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Ergonomic Evaluation for Right Angle Power Tools: Direct Current Physical Demands Comparison – A Focus on Muscle Activity

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Ergonomic Evaluation for Right Angle Power Tools: Direct Current Physical Demands Comparison – A Focus on Muscle Activity

By

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ABSTRACT

The purpose of this study was to evaluate the differences in muscle activation and handle forces between three direct current right angle power tool fastening strategies: turbo tight, two stage without soft stop and two stage with soft stop. Thirty-six participants (20-60 yrs) were assigned to one of two experimental groups: hard-joints or soft-joints. Participants conducted fastenings at four different postures for three different target torques and muscle sEMG was collected on 16 muscles of the upper body. Data from the muscle sEMG, and forces collected at the handle were analyzed using repeated measures ANOVA with Tukey's post hoc test to determine statistical significance ($p<0.05$). Results found that the participants sEMG activation impulse was less for the turbo tight fastening strategy in comparison to the two-stage fastening strategy with and without soft stop. These findings were not impacted by joint type, posture or target torque.

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LIST OF ABBREVIATIONS

Ach: Acetylcholine

ADP: Adenosine Diphosphate

ANOVA: Analysis of Variance

ATP: Adenosine Triphosphate

Ca^{++}: Calcium

Cl^{-}: Chloride

CNS: Central Nervous System

CTD: Cumulative Trauma Disorders

dB: Decibels

DC: Direct Current

GΩ: Gigaohm

G-Actin: Globular Actin

GTO: Golgi Tendon Organs

H^{+}: Hydrogen

Hz: Hertz

K^{+}: Potassium

ms: Milliseconds

MU: Motor Unit

MVE: Maximum Voluntary Exertions

Na^{+}: Sodium

N: Newtons

Nm: Newton Meters

Pi: Inorganic Phosphate

RAPT: Right Angle Power Tool

RMP: Resting Membrane Potential

RPE: Ratings of Perceived Exertion

sEMG: Surface Electromyography

SR: Sarcoplasmic Reticulum

TS: Two Stage Without Soft Stop

TSS: Two Stage with Soft Stop

TT: Turbo Tight

T-Tubules: Transverse Tubules

Type I: Slow Twitch

Type IIA: Fast Twitch Oxidative Glycolytic

Type IIB: Fast Twitch Glycolytic

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Workplace injuries can occur acutely or chronically to workers in all fields of employment. Cumulative trauma disorders (CTDs) are injuries that have been sustained through repetitive tasks occurring over a long period of time, usually weeks to months (Rempel, Harrison, & Barnhart, 1992). Apart from repetition, CTD's can develop from tasks that require a high force, awkward joint posture, direct pressure, vibration and prolonged constrained posture (Rempel et al., 1992). When any of these factors are in combination, there is an increased risk of developing a musculoskeletal injury (Silverstein, Fine, & Armstrong, 1986). The most common musculoskeletal injuries that can develop with CTD's are tendon and ligament disorders, muscle tears, degenerative joint disease, bursitis or nerve entrapment (Rempel et al., 1992). With the new technology that has been introduced in the recent years allowing tasks to be completed faster, workplaces are increasing the demand to fill the extra time that has been created, increasing the repetition of the tasks to be performed.

Power tools are one of the technical advances that have helped the automobile industry advance to the point it is today. It is estimated 75% of the automobile manufacturing population uses power tools to secure on average 1500 fasteners per vehicle in a typical plant (Radwin, Vanbergeijk, & Armstrong, 1989; Van Bergeijk, 1987). These fasteners are secured using either a pneumatic or electrical (direct current) power tool, although pneumatic has been the most common power source, recently direct current (DC) power tool use has been increasing (Potvin, Agnew, & Ver Woert, 2004). A recent survey conducted at Ford and Chrysler automotive assembly plants in Windsor, ON found that 95% of jobs using right angle power tools (RAPT) are completed with a DC power tool (Lidstone, Balch, & Cort, 2015).

During fastening secures operators are required to produce forces to ensure that the tool maintains contact with the fastener and resist the external forces created by the tool. When these external forces from the tool are greater than the capacity of the operator they experience a rapid and forceful jerk as the fasteners become fully tightened. This jerk results in a forceful displacement of the arms, which ultimately causes eccentric contractions of the muscles opposing the displacement. Research has shown that forceful eccentric contractions lead to significant muscle damage (Proske & Morgan, 2001). With repeated muscle damage from the continuous rapid eccentric movements, the muscle has been shown to experience fatigue, a reduction in force production, a fall in active tension and a rise in passive tension (Proske & Morgan, 2001). These factors associated with power tool operations are hypothesized to contribute to an increase in injury risk associated with their use and therefore require investigation.

1.2 STATEMENT OF PURPOSE

The purpose of the current study was to evaluate the effects of RAPT on the muscle activity during operation. Specifically, this study determined the physical demands associated with the fastening tasks using DC power tools and their various tightening strategies by examining the surface electromyography (sEMG) of the muscles associated with the fastening operation, as well as the operators' subjective rating of perceived exertion (RPE) during fastening operation.

1.3 HYPOTHESES

1. Greater increase in sEMG activation impulse and Borg RPE magnitudes with the increase in target torque will be found. Specifically, the biceps brachii and pectoralis major having greater sEMG activation impulse during the fastenings as target torque increases.

Previous studies have shown that EMG activity increased with increasing peak spindle torque for pneumatic tools (Radwin et al., 1989). A study conducted by Kihlberg, Kjellberg, & Lindbeck (1993) showed that subjects would rate tools with longer torque build up times with greater ratings of perceived exertions than the shorter build up times. In addition, they showed that muscle activation were 20-40% lower with the shorter build up times further supporting their RPE results. These previous studies have all been conducted on pneumatic power tools but similar results are expected with DC power tools. As with pneumatic tools, operators using electrical power tools have to generate more force with longer torque build up time, as well as with jobs that occur on a vertical work station rather than a horizontal one (Oh & Radwin, 1998).

2. Lesser muscle sEMG activation impulse and Borg RPE magnitudes for all muscles will be observed when using turbo tight fastenings strategy compared to a two-stage fastening strategy with and without soft stop.

At the present time, there are no studies to show the physical demand differences between the DC power tool fastening strategies most commonly used in automotive assembly. Based on the mechanical rationale between the different strategies, it is believed that the turbo tight fastening strategy will produce a lesser muscle sEMG activation impulse for all 8 bilateral muscles being examined. This lower sEMG activation impulse is hypothesized based on the decrease in the spindle speed as target torque is reached which may reduce the physical demands experienced by the operator.

3. Non-neutral postures will show an increase in sEMG activation impulse and an increase in Borg RPE magnitudes compared to neutral postures. Specifically, locations B and D will show an increase in sEMG activation impulse compared to locations A and C. The

anterior deltoid and pectoralis major will show the greatest increases during these time periods for both locations B and C.

Hard-joints are shown to have results in the lower RPE's and the least force production (Forsman, Cyrén, Möller, Kadefors, & Mathiassen, 2002; Oh & Radwin, 1998). A study completed by Freivalds & Eklund (1993) also reached the same conclusion that soft-joints will experience a significantly larger impulse than that experienced by the hard-joints. This difference is due to the shorter torque build up time associated with hard-joints (Oh & Radwin, 1998). All these studies were conducted on pneumatic tools but the same results are expected to be seen with the results obtained from the operation of DC tools.

CHAPTER 2: LITERARTURE REVIEW

2.1 POWER TOOL USE IN THE AUTOMOTIVE INDUSTRY

The automotive industry is a very influential industry in today's society, creating jobs across the world for many workers. According to Industry Canada (2014), the total number of employees within the automobile and light duty motor vehicle manufacturing sector has increased 6.9% between 2010 and 2011, with the number of production employees alone increasing 8% between 2010 and 2011. With the shear demand for vehicles across the globe, the manufacturing industry is compelled to keep up with the ever changing consumer needs, the always developing technology, as well as the global competition (Laosirihongthong & Dangayachm, 2005). These demands put great pressure on the manufacturer to keep up with the increasing quality and quantity while, decreasing costs and ensuring safe working conditions (Laosirihongthong & Dangayachm, 2005).

Automotive assembly operators are responsible for an array of tasks that when completed result in the production of a fully functional vehicle. Most assembly operations require manually securing various parts using methods such as: fastening, welding, snapping or forcing parts into their specific location. The securing of fasteners are commonly completed using power tools to achieve the rotational forces necessary to fully tighten the two independent parts together. Low force tasks are completed by workers as humans are able to handle these forces safely as well as being cost effective, while robotic tools are commonly used on tasks that require a high force to complete that humans are not able to handle safely. However, as the production demand for vehicles has increased, there has been an increase in the demand for the use of powered hand tools to complete fastening jobs faster, more accurately and safer (Freivalds & Eklund, 1993).

2.1.1 POWER TOOL VARIETY

There is an array of power tools available, depending on the jobs that are required for vehicle assembly (Radwin et al., 1989). Power tools differ on power source, handle configuration, torque output, shut off mechanism, speed, weight and spindle diameter (Freivalds & Eklund, 1993). The available handle configurations for power tools are pistol grip, in-line and right angle, seen in Figure 1. While both pistol grip and in-line tools are used for low torque jobs, pistol grip is best for jobs on a vertical axis while in line is best for jobs on a horizontal axis (Freivalds & Eklund, 1993). Pistol grip and inline are best used in the vertical and horizontal axis respectively, to aid operators in maintaining a straight back, vertical upper arms along with a neutral wrist to minimize injury (Freivalds & Eklund, 1993). For those jobs that require high torques, RAPT are preferred due to its long handle that creates for a longer moment arm and thus, a mechanical advantage when securing fasteners with high torque requirements. In fact, RAPT are designed to produce torque outputs that range from 0.1 Nm to 5000 Nm (Freivalds & Eklund, 1993). While these tools may be able to reach torques up to 5000 Nm, humans are not able to operate at those high ranges due to these demands exceeding the human strength capacity, and then robotics are used to complete these specific jobs.

Figure 1: A) Atlas Copco electric RAPT, model Tensor ETV ST61-70-13 shown. B) Atlas Copco electric pistol grip power tool, model Tensor ETP DS7-30-10S shown. C) Atlas Copco electric inline power tool, model Tensor ETD DS4-05-10S (Atlas Copco, 2014).

2.1.2 POWER TOOL FASTENING PROCEDURE

The fastening of two parts is completed in the same manner for all power tools. The operator starts the rotation of the power tool spindle head by pressing the trigger on the tool which, causes free rotation of one of the parts of the fastener in the threads of its mate. Snug fit of the two fastener parts occurs when the two parts stop freely rotating and resistance is met. This increase in resistive forces of the fastener requires the operator to exert muscle force to overcome the generated resistance, this is known as the torque reaction force. This resistance of the two parts continues to increase until the fastener becomes fully tightened and the operator experiences peak torque reaction force. If the torque produced by the tool and the fastener during tightening is greater than the physical capacity of the operator to oppose the force of the tool, the operator is pulled in the direction of the torque reaction in a jerk motion (Sommerich, Gumpina, Roll, Le, & Chandler, 2009). This jerk motion, which is the rate of change in acceleration, pulls the arm that is holding the distal end of the power tool rapidly causing eccentric contraction (muscle lengthening) of the upper extremity muscles (Radwin et al., 1989). As mentioned by Allen (2001), Friden, Sjostrom, & Ekblom (1981) and Proske & Morgan (2001), the rapid eccentric contraction experienced by the operators can cause damage to the muscles if experienced repeatedly, and will be discussed later.

2.1.3 PNEUMATIC RIGHT ANGLE POWER TOOLS

RAPT are available in two different power sources: pneumatic and direct current (DC). Pneumatic tools, while more popular years ago, now only account for 5% of jobs using RAPT (Lidstone et al., 2015). Pneumatic tools are powered using pressure via compressed air, where the fastening from this tool begins as the operator squeezes its trigger, allowing the pressure from the air to rotate its spindle head, which through the help of mechanical gears produces rotational forces. The rotation from the tool continues until the fastener is fully fastened (final clamping of the two parts), however the rotation will continue in its attempt of tightening until the trigger is released, which increases the exposures of unnecessary handle forces, this is also known as a stall tool (Kihlberg, Kjellberg, & Lindbeck, 1993; Radwin et al., 1989). With stall tools, the operator has to resist the reaction torque fully with their own muscle force (Kihlberg et al., 1993). To counteract this continual rotation and lessen the torque reaction force experienced by the operator, some pneumatic power tools are equipped with a shut off mechanism called an air flow shut off (Freivalds & Eklund, 1993; Kihlberg et al., 1993). This mechanism allows the pneumatic tool to fully rotate and mate the two fastener parts until the desired torque is reached and then the mechanism becomes activated, shutting the tool off by stopping air flow to the tool resulting in a shorter torque reaction time (Freivalds & Eklund, 1993; Kihlberg et al., 1993; Radwin et al., 1989).

2.1.4 DIRECT CURRENT RIGHT ANGLE POWER TOOLS

In automotive assembly plants today, 95% of jobs using RAPT are DC driven power tools (Lidstone et al., 2015). DC tools are designed with electrical motors that are computer controlled, such that when the tools trigger is engaged an electrical signals is sent to the computer, which then sends commands to control the motor for a finely tuned rotation of the spindle head (Sommerich et al., 2009). In addition to the DC tools ability to accurately control each fastening strategy, its integrated torque transducer provides real-time torque feedback to the end-user, which has been primarily used for quality assurance, an option not commonly available with pneumatic tools. However, in addition to quality measures, these transducerized DC tools provide direct data that can be used for operator safety, for example in an attempt to reduce torque reactions. Oh & Radwin (1998) found in their study using DC RAPT that the operators experienced greater instability and, work done by the operator with the DC tools that had larger torque build up times as well as larger target torques.

There are various fastening strategies that can be used to control DC RAPT during the fastening operations, however, most of these strategies have commonality in their procedures. These profiles are generally split into one of two categories; one stage and two stage (seen in Figure 2). For the one stage strategy, the tool will secure the fastener at a constant velocity in one step until the final torque has been met (Atlas Copco, 2013b). A two stage tightening strategy has two stages: the first stage consists of the fastening being done at a high speed while the second stage runs at a lower speed (Atlas Copco, 2013b). There is a 50 ms break between the two stages to reduce the torque experienced by the operator (Atlas Copco, 2013b). These two strategies can be modified to fit the task that is being worked on by altering the

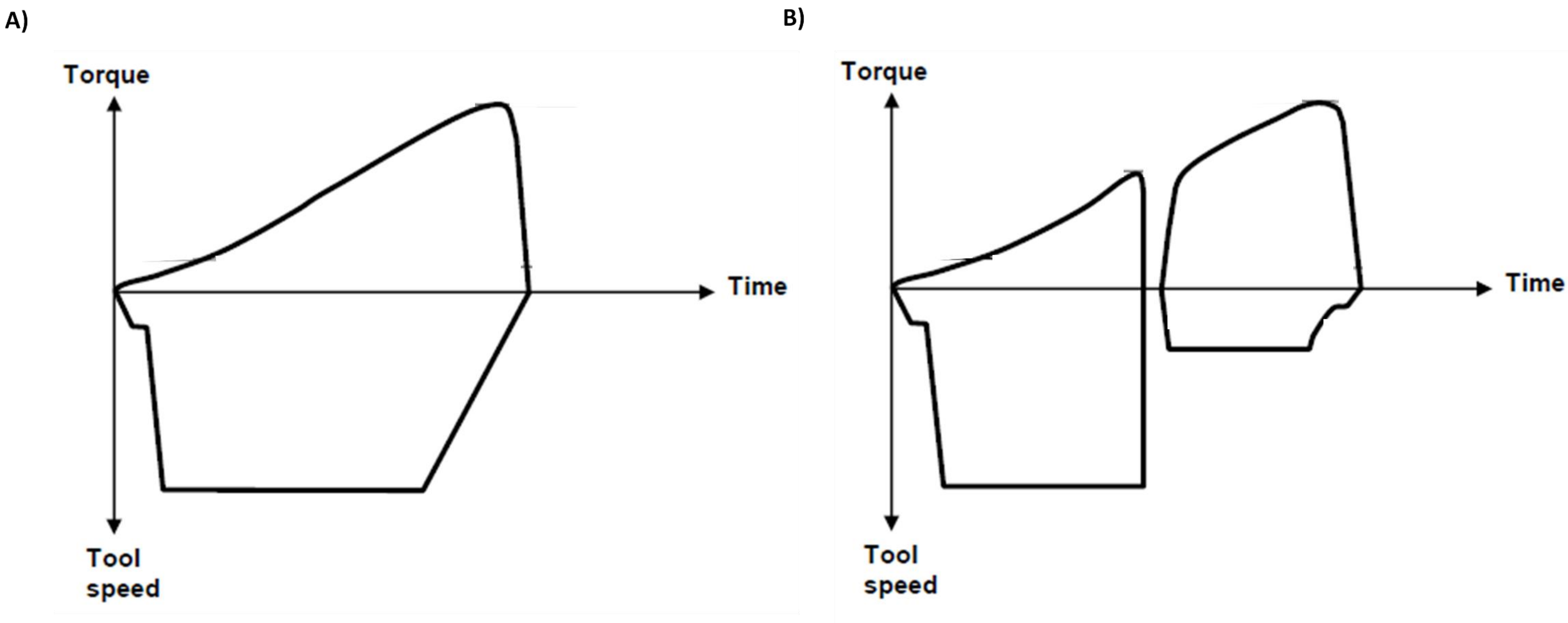

Figure 2: Tightening profiles: A) One stage with one constant velocity B) Two stage with high speed first step, a break and a lower speed second step (Atlas Copco, 2013b).

speed at which the fastening occurs, the length of pause in the two stage strategy as well as, the rate at which the torque increases (Atlas Copco, 2013b).

One specific one stage tightening strategy used by Atlas Copco is the turbo tight (TT). For this strategy, the tool's computer controller takes into account the joint stiffness and alters the energy needed to achieve target torque and adjusts the speed to ensure reliable accuracy (Atlas Copco, 2013a). This tightening strategy is able to calculate the energy requirements through the target torque as well at the torque rate or tightening angle (discussed below), along with the rotor inertia and rotor speed, and can adjust the speed accordingly (Atlas Copco, 2013a). This strategy is known for its short duration and high speeds during fastening with low speeds as target torque is reached, seen in Figure 3 (Atlas Copco, 2013a). This tool strategy uses its own inertia to absorb most of the reaction forces it creates and thus reduces the forces felt by the operator (Atlas Copco, 2013a).

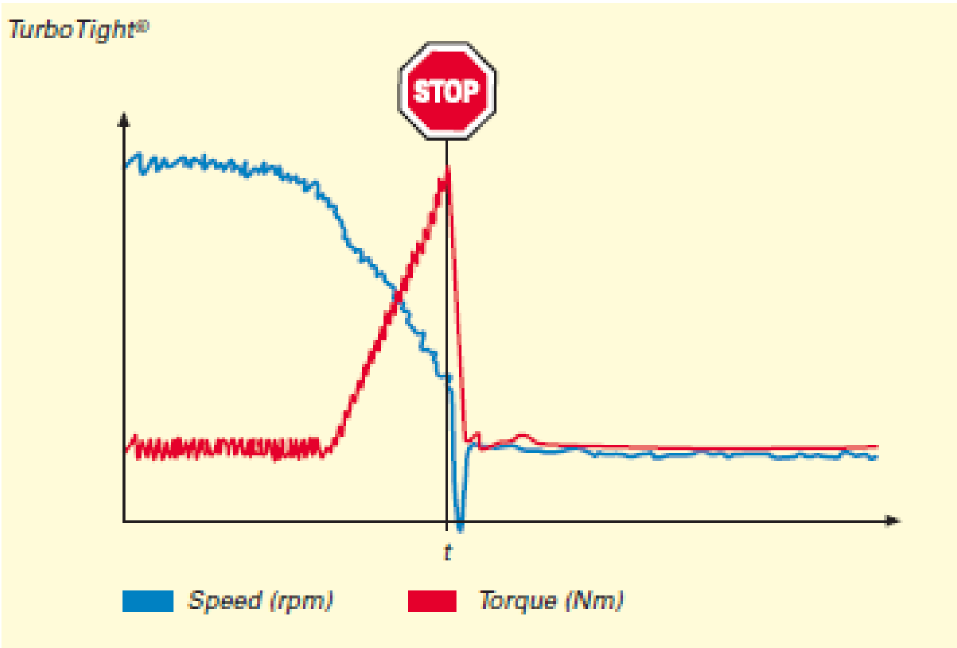

Figure 3: Turbo tight fastening strategy showing torque and speed profile during rundown (Atlas Copco, 2013a).

Soft stop is a feature you can add to tightening strategies that changes the way the load is released in an attempt to reduce the jerk felt by the operators, which is caused by the rapid releasing of the load at the end of the rundown (Mukherji, 2008). This feature works as follows: once the final torque has been reached, the controller shuts off the tool and pauses for a brief period of time termed the current off time (Mukherji, 2008). Once the pause is completed, the current is restored to a level slightly below the peak torque of the shut off point and, is held at the level for a period of time termed the current hold time (Mukherji, 2008). Once the hold time is finished, the electrical current is ramped down linearly to zero over a length of time, deemed the current ramp time (Mukherji, 2008). Figure 4 showcases the current off time, hold time and ramp time associated with the soft stop feature with the default times associated with each phase, though these times can be altered (Mukherji, 2008). If the fastening strategy does not include the soft stop feature the current off time, hold time and ramp times will not be present (Mukherji, 2008).

2.1.5 JOINT TYPES

There are two common types of joints that RAPT secure during automotive assembly: hard-joints and soft-joints. Joint types are determined by their rundown angle, which is the number of degrees the fastener will rotate from when it reaches snug fit (when the fastener has stopped freely rotating and has met the resistance associated with the secure) to when it is fully tightened (Figure 5). According to The International Standards Organization (1994) standard 5393, hard-joints have a rundown angle of less than 27° of rotation from snug fit to final torque, 10% to 100% of torque level, with a complete rundown angle of 30°. For this rundown angle to be achieved, the fastener runs freely nearly all of the way until the final torque has been reached (Forsman et al., 2002). The torque build up time, which is the time between snug fit and fully tightened, is minimal in length for hard-joints (Figure 6) (Freivalds & Eklund, 1993).

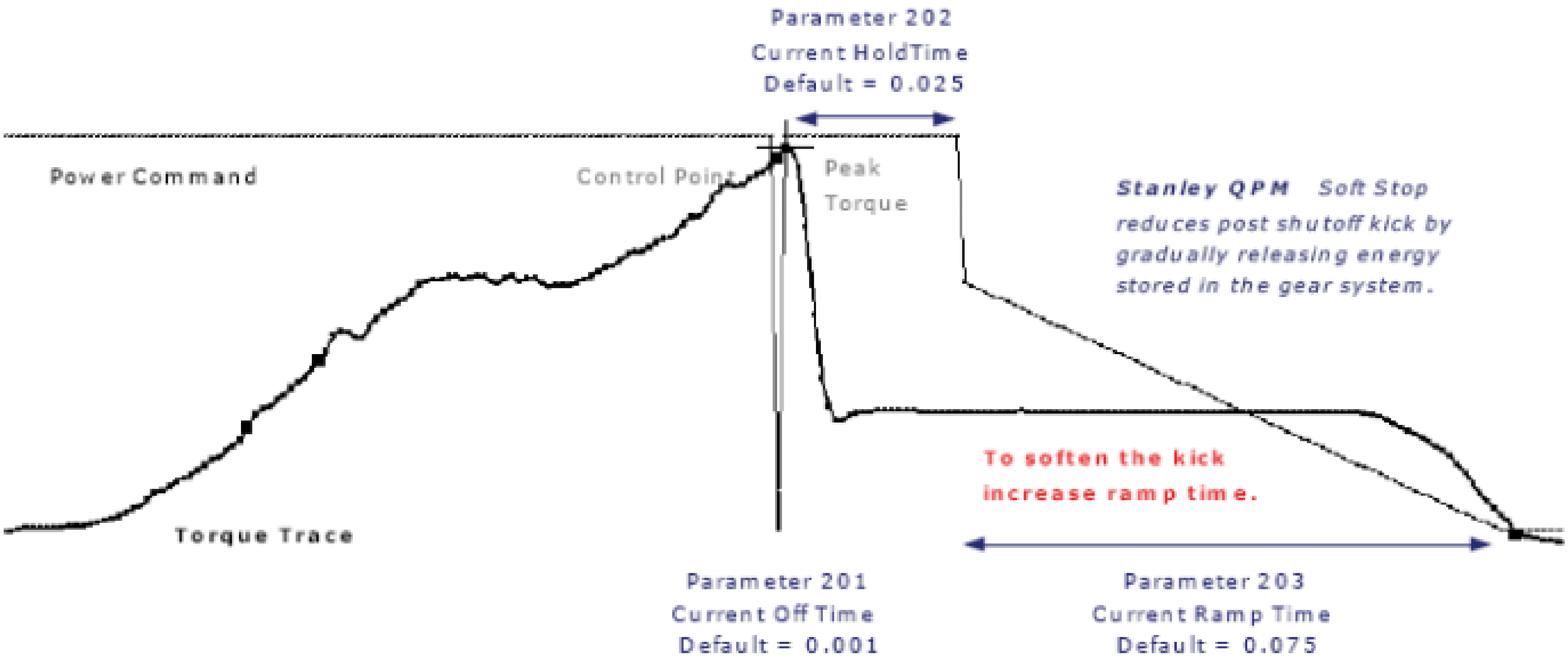

Figure 4: Fastening rundown profile with soft stop feature added, showing current off time, hold time and ramp time of the feature with the default times associated with each phase (Mukherji, 2008).

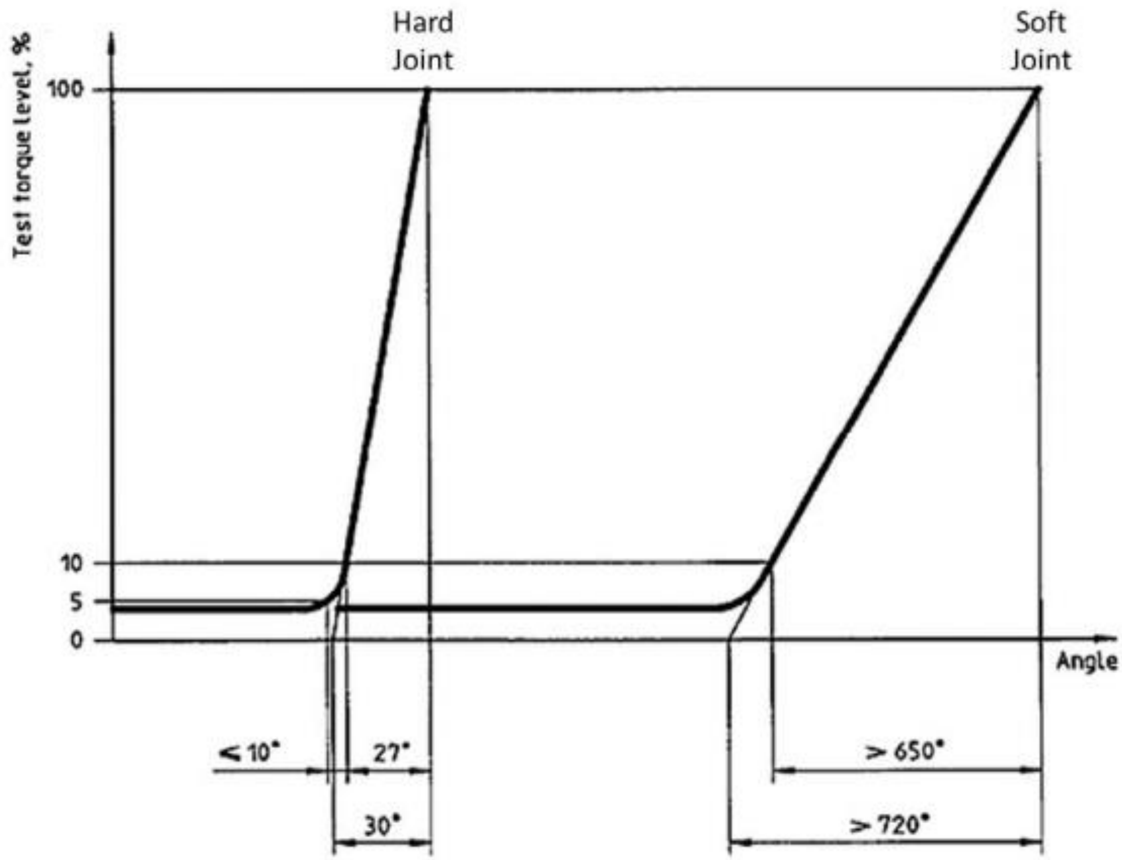

Figure 5: Spindle head angle vs. torque level in hard and soft-joints (International Standards Organization, 1994).

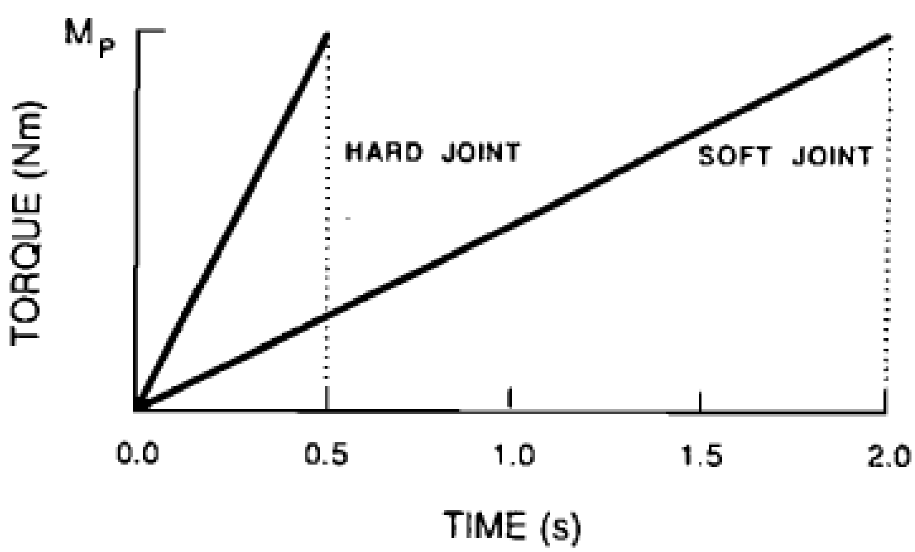

Figure 6: Torque buildup time for hard and soft-joints (Radwin et al., 1989) .

For soft-joints, a rundown angle of at least 650° of rotation must be reached between snug fit and final torque (10% to 100% of torque level), with total rundown angle of 720° (International Standards Organization, 1994). Soft-joints include a spring action in the joint so that the final torque is built up over a longer period of time (Figure 6), and due to this, the resulting torque reaction force will be larger than that found in hard-joints (Forsman et al., 2002; Freivalds & Eklund, 1993; Potvin et al., 2004).

2.1.6 POWER TOOL EFFECTS ON THE HUMAN BODY

As mentioned above, pneumatic and DC tools behave in very different ways when the operator is completing a fastening. In a study conducted by Potvin et al. (2004) comparing pistol grip pneumatic to DC power hand tools, it was discovered that the air tools would cause the hand to undergo greater accelerations than when the DC tools were used. They also found that for EMG amplitudes for the forearm muscles, air tools would generally show greater magnitudes than that recorded when using DC tools (Potvin et al., 2004). The three muscles, extensor carpi ulnaris, extensor carpi radialis longus and flexor carpi ulnaris, which showed the highest maximum electrical activation of muscle when using the

pneumatic tools all showed a significant decrease in activation when they moved to operating the DC tools (Potvin et al., 2004).

As mentioned earlier, the torque reaction force is the force produced by the tool on the operator when the resistance between the tool and the fastener increases. The amplitude and time duration of the torque reaction force depends on the tool's spindle speed, tool design, preset torque, joint stiffness, shut off mechanism and the operator themselves (Forsman et al., 2002). High torque reaction forces are associated with the risk of injury, however, small torque reaction forces can also lead to upper extremity cumulative trauma disorders (CTD) due to their repetitive nature and the awkward postures that the operators may need to adopt (Rempel et al., 1992). While RAPT have increased productivity and ensured the accuracy of the fastener secures, these fastening tasks have become increasingly repetitive and have been linked to large torque reaction forces (Freivalds & Eklund, 1993; Kihlberg et al., 1993; Lindqvist, 1993; Radwin et al., 1989). For high torque jobs above 100 Nm, the right angled power tool requires a reaction bar to counteract the torque reaction force (Forsman et al., 2002). A reaction bar (Figure 7) is a stationary stable bar that is attached to a solid support and helps to absorb torque

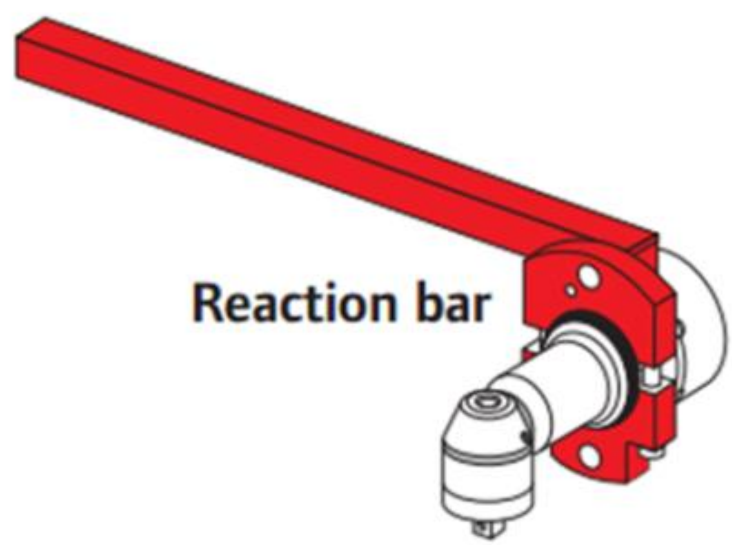

Figure 7: Reaction bar placed on a RAPT to help reduce the force produced by the tool (Ingersoll Rand, 2008).

reaction forces to lessen what the operator experiences (Radwin et al., 1989). Unfortunately, this reaction bar can add weight and restrict tool placement so it may only be suitable for specific jobs and joints (Forsman et al., 2002).

2.2 MECHANICS OF MUSCLE CONTRACTION

2.2.1 MOTOR UNIT

A motor unit (MU) is composed of bundles of skeletal muscle fibers that is innervated by a single motor control nerve. Muscle (structure shown in Figure 8), enclosed by the connective tissue epimysium, is composed of many fascicles which are surrounded by the perimysium, with these fascicles made up of numerous individual muscle fibers that are surrounded by endomysium (Enoka, 2008). Muscle fibers (Figure 9) are surrounded by an excitable membrane known as the sarcolemma, which allows electrical impulses to travel deep into the muscle through channels in this membrane known as transverse tubules (t-tubules), to trigger quick and forceful muscle contractions (Silverthorn, 2010). Muscle fibers are comprised of myofibrils and surrounding each myofibril is the sarcoplasmic reticulum (SR) (Silverthorn, 2010). The SR releases Calcium (Ca^{++}) ions, used for muscle contraction, which are stored in the terminal cisternae at the end of the SR (Silverthorn, 2010). The terminal cisternae act as reservoirs for more Ca^{++} storage and border the t-tubules on either side (Silverthorn, 2010).

As mentioned earlier, a motor unit also includes the nerve that innervates specific muscle fibers, though these muscle fibers are not always identical and different types of muscle fibers tend to make up a complete motor unit. There are three different muscle fiber types that make up muscles: slow twitch (type I), fast twitch oxidative glycolytic (type IIA) and fast twitch glycolytic (type IIB) (Silverthorn, 2010). Type II fibers can contract more quickly than type I fibers due to the presence of fast myosin ATPase activity. These myosin ATPase in fast twitch fibers are able to break down adenosine triphosphate (ATP), an energy source in the body, at a faster rate to allow the contraction to also occur faster (Silverthorn, 2010). Type II fibers also contract faster than type I due to the speed in which Ca^{++} is

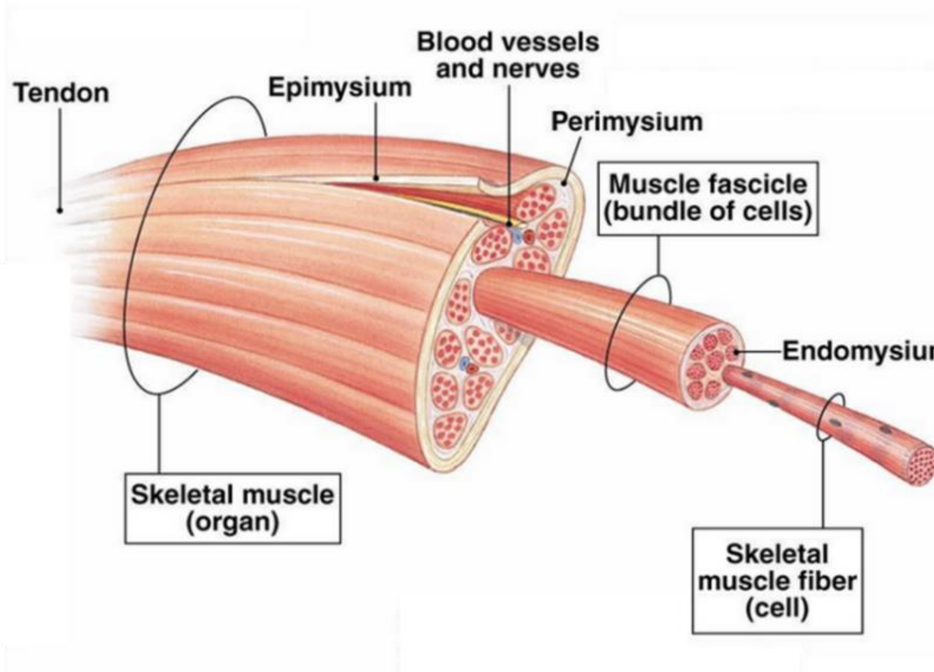

Figure 8: Structure of a skeletal muscle connective tissue (Silverthorn, 2010).

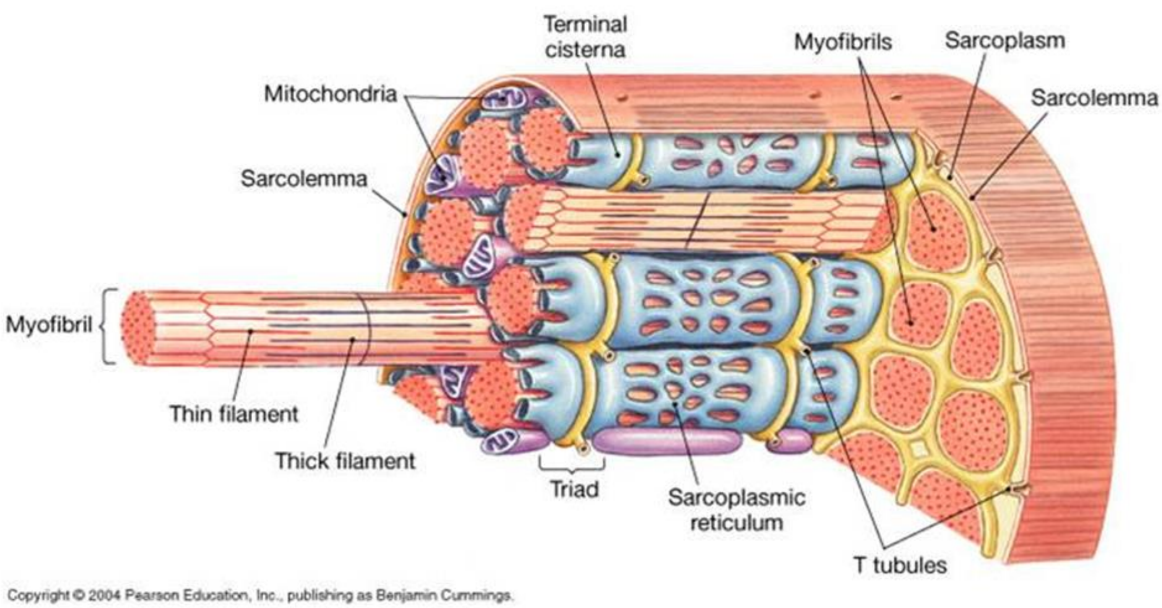

Figure 9: Muscle fiber structure and internal components (Silverthorn, 2010).

pumped back into the SR through the Ca^{++} ATPase pumps (faster in type II) (Silverthorn, 2010). Type I and type IIA fibers are fatigue resistant due to the oxidative nature of these fibers (oxygen is present in these fibers), while type IIB fibers do become fatigued because of their anaerobic qualities and the buildup of hydrogen (H^+) ions (there is no oxygen to help remove the H^+ ions) (Silverthorn, 2010). Lastly, the three types of muscle fibers all differ in diameter. Type I fibers are small in diameter, type IIA fibers have a medium diameter while type IIB fibers are the largest of the three (Silverthorn, 2010). The nerves that innervate these muscle fibers will only innervate the same type of muscle fiber allowing all of the same type of fiber to contract together.

Myofibrils are made up of a series of sarcomeres which act as the basic contractile unit of the muscle which aid in movement of the skeleton. These sarcomeres are repeating units of myofilaments, combination of thick and thin filaments, which show the striations seen in muscle tissue (Figure 10) (Enoka, 2008). Sarcomeres can be broken down into different fragments that together form the whole sarcomere. The A band runs the entire length of the thick filament and encompasses both the thick and

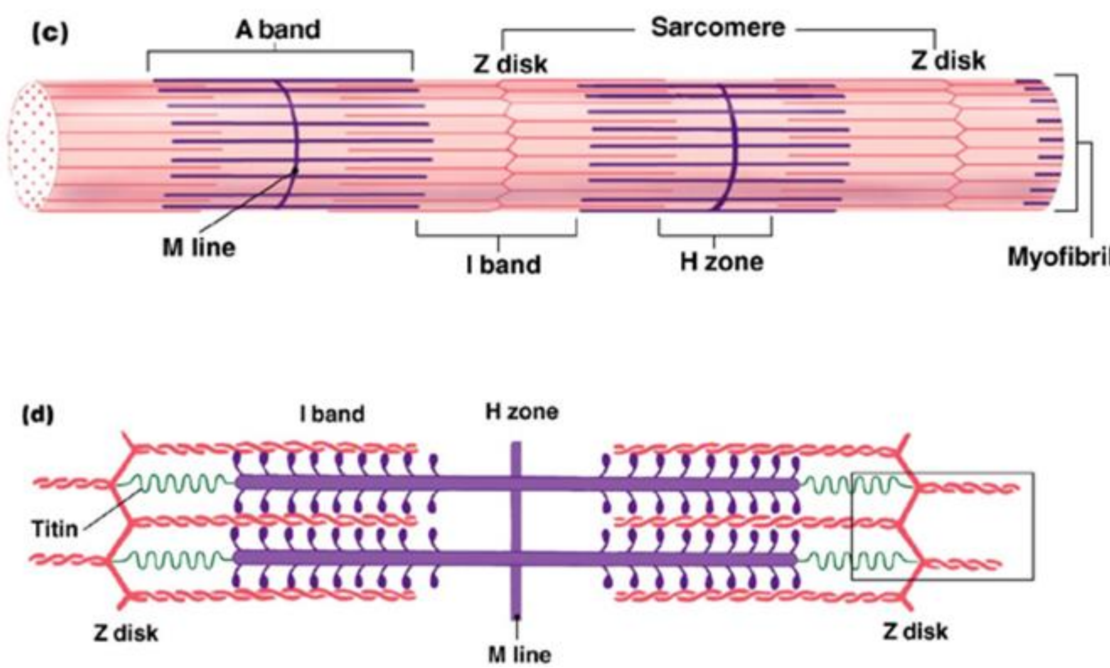

Figure 10: Structure of a sarcomere(Silverthorn, 2010).

thin filaments (Silverthorn, 2010). Where the H zone only contains thick filaments and the I band is only thin filaments (Silverthorn, 2010). The M line is the attachment site for thick filaments and it divides the A band in half (Silverthorn, 2010). Each sarcomere has two Z disks, the myofilaments run between them, and they serve as an attachment site for the thin filaments (Silverthorn, 2010). The I band is cut in half by the Z disk.

The thick and thin myofilaments that make up the sarcomeres are composed of several proteins. Thin filaments are comprised of actin, troponin and tropomyosin (Enoka, 2008). Actin is made from two helical strands of fibrous actin (F actin) that are formed from free globular actin (G actin) (Enoka, 2008). Located in the grooves of the F actin are two coiled strands of tropomyosin (Enoka, 2008). Located along the actin-tropomyosin chain is a troponin complex composed of three parts: troponin T which binds troponin to tropomyosin, troponin I which inhibits the binding of tropomyosin and troponin C which binds to Ca^{++} ions (Enoka, 2008). Thick filaments, also known as myosin, are long, two chain helical structures with two large globular heads (Enoka, 2008). Each of the two myosin heavy chains are made up of one essential myosin light chain and one regulatory myosin light chain (Enoka, 2008). Each globular head has a binding site for ATP as well as actin (Enoka, 2008). Along with these thick and thin filaments, there are other accessory proteins that aid the sarcomeres with muscle contraction. Titin is a protein that helps to stabilize the position of the contractile filaments. This protein extends from one Z disk to the M line and its elasticity helps to return the stretched muscles back to their resting length (Enoka, 2008). Nebulin is another accessory protein that lies along the thin filaments and attaches to the Z disk, it is however inelastic but aids is aligning the actin filament (Enoka, 2008). All of these myofilaments and accessory proteins work together to compress or stretch the sarcomere, creating muscle movement as well as generating force, which will be described in more detail further on.

2.2.2 MUSCLE FIBER RECRUITMENT

The force generated by motor units are directly dependent on the magnitude of force required for any given task. Depending on the required force, motor units are recruited based on two principles: the size principle and rate coding. The size principle relates to the type of motor units that are recruited, where during a ramping of force intensity, recruitment begins with small motor units being enlisted first and as more force is required large motor units are procured, and derecruited occurs in the inverse order, largest to smallest (Latash, 2008; Winter, 2005). The larger, fast twitch muscle fibers are used to generate larger forces while low forces are reached using smaller, slow twitch muscle fibers. Therefore, slow twitch muscle fibers are recruited first and if force demands increase then additional slow twitch fibers are recruited until all fibers are saturated (Latash, 2008; Winter, 2005). Then once all the slow twitch fibers are saturated, the fast twitch motor units are recruited until the force requirements are fulfilled (Latash, 2008; Winter, 2005).

Rate coding is the process of how the quickly the motor unit fires and is also dependent on the force demands (Winter, 2005). A low force will have a lower firing rate than that of a greater force, which will need a greater firing rate. For high forces, the slow twitch motor units recruited begin with a slower firing rate and as further tension is required, firing rate increases to meet these demands until firing rate is saturated and maximum tension occurs (Winter, 2005). Once all the slow twitch muscle fibers are saturated then fast twitch muscle fibers are recruited where the same process of firing patterns occur until the necessary force is met (Winter, 2005). Therefore, the faster the firing rate, the more force the muscle is able to produce. The reduction of muscle tension is again done in the reverse order, lowering of the firing rate with the fast twitch muscle fibers being dropped first (Winter, 2005).

2.2.3 RESTING MEMBRANE POTENTIAL

A motor unit action potential is an electrical stimulus that depolarizes the muscle membrane to trigger a muscle contraction (Silverthorn, 2010). However, before this signal can be passed along the membrane, it is beneficial for the muscle membrane to be within a state of resting membrane potential (RMP). It is best that the membrane is at or near resting potential so that a stronger stimulus is not needed to trigger additional action potentials. This resting potential is determined by the quantities of ions inside and outside the cell. Sodium (Na^+), chloride (Cl^-) and Ca^{++} are more concentrated outside of the cell while potassium (K^+) is more concentrated inside of the cell (Silverthorn, 2010). Na^+ and K^+ are the main ions whose movements across the membrane help determine the membrane potential (Silverthorn, 2010). Resting membrane potential is the potential that occurs when the ions inside and outside of the cell have found a steady state and are at 'rest'. To achieve this state there is a transfer of ions through the cell membrane, however, the cell membrane is more permeable to K^+, which allows it to play a major role in RMP (Silverthorn, 2010). The K^+ will travel out of the cell through K^+ leak channels and Na^+ enter the cell following the electrochemical gradient that forms (Silverthorn, 2010). To correct this movement of ions with the help of the Na^+/K^+ ATPase pump, 3 Na^+ are pumped out of the cell for every 2 K^+ pumped into the cell (Silverthorn, 2010). This Na^+/K^+ ATPase pump is used to return the membrane back to its resting potential because more Na^+ are pumped out allowing the inside of the cell to become negative, returning the membrane to its resting potential of -70 mV.

2.2.4 ACTION POTENTIAL PROPAGATION

Action potentials start off as graded potentials before they propagate down the muscle membrane, and these graded potentials are directly proportional to the strength of the stimulus that triggers them. As the stimulus travels down the membrane, the membrane potential changes due to voltage gated ions channels opening in respond to the stimulus. This electrical signal triggers the opening of the voltage gated Na^+ channels and Na^+ enters the cell, depolarizing the cell and making the cell become more positive (Silverthorn, 2010). The stronger the signal, the more voltage gated Na^+ channels open and the more positive the cell will become. If the signal is strong enough and enough Na^+ enters the cell, and the cell membrane potential raises from -70 mV to - 55 mV (threshold) than the graded potential becomes an action potential (Silverthorn, 2010). This means that the electrical signal will be propagated all the way down the membrane and will not die out like graded potentials eventually do if not strong enough. Once the membrane depolarizes to threshold, the remaining voltage gated Na^+ channels open quickly and Na^+ rushes into the cell, along with the voltage gated K^+ channels that also begin to open, only at a much slower pace (Silverthorn, 2010). With the rapid Na^+ entry, the cell membrane depolarizes to approximately +30 mV (Silverthorn, 2010). At the peak depolarization, the Na^+ channels close and the slower K^+ channels are now open. K^+ now starts to move out of the cell into the extracellular fluid and the membrane begins to repolarize, but with the K^+ channel delays, the channels are slow to close and additional K^+ leaves the cell causing the membrane to hyperpolarize (Silverthorn, 2010). Once these delayed voltage gated K^+ channels close, the membrane returns to resting membrane potential with the aid of the Na^+/K^+ ATPase pumps located on the membrane, as described earlier (Silverthorn, 2010). The full action potential sequence can be seen in Figure 11 (Silverthorn, 2010). These action potentials trigger a consecutive line of action potentials down the membrane until the axon terminal is reached at the end of the neuron that borders the muscle membrane, creating a synapse.

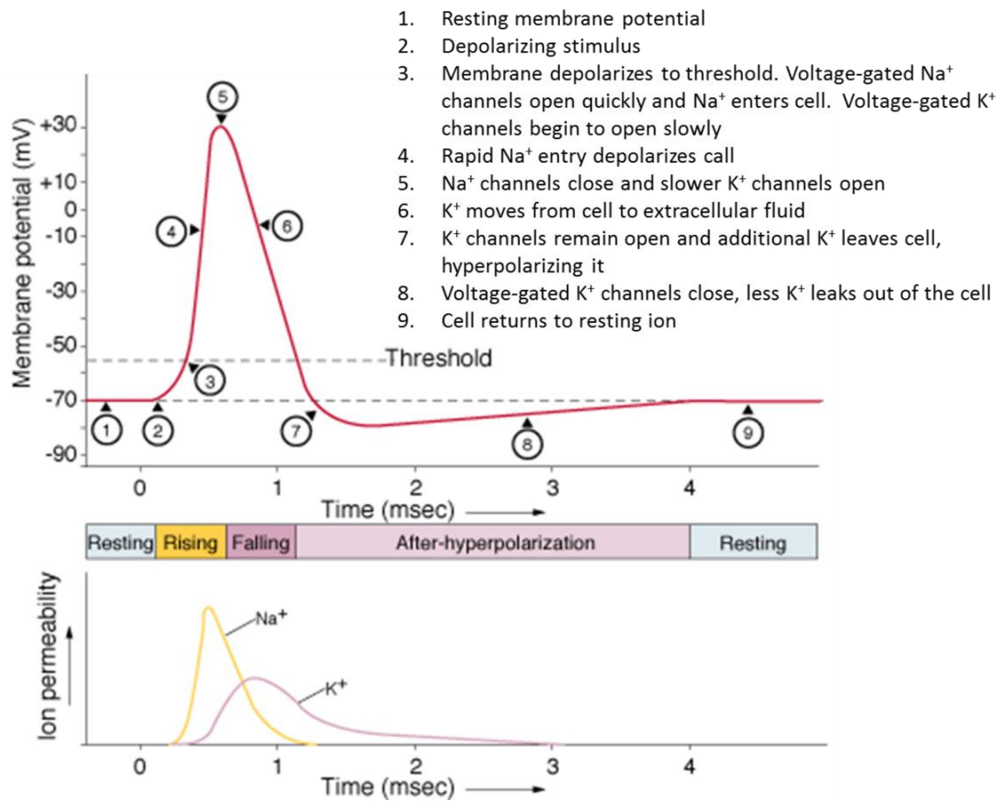

Figure 11: Action potential sequence from resting potential, through graded potential to threshold triggering an action potential and then back to resting membrane potential (Silverthorn, 2010).

2.2.5 EXCITATION-CONTRACTION COUPLING

Once an action potential reaches the axon terminal, an event termed excitation contraction coupling takes place. Excitation contraction coupling is a combination of electrical and chemical events that lead to a muscle contraction (Silverthorn, 2010). This synaptic transmission (Figure 12) from presynaptic cell to postsynaptic cell begins when an action potential reaches the axon terminal and triggers voltage gated Ca^{++} channels to open, allowing an influx of Ca^{++} to enter the terminal (Silverthorn, 2010). The inside of axon terminals contain vesicles which hold the neurotransmitter, acetylcholine (Ach). The Ca^{++} that enters the terminal binds to these vesicles and allows a conformational change. This change in structure of the vesicle allows it to bind to the presynaptic membrane, which is the membrane that borders the gap between the axon and the muscle otherwise known as the neuromuscular junction (Silverthorn, 2010). With the

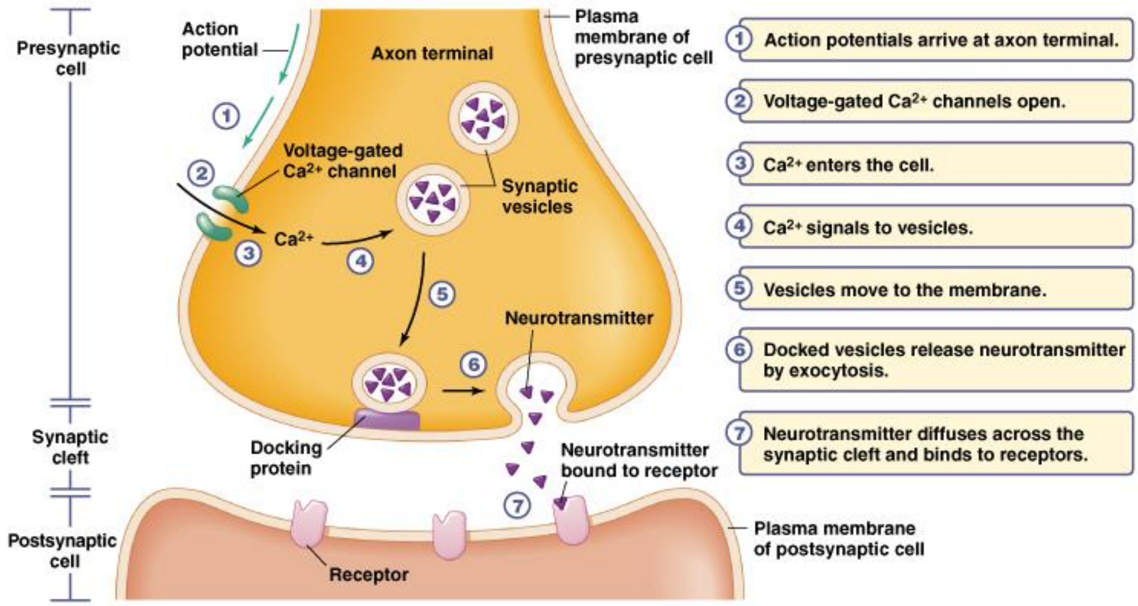

Figure 12: Synaptic transmission between an axon terminal and a muscle membrane (Moyes & Schulte, 2008).

vesicle now bound to the presynaptic membrane, the Ach inside the vesicle is released into the synaptic cleft, the space between the pre and post synaptic membranes

(Silverthorn, 2010). Two Ach bind to each chemically (ligand) gated Na^+/K^+ channels which cause the channels to open (Silverthorn, 2010). Similar to the Na^+/K^+ ATPase pump, 3 Na^+ enter the muscle fiber while 2 K^+ leave. This trade of ions depolarizes the muscle membrane and in turn the depolarization travels to voltage gated Na^+ channels. These Na^+ channels allow Na^+ to enter the cell and, like the depolarization of the axon membrane, the muscle fiber membrane depolarizes and the action potential is now able to travel further along this surface. The action potential propagates along the muscle fiber membrane and enters the t-tubule where it encounters the voltage sensitive dihydropyridine receptors (Silverthorn, 2010). The dihydropyridine receptors undergo a conformational change when the electrical stimulus comes into contact, and this change pulls open the ryanodine receptor which is located on the sarcoplasmic reticulum (Silverthorn, 2010). The opening of the ryanodine receptors allow Ca^{++} to enter the cytoplasm of the muscle fiber and aid in muscle contraction (Silverthorn, 2010). This calcium release mechanism in the excitation-contraction coupling is seen in Figure 13.

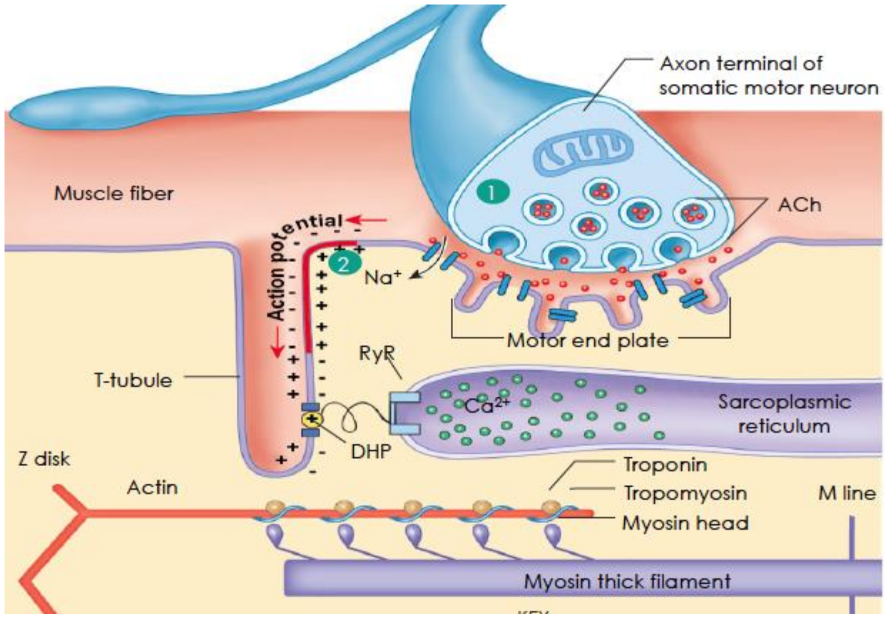

Figure 13: Calcium release mechanism involving the t-tubules and the sarcoplasmic reticulum (Silverthorn, 2010).

2.2.6 SLIDING FILAMENT THEORY

The Ca^{++} that enters the cytoplasm plays an important role in muscle contraction, specifically at the onset of the sliding filament theory. The Ca^{++} that is now in the cytoplasm binds to troponin C forming the Ca^{++}-troponin complex (Silverthorn, 2010). The Ca^{++}-troponin complex pulls tropomyosin completely away from the myosin binding sites allowing the myosin heads to form a strong, high force cross bridge with actin to carry out the cross bridge cycle (Figure 14) (Silverthorn, 2010). When the myosin head is lacking a nucleotide it is locked tightly onto the actin filament. Once adenosine triphosphate (ATP) binds to the myosin head, there is a slight conformational change that reduces the affinity of the myosin head to actin, allowing the myosin head to be released (Silverthorn, 2010). The ATP attached to the myosin head is then undergoes hydrolysis which gives you energy, adenosine diphosphate (ADP) and inorganic

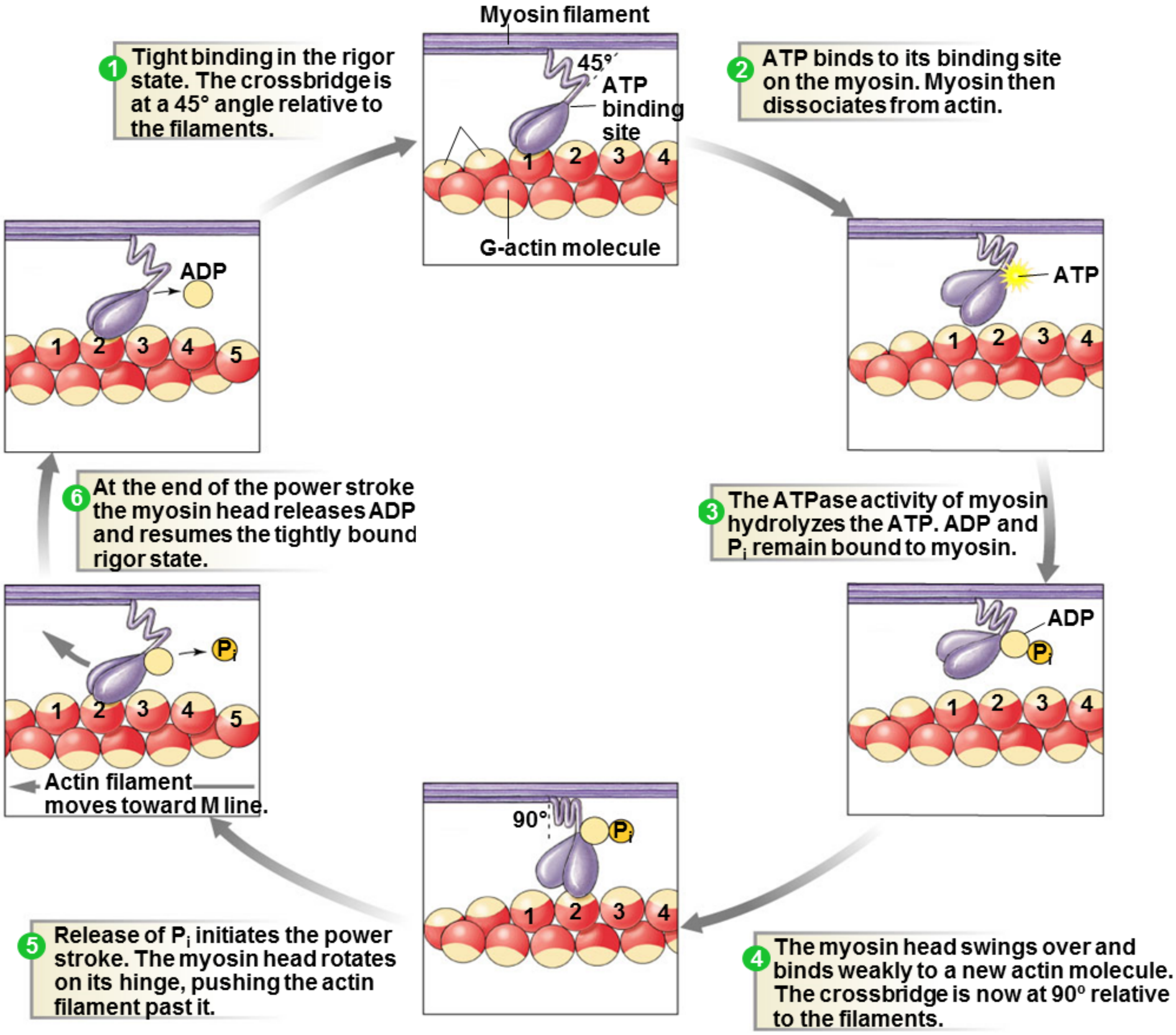

Figure 14: The cross bridge cycle (Silverthorn, 2010).

phosphate (Pi). The hydrolysis is what causes the displacement, or cocking, of the myosin head along the filament and the myosin head then reattaches to the actin filament (Silverthorn, 2010). The weak binding of the myosin head to the new site on the actin filament is what causes the release of Pi which triggers the power stroke, which is the force generating change in shape during which the myosin head returns to its original conformation (Silverthorn, 2010). During the power stroke, the myosin head loses its bound ADP which then firmly locks the myosin head to the actin filament and the actin-myosin complex is ready to undergo another cross bridge cycle (Silverthorn, 2010). The actin filaments move and the contractile cycles repeat as long as binding sites are uncovered. Muscle relaxation occurs once Ca^{++} unbinds from troponin C and tropomyosin returns back to blocking the myosin binding sites on actin, then actin and myosin slide back to their resting position with the aid of titin (Silverthorn, 2010). The Ca^{++} that was released from troponin C undergoes reuptake back into the sarcoplasmic reticulum as well as into the extracellular fluid with the aid of the Ca^{++} ATPase pump (Ca^{++} pumped through with the help of ATP) and the Na^{+}/Ca^{++} exchanger (3 Na^{+} ions in for every 1 Ca^{++} pumped out) (Silverthorn, 2010).

2.2.7 MUSCLE PROPRIOCEPTORS

Muscle spindles (Figure 15) are slowly adapting nerve endings that are aligned parallel to and wrap around specialized muscle fibers called intrafusal fibers (Marieb, Wilhelm, & Mallatt, 2012). The intrafusal fiber and its sensory nerve ending are anchored to the endomysium and perimysium through the connective tissue capsule that encloses them (Marieb et al., 2012). Muscle spindles sense muscle length and stretch and are abundant in muscles that produce fine movement but sparse in muscles that produce more forceful movement (Marieb et al., 2012). When a muscle stretches, the muscle spindle sends information quickly up the sensory neurons to the somatic sensory areas of the cerebral cortex which allows for conscious awareness of limb position and movement (Marieb et al., 2012). The information is then transmitted to the cerebellum where the input is used to coordinate muscle contraction in response to the stimulus (Marieb et al., 2012). The impulse then travels from the cerebellum in the central nervous system (CNS) down the gamma motor neurons where they terminate near both ends of the intrafusal fibers (Marieb et al., 2012). The gamma motor neurons help the muscle spindles adjust for tension in the variations in the muscle length to keep the intrafusal fibers tight and to help maintain their sensitivity to stretching (Marieb et al., 2012). There are also extrafusal

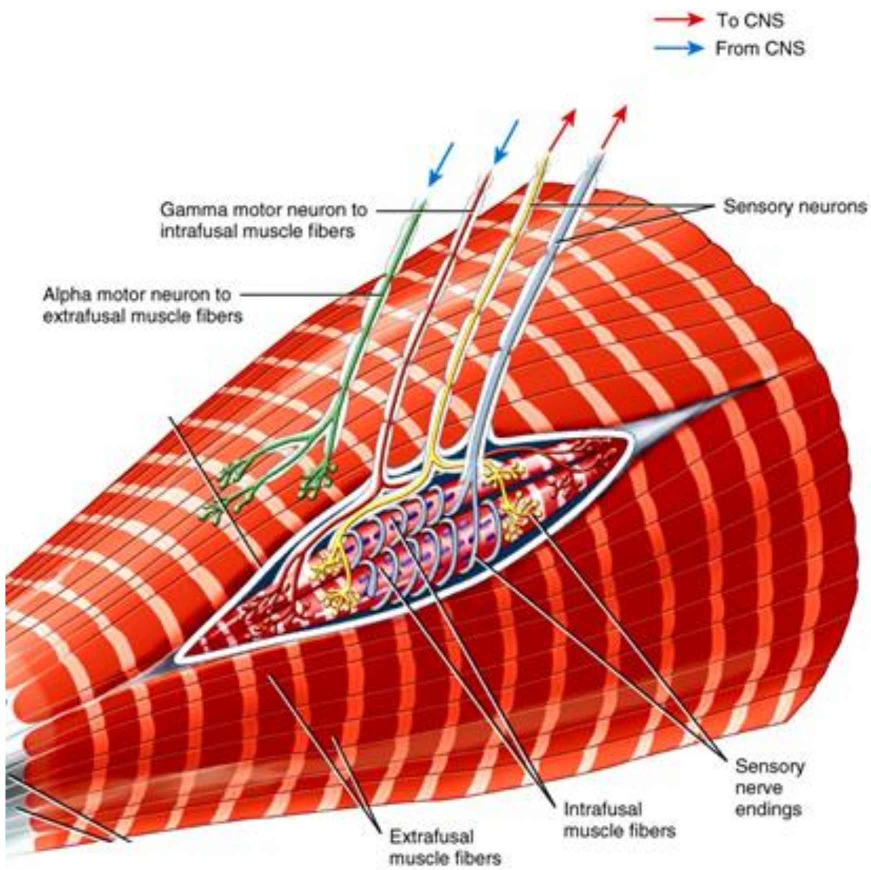

Figure 15: Muscle spindle (Tortora & Neilson, 2012).

muscle fibers surrounding the muscle spindles, and these fibers are innervated by alpha motor neurons (Marieb et al., 2012). When a muscle stretches, an electrical signal is transmitted up the sensory axons into the spinal cord and the brain for interpretation of the signal. Once the response to the signal has been determined, the alpha motor neurons are activated and they trigger the extrafusal fibers to contract, which relieves the stretching (Marieb et al., 2012).

Golgi tendon organs (GTO) are slowly adapting proprioceptors that are located at the junction of the tendon and the muscle, and sense excessive tension (Figure 16) (Marieb et al., 2012). Every few tendon fascicles are enclosed in a capsule of connective tissue with sensory nerve endings innervating each capsule and winding among the collagen fibers, this makes up a GTO receptor (Marieb et al., 2012). Once a muscle experiences tension, the GTO generates an impulse about the tension that is transmitted into the CNS (Marieb et al., 2012). The CNS then triggers the tendon reflex causes relaxation by decreasing muscle tension (Marieb et al., 2012).

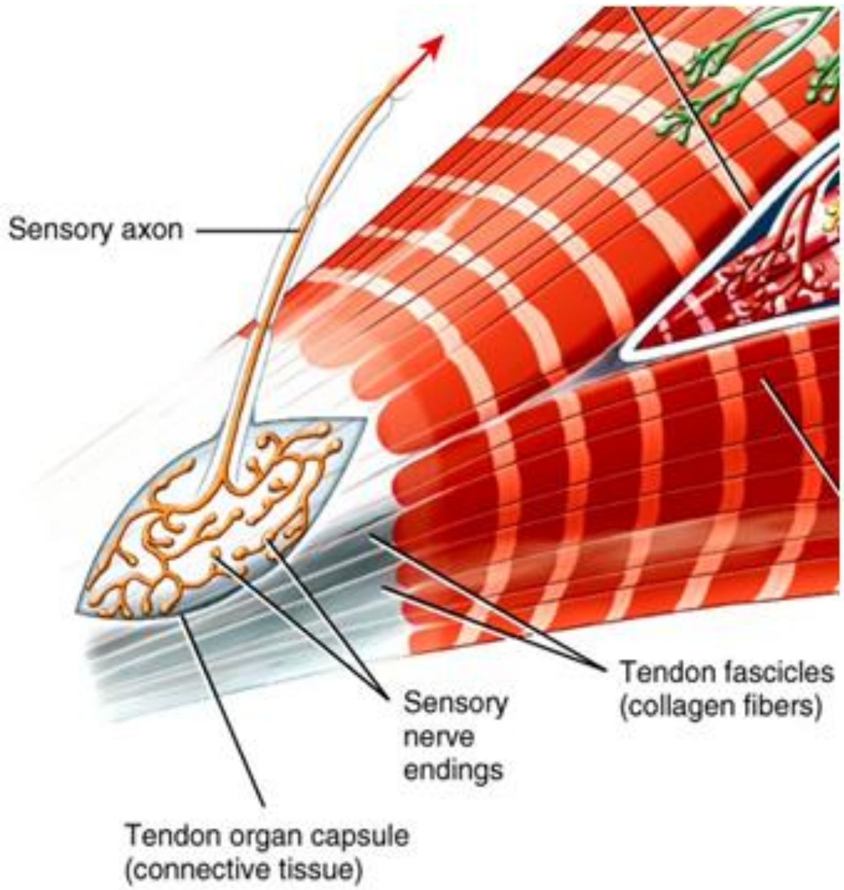

Figure 16: Golgi tendon organ (Tortora & Neilson, 2012).

2.3 MUSCLE FORCE PRODUCTION

2.3.1 CONTRACTIONS

Muscle is able to contract in three different ways: isometric, concentric and eccentric. Isometric contractions are a static contraction in which muscle fibers maintain a constant length (Criswell, 2011). This constant length occurs because the contractile force is not able to overcome the force of resistance, therefore there is no change in muscle length (Criswell, 2011). Isometric contractions are typically used for postural control, stability, as well as during maximum voluntary exertions (MVE) (Criswell, 2011).

Concentric contractions are defined as the length shortening of the muscle during contraction (Criswell, 2011). This shortening occurs because the contractile force is enough to overcome the external resistance, and is normally experienced by the primary muscle during a movement pattern (Criswell, 2011). Due to the shortening of the muscle, 20% of its energy efficiency is lost during concentric contraction leaving the muscle with only 80% of the load that is seen during MVE (Criswell, 2011).

Inverse to concentric contractions are eccentric contractions, which is defined as the lengthening of muscles (Criswell, 2011). Technically, eccentric contractions occur when the tension in the muscle cannot overpower the external force that is being experienced (Criswell, 2011). Any movement that follows the direction of gravity is considered an eccentric contraction. Lengthening muscles tend to expend less energy to complete that action than it does to shorten a muscle, about one-third to one-thirteenth the work needed to perform a concentric contraction (Criswell, 2011).

2.3.2. TENSION

Muscle tension can occur both passively and actively. Passive tension occurs when the muscle undergoes a gradual stretch, and the connective tissues of that muscle (endomysium, perimysium, epimysium, and tendon) resist the stretching (Enoka, 2008). Passive tension is not present when the muscle is at its resting length or less, but as soon as the muscle begins to lengthen, passive force increases (Winter, 2005). Active force is the force produced when the muscle undergoes contraction using cross bridge cycling and sliding filament theory to produce movement (Enoka, 2008). Active force, force created using contractile elements, has an optimal length at where maximum force is produced and as it moves away from this length, the force decreases (Winter, 2005). Therefore, total tension that the muscle experiences is affected by both the passive and active forces acting on the muscle (Winter, 2005).

2.4 MUSCLE RELATIONSHIPS

2.4.1 EMG TO FORCE

The force that the muscle can generate is correlated to the amplitude of the muscles captured using EMG. This relationship between force and captured muscle amplitude can differ when comparing different muscles, different individuals as well as different actions (seen in Figure 17). It has been found by Lawrence & DeLuca (1983) that smaller, less force producing, muscles tend to have a more linear relationship between EMG signal and force while larger, greater force producing muscles have a more curvilinear relationship. This is shown in Figure 17, with the first dorsal interosseous muscle, which is a small muscle, being more linear than the biceps brachii or deltoid. This curvilinear relationship between force and EMG is thought to be due to different firing rates of the muscle fibers, recruitment properties of the muscle fibers, the amount and location of slow and fast twitch muscle fibers as well as agonist-antagonist (aids in the movement – resists the movement) muscle interaction (Criswell, 2011; Lawrence & DeLuca, 1983). EMG amplitudes are also seen to be greater for concentric (muscle shortening) contractions compared to eccentric (muscle lengthening) contractions when using the same weight (Criswell, 2011).

2.4.2 LENGTH-TENSION

The amount of active force that a muscle can produce is related to the resting length of the muscle. Each sarcomere has the ability to produce optimum force only if it resides within its resting length before the mechanical events of a contraction occurs, as shown in Figure 18 (Criswell, 2011). It is favorable for the muscle to be within its resting length because the number of cross bridges that actin

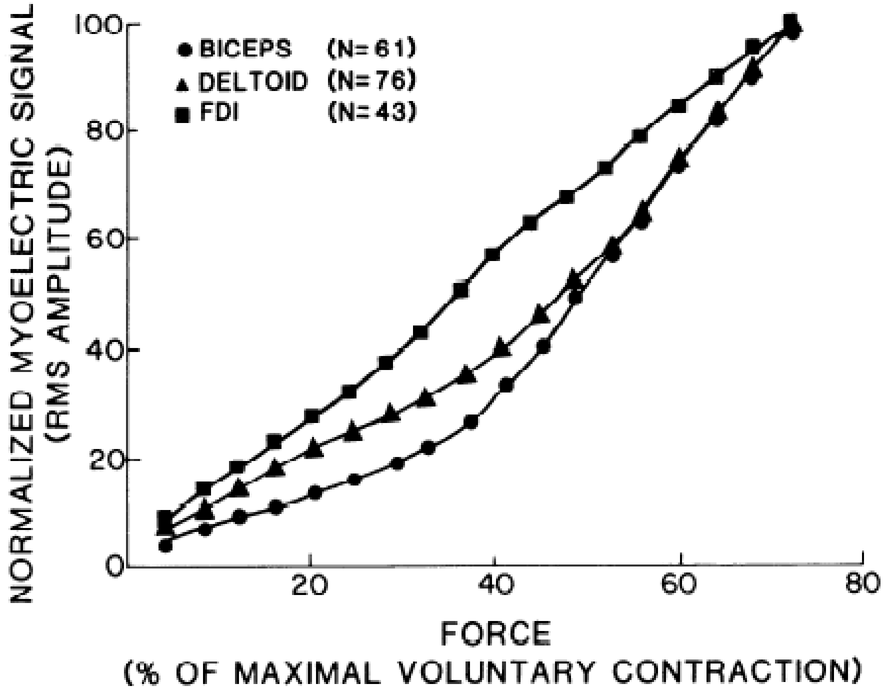

Figure 17: Force – EMG relationship between the biceps brachii, deltoid and first dorsal interosseous muscles, showing the linear and curvilinear differences (Lawrence & DeLuca, 1983).

and myosin are able to form is directly proportional to the tension that the muscle fiber is able to produce (Criswell, 2011). If the sarcomere lengthened beyond the resting length then the filaments are not overlapping an appropriate amount and, very few cross bridges will form resulting in low force generation (Criswell, 2011). On the other hand, if the sarcomere is shorter than resting length the filaments have too much overlap and can only move a short distance, negatively affecting force production (Criswell, 2011).

Active force alone does not create total muscle tension, it is a combination of active and passive forces. Passive force is produced through the connective tissues associated with each muscle, and aids in the opposition of a lengthening of muscle (Figure 18) (Winter, 2005). At shorter lengths, the passive forces are not present as the muscles are not being stretched and the force produced will be created fully by the active contractile elements (Caldwell, 2004). As the muscle length increases, the passive connective tissues become stretched and produce force which is added to the active forces already present, creating total tension (Figure 18) (Caldwell, 2004; Morgan & Allen, 1999).

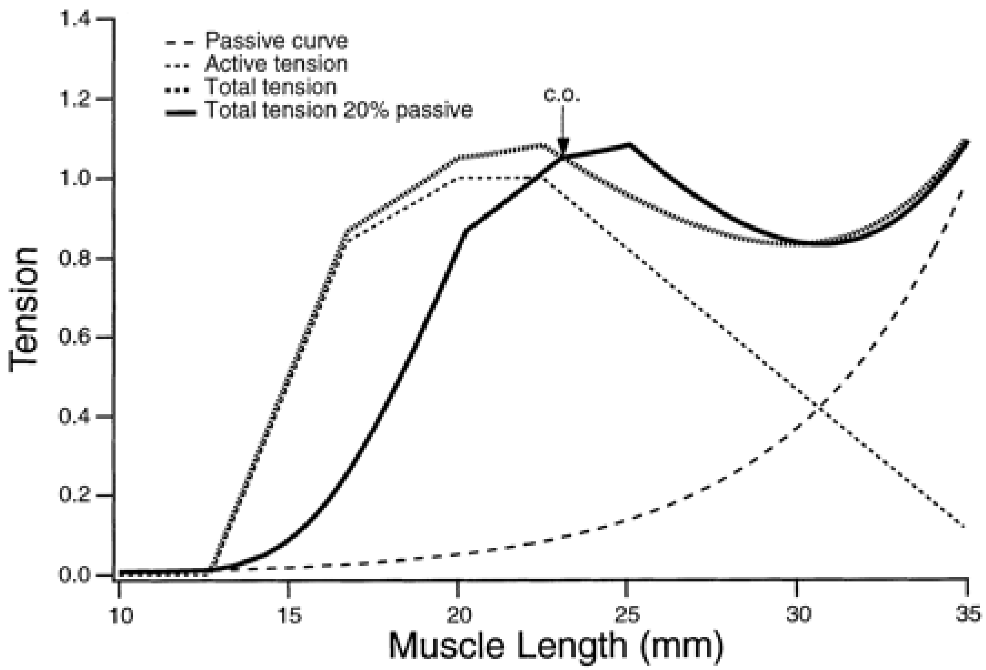

Figure 18: Muscle length – tension relationship showing passive, active and total tension (Morgan & Allen, 1999).

2.4.3 FORCE-VELOCITY

The speed at which a muscle contracts affects the force that the muscle produces (Figure 19), and this contractile speed is limited by the rate at which the thick and thin filaments can complete the cross bridge cycle (Criswell, 2011). Compared to eccentric contractions, concentric contractions produce less force due to the formation of the cross bridge complex in a shortened length than what is optimal, muscle length-tension relationship shown in Figure 18 (Criswell, 2011; Winter, 2005). Faster concentric contractions also develop less force than slower concentric contractions as a result of the greater speed and the lack of time to complete the necessary cross bridge complexes to increase the force (Criswell, 2011; Winter, 2005). As alluded to earlier, eccentric contractions produce more force than concentric contractions. The force that eccentric contractions produce also increase as velocity increases due to the greater force needed to break the cross bridge attachment than that needed to keep the muscle in an isometric contraction (Criswell, 2011; Winter, 2005).

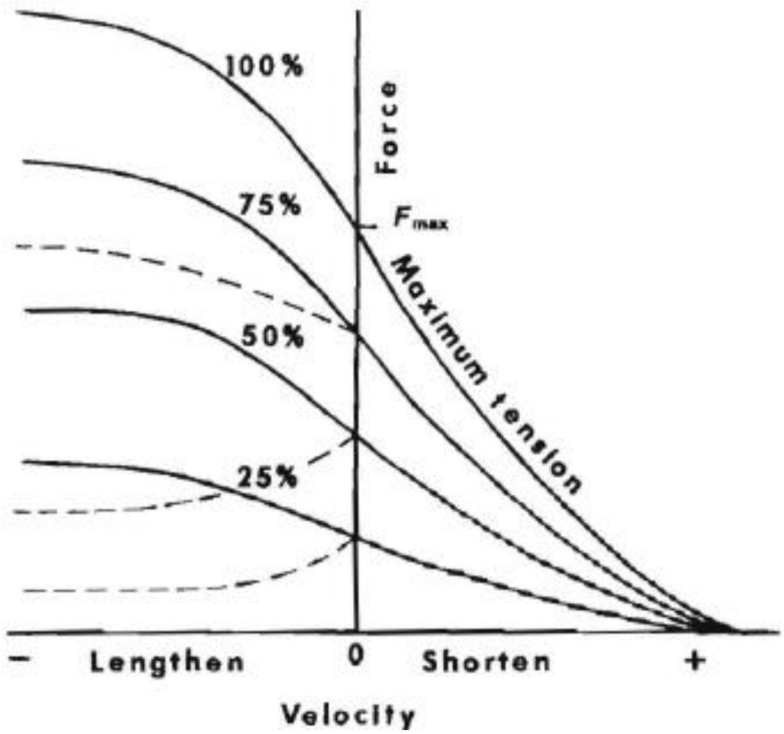

Figure 19: Force – velocity relationship: effects of force between different velocities as well as during the lengthening or contracting of muscles (Winter, 2005).

2.5 WORK-RELATED MUSCULOSKELETAL INJURIES OF THE UPPER EXTREMITY

With the high demand for automobiles and the greater use of power tools used in the industry operators are being exposed to repetition, overexertion and awkward posture related injuries (Freivalds & Eklund, 1993; WSIB, 2013). Based on the statistics from the Workplace Safety Insurance Board from 2013 both automotive and manufacturing (construct the parts used on automotive field) account for 19% of the total lost time claims in Ontario.

As described earlier, the torque reaction forces that operators experience can cause muscles in the hand-arm system to become damaged when the muscles undergo rapid eccentric contractions. These damaged muscle fibers can cause the operator to experience a decrease in muscle force, which will be discussed below, and along with the repetitious nature of some work, this can potentially lead to even more serious injuries because the operators will not be able to oppose the peak torque reaction force that they experience on the job.

Work-related cumulative trauma disorders result from repetitive tissue damage, no matter how small (Rempel et al., 1992). This tissue damage can eventually lead to tendon disorders, degenerative joint disease, bursitis and nerve entrapment (Rempel et al., 1992). The operators may also need to adopt awkward postures to complete the task and repeatedly getting into these postures can lead to joint or back problems (Rempel et al., 1992). An example of work related musculoskeletal disorder is chronic shoulder pain. The pain is caused by damaged type 1 muscle fibers that degenerate as a result of being activated for too long of a time periods and/or being associated with too short of a recovery time (Forsman, Birch, Zhang, & Kadefors, 2001). These type 1 muscle fibers are part of the low threshold motor units which are recruited at the onset of muscle activation and are firing continuously until the muscle is relaxed, which fatigues the fibers and makes the susceptible to injuries (Forsman et al., 2001).

2.5.1 FATIGUE AND MUSCLE DAMAGE

Muscle tissue fatigue occurs when muscles are no longer able to contract at the force necessary to complete desired tasks. This decrease in force production can be associated with the decrease in energy sources (ATP, glucose) as well as the buildup of metabolites (P_i and ADP) (Ament & Verkeke, 2009; Criswell, 2011; Debold, 2012). The increase in inorganic phosphate (P_i), which comes from the breakdown of ATP, inhibits cross bridge formation (Ament & Verkeke, 2009; Debold, 2012). While the increase in ADP, which also comes from the breakdown of ATP, slows the cross bridge cycle velocity (Ament & Verkeke, 2009; Debold, 2012).

The EMG signal and its associated frequency spectrum has been shown to shift from high frequency to lower frequencies with fatigue (Criswell, 2011; Latash, 2008). This shift in frequencies can be attributed to the synchronization of motor unit recruitment patterns, a slowing of the conduction velocities of the muscle fibers, a shift in dominance from fast twitch to slow twitch as a result of the fatigability of the fast twitch fibers or, a combination of both factors (Ament & Verkeke, 2009; Criswell, 2011; Debold, 2012).

2.5.2 ECCENTRIC STRETCHING DAMAGE

2.5.2.1 SARCOMERE DISRUPTION

Rapid eccentric lengthening has been proven to tear muscle fibers (Proske & Morgan, 2001). When this eccentric stretching occurs, the change in length is mainly a result of the weakest sarcomeres lengthening (Morgan, 1990). As the muscles reach the descending area of the length-tension curve (Figure 16), these sarcomeres become increasingly weaker (Morgan, 1990). Once the sarcomeres reach their yield point they will rapidly and uncontrollably lengthen until there is no longer any myofilament overlap (Morgan, 1990). This occurs with the next weakest sarcomere and so on until there is no longer any stretching. Once the lengthening is complete and the muscle relaxes then the myofilaments can realign into their previous overlapping structure to return to their normal function (Morgan, 1990). If the lengthening is too severe than the sarcomeres may fail to realign and become disrupted (Talbot & Morgan, 1996). As the eccentric contractions are repeated, the number of disrupted sarcomeres grow until damage occurs to the membrane, and the excitation contraction coupling mechanism becomes damaged (this will be discussed below) (Proske & Morgan, 2001). Sarcomere disruption could be due to damage to the elastic filament titin which aids the sarcomere in structural support, as well as, returning the sarcomere to resting length after undergoing a lengthening (Allen, 2001). The disrupted sarcomeres structure after eccentric stretching is composed to an overstretched half sarcomere with the other half of the sarcomere contracted down to a short length (Talbot &

Morgan, 1996). Shift in optimum length for active tension would take place, favoring longer muscle lengths (Katz, 1939).

2.5.2.2 EXCITATION-CONTRACTION COUPLING DAMAGE

Eccentric lengthening has also been shown to cause damage to the excitation-contraction coupling mechanism through damage to the sarcomere membrane (Proske & Morgan, 2001). Eccentric lengthening would cause the muscle membrane to become damaged and the t-tubules to rupture and the ends to seal off which in turn inactivate some of the sarcomeres (Takekura, Fujinami, Nishizawa, Ogasawara, & Kasuga, 2001). With the rupture of the t-tubules, the action potential cannot travel down the muscle membrane and trigger the release of Ca^{++} to signal muscle contraction. If all the sarcomeres were located in specific myofilaments than a fall in tension would occur (Takekura et al., 2001). If the damaged sarcomeres were scattered throughout the muscle then a shift in optimum length for active tension would take place, favoring longer muscle lengths (as seen with the sarcomere disruption) (Takekura et al., 2001).

2.5.3 CHANGES SEEN AFTER ECCENTRIC EXERCISE

2.5.3.1 DECREASE IN FORCE

After a muscle undergoes eccentric contraction, whether its once or many times, a decline in force will be seen from the buildup of metabolites such as Pi (Ament & Verkeke, 2009; Debold, 2012). The increase in Pi can lead to the unbinding of cross bridges due to Pi binding onto the myosin heads instead of ATP, causing myosin to detach and reducing the number of strongly bound cross bridges (Debold, 2012). This decline in force can also be caused from the damage to the sarcomeres and the disruption to the excitation-contraction coupling. These damages caused from eccentric lengthening can limit the action potentials from traveling down the sarcomere and stop the muscle contraction signal so that there are less cross bridges formed and therefore less muscle force.

2.5.3.2 FALL IN ACTIVE TENSION

Once an individual has undergone eccentric contractions, a fall in active tension is seen (Proske & Morgan, 2001). While this decline in tension will partly be due to metabolic fatigue (seen with all exercise), it could also be caused by a combination of sarcomere disruption, as well as, damage to the myofibril and membrane leading to excitation-contraction coupling damage (Proske & Morgan, 2001). There is a point for the muscle fibers where the damage is too severe and the muscle fibers die, also resulting in a decline in tension (Proske & Morgan, 2001). MacIntyre, Reid, & McKenzie (1995) state that there is also a delayed fall in tension associated with eccentric exercise. There is an initial fall after the exercise (metabolic fatigue) followed by a slow rise over 2-4 hours (metabolic exhaustion recovery), then 24 hours later there is a second fall in tension (possible death of some muscle fibers) (MacIntyre, Reid, & McKenzie, 1995). This fall in active tension will affect the amount of force that can be produced of the decline in the number of possible muscle fibers or the damage to the sarcomeres that limit the action potentials from travels down to trigger muscle contraction.

2.5.3.3 SHIFT IN OPTIMAL LENGTH FOR ACTIVE TENSION

With eccentric exercise, the sarcomeres remain overextended and are not overlapping. Due to this lack of overlapping, the neighboring sarcomeres must take up a shorter length than before the contractions. Therefore, the muscles also have to be stretched further before passive tension in the shorter sarcomeres become measurable (Proske & Morgan, 2001). Since muscles are composed to multiple fiber types which each have their own specific optimal length, stretching whole muscles lead to fibers being stretched further down their descending limb of their length-tension curve than is desirable (Proske & Morgan, 2001). This shift in optimal length for active tension will lead to a decline in force production because the same number of cross bridges will not be able to be formed.

2.5.3.4 RISE IN PASSIVE TENSION

Passive tension in muscles that have undergone eccentric contractions have more than doubled after the exercise was completed and has remained elevated over the next four days (Howell, Chleboun, & Conaster, 1993). This four day elevation is thought to be due to stretch activated calcium release within the muscle fibers (Howell et al., 1993; Proske & Morgan, 2001). It is also believed that this rise in passive tension can be linked to the permanent damage to muscle fibers from the eccentric stretching and these muscle fibers now act as elastic elements in the muscle (Allen, 2001; Katz, 1939).

2.6 EMG

Surface electromyography or sEMG is the collection and analysis of a muscles electrical activity in a noninvasive approach (Criswell, 2011). EMG can be used by many different professionals in many settings such as assessment, treatment planning, ergonomic design, rehabilitation, research and more (Criswell, 2011). Surface EMG helps to distinguish between believed muscle function and actual muscle function and is commonly used to evaluate and treat different muscular problems (Criswell, 2011). EMG allows the observer to see how a muscle reacts when at rest to when it is undergoing contractions and helps to differentiate how different aspects of the muscle work (such as recruitment patterns, estimated force or muscle inactivity at specific times) (Criswell, 2011). Muscle activity is most commonly recorded with the use of electrodes that are placed directly on the surface of the skin. The electrodes are held on with a sticky adhesive, best stuck on clean and shaven skin to lower the change of impedance (Criswell, 2011). For proper recording of electrical activity, the electrodes should be places parallel to the muscle fibers to maximize selectivity and sensitivity (Criswell, 2011). These electrodes record the motor unit action potential as it travels down the muscle fibers to trigger a contraction (Criswell, 2011).

Different tissues, materials and other electrical activity in, on and around the human body can affect the EMG signal. Intermediate to the muscle fibers and the electrodes are materials that dampen the electrical signal from recording its un-filtered amplitude. The materials that filter some of the signal from reaching the electrode are known as impedance, a resistance to a direct current (Criswell, 2011). Skin can cause impedance due to the oils and dead skin cells on the surface, as well as the sweat that can be produced (Criswell, 2011). Fat tissue that underlies the skin can also act as resistance to the electrical signal, therefore, as the amount of adipose tissue present increases, the amount of signal that is blocked increases as well (Criswell, 2011). The medium that adheres the electrodes onto the skin can also imped the electrical signal from showing its true form (Criswell, 2011). If the impedance that the electrode experiences is too high or too imbalanced, than the common mode rejection ratio (the rejection ratio that eliminates common noises) is defeated (Criswell, 2011). Another factor that can affect the EMG signal is noise. Noise is anything that is captured in the EMG signal that isn't part of the muscles electrical activity (Criswell, 2011). These added signals could come from the participant's heartbeat, another muscle (crosstalk), movement of the electrode, noise from lights or other electrical devices or breathing among others (Criswell, 2011). Certain filters are used to help reduce and remove the noises in the signal (Criswell, 2011).

Once the muscles electrical activity is picked up by the electrodes on the skin surface, the signal is sent to an amplifier with the level of amplification depending on the strength of the signal that was collected. After amplification the signal than undergoes the common mode rejection ratio to remove the common noises (Criswell, 2011). This signal will then undergo analog filtering using a band pass filter of 10-1000 Hz that allows any signals within that frequency range to pass (Criswell, 2011). By removing the lower frequency electrical noise, such as a moving wire, and greater frequency tissue noise would be eliminated (Criswell, 2011). After analog filtering, the signal than gets digitized so that it can be used for computer analyses. The digital signal will undergo high pass filtering at 140 Hz (6^{th} order) (Potvin & Brown, 2004) and will then be rectified and filtered using a Butterworth filter at 2 Hz. EMG signals are recorded in both the positive and negative voltage direction, by rectifying the signal all the negative values become positive (absolute) values (Kamen, 2004). The rectified signals of the MVE's will be used to determine the peak values which will aid in the normalization of the data collected from the trials by comparing the two to determine how much of the maximum the muscles were performing at when undergoing the trials (Kamen, 2004).

CHAPTER 3: METHODS

3.1 PARTICIPANTS

Thirty-six healthy, injury free participants (18 males, 18 females) between the ages of 20-60 years old with no experience in automotive manufacturing were recruited for this proposed study. The recruited population were divided into three groups of 12 participants: 20-29 years (6 males, 6 females), 30-45 years (6 males, 6 females) and 46-60 years (6 males, 6 females).

3.2 INSTRUMENTATION AND MEASUREMENT

Whole-body kinematics were captured at a sample rate of 120 Hz using a 52-marker set (Raptor-4, Motion Analysis, Santa Rosa, California), shown in Figure 20. In addition, 16 channels of surface electromyography were collected bilaterally from the following muscles: pectoralis major, superior trapezius, anterior deltoid, biceps brachii, triceps brachii, flexor carpi ulnaris,

Marker#	Location
1	Top center of head
2	Mid-back of head
3	Middle of forehead
4	Left side of head, above ear
5	Right-back corner of head
6	Top of shoulder midway between neck and acromion process
7	Top of shoulder midway between neck and acromion process
8	Back of neck, above T1
9	Middle of sternum
10	Upper-left side of back on scapula (approx. T5)
11	Right-mid back (approx. L1)
12	Midway along long axis of humerous, top of bicep, offset laterally
13	Lateral side of elbow joint, over the joint center
14	Distal end of the humerus behind the elbow
15	midway along long axis of lower arm, on flat posterior surface
16	Lateral side of wrist over the radial styloid process
17	Medial side of wrist over the ulnar styloid process
18	Posterior side of hand, distal end of the 1st metacarpal
19	Posterior side of hand, middle of the 3rd metacarpal
20	Posterior side of hand, distal end of the 5th metacarpal
21	Midway along long axis of humerous, top of bicep, offset laterally
22	Lateral side of elbow joint, over the joint center
23	Distal end of the humerus behind the elbow
24	midway along long axis of lower arm, on flat posterior surface
25	Lateral side of wrist over the radial styloid process
26	Medial side of wrist over the ulnar styloid process
27	Posterior side of hand, distal end of the 1st metacarpal
28	Posterior side of hand, middle of the 3rd metacarpal
29	Posterior side of hand, distal end of the 5th metacarpal
30	On right ASIS
31	On left ASIS
32	On Right PSIS
33	On Left PSIS
34	Mid-back-top of sacrum
35	Right, lateral side of pelvis near greater trochanter
36	Left, lateral side of pelvis near greater trochanter
37	Antero-lateral of area thigh, 1/3 along length of femur
38	Postero-lateral of area thigh, 1/3 along length of femur
39	Lateral side of knee, approximately over the joint center
40	Anterior side of lower leg, midway along its length
41	On the lateral malleolus of the right fibula
42	On the posterior side of the heel
43	On the head of the 3rd metatarsal
44	Lateral side of 5th metatarsal, midway along its length
45	Antero-lateral of area thigh, 1/3 along length of femur
46	Postero-lateral of area thigh, 1/3 along length of femur
47	Lateral side of knee, approximately over the joint center
48	Anterior side of lower leg, midway along its length
49	On the lateral malleolus of the right fibula
50	On the posterior side of the heel
51	On the head of the 3rd metatarsal
52	Lateral side of 5th metatarsal, midway along its length

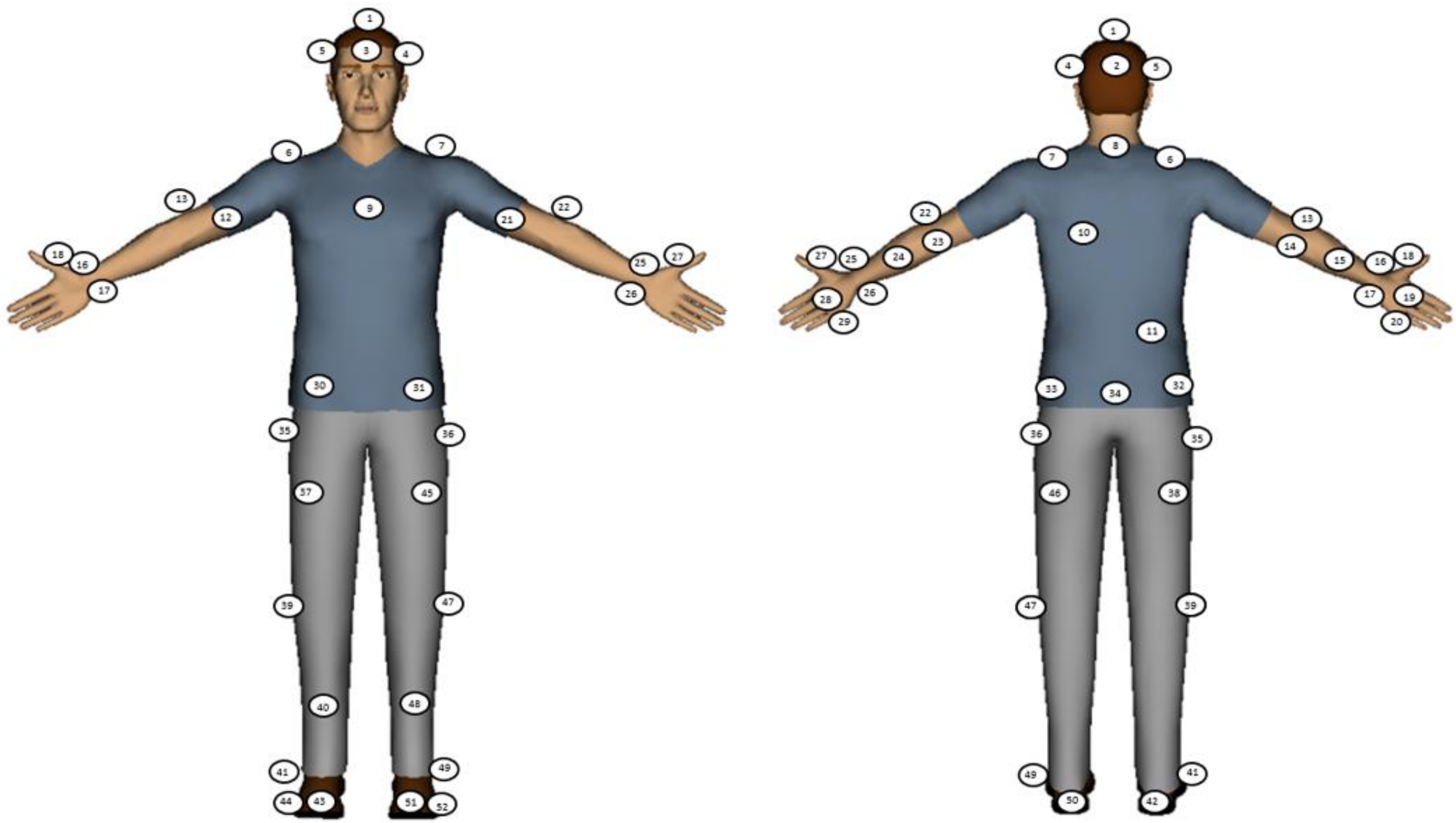

Figure 20: Configuration of the 52 passive marker placement that will be used on each participant

flexor carpi radialis, extensor carpi ulnaris. To measure the electrical activity of these muscles, wireless sensors were used with their four silver bars placed perpendicular to the direction of the muscle fibers and the arrow (on the top) placed parallel to the muscle fibers (Trigno EMG Sensors, Delsys, Boston, Massachusetts). These sensors were placed in the center of the muscle belly using a Delsys Adhesive Sensor Interface to attach the sensor to the skin. Surface EMG signals were amplified at 10-1000 Hz, with a common mode rejection ratio of 115 dB, a gain of 500-1000, input impedance of 10 GΩ, and a sample rate of 2000 Hz.

Each participant operated a direct current RAPT (Tensor ETV ST61-70-13, Atlas Copco, Mississauga, Ontario) with an instrumented handle attached to the distal end that will both control the tool, as well as record the 3 linear forces experienced while operating the tool, shown in Figure 21. Each fastener secure was performed on a stand designed for this study that

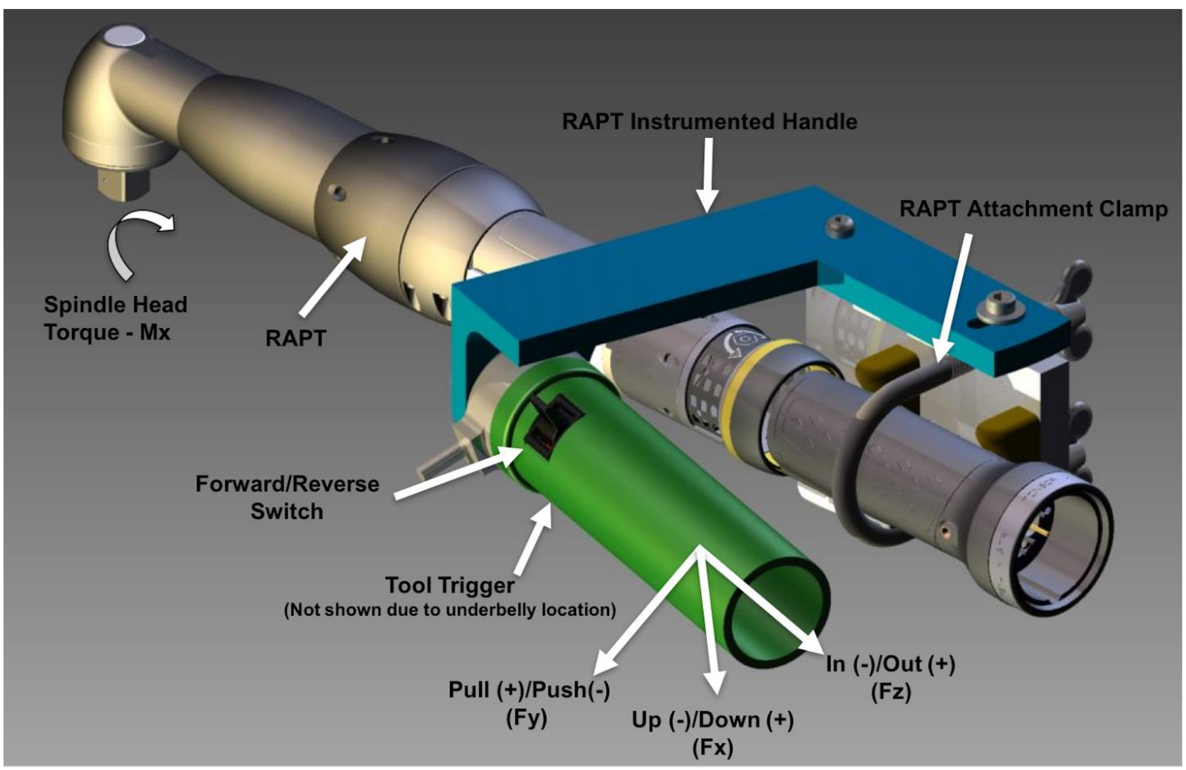

Figure 21:RAPT and Instrumented Handle Attached with Direction of Forces and components of the instrumented handle

allows for the exchange of the different joints that were used. The tool controller was adjusted for tightening strategy, joint type and desired target torque. This bench was also adjusted for each of the designated locations used in the study, which will be discussed later, and the researcher unfasten each joint once it had been tightened.

3.3 EXPERIMENTAL DESIGN

Each of the participants had their age, weight, height, and previous injury data collected. The participant's previous injury data was collected using the Standardized Nordic Questionnaire for Analysis of Musculoskeletal Symptoms (Kuorinka et al., 1987), available in appendix C. If the participant had a previous injury to the back or arms, they were excluded from the study. If the participants were deemed physically fit to take part in the study, the researched read the script describing the task to the participants (Appendix D), and they were allowed to spend 15 minutes becoming accustomed to the tool and joints that they were using by completing fastenings with the tool at the same target torques, fastening strategies and location-orientation they experienced during the study.

Prior to the experimental trials, the participants performed maximal voluntary exertions (MVE, maximum effort performed against a resistance) for each muscle. These MVE's were used during post-processing to normalize the surface EMG data collected during the experimental trials. The maximum voluntary exertions were performed with the research assistant providing resistance against the movement, examples of some of the MVE's shown in Figure 22. For the pectoralis major and the anterior deltoid, the participant performed a forward flexion of the arm against resistance placed on the upper extremity. For the biceps brachii, the participants performed a bicep curl against resistance that will occur on a supinated wrist. The participants performed a shoulder elevation (shrug) against a resistance to collect the maximum exertion for

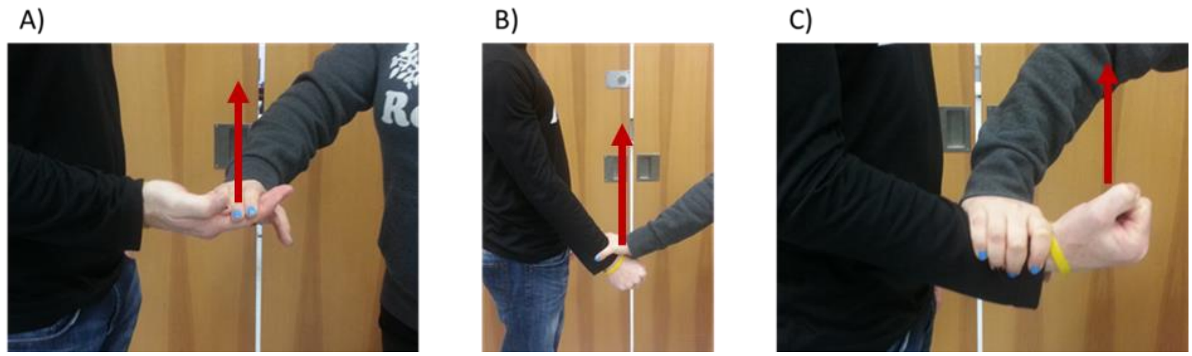

Figure 22: Maximum voluntary exertions with resistance provided by research assistant for A) flexor carpi ulnaris and flexor carpi radialis, B) pectoralis major and anterior deltoids, C) Biceps brachii. Direction of the arrows indicates the direction of movement of the subjects against the assistant provided resistance.

the superior trapezius. The triceps brachii required a forearm extension against a resistance placed on the dorsal aspect of the wrist to collect this exertion. For the flexor carpi ulnaris, flexor carpi radialis and extensor carpi ulnaris, the participant attempted to flex and extend the wrist respectively against a resistance placed on the fingers to capture the maximum voluntary exertion. Each of these maximal exertions were held for 2-3 seconds with a 60 second rest between each effort, with three sets for each muscle.

Once the maximum voluntary exertions had been collected, each participant performed 5 sets for each RAPT fastening conditions. The participants had their right hand located at the distal trigger handle in a pronated wrist posture (distal aspect from the RAPT spindle head) and the left hand was located at the spindle head in the supinated wrist posture. The fastening conditions consisted of a combination of variables: DC RAPT torque tightening strategies profile (two-stage with soft stop (TSS), two-stage without soft stop (TS), and turbo tight (TT)), target torque (30, 55, and 75 Nm), fastener location-orientation (pictorial representation of the locations shown in Figure 23; table of location coordinated listed in Table 1), as well as joint fastening type (hard and soft).

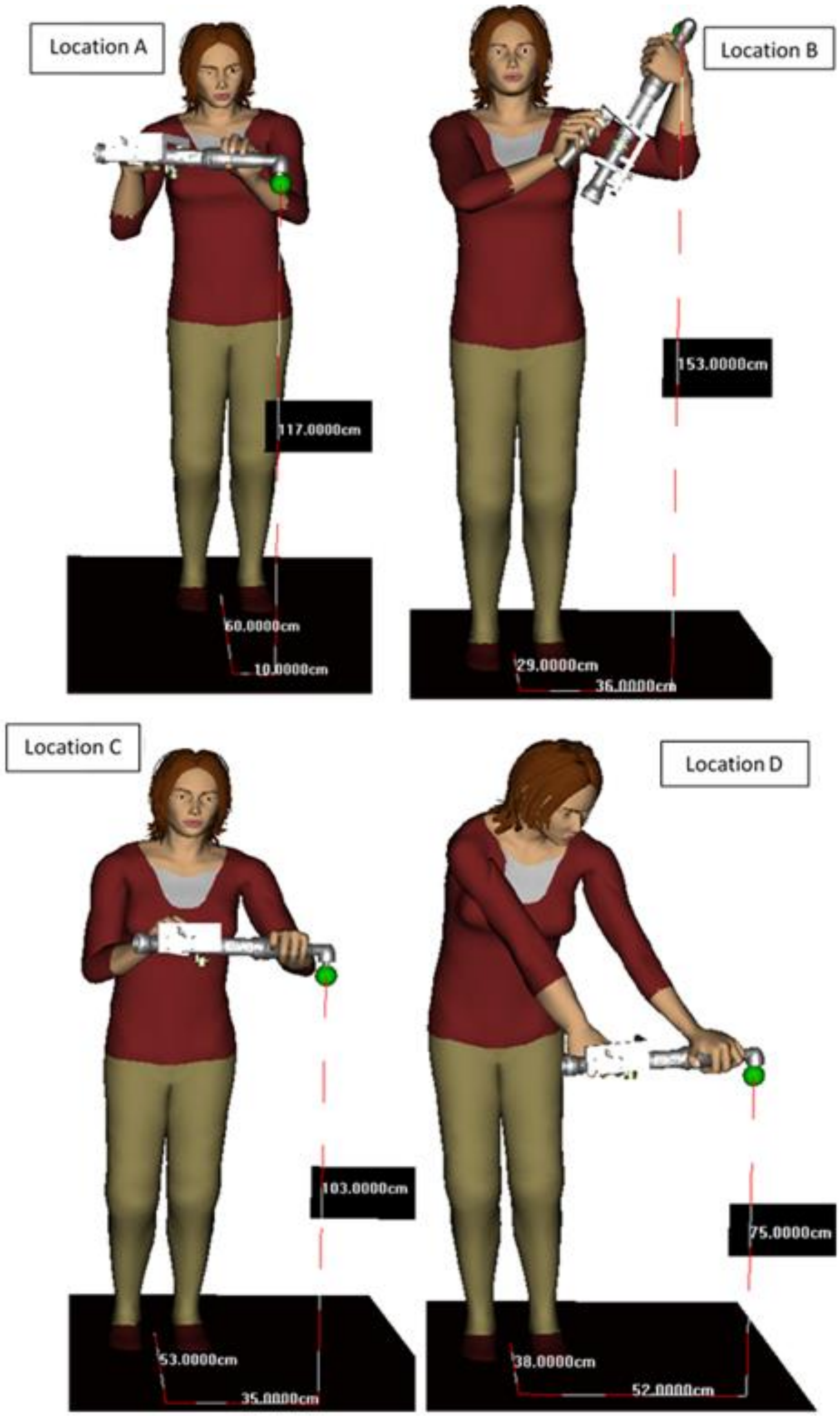

Figure 23: Portrayal of fastener location-orientation. This figure depicts the 4 locations and orientations as well as their geometrical locations with respect to the mid ankle position and the ground. Location ID: A, B, C, D.

Table 1: Coordinates of the 4 locations (A, B, C, D) and fastening direction in reference to the midpoint of the operators ankles and the ground in cm with the X coordinates being in the left/right direction from the participants midline, the Y coordinates being in the up/down direction from the ground and Z coordinates being in the anterior/posterior (forwards/backwards) directions from the participant.

	Location ID			
	A	**B**	**C**	**D**
X	-10	-36	-35	-52
Y	117	153	103	75
Z	60	29	53	38
Fastening direction	Down	Towards	Down	Down

Instead of having the participants complete both joint fastener type, 6 participants (3 males and 3 females) from each age group were randomly assigned to the hard-joint group {n=18) and, 6 participants (3 males and 3 females) from each age group were randomly assigned to the soft joint group (n=18). Within their assigned joint fastening type, each participant completed all the remaining

RAPT conditions resulting in a total of 36 RAPT fastening conditions (3 DC RAPT torque tightening strategies profile x 3 target torques x 4 fastener location-orientations). As per Potvin et al. (2004), one set consisted of 5 individual RAPT fastening secures within a 60 second window and a timed sound was used to inform participants. Participants performed 5 sets for each of the RAPT fastening conditions, therefore 5 minutes of continuous work was required for each condition, with a two minute rest period between each. After each condition, the participants recorded their RPE using the Borg CR10 scale, seen in Figure 24 (Borg, 1982). Participants completed all 36 conditions in two day (18 each day) with approximately three days of rest in between to help minimize fatigue and, provide an accurate and valid evaluation of the right-hand power tool operation variables. Cleared through the University of Windsor Research Ethics Board REB# 14-258.

0	None
0.5	Very, very light
1	Very light
2	Light
3	Moderate
4	Not very intense
5	Intense
6	
7	Very Intense
8	
9	Very, very intense
10	Maximum

Figure 24: Borg CR10 scale to rate subjects perceived exertions while performing certain tasks (Borg, 1982).

3.4 DATA ANALYSIS

The 6D force transducer data underwent low pass Butterworth filtering using a 50 Hz cut off (4^{th} order). All sEMG data was conditioned by removing the DC bias, high pass filtering at 140 Hz (6^{th} order) (Potvin & Brown, 2004; Staudenmann, Potvin, Kingma, Stegeman, & van Dieen, 2006), rectifying, and then low pass filtering at 2.5 Hz (2^{nd} order). The EMG collected during the fastening trials was then normalized to the maximum voluntary exertions integrated EMG's for each muscle (sEMG %MVE·s).

Each muscles' sEMG data was compared to a time history of a torque curve during a fastening secure, example seen in Figure 25, to determine if operating a specific DC RAPT tightening strategy produced any significant differences. For each sEMG signal collected during a secure, we looked at the time-period between two variables depicted in Figure 25: Impulse or the area under the curve, time-period between points A (trigger initiation) and B (completion of the rundown).   As we only examined the EMG amplitudes during operation, the rest period data will be disregarded. For each of the 5 sets

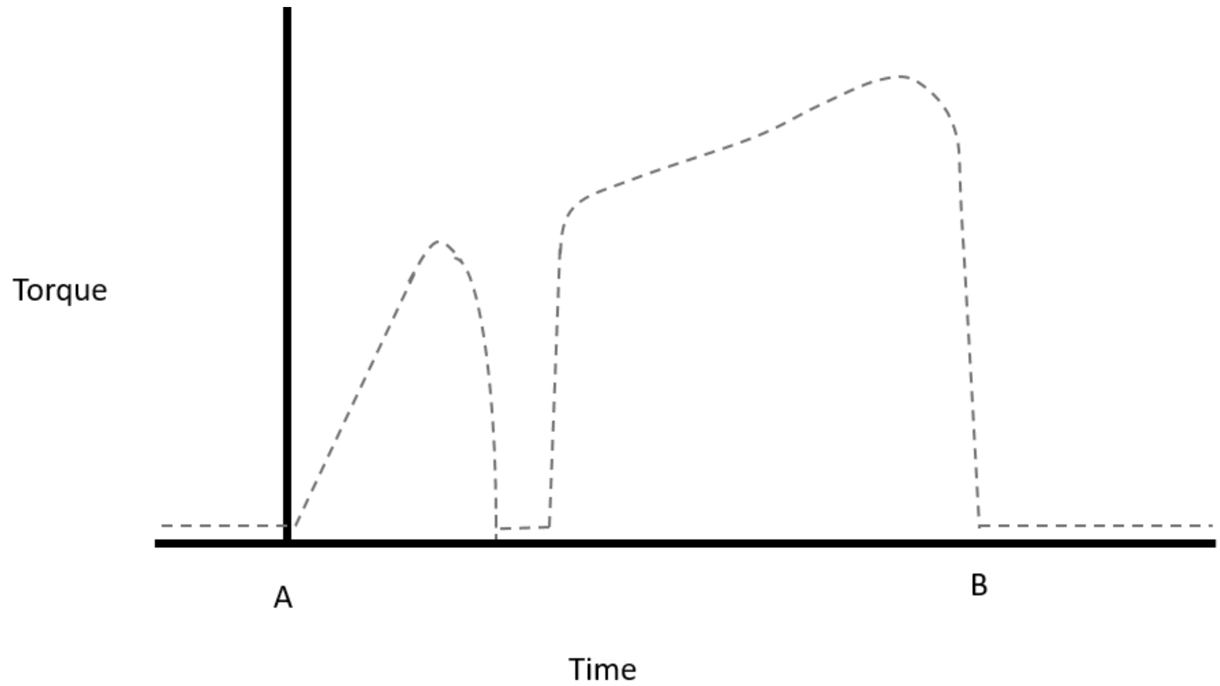

Figure 25: Time history of a torque curve during fastening rundown broken into impulse time periods: A. Trigger initiation. B. End of rundown.

of fastening conditions, each muscles surface EMG's was separated and the overall average, peak and minimal amplitudes within each set was recorded. The average, peak, minimal and impulse EMG amplitudes was also separated for each set for the five-individual fastening secures. The average Borg RPE collected was calculated for each individual as well as for each condition. For every condition and dependent variable, each participants' mean and standard deviation was calculated. The mean that is calculated was used in further statistical analysis, representing the participant's response to that condition.

3.5 STATISTICAL ANALYSIS

A 3 x 3 x 4 x 16 independent analysis of variance (ANOVA), with repeated measures (significance level of $p < 0.05$) was used to determine if the 5 independent variables (DC RAPT tightening strategy, target torque, and fastener location-orientation, joint type and muscle) had any influence. The dependent variables included the impulse during the torque time history curve as mentioned earlier as well as the Borg's RPE average. To look for significant main and interaction effects, the means were compared using Tukey's post hoc test. A partial Eta-squared analyses was performed on the significant interactions to determine if the effect's explained variance meets the threshold of >6% (medium size effect) to be considered functionally relevant.

CHAPTER 4: RESULTS

SEMG amplitude data was examined for all 16 muscles in four sections, all muscles significances for the right arm during the impulse time-period will be reported out, but only those muscles specific to the hypotheses are discussed in detail. As the right arm of each subject was used to control the handle of the RAPT and thus was directly affected by the tool, whereas the left arm was used to minimally support the RAPT, only right arm sEMG is reported, shown in appendix F.

4.1 HANDLE FORCES

A significant interaction for handle forces during hard joint fastenings was seen between posture, target torque and tightening strategy ($F=4.2$, $p=0.01$, $\eta^2= 0.2$), results shown in Figure 26. For those fastening joints to a target torque of 30 Nm in posture A, significant increases in handle force impulse of 81% were seen between TS and TT, and 82% increase when using TSS than when using TT; for the target torque of 55 Nm in posture A, a significant increase of 73% when using TS than TT and, 71% when using TSS than TT (71%); and finally, when tightening to 75Nm in posture A an 85% increase when using TS than TT (85%) and, 84% when using TSS than TT (84%). For those fastening joints in posture B, significant increases in force impulse were seen between TS and TT (increase of 82%) and, TSS and TT (increase of 82%) when fastening to 30 Nm, TS and TT (increase of 69%) and, TSS and TT (increase of 69%) when fastening to 55 Nm and TS and TT (increase of 85%) and, TSS and TT (increase of 84%) when fastening to 75 Nm. For those fastening joints in posture C, significant increases where seen when tightening to 30 Nm where there was an 82% increase in force impulse when using TS than TT, and 81% when using TSS rather than TT; when tightening to 55Nm there was a 75% increase when comparing TS to TT, and 74% when comparing TSS to TT; when tightening to 75 Nm there was an increase was found of 85% when comparing TS to TT and, 85% when comparing TSS to TT. For those fastening joints in posture D, significant increases in force impulses of 84% were found during 30 Nm tightening's between TS and TT, and 84% between TSS and TT; during the 55 Nm tightening a 73% increase occurred when using TS rather than TT, and 73% when using TSS than TT; finally

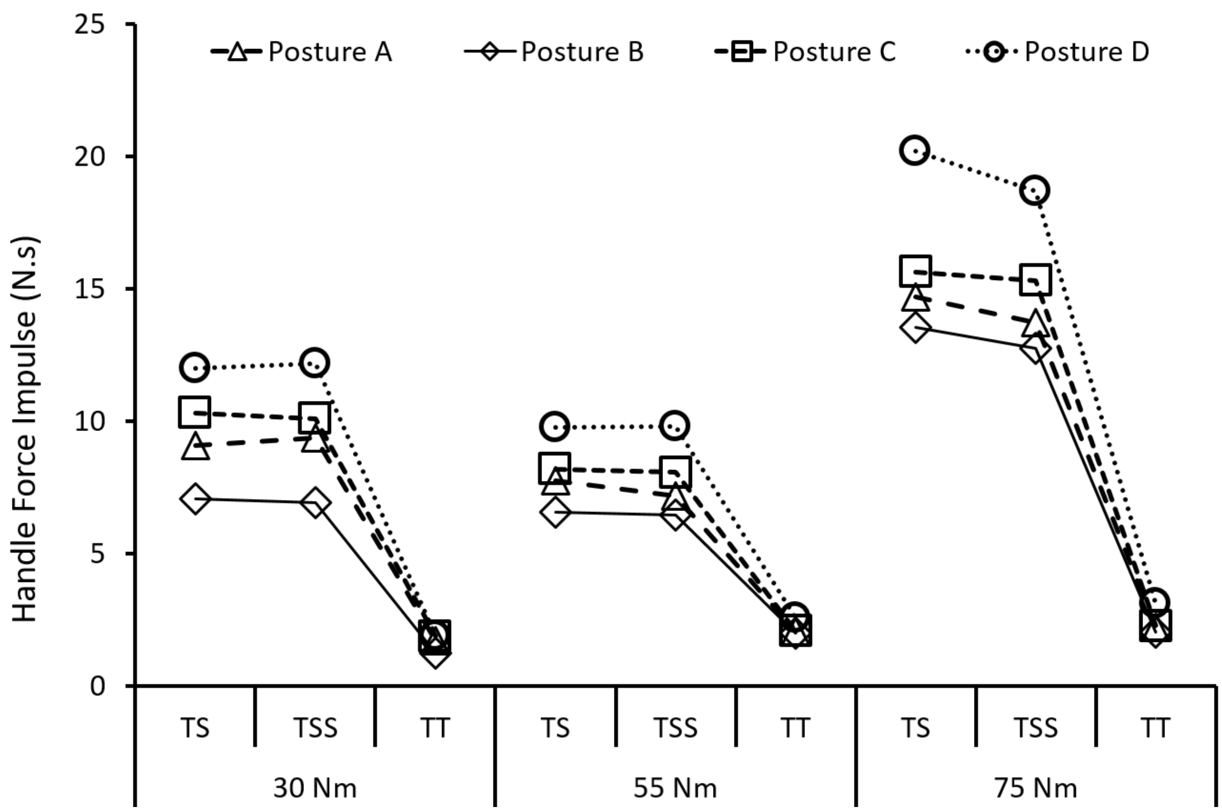

Figure 26: Handle forces magnitudes for posture, target torque and fastening strategy for hard joints. Significances seen between TS and TT and TSS and TT for all postures and target torques.

when tightening to 75 Nm there was a 84% increase when using TS rather than TT and 83% when using TSS rather than TT.

A significant interaction for handle forces was also seen for soft joint fastenings between posture, target torque and tightening strategy (F=4.2, p=0.01, η^2= 0.2), results for hard joints shown in Figure 27. For those fastening joints in posture A, significant increase in force impulse was seen when tightening the 30 Nm joint with TSS than TS (increase of 52%), TS than TT (increase of 74%) and TSS than TT (increase of 87%); for the 55 Nm joint an increase of 68% when using TS to TT, and 70% when using TSS rather than TT; and when using the 75 Nm joint there was a 68% increase when TS rather than TT and, 68% when using TSS rather than TT. For those fastening joints in posture B, significant increases in force impulses were found during the 30 Nm joints of 48% when using TSS rather than, 76% when using TS rather than TT, and 87% when using TSS rather than TT; when fastening 55 Nm joints and increase of 2% was found when using TSS rather than TS, 72% when using TS rather than TT and 75% when using TSS rather than TT; and for the 75 Nm joints and increase of force impulse of 0.1% between TSS and TS, 67% increase when using TS rather than TT; and 69% increase when using TSS rather than TT for the 75 Nm joints. For those fastening joints in posture C, significant increases of force impulse were shown between TSS and TS (increase of 55%), TS and TT (increase of 72%) and TSS and TT (increase of 87%) for 30 Nm; TS and TT (increase of 75%) and, TSS and TT (increase of 74%) for 55 Nm; TS and TSS (increase of 0.1%), TS and TT (increase of 70%) and TSS and TT (increase of 68%) for 75 Nm. For those fastening joints in posture D, significant increases of force impulse were found between TSS and TS (increase of 54%), TS and TT (increase of 71%) and TSS and TT (increase of 87%) for 30 Nm; TSS and TS (increase of 12%), TS and TT (increase of 71%) and, TSS and TT (increase of 74%) for 55 Nm; TS and TT (increase of 67%) and, TSS and TT (increase of 66%) for 75 Nm.

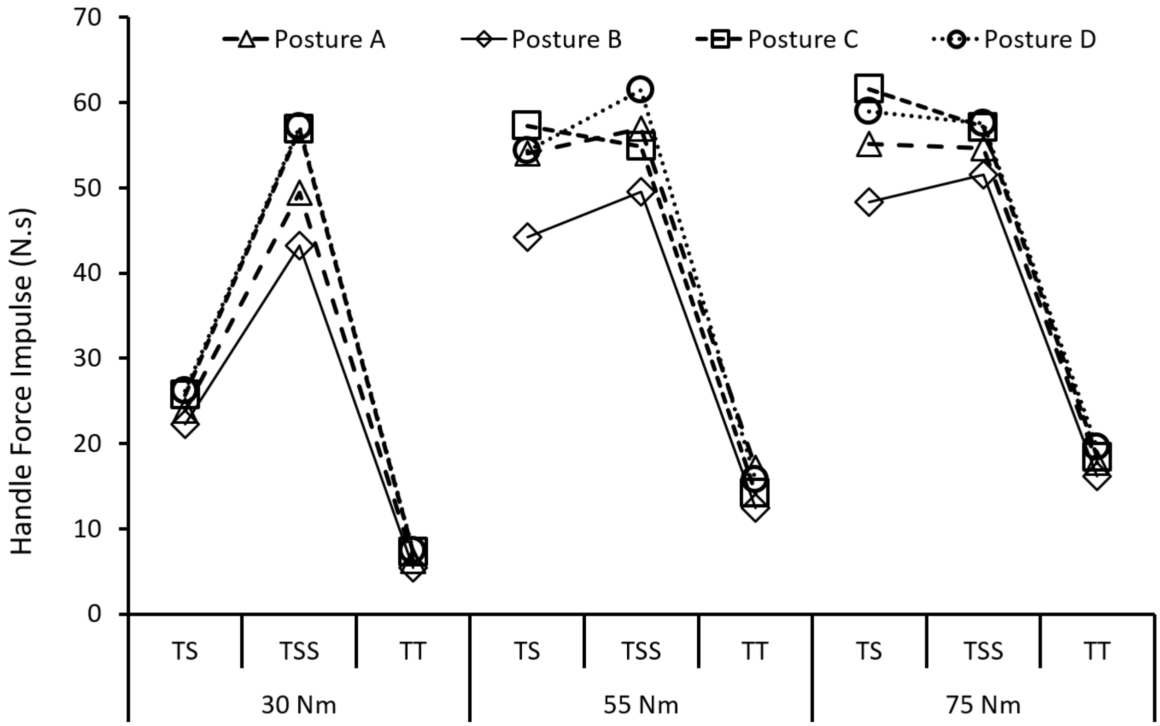

Figure 27: Handle forces magnitudes for posture, target torque and fastening strategy for soft joints. Significances seen between TS and TT and TSS and TT for all postures and target torques. Significances seen between TS and TSS for posture A at 30 Nm, posture B for all target torques, posture C for 30 and 75 Nm and posture D for 30 and 55 Nm.

4.2 MUSLCE IMPULSE

4.2.1 RIGHT ANTERIOR DELTOID

For right anterior deltoid, a significant interaction between the participants' gender and tightening posture (F=7.73, p=0.002, η^2= 0.243) was seen, results shown in Figure 28. For females, significant increases were seen between postures A and C (54%), postures A and D (32%), postures B and C (52%), postures B and D (31%) and postures D and C (32%). Males showed significant increases between postures A and D (20%) and postures B and D (12%).

Another significant interaction was seen between participants' gender and tightening strategy (F=5.08, p=0.025, η^2= 0.175), results shown in Figure 29. Females showed significant increases between strategies TS and TT (65%) and TSS and TT (70%). Males found significant increases between strategies TS and TT (64%) and TSS and TT (65%).

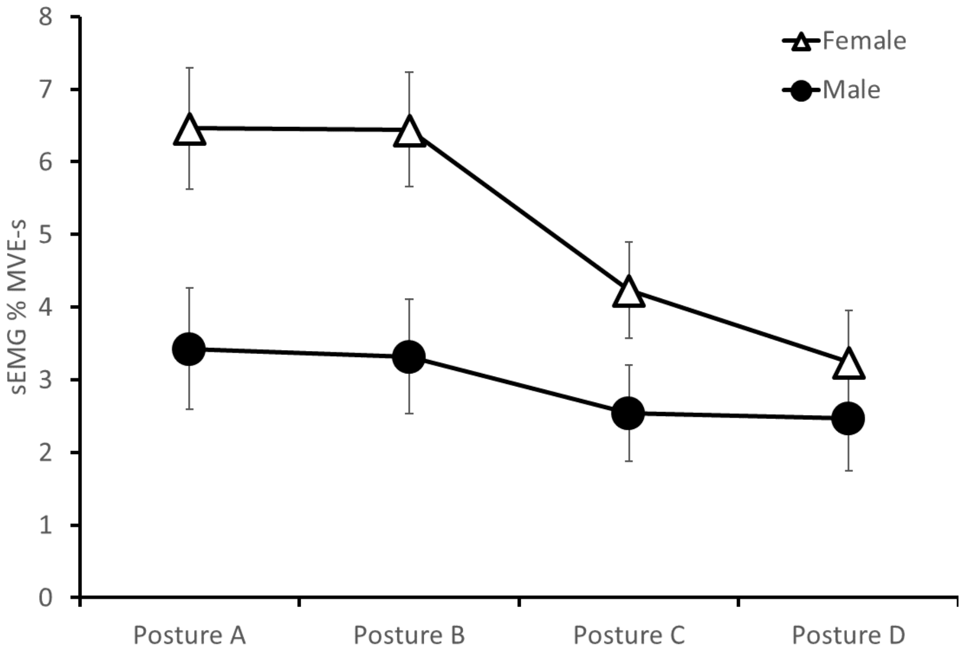

Figure 28: Right Anterior Deltoid Impulse Magnitudes for Gender and Fastening Location. Significant increases were seen between males for postures A and A and B and D and female for postures A and C, A and D and B and C. Results reported on the sEMG %MVE-s means and standard error bars.

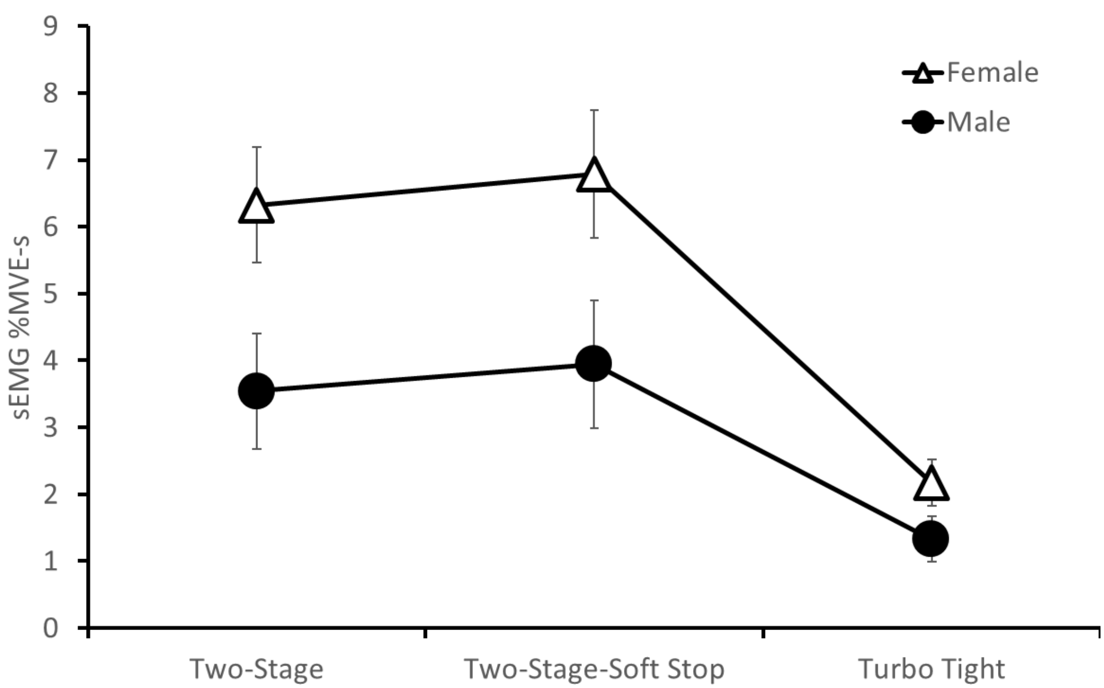

Figure 29: Right Anterior Deltoid Impulse Magnitudes for Gender and Fastening Strategy. Significant interactions were seen between tightening strategies TS and TT and TSS and TT for both males and females. Results reported on the sEMG %MVE-s means and standard error bars.

A significant interaction between joint hardness, target torque and posture ($F=4.71$, $p=0.003$, $\eta^2= 0.164$) was also seen, results shown in Figure 30. For hard-joints at 30 Nm target torque, a significant increase was seen between postures A and C (47%). For soft-joints at 30 Nm target torque, significant increases were seen between postures A and C (50%), postures A and D (34%), postures B and C (51%), postures B and D (23%) and postures D and C (23%). Soft-joints at 55 Nm target torque showed significant increases between postures A and C (52%), postures A and D (37%), postures B and C (56%), postures B and D (42%) and postures D and C (24%). For soft-joints at 75 Nm target torque, significant increases were seen between postures A and D (17%) and postures B and D (10%).

Lastly, a significant interaction was seen between joint hardness, participants' age, target torque and tightening strategy ($F=2.37$, $p=0.048$, $\eta^2= 0.165$), results shown in Figure 31. For participants aged 30-45 fastening hard-joints at 30 Nm, a significant increase was seen between strategies TS and TT (85%). For participants aged 30-45 fastening hard-joints at 75 Nm, a significant increase was seen between strategies TSS and TT (77%). For participants aged 20-29 fastening soft-joints at 30 Nm, a significant increase was seen between strategies TSS and TT (73%). For participants aged 20-29 fastening soft-joints at 55 Nm, a significant increase was seen between strategies TS and TT (61%). For participants aged 20-29 fastening soft-joints at 75 Nm, a significant increase was seen between strategies TSS and TT (58%). For participants aged 30-45 fastening soft-joints at 30 Nm, significant increases were seen between strategies TSS and TS (18%), TS and TT (60%) and TSS and TT (67%). For participants aged 30-45 fastening soft-joints at 55 Nm, significant increases were seen between strategies TSS and TS (20%), TS and TT (65%) and TSS and TT (72%). For participants aged 30-45 fastening soft-joints at 75 Nm, significant increases were seen between strategies TS and TSS (28%), TS and TT (56%) and TSS and TT (39%). For participants aged 46+ fastening soft-joints at 30 Nm, significant increases were seen between strategies TSS and TS (42%), TS and TT (77%) and TSS and TT (87%). For participants aged 46+ fastening soft-joints at 55 Nm, significant increases were seen between strategies TS and TT (62%) and TSS and TT (64%). For participants aged 46+ fastening soft-joints at 75 Nm, significant increases were seen between strategies TS and TT (59%) and TSS and TT (58%).

4.2.2 RIGHT BICEP BRACHII

For right bicep brachii, a significant interaction was seen between joint hardness, participant gender, target torque and tightening strategy ($F=4.15$, $p=0.014$, $\eta^2= 0.148$), results shown in Figure 32. Females in the hard-joint group at 30 Nm target torque showed a significant increase between strategies TS and TT (84%). Females in the hard-joint group at 75 Nm target torque showed significant increases between strategies TS and TT (85%) and TSS and TT (82%). Females fastening soft-joints at 30 Nm target torque showed significant increases between strategies TSS and TS (48%), TS and TT (81%) and TSS and TT (90%). Females fastening soft-joints at 55 Nm target torque showed significant increases between strategies TS and TT (75%) and TSS and TT (78%). Females fastening soft-joints at 75 Nm target torque showed significant increases between strategies TS and TT (75%) and TSS and TT (76%). Males fastening soft-joints at 30 Nm target torque showed significant increases between strategies TSS and TS (42%), TS and TT (80%) and TSS and TT (88%). Males fastening soft-joints at 55 Nm target torque showed significant increases between strategies TS and TT (77%) and TSS and TT (74%). Males fastening soft-joints at 75 Nm target torque showed significant increases between strategies TS and TT (74%) and TSS and TT (69%).

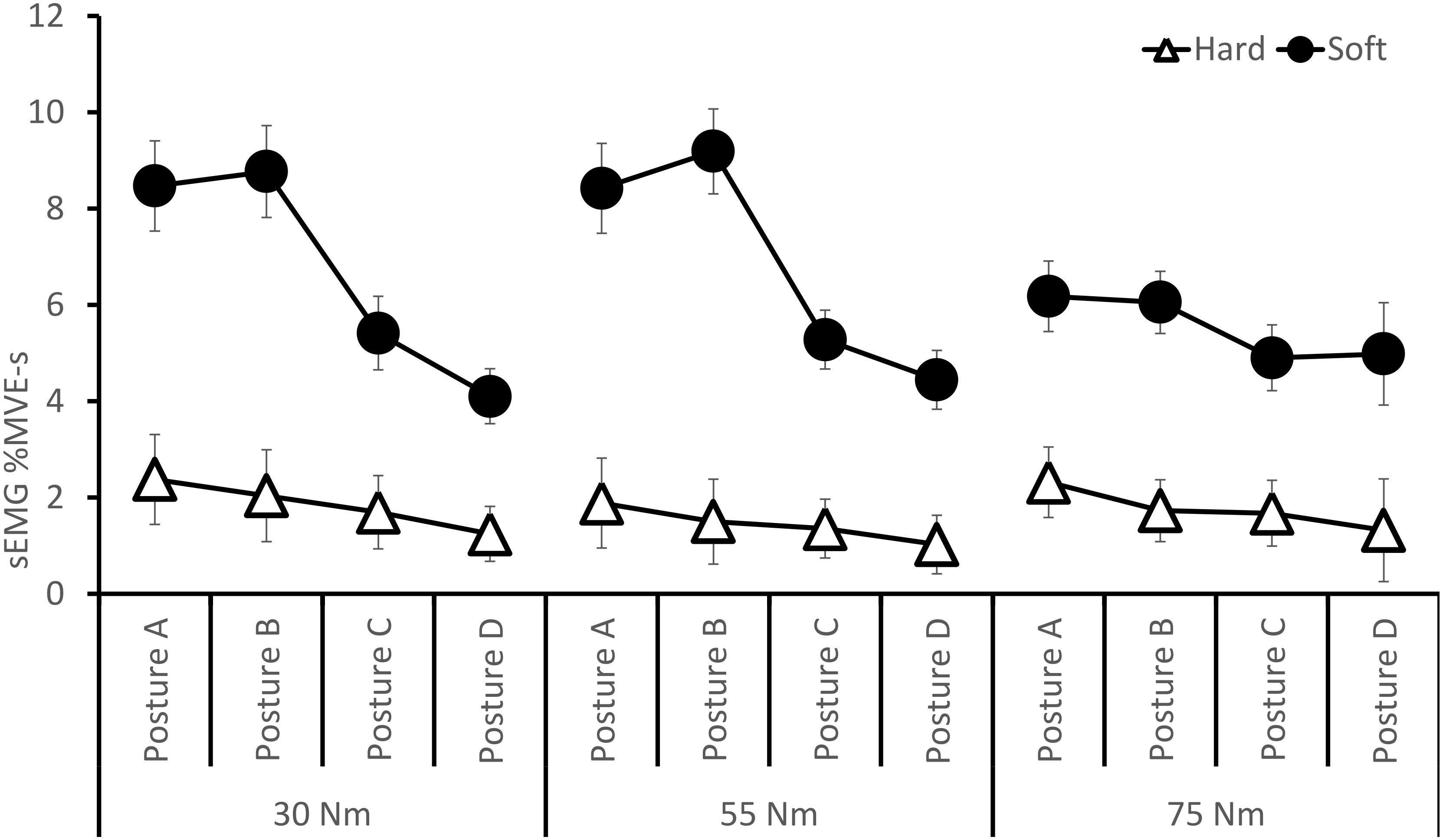

Figure 30: Right Anterior Deltoid Impulse Magnitudes for Joint Hardness, Fastening Location and Target Torque. Significant interactions were seen between postures A and C for hard joints at 30 Nm. Soft joints showed significant interactions between postures A and C, A and D, B and C, B and D and D and C for 30 Nm and 55 Nm joints. Soft joints at 75 Nm showed significances between postures A and D and B and D. Results reported on the sEMG %MVE-s means and standard error bars.

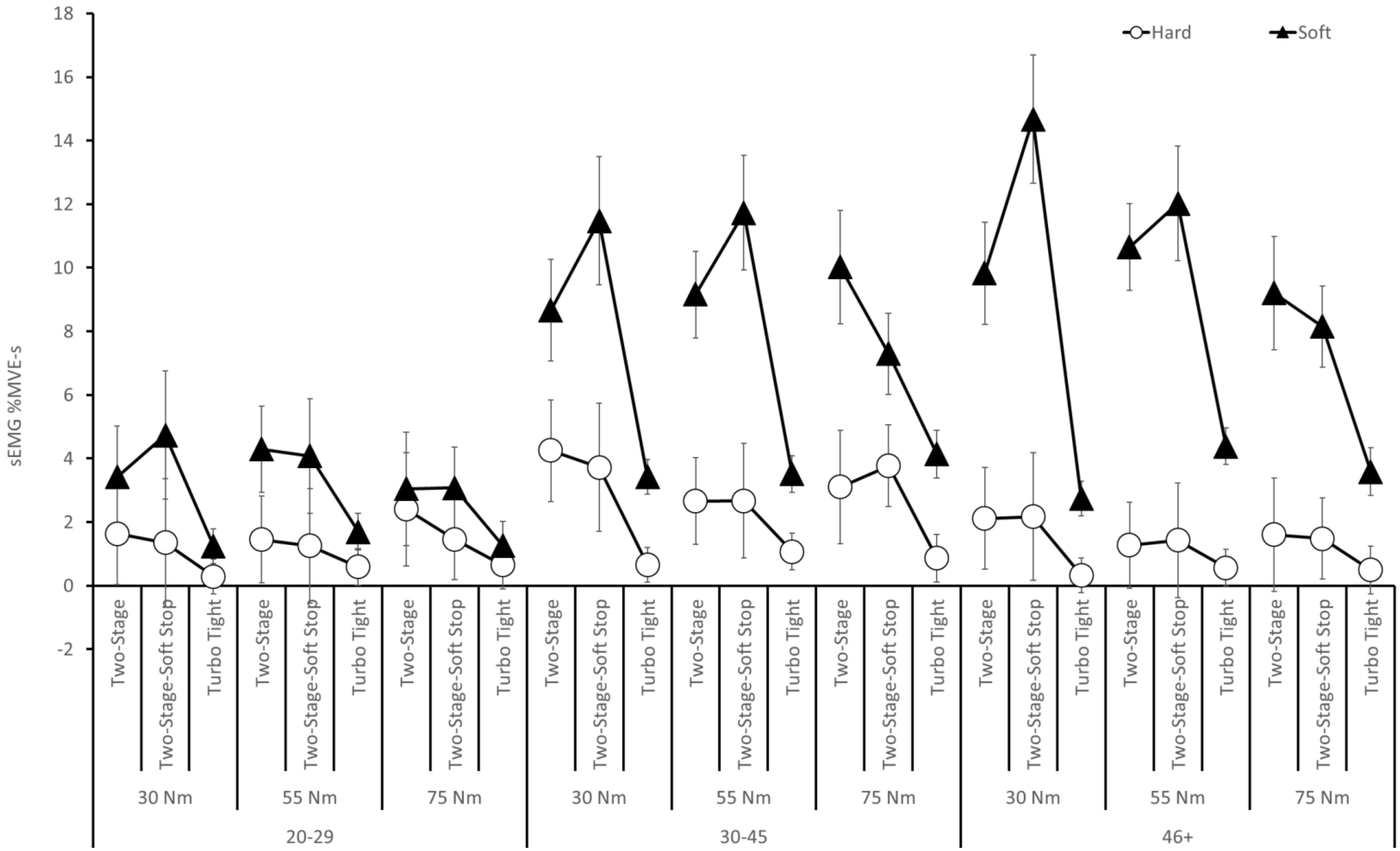

Figure 31: Right Anterior Deltoid Impulse Magnitudes for Joint Hardness, Fastening Strategy, Target Torque and Age. Significant interactions were seen between TS and TT only for participants aged 30-45 at 75 Nm with hard joints, aged 20-29 at 55 Nm for soft joints. Significant interactions were seen between TSS and TT only for participants aged 30-45 at 75 Nm for hard joints, and aged 20-29 at 30 Nm and 75 Nm for soft joints. Significances were seen between TS and TT and TSS and TT for participants aged 46+ for soft joints at 55 Nm and 75 Nm. Significances were seen between all three fastening strategies (TSS, TS and TT) for participants aged 30-45 for 30, 55 and 75 Nm for soft joints and participants aged 46+ for soft joints at 30 Nm. Results reported on the sEMG %MVE-s means and standard error bars.

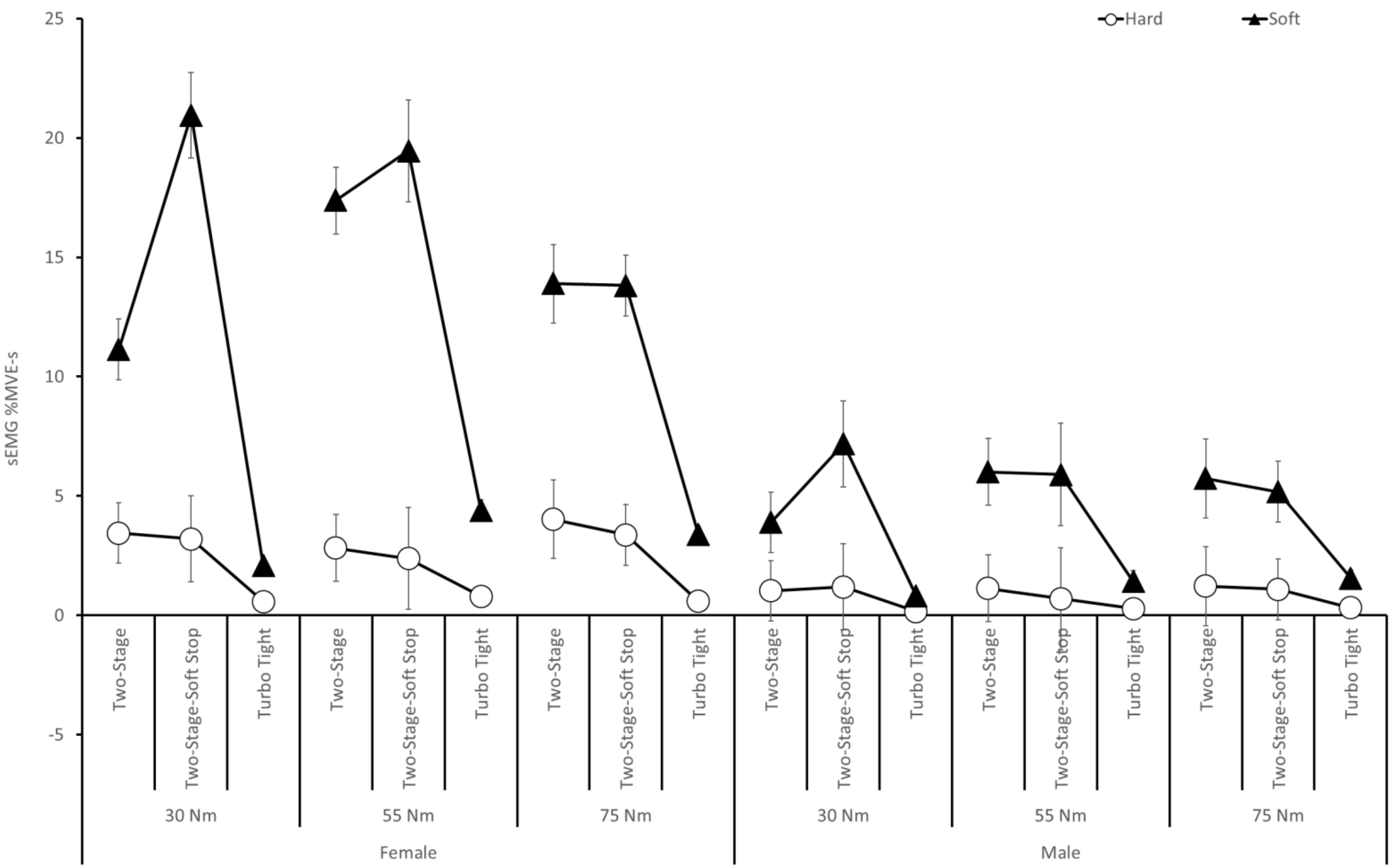

Figure 32: Right Bicep Brachii Impulse Magnitudes for Joint Hardness, Gender, Target Torque and Fastening Strategy. Significant interactions were seen between TS and TT only for females with hard joints at 30 Nm. Significant interactions were seen between TS and TT and TSS and TT for females and males with hard joints at 75 Nm, females with soft joints at 55 Nm and 75 Nm. Significances were seen between all three fastening strategies (TSS, TS and TT) for females and males with soft joints at 30 Nm. Results reported on the sEMG %MVE-s means and standard error bars.

4.2.3 RIGHT EXTENSOR CARPI ULNARIS

For right extensor carpi ulnaris, a significant interaction was seen between joint hardness, participant gender and posture (F=4.42, p=0.027, η^2= 0.155), shown in Figure 33. For females fastening soft-joints, a significant increase was seen between postures C and A (10%). For males fastening soft-joints, significant increases were seen between postures A and B (39%), postures A and C (20%), postures D and B (39%) and postures D and C (20%).

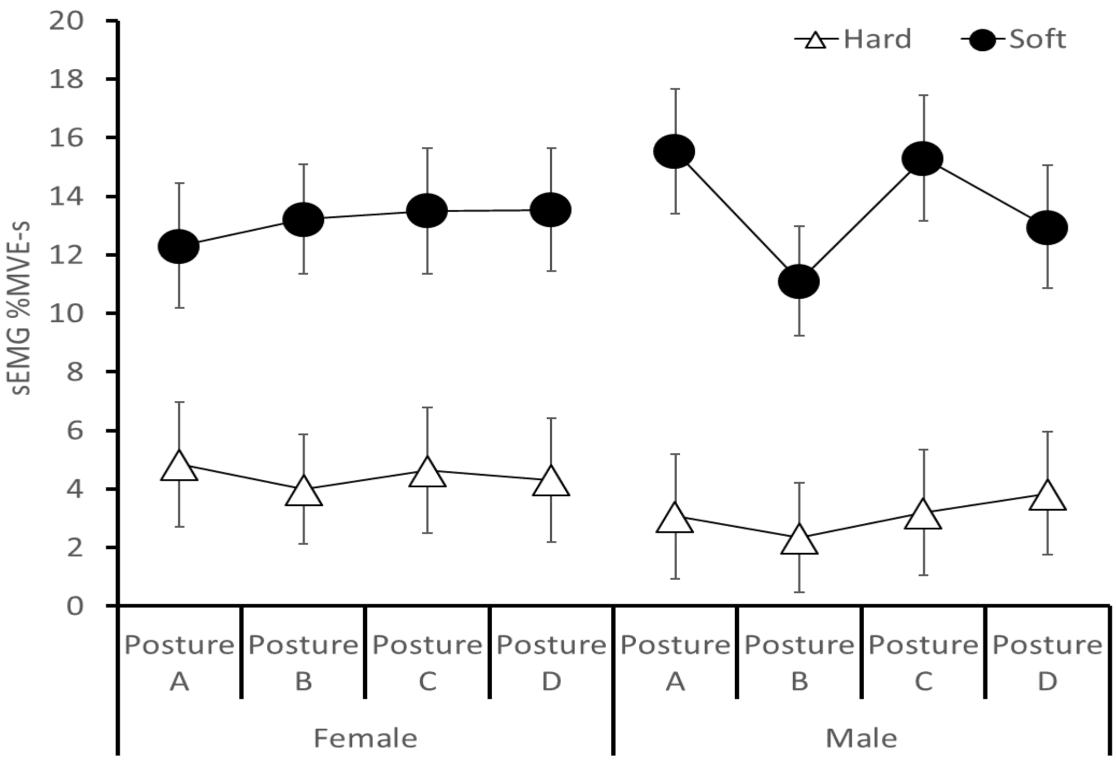

Figure 33: Right Extensor Carpi Ulnaris Impulse Magnitudes for Joint Hardness, Gender and Fastening Location. Females showed significant interactions between postures C and A for soft joints. Males showed significant interactions between postures A and B, A and C, D and B and D and C for soft joints. Results reported on sEMG %MVE-s means and standard error.

Another significant interaction was seen between joint hardness, target torque and tightening strategy (F=5.47, p=0.006, η^2= 0.186), results shown in Figure 34. For hard joint at 30 Nm, significant interactions were seen between strategies TS and TT (84%) and TSS and TT (84%). For hard joint at 75 Nm, significant interactions were seen between strategies TS and TT

(70%) and TSS and TT (70%). For soft joint at 30 Nm, significant interactions were seen between strategies TSS and TS (28%), TS and TT (68%) and TSS and TT (77%). For soft joint at 55 Nm, significant interactions were seen between strategies TS and TT (65%) and TSS and TT (61%). For soft joint at 75 Nm, significant interactions were seen between strategies TS and TT (63%) and TSS and TT (63%).

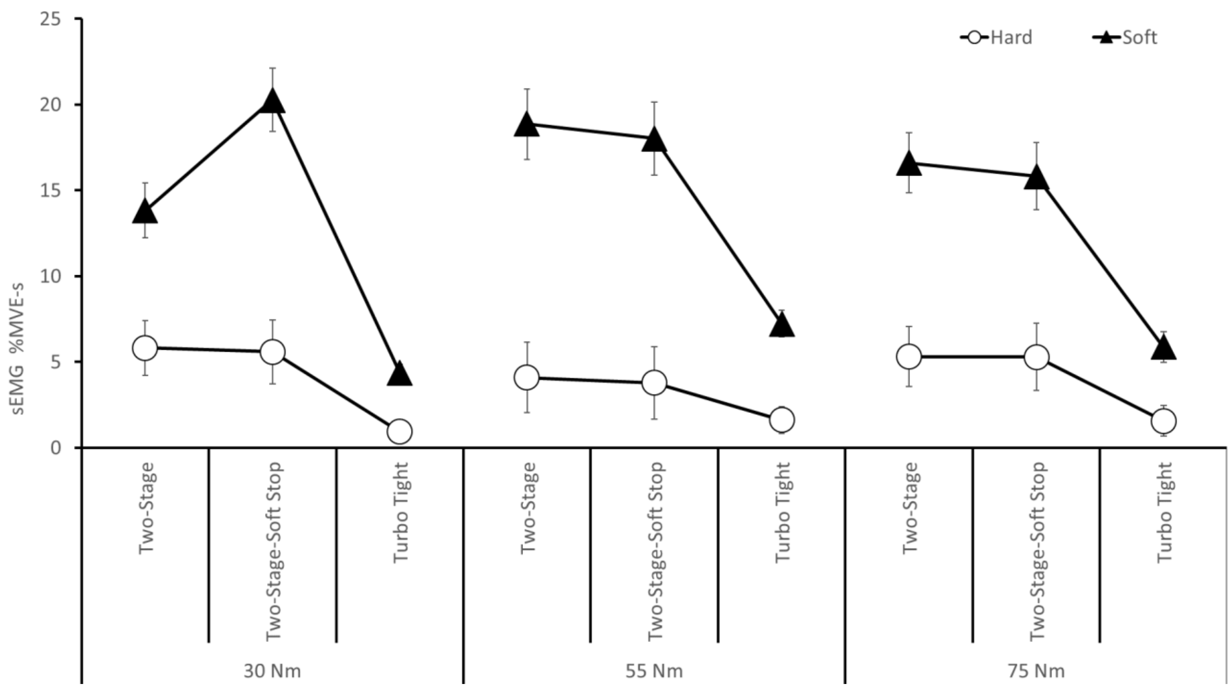

Figure 34: Right Extensor Carpi Ulnaris Impulse Magnitudes for Joint Hardness, Target Torque and Fastening Strategy. Significant interactions were seen between TS and TT and TSS and TT for hard joints at 30 Nm and 75 Nm and for soft joints at 55 Nm and 75 Nm. Soft joints at 30 Nm showed significant interactions between TS and TT, TSS and TT and TSS and TS. Results reported on the sEMG %MVE-s means and standard error bars.

4.2.4 RIGHT FLEXOR CARPI RADIALIS

For right flexor carpi radialis, a significant interaction was seen for joint hardness, target torque and tightening strategy ($F=6.10$, $p=0.002$, $\eta^2= 0.203$), results shown in Figure 35. Soft-joints at 30 Nm showed significances between strategies TSS and TS (56%), TS and TT (79%) and TSS and TT (91%). Soft-joints at 55 Nm showed significant increases between strategies TS and TT (75%) and TSS and TT (78%). Soft-joints at 75 Nm showed significant increases between strategies TS and TT (72%) and TSS and TT (74%).

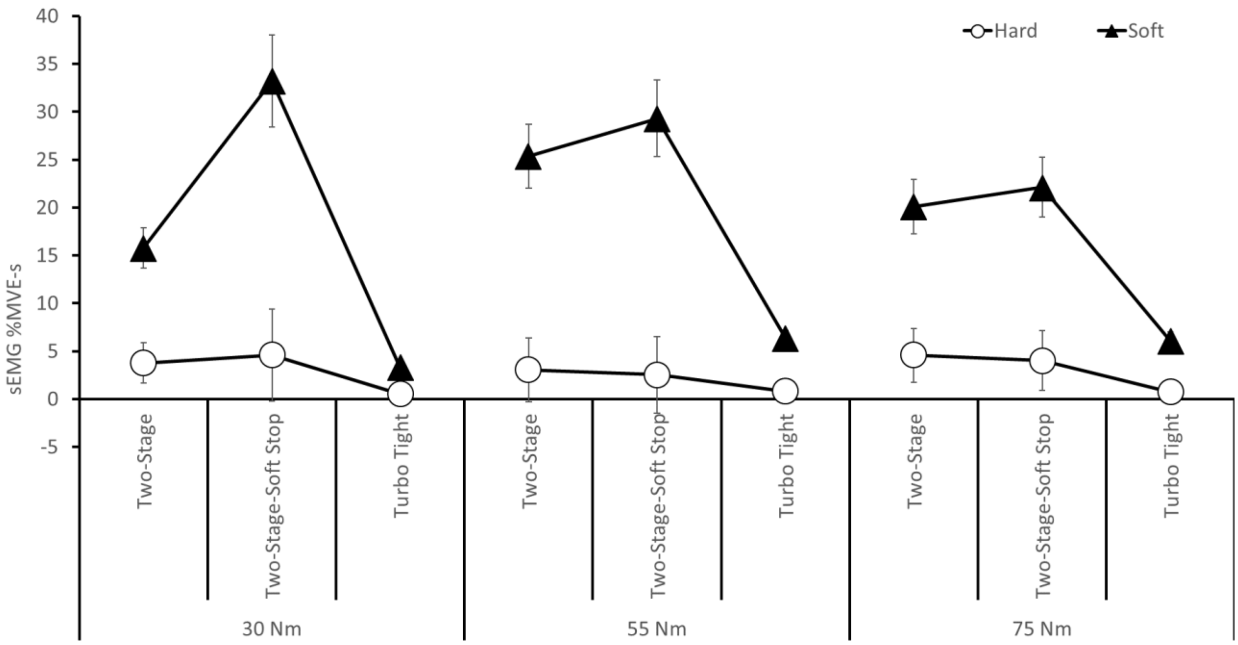

Figure 35: Right Flexor Carpi Radalis Impulse Magnitudes for Joint Hardness, Target Torque and Fastening Strategy. Soft joints at 55 Nm and 75 Nm showed significant interactions between TS and TT and TSS and TT. Soft joints at 30 Nm showed significant interactions between TSS and TT, TS and TT and TSS and TS. Results reported on the sEMG %MVE-s means and standard error bars.

Another significant interaction was seen between joint hardness, participant age and gender and target torque ($F=2.89$, $p=0.034$, $\eta^2= 0.194$), results shown in Figure 36. Females age 20-29 fastening soft-joints showed significant increases between target torques 55 Nm and 30 Nm (18%) and 55 Nm and 75 Nm (28%). Females age 30-45 fastening soft-joints showed significant increases between target torques 55 Nm and 30 Nm (39%), 75 Nm and 30 Nm (14%) and 55 Nm and 75 Nm (29%). Males age 30-45 fastening soft-joints showed a significant increase between target torques 30 Nm and 75 Nm (48%). Females age 46+ fastening soft-joints showed significant increases between target torques 30 Nm and 75 Nm (33%) and 55 Nm and 75 Nm (32%).

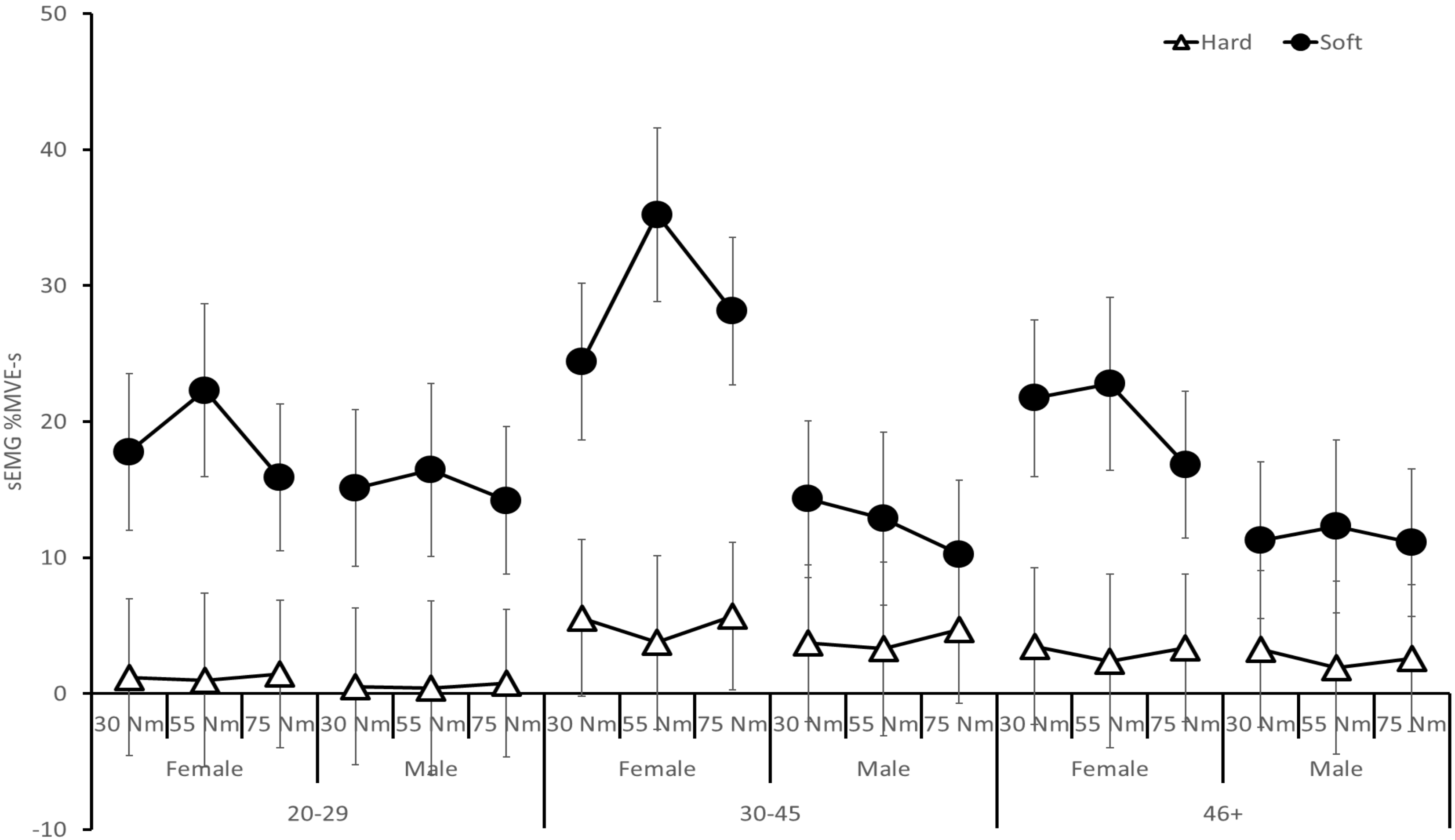

Figure 36: Right Flexor Carpi Radialis Impulse Magnitudes for Joint Hardness, Gender, Age and Target Torque. Females aged 20-29 fastening soft joints showed significant interactions between 55 Nm and 30 Nm, 55 Nm and 75Nm. Females aged 30-45 with soft joints showed significant interactions between 55 Nm and 30 Nm, 75 Nm and 30 Nm and 55 Nm and 75 Nm. Males aged 30-45 with soft joints showing a significant interaction between 30 Nm and 75 Nm. Females 46+ with soft joints showed significances between 30 m and 75 NM and 55 Nm and 75 Nm. Results reported on the sEMG %MVE-s means and standard error bars.

4.2.5 RIGHT FLEXOR CARPI ULNARIS

For right flexor carpi ulnaris, a significant interaction was seen between joint hardness, participant age and gender and tightening strategy ($F=3.23$, $p=0.043$, $\eta^2= 0.212$), results shown in Figure 37. Females age 20-29 fastening soft-joints showed significant increases between strategies TSS and TS (17%), TS and TT (79%) and TSS and TT (82%). Males age 20-29 fastening soft-joints showed significant increases between strategies TSS and TS (20%), TS and TT (71%) and TSS and TT (77%). Females age 30-45 fastening soft-joints showed significant increases between strategies TSS and TS (21%), TS and TT (76%) and TSS and TT (81%). Males age 30-45 fastening soft-joints showed significant increases between strategies TS and TT (79%) and TSS and TT (80%). Females age 46+ fastening soft-joints showed significant increases between strategies TS and TT (74%) and TSS and TT (75%). Males age 46+ fastening soft-joints showed significant increases between strategies TSS and TS (15%), TS and TT (77%) and TSS and TT (80%).

Another significant interaction was seen between joint hardness, target torque and tightening strategy ($F=24.50$, $p=0.000$, $\eta^2= 0.505$), result shown in Figure 38. Hard-joints at 30 Nm target torque showed significant increases between strategies TS and TT (89%) and TSS and TT (89%). Hard-joints at 75 Nm target torque showed significant increases between strategies TS and TT (80%) and TSS and TT (78%). Soft-joints at 30 Nm target torque showed significant increases between strategies TSS and TS (41%), TS and TT (80%) and TSS and TT (88%). Soft-joints at 55 Nm target torque showed significant increases between strategies TS and TT (76%) and TSS and TT (75%). Soft-joints at 75 Nm target torque showed significant increases between strategies TSS and TS (4%), TS and TT (73%) and TSS and TT (74%).

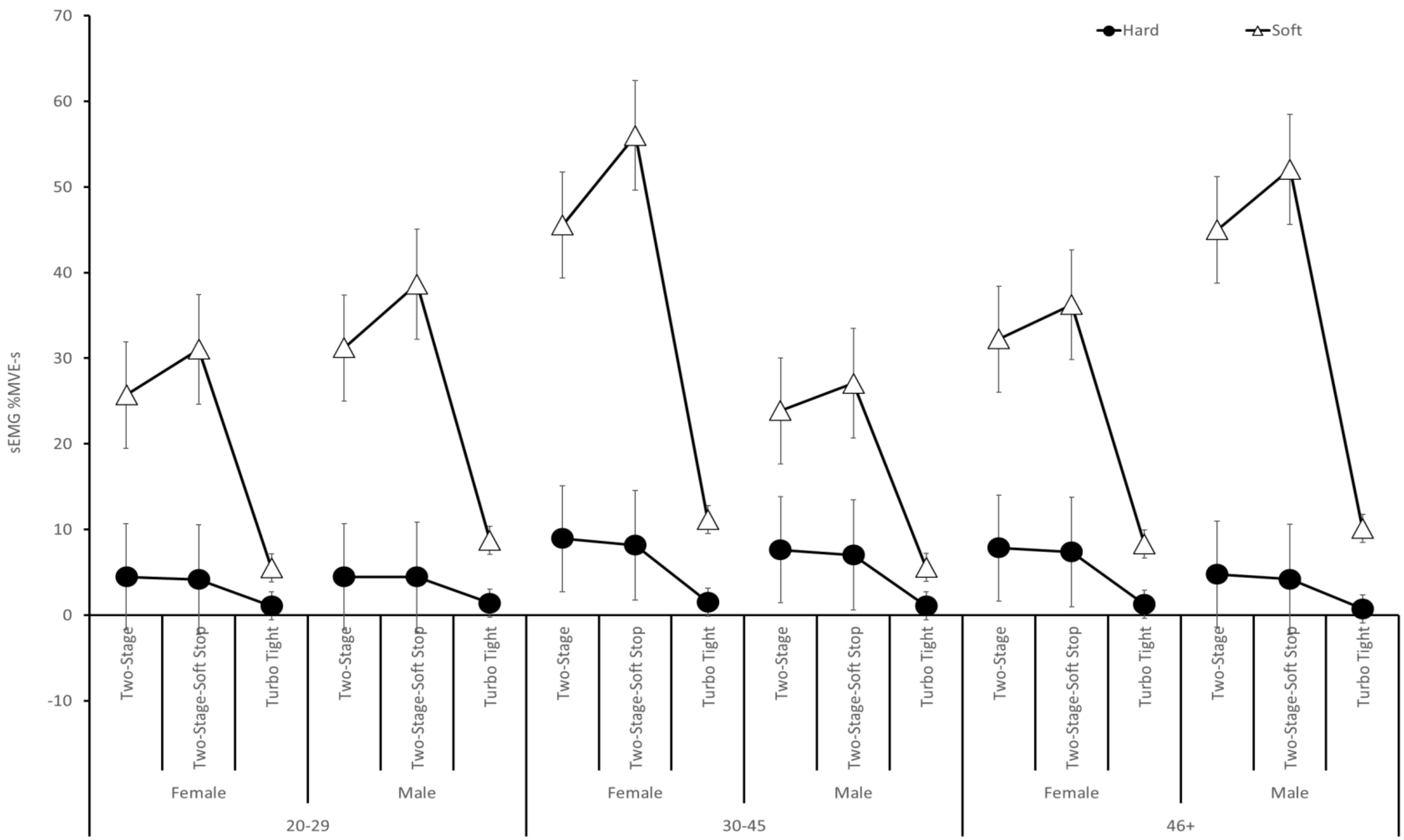

Figure 37: RIght Flexor Carpi Ulnaris Impulse Magnitudes for Joint Hardness, Age, Gender and Fastening Strategy. Significant interactions between TS and TT and TSS and TT were seen by males age 30-45 and females aged 46+ fastening soft joints. Significances were also seen between TS and TT, TSS and TT and TSS and TS for females and males aged 20-29, females aged 30-45, and males aged 46+ fastening soft joints. Results reported on the sEMG %MVE-s means and standard error bars.

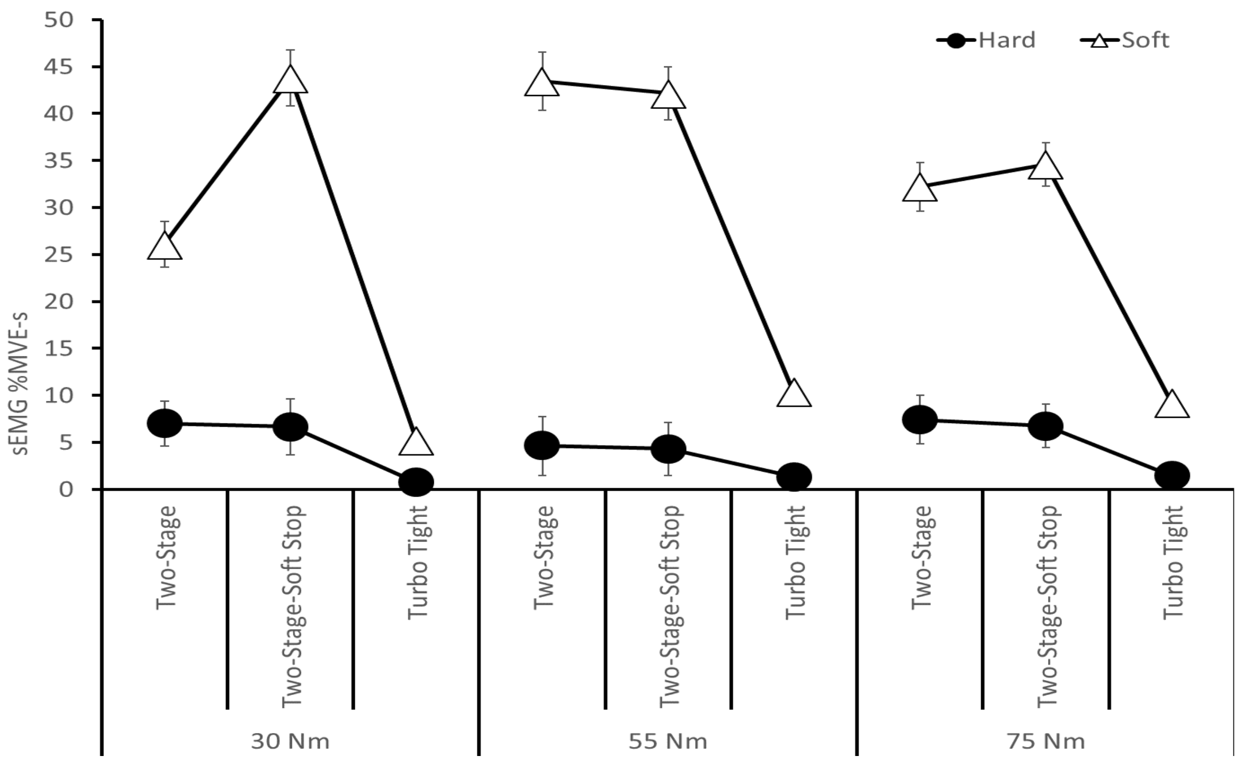

Figure 38: Right Flexor Carpi Ulnaris Impulse Magnitudes for Joint Hardness, Target Torque and Fastening Strategy. Significant interactions between TS and TT and TSS and TT were seen between hard joints at 30 Nm and 75 Nm and soft joints at 55 Nm. Significances were seen between TSS and TS, TS and TT and TSS and TT for soft joints at 30 Nm and 75 Nm. Results reported on the sEMG %MVE-s means and standard error bars.

4.2.6 RIGHT PECTORALIS MAJOR

For right pectoralis major, a significant interaction was seen between joint hardness, target torque and tightening strategy (F=5.99, p=0.007, η^2= 0.200), results shown in Figure 39. Hard-joints at 30 Nm target torque showed a significant increase between strategies TS and TT (84%). Hard-joints at 75 Nm target torque showed significant increases between strategies TS and TT (77%) and TSS and TT (77%). Soft-joints at 30 Nm target torque showed significant increases between strategies TSS and TS (76%), TS and TT (84%) and TSS and TT (96%). Soft-joints at 55 Nm target torque showed significant increases between strategies TS and TT (89%) and TSS and TT (69%). Soft-joints at 75 Nm target torque showed significant increases between strategies TSS and TS (18%), TS and TT (62%) and TSS and TT (69%).

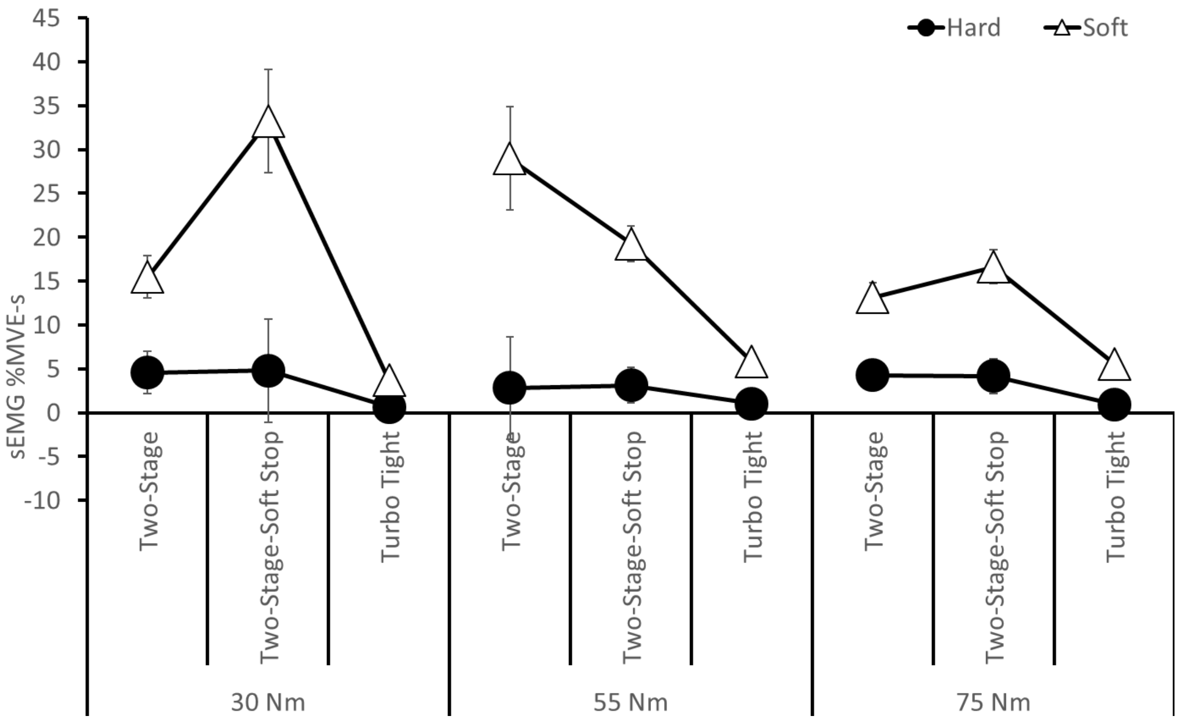

Figure 39: Right Pectoralis Major Impulse Magnitudes for Joint Hardness, Target Torque and Fastening Strategy. Hard joints at 30 Nm showed significances between TS and TT only. Significant interactions between TS and TT and TSS and TT for hard joints at 75 Nm and soft joints at 55 Nm. Significances were seen between TSS and TS, TS and TT and TSS and TT for soft joints at 30 Nm and 75 Nm. Results reported on the sEMG %MVE-s means and standard error bars.

4.2.7 RIGHT TRICEPS BRACHII

For right triceps brachii, a significant interaction was seen between joint hardness and tightening strategy (F=12.40, p=0.000, η^2= 0.341), results shown in Figure 40. For soft-joints, significant increases were seen between strategies TS and TT (77%) and TSS and TT (80%).

4.2.8 RIGHT UPPER TRAPEZIUS

For right upper trapezius, a significant interaction was seen between the participants' age, posture and tightening strategy (F=2.24, p=0.029, η^2= 0.157), results shown in Figure 41. For participants age 20-29 in posture A, significant increases were seen between strategies TS and TT (70%) and TSS and TT (73%). For participants age 20-29 in posture B, significant increases were seen between strategies TS and TT (73%) and TSS and TT (80%). For participants age 20-29 in posture C, significant increases were seen

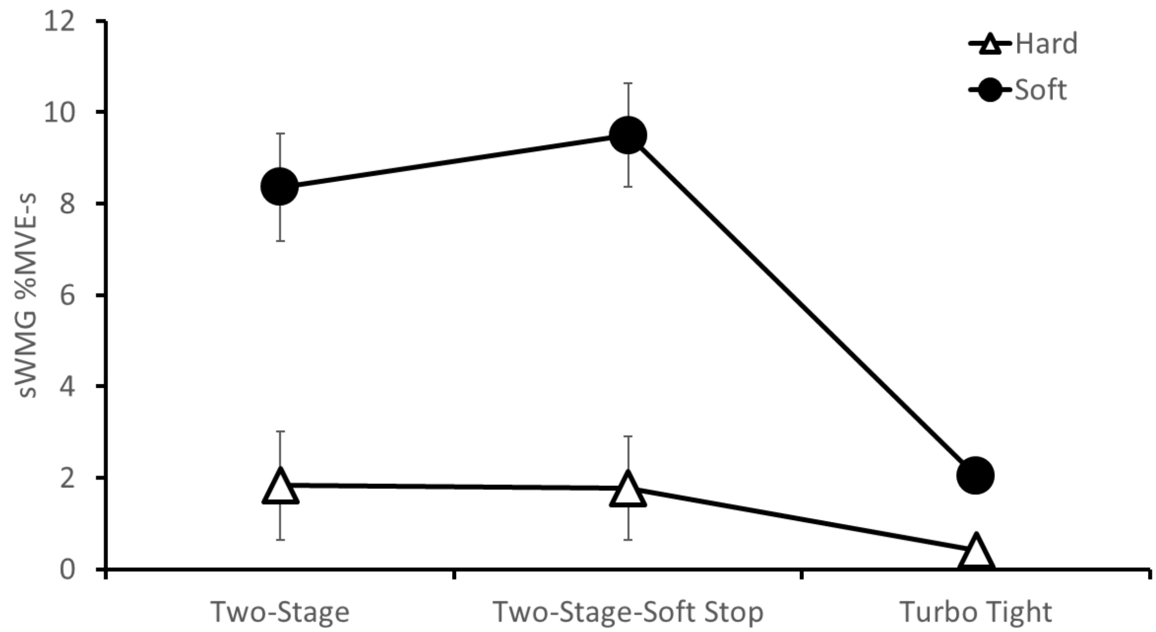

Figure 40: Right Triceps Brachii Impulse Magnitudes for Joint Hardness and Fastening Strategy. Significant interactions were seen for soft joints between TS and TT and TSS and TT. Results reported on the sEMG %MVE-s means and standard error bars.

between strategies TS and TT (69%) and TSS and TT (71%). For participants age 30-45 in posture A, significant increases were seen between strategies TSS and TS (27%), TS and TT (69%) and TSS and TT (77%). For participants age 30-45 in posture B, significant increases were seen between strategies TS and TT (70%) and TSS and TT (73%). For participants age 30-45 in posture D, significant increases were seen between strategies TS and TT (68%) and TSS and TT (72%). For participants age 30-45 in posture C, significant increases were seen between strategies TS and TT (70%) and TSS and TT (74%). For participants age 46+ in posture A, significant increases were seen between strategies TS and TT (59%) and TSS and TT (70%). For participants age 46+ in posture B, significant increases were seen between strategies TS and TT (74%) and TSS and TT (81%). For participants age 46+ in posture D, significant increases were seen between strategies TS and TT (57%) and TSS and TT (71%). For participants age 46+ in posture C, significant increases were seen between strategies TSS and TS (26%), TS and TT (67%) and TSS and TT (75%).

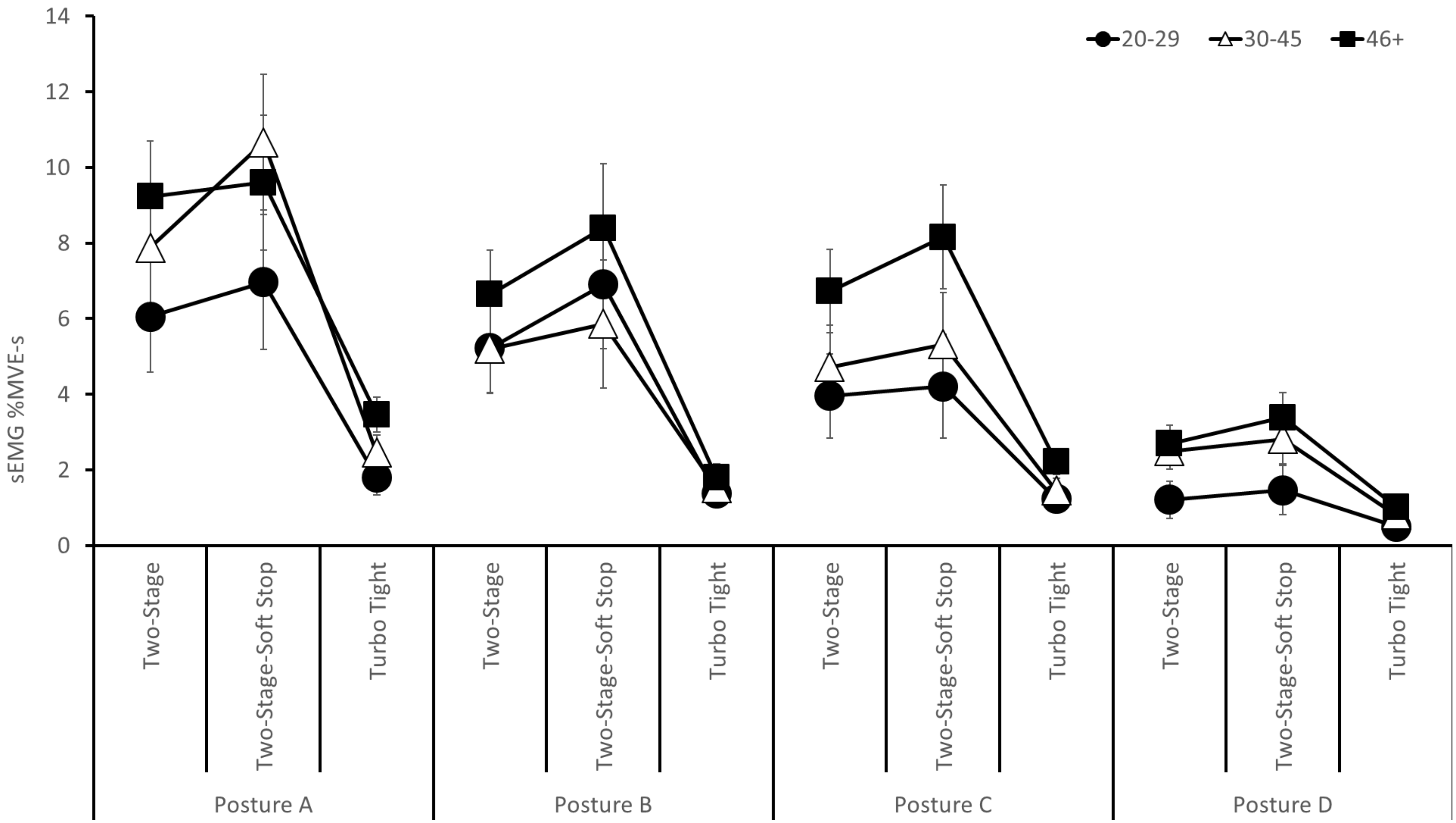

Figure 41: Right Upper Trapezius Impulse Magnitudes for Age, Fastening Location and Fastening Strategy. Significant interactions were seen between TS and TT and TSS and TT for participants aged 20-29 in posture A, B, and C, participants aged 30-45 in posture B, C and D, and participants aged 46+ in postures A, B and D. Significant interactions were seen between all three fastening strategies (TS, TSS and TT) for participants age 30-45 in posture A and participants age 46+ in posture C. Results reported on the sEMG %MVE-s means and standard error bars.

Another significant interaction was seen between joint hardness, participants age and gender, target torque and tightening strategy (F=3.05, p=0.031, η^2= 0.203), results for hard joints shown in Figure 42 and soft joints in Figure 43. For females age 30-45 fastening hard-joints at 75 Nm target torque, a significant increase was seen between strategies TSS and TT (77%). For females age 20-29 fastening soft-joints at 30 Nm target torque, significant increases were seen between strategies TS and TT (84%) and TSS and TT (89%). For females age 20-29 fastening soft-joints at 55 Nm target torque, significant increases were seen between strategies TS and TT (71%) and TSS and TT (73%). For females age 20-29 fastening soft-joints at 75 Nm target torque, significant increases were seen between strategies TS and TT (65%) and TSS and TT (68%). For males age 20-29 fastening soft-joints at 30 Nm target torque, significant increases were seen between strategies TS and TT (61%) and TSS and TT (85%). For males age 20-29 fastening soft-joints at 55 Nm target torque, significant increases were seen between strategies TS and TT (74%) and TSS and TT (70%). For males age 20-29 fastening soft-joints at 75 Nm target torque, a significant increase was seen between strategies TSS and TT (69%). For females age 30-45 fastening soft-joints at 30 Nm target torque, significant increases were seen between strategies TS and TT (71%) and TSS and TT (79%). For females age 30-45 fastening soft-joints at 55 Nm target torque, significant increases were seen between strategies TS and TT (67%) and TSS and TT (71%). For females age 30-45 fastening soft-joints at 75 Nm target torque, significant increases were seen between strategies TS and TT (57%) and TSS and TT (64%). For males age 30-45 fastening soft-joints at 30 Nm target torque, significant increases were seen between strategies TSS and TS (37%), TS and TT (73%) and TSS and TT (83%). For males age 30-45 fastening soft-joints at 55 Nm target torque, significant increases were seen between strategies TS and TT (80%) and TSS and TT (82%). For males age 30-45 fastening soft-joints at 75 Nm target torque, significant increases were seen between strategies TS and TT (41%) and TSS and TT

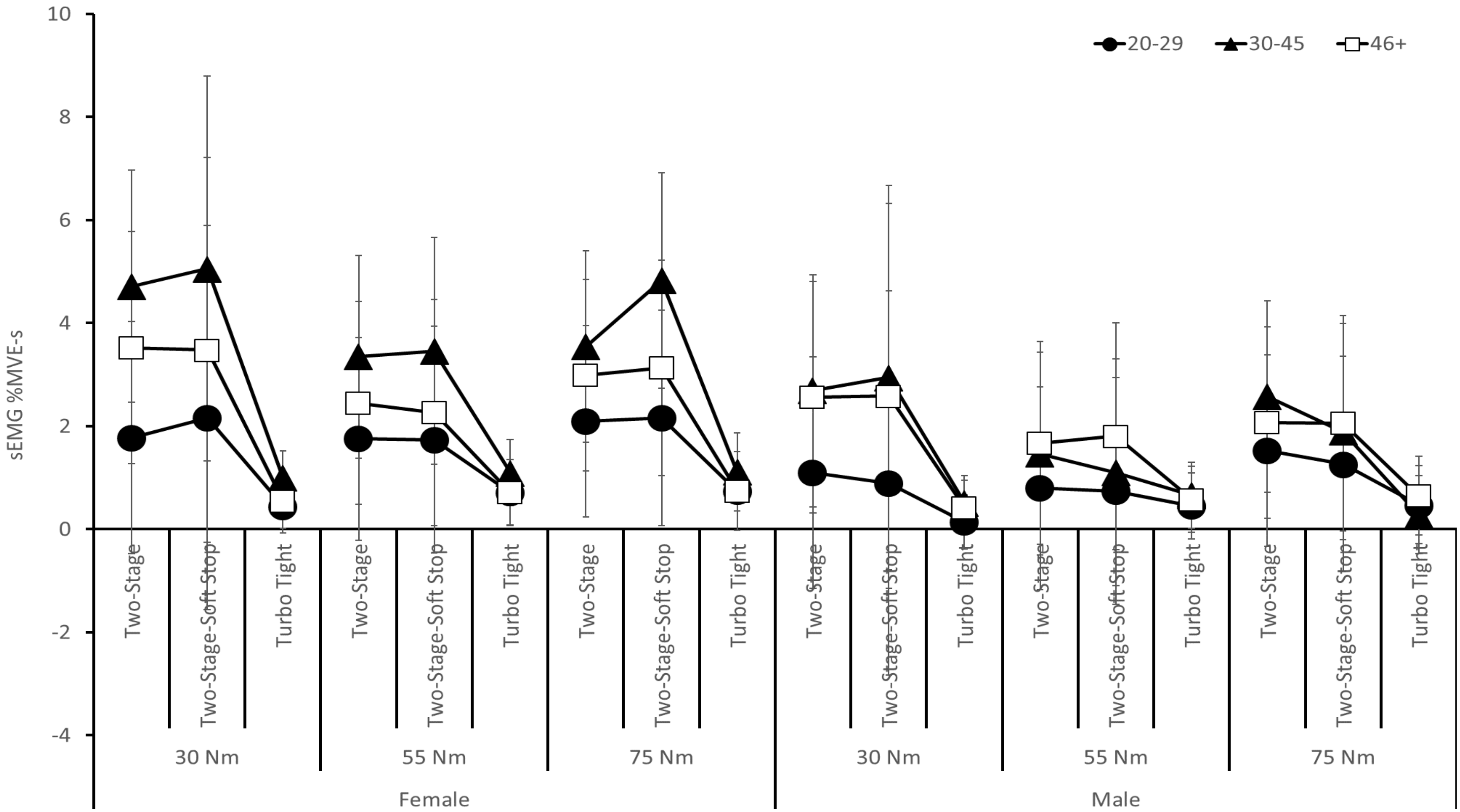

Figure 42: Right Upper Trapezius Impulse Magnitudes for Age, Gender, Target Torque and Fastening Strategy for Hard Joints. Significant interactions were seen for females aged 30-45 at 75 Nm between TSS and TT. Results reported on the sEMG %MVE-s means and standard error bars.

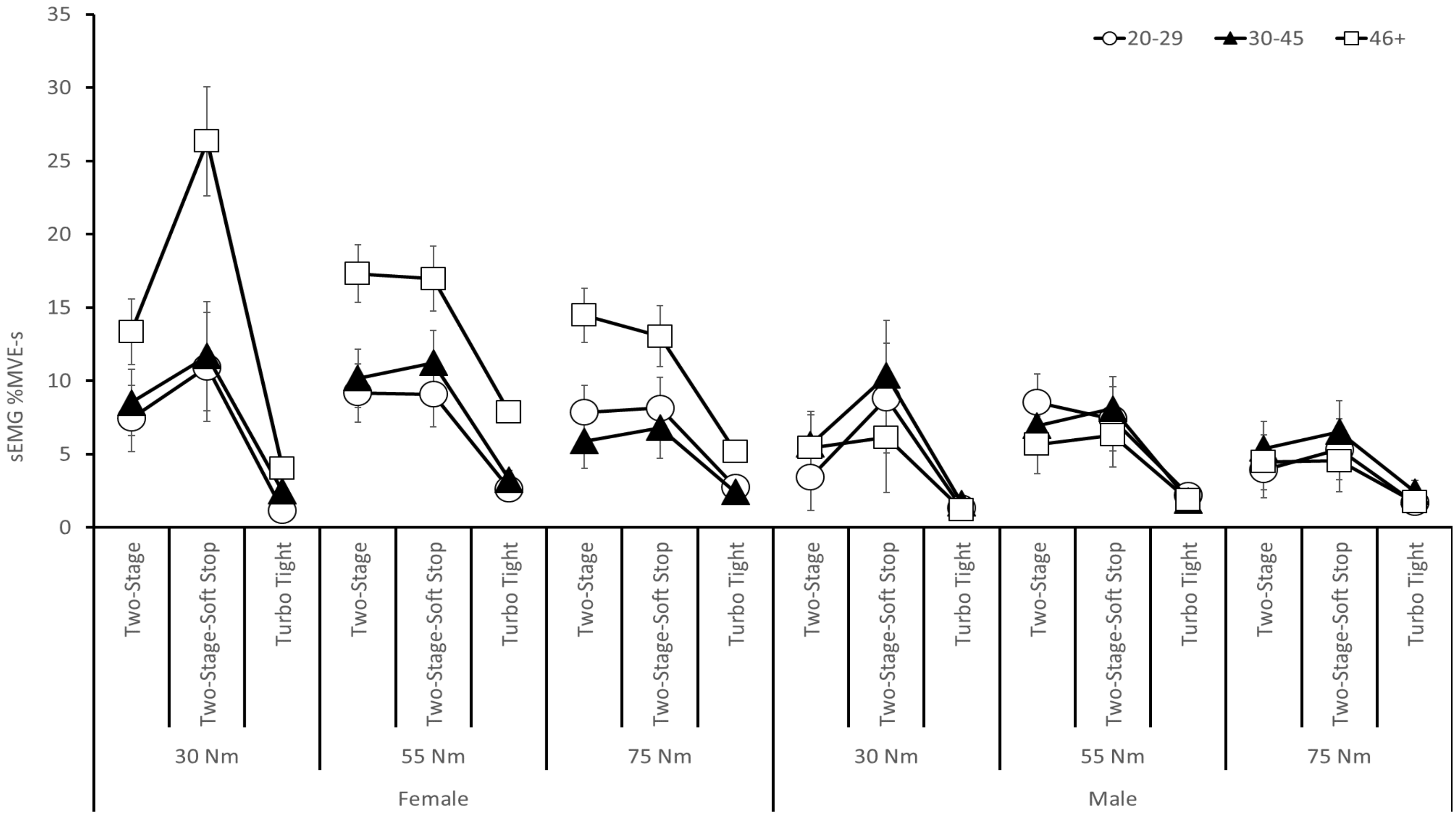

Figure 43: Right Upper Trapezius Impulse Magnitudes for Age, Gender, Target Torque and Fastening Strategy for Soft Joints. Significant interactions were seen between TSS and TT only for males aged 20-29 at 75 Nm. Significances were only seen between TS and TT for males aged 46+ for 30 Nm and 75 Nm. Significant interactions were seen between TS and TT and TSS and TT for females aged 20-29 for 30, 55 and 75 Nm, males aged 20-29 for 30 and 55 Nm, females aged 30-45 for 30, 55 and 75 Nm, males aged 30-45 for 55 and 75 Nm, females aged 46+ at 55 and 75 Nm and males aged 46+ at 55 Nm. Significances are seen for all three fastening strategies (TSS, TS and TT) for males aged 30-45 for 30 Nm and females aged 46+ for 30 Nm. Results reported on the sEMG %MVE-s means and standard error bars.

(59%). For females age 46+ fastening soft-joints at 30 Nm target torque, significant increases were seen between strategies TSS and TT (67%), TS and TT (68%) and TSS and TT (89%). For females age 46+ fastening soft-joints at 55 Nm target torque, significant increases were seen between strategies TS and TT (49%) and TSS and TT (54%). For females age 46+ fastening soft-joints at 75 Nm target torque, significant increases were seen between strategies TS and TT (63%) and TSS and TT (59%). For males age 46+ fastening soft-joints at 30 Nm target torque, a significant increase was seen between strategies TS and TT (77%). For males age 46+ fastening soft-joints at 55 Nm target torque, significant increases were seen between strategies TS and TT (67%) and TSS and TT (72%). For males age 46+ fastening soft-joints at 75 Nm target torque, a significant increase was seen between strategies TS and TT (62%).

4.3 BORG RATINGS OF PERCIEVED EXERTION

A significant interaction for the Borg RPE's was seen between joint hardness, target torque and tightening strategy ($F=2.829$, $p=0.04$, $\eta^2= 0.105$), results shown in Figure 44. Significant increases in ratings for hard joints are seen between TS and TT (increase of 25%) and TSS and TT (increase of 29%) for 30 Nm; TS and TT (increase of 18%) and, TSS and TT (increase of 15%) for 55 Nm; TS and TT (increase of 38%); TSS and TT (increase of 36%) for 75 Nm. Significant increases in ratings for soft joints are seen between TS and TSS (increase of 12%) and, TS and TT (increase of 17%) for 75 Nm.

A significant interaction for the Borg RPE's was seen between posture and tightening strategy ($F=2.429$, $p=0.05$, $\eta^2= 0.092$), results shown in Figure 45. Significant increases in ratings were seen between TS and TT (increase of 14%) and, TSS and TT (increase of 14%) for posture A; and between TS and TT (increase of 26%) and, TSS and TT (increase of 22%) for posture B. Significant increases were also seen between TS and TT (increase of 15%), and TSS and TT (increase of 15%) for posture C; and between TS and TT (increase of 26%) and, TSS and TT (increase of 23%) for posture D.

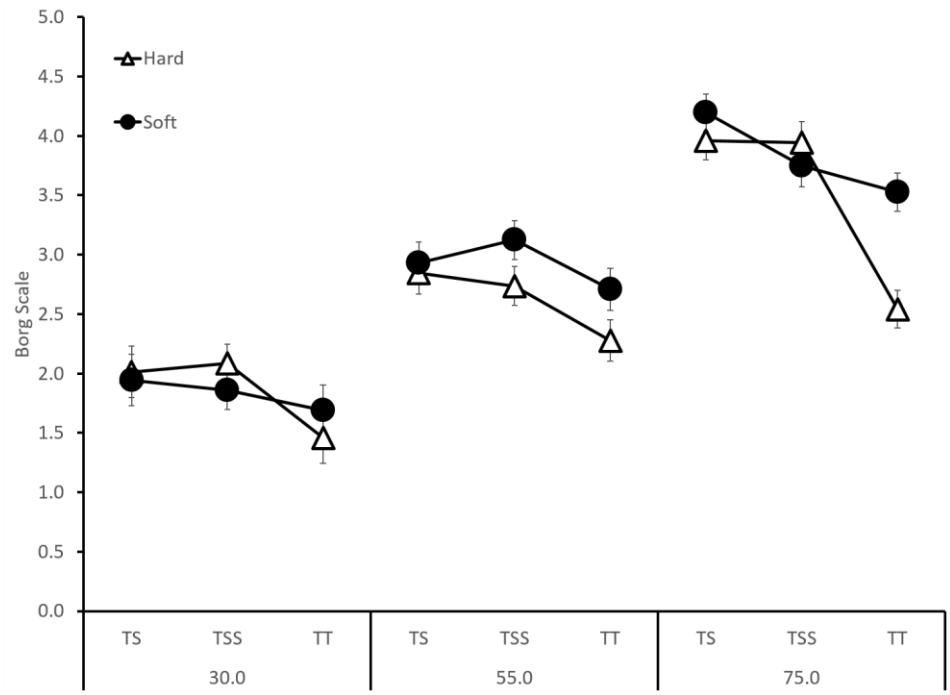

Figure 44: Borg rating of perceived exertions for joint hardness, target torque and fastening strategy. Significances seen between TS and TT and TS and TSS for all target torques for hard joints and for 75 Nm soft joints.

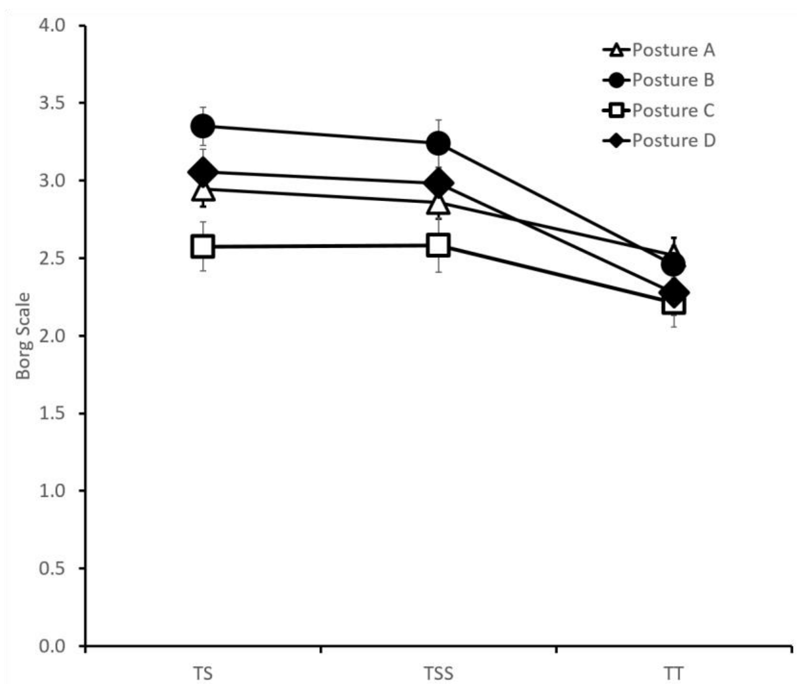

Figure 45: Borg rating of perceived exertions for posture and fastening strategy. Significances seen between TS and TT and TS and TSS for all postures.

CHAPTER 5: DISCUSSION

The purpose of this study was to investigate the physical demands associated with RAPT operation on the muscles of the upper body. Specifically, we set out to determine any differences in muscle effort levels, via sEMG recordings, when performing fastenings using various RAPT fastening strategies, of different torque intensities and hardness' all while working at various heights. Additionally, we recorded handle forces and recorded participant's subjective rating of perceived exertion to aid in the understanding of how different fastening techniques during RAPT operations effect the humans. This work identified that turbo tight fastening strategy, where high speeds are used at the beginning of the fastening and lower speeds are used when close to target torque (Atlas Copco, 2013a), results in lower sEMG and handle force impulse than the other fastening strategies tested. These sEMG results collected in this study show that muscles are activated for a shorter time due to the short time associated with run down while using the turbo tight strategy and is corroborated in our findings shown in Figure 42 and 43 and in table 2.

Table 2: Average fastening durations for the three strategies studied for each of the joint hardness's.

Joint Hardness	Fastening Strategy		
	Two Stage	**Two Stage w/ Soft Stop**	**Turbo Tight**
Hard	0.55	0.64	0.36
Soft	0.98	1.21	0.57

Contrary to the original hypotheses, all the muscles studied did not show an increase in impulse magnitude when the greater target torques were used. As well, it was discovered that among the muscles studied, the non-neutral postures did not cause a greater sEMG impulse magnitude compared to the more neutral postures as hypothesized. Lastly, the BORG perceived exertion ratings indicated that the participants judge turbo tight as easier and, increasing the target

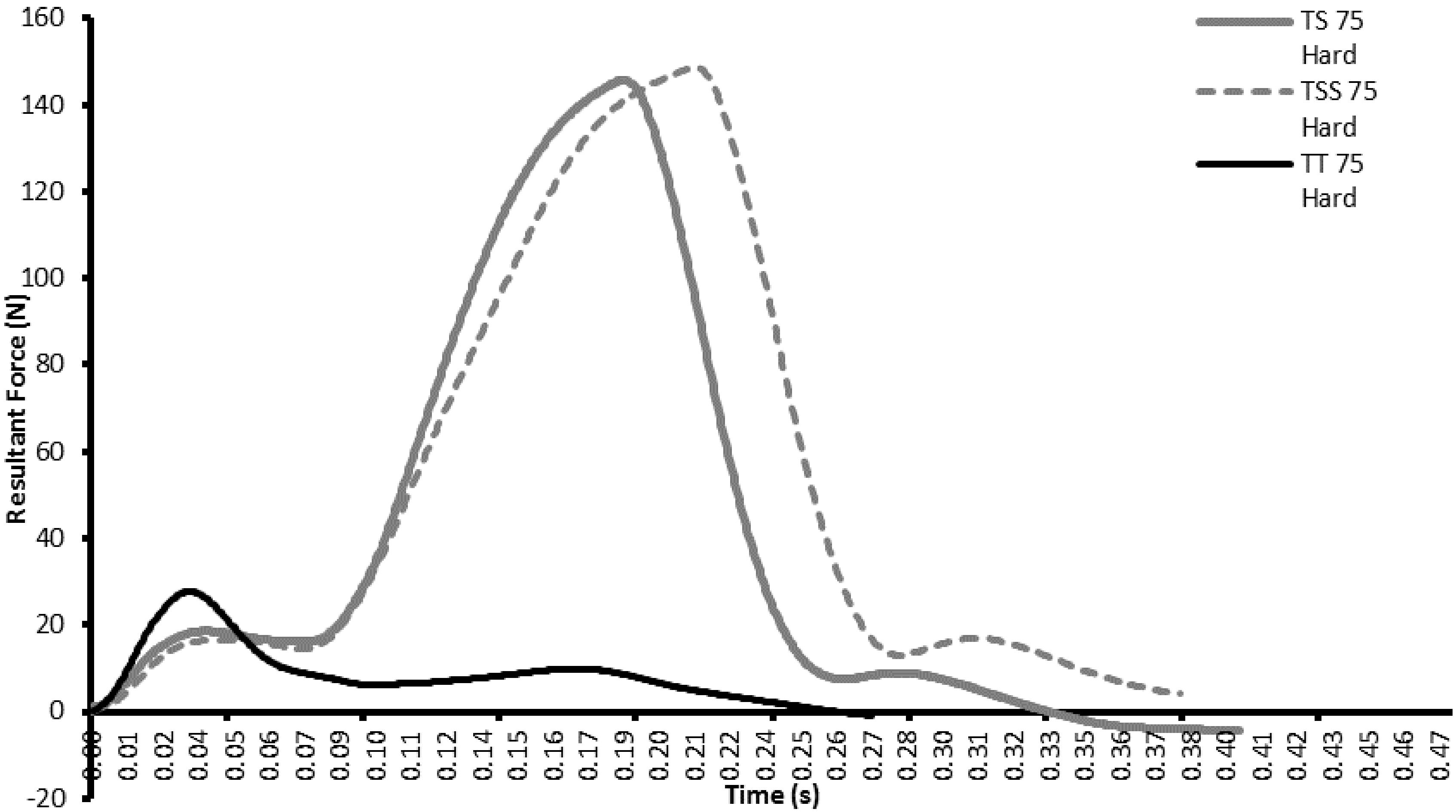

Figure 46: A visual representation of the three fastening strategies recorded by the RAPT handle for hard joints displaying the time periods and resultant forces for 75 Nm hard joints. This shows that the turbo tight fastening strategy takes place over a short period of time and results in a lower force occurring at the RAPT handle.

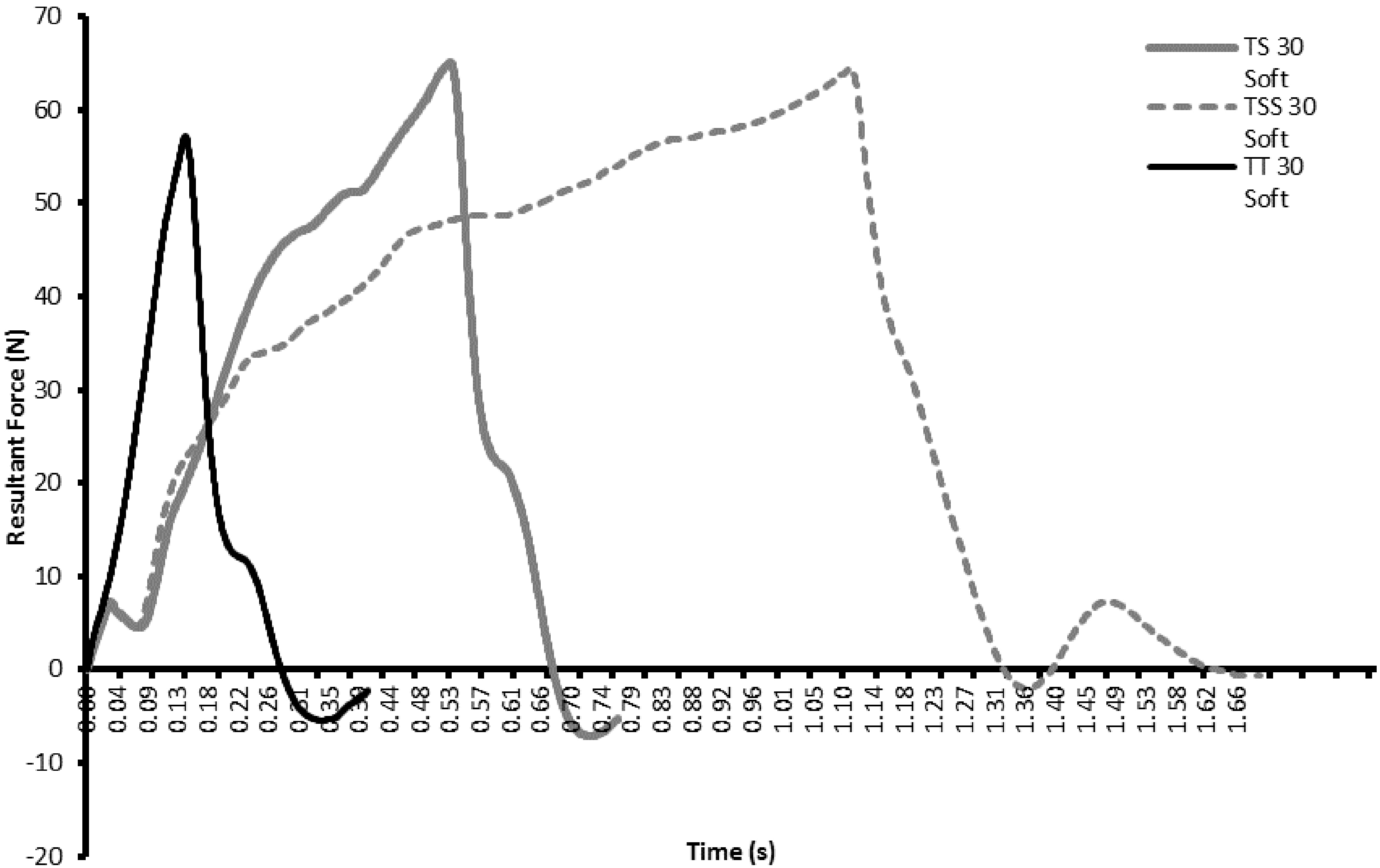

Figure 47: A visual representation of the three fastening strategies recorded by the RAPT handle for soft joints displaying the time periods and resultant forces for 30 Nm hard joints. This shows that the turbo tight fastening strategy takes place over a short period of time and results in a lower force occurring at the RAPT handle.

torque was deemed more physically demanding, and the non-neutral postures were more difficult to complete with the longer duration fastening strategies.

5.1 HANDLE FORCES

An external handle, designed to measure forces in all 3 dimensions, was attached to the RAPT during each fastening, this was completed to quantify hand forces during the tool operation (see Figure 21). Rather than report peak forces, common in ergonomics, we decided that the impulse, also known as integral of the force-time magnitudes, was more representative as it accounts for the muscle activity during the entire fastening and not just one point in time. The study conducted by Freivalds and Eklund (1993) state that the impulse may be the most useful parameter because it considers both time factors and torque levels and shows both their effects on the muscles. This length in time can be directly related to fatigue which in turn is related with the decreased ability to produce the necessary force to successfully complete the task. If an individual keeps becoming fatigued, then they are reducing their ability to complete the task and putting themselves at a greater risk of injury. Pertaining to the forces required to maintain the vertical position (opposing the gravitational effect of the tool, X axis), participants experienced lower impulse magnitudes when fastening joints using turbo tight independent of posture and target torque. Kilhberg et al (1993) corroborate these findings, as they found that that heavier, slow shut off tools required more force to keep the tool in a position compared to fast shut off tools. Similar to the gravitational based forces, when performing the fastenings with turbo tight, the horizontal push/pull impulse magnitudes (Y axis) were significantly less during all fastenings, independent of joint hardness and/or target torque. Since turbo tight is designed to fasten joints in a ballistic fashion, these fastenings are much shorter in duration than either the two stage or two stage with soft stop strategies and end up applying less force at the handle. These longer fastenings tend to have a large reaction torque, where the time duration of the torque reaction force depends on the tool's spindle speed, tool design, preset torque, joint stiffness, shut off mechanism and the operator themselves (Forsman et al., 2002). Due to all these variables, two stage with and without soft stop cause a longer reaction torque than turbo tight, and more displacement of the upper extremities as they are pulled away from the body. This torque reaction forces that operators experience can cause muscles in the hand-arm system to become fatigued due the continued work done to oppose the reaction torque. Fatigued muscles will not be able to produce the same force required to resist this pull and the muscles may become damaged when they undergo rapid eccentric contractions. Along with the repetitious nature of some work and the increased activation, this can potentially lead to pain or an even more serious injury as the operators may not be able to produce the forces required to complete the task (Forsman et al., 2001; Rempel et al., 1992).

5.2 MUSCLES OF THE SHOULDER GIRDLE

The data revealed that all three muscles of the shoulder girdle required less muscle effort, as shown from the muscle sEMG activation impulse data, when fastening with the turbo tight, independent of gender, ages, joint types, target torques and postures. This indicates that not only less time is occupied by the rundown but less force was used, leading to a reduced impulse which calculated as the force-time integral. This is corroborated by the findings of the forces occurring at the handle, where the turbo tight fastening strategy showed less impulse force occurring for the push/pull and lift/lower actions during the duration of the rundown. The data indicates that the anterior deltoid, pectoralis major and the upper trapezius, which have the responsibility to flex, rotate and adduct the shoulder joint (Tortora & Neilson, 2012), are physically demanded less during turbo tight. Similar work by Kihlberg et al. (1993) showed that slow shut off or, delayed shut off tools resulted in a 20-40% increase in muscle activity compared to the fast shut off tools. This fastening is ballistic in nature and produces less force overall to the muscles of the shoulder girdle and therefore, the muscles are not demanded at the same level to maintain the required arm posture, stabilize the tool from falling to the ground and, providing resistive forces associated with longer duration fastenings, such as both two-stage strategies. Others have concluded that the increase in muscle activation with two-stage fastening strategies will lead to overexertion and fatigue of the muscles when done continuously over work days, weeks or more (Freivalds & Eklund, 1993; WSIB, 2013). The fatigue may limit the operators' ability to generate the muscle effort necessary to simply carry out RAPT operation resulting in the failure to optimally control the RAPT which may cause large magnitudes of jerk, which can cause in rapid eccentric contractions of the muscle of the upper extremity. When the muscle undergoes rapid eccentric contraction, the buildup of inorganic phosphate that occurs results in a decline in the amount of force that the muscle can produce (Ament & Verkeke, 2009; Debold, 2012). A fall in active tension also occurs due to sarcomere disruption and excitation contraction coupling damage due to the rapid stretching (Proske & Morgan, 2001). This decline in force production can potentially cause damage of the muscle fibers by not being able to produce force necessary to oppose the reaction, which could lead to pain and serious injury (Forsman, Birch, Zhang, & Kadefors, 2001; Rempel et al., 1992). Our quantifiable data gathered from the sEMG and handle forces gives credence to the qualitative analysis of the BORG RPE's which showed that the lower sEMG showed that a lower effort was used during turbo tight and that may explain why the RPE's were rated as being of a lesser exertion. We conclude that the longer impulse of the two stage strategies may have caused undue muscle fatigue and thus, participants in this study to rate the turbo tight strategy at a lower percieved exertion than the other strategies studied (Freivalds and Eklund, 1993; Oh and Radwin, 1998).

5.3 MUSCLES OF THE UPPER ARM

While the data collected in this study showed that the triceps brachii and biceps brachii muscles were unaffected (no increase in sEMG impulse) by the postures adopted for the fastening location, it did show that the turbo tight tightening strategy had a lesser impulse than two stage with and without soft stop for both joint types and both sexes. Due to the shorter nature of the turbo tight strategy and the reduced force experienced at the handle in the push/pull and lift/lower direction during this rundown (Atlas Copco, 2013a), the biceps are extended and triceps contracted (Tortora & Neilson, 2012) for a shorter time period during the run down, showing a lesser impulse. The upper arm muscles also do not have to resist the reaction torque or, pauses and ramp downs associated with the two stage tightening strategies, leading to a greater length of time and a larger impulse in those rundowns (Atlas Copco, 2013b). Kilhberg at al. (1993) also shows this result as they found that fast shut off tools, like turbo tight, had a 20-40% lower muscle activity level than slow shut off and delayed shut off tightening strategies, two stage with and without soft stop. Due to the shorter nature of the turbo tight fastening strategy, the participants are exerting less force during the rundown. Since the two stage with and without soft stop are longer in duration and have a more pronounced jerk, more force is needed stabilize the arm and resist the reaction torque created during this fastening. As concluded for the muscles of the shoulder girdle, this extra force will lead the muscle to fatigue and will cause a decrease in force production which would be detrimental to help resist the reaction force created and could lead to pain and injury of the muscle. This was supported by the BORG RPE's given by the participants, which showed that among the different fastening strategies, turbo tight was rated at a lower perceived exertion compared to the other strategies tested because less force is needed and less fatigue is experienced for turbo tight. Our results are supported by the work of Oh and Radwin (1998) and Freivalds and Eklund (1993), who stated that short exertions and durations could lead to lower subjective ratings since RPE's are significantly correlated with length of the rundown. Along with the findings on the turbo tight fastening strategy, it was seen that only the bicep brachii muscles in males showed a smaller impulse for turbo tight as target torque increased, and triceps brachii muscles did not show any significances as target torque increased. This may be due to the males having more upper body strength and being able to control the tool more than the females (Frontera, Hughes, Lutz & Evan, 1991; Monteiro et al., 2016). Females, with all tightening strategies and joint types, showed a higher sEMG impulse than males showing more muscle activation and more force production to stabilize and control the tool at each target torque. Similar to Oh and Radwin (1998), as target torque increases, our data suggests that female's biceps were unable to produce the necessary force needed to control the tool as handle displacement occurred. These findings by Oh and Radwin (1998) were reciprocated in our findings where even though females did not show a significant difference in impulses between the different fastening strategies as target torque increased, their BORG RPE's did show that ratings increased as target torque increased. This increase in perceived exertion as target torque increased may be due to the fact that the females could perceive a stronger reaction torque as target torque increased.

5.4 MUSCLES OF THE FOREARM

All muscles of the forearm, extensor carpi ulnaris, flexor carpi ulnaris and flexor carpi radialis showed that the turbo tight fastening strategy caused a lower sEMG impulse than both the two stage and two stage with soft stop. As addressed earlier, this is due to the increase in force production and force experienced at the handle in the push/pull and lift/lower direction and longer time period of the two stage tightening strategies because of the pause and the ramp down that occur to try to lessen the kick back that occurs (Atlas Copco, 2013b). This increase in time just leads to a longer time that the participant has to produce the necessary force to control the tool and resist the reaction torque. This increase in force production to control the tool increases the activation of the muscles while flexing and extending and adducting and abducting the wrists (Tortora & Neilson, 2012), trying to resist the kick back at the end of the rundown. This increased activation from the increased force production causes over exertion of the muscles of the wrist which leads to fatigue. The fatigues muscles can no longer produce the same force as before and cannot resist the reaction torque produced during the rundown, and this failure to resist these external forces can lead to pain and injury. Kilhberg et al. (1993) showed similar results in their study where fast shut off tools similar to turbo tight utilized 20-40% less muscle activity than slow shut off tools or delayed shut off tools, similar to two stage and two stage with soft stop. This study also showed that slow shut off tools required more force over a longer time to keep the tool in position compared fast shut of tools and the wrist would flex and extend and rotate while trying to keep the tool in position (Kilhberg et al., 1993; Tortora & Neilson, 2012). The participants RPE's also represent these findings from the data, where ratings were lower for turbo tight fastener strategy compared to the ratings given for two stage with and without soft top as well as increases in ratings as target torque increases.

5.5 HYPOTHESES REVISITED

1. Greater increase in sEMG activation impulse and Borg RPE magnitudes with the increase in target torque will be found. Specifically, the biceps brachii and pectoralis major having greater sEMG activation impulse during the fastenings as target torque increases.

The results from this study accept the null hypothesis as differences in muscle activation among the different target torque impulses were not found for the muscles of the shoulder girdle, upper arm and forearm. Only two muscles showed increased activation impulse as target torque increases and only in certain conditions. The anterior deltoid showed an increase in impulse as target torque increased with soft-joints in posture D and, the biceps brachii showed an increase in impulse as target torque increased for males during the turbo tight fastening strategy; all other muscles did not show this increase. The BORG rating of perceived exertion however, did show increases with target torque increase, as also shown in the study conducted by Freivalds & Eklund (1993), but since this wasn't seen across all the muscles sEMG data, we still accept the null hypothesis.

2. Lesser muscle sEMG activation impulse and Borg RPE magnitudes for all muscles will be observed when using turbo tight fastenings strategy compared to a two-stage fastening strategy with and without soft stop.

The data proved to reject the null hypothesis as participants required lesser sEMG activation impulse and lesser BORG ratings when fastening with turbo tight, compared to both the two stage and two stage with and without soft stop. Similar results were found in the study conducted by Kilhberg et al. in 1993 on pneumatic tools. Their study found that muscle activity was 20-40% lower for fast shut off tools, similar to the turbo tight strategy, in comparison to delayed or slow shut off tools. These delayed or slow shut of tools are similar to two stage strategies, and these tools require more force to stay in position leading to increased muscle activation (Kilhberg et al., 1993). Kihlberg et al. (1993) also found that BORG RPE were also greater for delayed or slow shut off tools than fast shut off tools, similar to the findings in this study.

3. Non-neutral postures will show an increase in sEMG activation impulse and an increase in Borg RPE magnitudes compared to neutral postures. Specifically, locations B and D will show an increase in sEMG activation impulse compared to locations A and C. The

anterior deltoid and pectoralis major will show the greatest increases during these time periods for both locations B and C.

The data from this work accepts the null hypothesis, no significant differences in sEMG activation impulse and BORG RPE between the different postures were found. The shoulder girdle aids in posture stabilization, the upper arm functions to help resist the kickback created, while the forearm muscles help in stabilizing the tool and resisting the forces at the handle. Previous studies showed that low postures and postures on vertical surfaces provide increased muscle exertion (Forsman et al., 2002; Oh & Radwin, 1998). Oh and Radwin (1998) conducted a study using RAPT on horizontal and vertical work surfaces and showed that vertical work stations provide more handle instability than horizontal work station, but this was not seen in this study. As well, Forsman et al. (2002) conducted a study examining various heights and positions around an object and found that lower postures put higher loads on the lower back and wrist while higher postures produced higher loads on the shoulders. While the anterior deltoid and upper trapezius muscles in this study did show that postures A and B, chest height and vertical surface postures showed the highest sEMG activation impulse, it is not what was predicted to be seen in these results.

5.6 LIMITATIONS AND ASSUMPTIONS

It must be noted that this work contained both limitations and assumptions. Firstly, the BORG RPE scale given to the participants did not adequately describe to them all the information needed to obtain more accurate rating. While many studies still used the BORG CR10 scale, it is imperative that the questions used are specific and with adequate direction such that they allow for an optimal understanding and interpretation of the scale (Freivalds & Eklund,1993; Kihlberg et al., 1993; Oh & Radwin, 1998). To improve this, we could have allowed the participants to complete the worst task first to determine their upper limit of the rating scale and be better able to anchor their responses, as well as given a better, more descriptive rating scale to better accurately define the ratings for the participants. Secondly, the participant pool was designed to include only those with no experience in the automotive industry and, no experience with RAPT operations. While this allows for unbiased results, we are aware that experienced workers may have shown different results. For example, experienced workers could potentially be stronger than inexperienced workers from the years of work as well as potentially having developed a strategy to resist the kick back that these unexperienced individuals lack. However, this sample did allow the results to be attributed purely on the effects of the experimental conditions and were not linked to other extraneous variables that could have been acquired by an automotive worker.

CHAPTER 6: CONCLUSIONS

In conclusion, the results from this study showed the turbo tight fastening strategy provided significantly less sEMG activation impulse and handle force impulse in the push/pull and lift/lower direction when compared to two stage with and without soft stop, regardless of posture adopted or target torque used. This difference between these strategies is due to a combination of the reduction in fastening time and lesser overall the reaction forces created throughout the duration of the fastening. This proves that fastening with turbo tight reduced the overall physical demand on the muscles compared to the other strategies examined, and potentially allow the muscles to reduce the effects of fatigue, which may help reduce the risk associated with musculoskeletal injury. These findings were also correlated in the results from the BORG scale ratings, which showed the participants perceived the turbo tight fastening strategy to provide a lesser exertion compared to two stage with and without soft stop.

6.1 IMPLICATIONS FOR INDUSTRY

This study incorporated tools and joint types and postures commonly used within the automotive industry. This enabled the results of this study to be applicable and representative to what RAPT operators would experience in the workplace. With taking that into consideration, there are a few key findings from this research that can be used as applications to industry:

- Implementing direct current power tools into all manufacturing areas as the rundown can be controlled for speed and target torque used. As previously discussed, pneumatic power tool shut off is in a large part controlled by the operator and rotation still occurs even when the joint is fully tightened, increasing exposure to unnecessary handle forces (Kihlberg, Kjellberg, & Lindbeck, 1993; Radwin et al., 1989).
- Implementing turbo tight fastening strategy on all direct current power tools regardless of joint type, posture and target torque. This fastening strategy aims to get to the target torque as quickly as possible by using a high speed, then decreases speed when it is close to the target torque to lower the reaction torque experienced by individual. As this study aimed to find which fastening strategy was better, it did determine that reaction torque experienced by the individuals was less with turbo tight.

6.2 FUTURE RESEARCH DIRECTIONS

Future research should concentrate on the other tool vendors that are used in the manufacturing environment. This study focused on Atlas Copco tools and fastening strategies incorporated into their devices. Other tool vendors may have a similar strategy or, may have a different strategy that would be better for the workers than turbo tight. Any strategy that would lessen the forces at the handle and lessen the reaction force experienced would be optimal for manufacturing workers.

Another research area that could be explored is using a more representative population of workers who would be using the tools on a regular basis. This research was conducted on individuals with no automotive manufacturing experience to receive unbiased results. Determining the acceptability and muscle response from workers who are experienced with these tools, whether pneumatic or direct current, and their various tightening strategy methods would provide the manufactures and tool vendors with application knowledge on what is best for their targeted demographic.

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APPENDIX A

Today's Date: January 14, 2015
Principal Investigator: Dr. Joel Cort
REB Number: 32134
Research Project Title: REB# 14-258: Ergonomic Evaluation for Right Angle Power Tools: Pneumatic vs. DC Physical Demands Comparison
Clearance Date: January 14, 2015
Project End Date: December 01, 2015
Milestones:
Renewal Due-2015/12/01(Pending)

This is to inform you that the University of Windsor Research Ethics Board (REB), which is organized and operated according to the Tri-Council Policy Statement and the University of Windsor Guidelines for Research Involving Human Subjects, has granted approval to your research project on the date noted above. This approval is valid only until the Project End Date.

A Progress Report or Final Report is due by the date noted above. The REB may ask for monitoring information at some time during the project's approval period.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the REB. Minor change(s) in ongoing studies will be considered when submitted on the Request to Revise form.

Investigators must also report promptly to the REB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

Forms for submissions, notifications, or changes are available on the REB website: www.uwindsor.ca/reb. If your data is going to be used for another project, it is necessary to submit another application to the REB.

We wish you every success in your research.

Alan Scoboria, Ph.D.
Chair, Research Ethics Board
Lambton Tower, Room 1102 A
University of Windsor
519-253-3000 ext. 3948
Email: ethics@uwindsor.ca

APPENDIX B

CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: Ergonomic Evaluation for Right Angle Power Tools: Physical Demands Comparison of Three Direct-Current Tightening Strategies.

You are asked to participate in a research study conducted by **Dr. Joel Cort ,** from the **Department of Human Kinetics** at the University of Windsor

If you have any questions or concerns about the research, please feel to contact **Dr. Joel Cort at (519) 253-3000 ext. 4980 (joel.cort@uwindsor.ca), Christian Steingraber (**steingr@**uwindsor.ca) or Danielle Devries (devriesd@uwindsor.ca) at 519-253-3000 ext. 4277.**

PURPOSE OF THE STUDY

The United States Council for Automotive Research (USCAR) has determined repetitive strain and sustained handling of tools at various heights can lead to an increased risk of acute and chronic work related injuries in automotive manufacturing. The purpose of this study is to parameterize and quantify ergonomic factors (end-reaction torque and handle displacement) associated with right angle power tool usage in order to reduce work related musculoskeletal disorders and improve worker safety.

PROCEDURES

Subjects will be recruited from 3 age groups (20-29, 30-45, 45+ years) with 6 males and 6 females from all groups for a total of 36 participants. Subjects will then be randomly assigned within their age group to one of two joint types (Hard or Soft).

Procedures

- Information such as age, height, weight and hand dominance will first be collected. You will be given a period of 15 minutes to familiarize yourself with all tools, locations, and joint orientations. Following familliarization, the investigator will attach 16 electrodes (these measure the electrical activity of the muscles) and motion-capture markers (these will help track your movements) to your skin and clothes.
- *Protocol*
    - **Maximal exertions**- participants will perform maximum exertions for forward flexion, shoulder elevation, forearm extension and wrist flexion to capture the muscle activity of the 16 muscles in the chest, back, shoulders and arms being studied.
      Each of these contractions will last 2-3 seconds—you will be given a 60 second rest between contractions
    - **Positioning:** You will be placed in a predefined foot position and hold the right angle power tool with the right hand on the trigger and left hand on the identified stabilizing handle. You will place the tool spindle head on the joint simulator to perform the task.
    - **Testing Days:** You will complete 18 conditions per day, on 2 separate days, resulting in a total of 36 conditions. Each condition will consist of a randomized power tool tightening strategy, target torque and fastener location-orientation. You will complete 5 sets per

condition, with a single set consisting of 5 joint tightening's in a 60 second period, resulting in a total of 5 minutes of continuous work per condition. You will receive a rest period of 2 minutes between each condition and will be asked to provide ratings of perceived exertion/effort based on a 10-point Borg scale.

- *Rest Days*
  - A minimum of 3 days rest will be provided between testing day 1 and testing day 2.

POTENTIAL RISKS AND DISCOMFORTS

Minimal risks are anticipated – the tasks that will be simulated are exactly as they are done within the working environment. The following are possible consequences associated with this experiment:

Muscle fatigue/soreness – as with any physical activity, there is a risk of the development of muscular fatigue or soreness. The exposure to the postures required to replicate the workplace tasks and the added weight from the right-angle power-tool may cause transient muscle soreness/discomfort. Any muscle soreness or discomfort that may occur will ordinarily subside within a few days after testing.

Muscle and joint injury – with any exertions there is always a risk of muscle or joint injury. However, these exertions do not differ from those performed in the workplace.

Skin irritation – the electrodes used to record muscle activation, as well as the tabs used to affix the reflective markers associated with the motion capture system, are adhered directly to the skin. As such, there is risk of skin irritation. The irritation is similar to that which may develop from the use of commercially available bandages and will disappear within 2-3 days after testing.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

Participants will be exposed to occupational biomechanics research practices which can benefit their awareness of personal ergonomics in activities of daily living. Furthermore, participants will experience the collection procedures of both electromyography and kinematics (Motion Analysis System) which may be useful in future academics and/or careers.

COMPENSATION FOR PARTICIPATION

Participants will be compensated with an hourly fee of $15.00 per hour as well as receiving a University of Windsor, Faculty of Human Kinetics research t-shirt for your participation in this study.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified to you will remain confidential and will be disclosed only with your permission. However, due to the nature of the study, you will not be able to remain anonymous to the investigators, but all electronic or hard copy data and personal information will be treated as confidential and a coding system will be employed to ensure confidentiality to others. Only the involved investigators will be familiar with the coding system.

All digital data will be stored on a password protected computer. All paper documentation will be secured in a locked filing cabinet, which will be placed in the locked office in the University of Windsor Human Kinetics building. Upon completion of the study, the digital data will be transferred to a hard disk, and the paper documents will be securely locked within the office of Dr. Joel Cort. One year past the completion of the study, the paper documents containing personal data will be shredded and disposed.

PARTICIPATION AND WITHDRAWAL

You are being invited to volunteer in this study. If you choose to volunteer, you are free to withdraw from the study without any consequence at any time either before or during the testing sessions. If you choose to withdraw, all of your digital data will be permanently deleted from the computers and all paperwork will be shredded.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS

Research findings will be posted online on the University of Windsor Research Ethics Board website (www.uwindsor.ca/reb) upon the completion on this study. You will be contacted via email to be informed when this is available. This website is accessible to the public. Results are expected to be posted during the Fall of 2015.

SUBSEQUENT USE OF DATA

These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS

If you have questions regarding your rights as a research participant, contact: Research Ethics Coordinator, University of Windsor, Windsor, Ontario, N9B 3P4; Telephone: 519-253-3000, ext. 3948; e-mail: ethics@uwindsor.ca

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I understand the information provided for the study **Ergonomic Evaluation for Right Angle Power Tools: Physical Demands Comparison of Three Direct-Current Tightening Strategies** as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Participant

____________________________________ ________________

Signature of Participant Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

____________________________________ ________________

Signature of Investigator Date

____________________________________ ________________

Signature of Investigator Date

APPENDIX C

SCRIPT

The Direct Current (DC) RAPT setup for this study includes a right angle power tool (RAPT), power tool controller and simulated handle. The controller, connected to RAPT via a power cord, provides the parameters associated with joint fastening and collects information regarding the tool tightening. In addition to the controller and RAPT, a simulated handle is placed onto the RAPT in order to collect forces experienced at the handle.

For this study, you will be completing a series of DC RAPT fastenings. A DC RAPT is powered by electricity and is initiated with the pull of the trigger. Once a preset torque (rotational force) or angle is met, the tool will automatically shut off.

In order to operate the tool, two hands will be placed on the RAPT as shown in picture below. The left hand will be placed near the spindle head while the right hand will be controlling the trigger. An instrumented handle will be attached to the tool, allowing for you to control the power source of the tool.

For data collection, your feet will be placed in a specified location on the ground and you will complete a series of joint fastenings per condition. Each condition will consist of 5 continuous minutes of joint fastenings every 12s. Following the 5 minutes, you will receive two minutes of rest as well as provide a rating of your perceived effort.

For the next 15 minutes you may practice with any variation of fastenings setups consisting of those you may experience during this study.

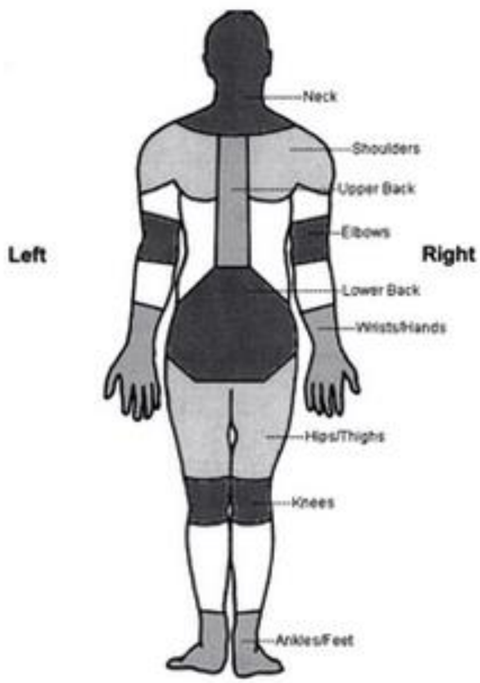
APPENDIX D

Mine: ____

Initial of first name: __ Initial of last name: __ Last 4 digits of social security number: __ __ __ __ Immediate Supervisor: ________________________ Date: ___/___/___

Job Title: __________________________ Section: ______________________ Gender: M F Age: ______ Height: ___ ft.___ in. Weight: ______

How long have you been doing this job? _____ years _____ months On average, how many hours do you work each week? _____



Back View

To be answered by everyone		To be answered by those who have had trouble			
Have you at any time during **the last 12 months** had trouble (ache, pain, discomfort, numbness) in:		Have you at any time during the **last 12 months been prevented from doing your normal work** (at home or away from home) because of the trouble?		Have you had trouble at any time during **the last 7 days?**	
Neck ☐ No	☐ Yes	☐ No	☐ Yes	☐ No	☐ Yes
Shoulders ☐ No	☐ Yes, right shoulder ☐ Yes, left shoulder ☐ Yes, both shoulders	☐ No	☐ Yes	☐ No	☐ Yes
Elbows ☐ No	☐ Yes, right elbow ☐ Yes, left elbow ☐ Yes, both elbows	☐ No	☐ Yes	☐ No	☐ Yes
Wrists/Hands ☐ No	☐ Yes, right wrist/hand ☐ Yes, left wrist/hand ☐ Yes, both wrists/hands	☐ No	☐ Yes	☐ No	☐ Yes
Upper Back ☐ No	☐ Yes	☐ No	☐ Yes	☐ No	☐ Yes
Lower Back (small of back) ☐ No	☐ Yes	☐ No	☐ Yes	☐ No	☐ Yes
One or Both Hips/Thighs ☐ No	☐ Yes	☐ No	☐ Yes	☐ No	☐ Yes
One or Both Knees ☐ No	☐ Yes	☐ No	☐ Yes	☐ No	☐ Yes
One or Both Ankles/Feet ☐ No	☐ Yes	☐ No	☐ Yes	☐ No	☐ Yes

***Based on the Nordic Questionnaire**

APPENDIX E

RAPT Physical Demands Data Collection Sheets (MoCap)

Experimental Group: **HARD** or **SOFT** Collection Day: 1 or 2

Subject Name: ____ Age: ________

Subject Height: _____________ Subject Weight: ___________ Subject Handedness: L or R

Calibration: Tools, Joints, MoCap
Consent From & Questionnaire
15 min. Familiarization
MVC (9 or 10 exercises)
Bias Trial
Markers & T-Pose & ROM

Condition #	TT	TS	Posture	Trial #	Comments
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					

Scrap Trials:

Coding	**TT**	**TS**	**Posture**
1	30	Two stage	A
2	55	Two Stage w/ Soft Stop	B
3	70	TurboTight®	C
4			D

APPENDIX F

Results of the Repeated Measure ANOVA Analysis for Impulse sEMG Amplitude For Pre to Peak Target Torque Time Period (Impulse)						
	df	*SS*	*MS*	*F*	*p*	*η2*
R Anterior Deltoid						
Posture*Sex	1.72	311.20	180.85	7.73	0.002	0.243
Strategy*Sex	1.24	279.93	226.15	5.08	0.025	0.175
Posture*Target Torque*Hardness	3.44	141.77	41.27	4.71	0.003	0.164
Target Torque*Strategy*Hardness*Age	5.11	132.31	25.87	2.37	0.048	0.165
R Bicep Brachii						
Target Torque*Strategy*Hardness*Sex	2.53	141.68	56.00	4.15	0.014	0.148
R Extensor Carpi Ulnaris						
Posture*Hardness*Sex	1.57	424.36	270.61	4.42	0.027	0.155
Target Torque*Strategy*Hardness	2.11	706.34	335.51	5.47	0.006	0.186
R Flexor Carpi Radialis						
Target Torque*Strategy*Hardness	2.38	2839.70	1194.61	6.10	0.002	0.203
Target Torque*Hardness*Age*Sex	3.85	617.14	160.37	2.89	0.034	0.194
R Flexor Carpi Ulnaris						
Strategy*Hardness*Age*Sex	2.54	3886.05	1529.79	3.23	0.043	0.212
Target Torque*Strategy*Hardness	2.59	5001.72	1928.49	24.50	0.000	0.505
R Pectoralis Major						
Target Torque*Strategy*Hardness	1.77	8583.04	4864.04	5.99	0.007	0.200
R Tricep Brachii						
Strategy*Hardness	1.63	2275.62	1399.35	12.40	0.000	0.341
R Upper Trapezius						
Posture*Strategy*Age	8.33	160.78	19.31	2.24	0.029	0.157
Target Torque*Strategy*Hardness*Age*Sex	3.60	174.84	48.64	3.05	0.031	0.203

VITA AUCTORIS

NAME:	Danielle DeVries
PLACE OF BIRTH:	Milton, ON
YEAR OF BIRTH:	1989
EDUCATION:	University of Windsor, B.H.K., Windsor, ON, 2012
	University of Windsor, M.H.K., Windsor, ON, 2017