30.45	31.66 ± 35.93	28.67 ± 41.19
	3	-11.12 ± 16.76	-27.80 ± 20.33	-29.00 ± 22.94	67.91 ± 20.63
	4	-7.00 ± 17.11	12.06 ± 19.64	-17.44 ± 22.00	12.38 ± 25.52
	5	-4.32 ± 9.90	-30.24 ± 13.60	18.36 ± 14.58	16.20 ± 16.09
Left Upper Arm Trunk	1	-10.04 ± 23.23	-109.93 ± 22.71	46.19 ± 32.79	73.77 ± 26.79
	2	9.21 ± 21.43	12.55 ± 25.52	-58.48 ± 29.77	36.71 ± 31.45
	3	6.34 ± 20.59	-26.80 ± 23.64	34.58 ± 26.97	-14.11 ± 24.83
	4	-4.09 ± 16.56	7.27 ± 20.48	6.59 ± 20.71	-9.76 ± 21.90
	5	-10.07 ± 13.99	-2.87 ± 19.96	5.38 ± 17.68	7.56 ± 14.29
	6	1.85 ± 11.00	-7.18 ± 13.68	8.64 ± 17.64	-3.31 ± 14.18
	7	9.01 ± 7.51	4.72 ± 11.26	-1.61 ± 12.76	-12.12 ± 10.52
Right Upper Arm Trunk	1	-8.13 ± 28.46	-77.75 ± 23.34	-0.53 ± 36.90	86.41 ± 27.03
	2	15.79 ± 21.30	25.52 ± 25.84	-3.39 ± 30.90	-37.92 ± 34.46
	3	-0.49 ± 21.83	-59.62 ± 22.16	90.32 ± 32.88	-30.21 ± 20.37
	4	-5.19 ± 17.65	-8.67 ± 23.28	8.57 ± 21.84	5.29 ± 23.13
	5	-6.71 ± 15.86	4.79 ± 17.84	-20.41 ± 22.44	22.33 ± 16.90
	6	4.69 ± 10.94	-12.69 ± 14.10	22.39 ± 16.07	-14.39 ± 13.22

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Publications

Articles published or accepted in refereed journals

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