DEGREE PROJECT IN TECHNOLOGY AND HEALTH,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2018

Ergonomic Evaluation of Power Tool Use at Different Task and Tool Related Conditions

Using a Mechanical Test Rig, Electromyography and Subjective Evaluations

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Ergonomiutvärdering av monteringsverktyg för olika uppgifts- och verktygsrelaterade parameterar

Genom att använda en mekanisk testrigg, elektromyografi och subjektiva utvärderingsmetoder

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Abstract

Workers within production and assembly lines are often exposed to ergonomically unfavorable tasks and conditions. Reaction forces and reaction torques generated by industrial power tools may cause not only discomfort but also health issues and injury. The forceful tasks in combination with highly repetitive hand-arm motions and prolonged tool use paves the way for loss in workforce capacity which in turn can lead to great losses in productivity and product quality. An umbrella term for the many injuries and diseases that may arise from the use of such tools is Cumulative Trauma Disorders (CTD).

This study aimed to investigate the ergonomic effect of power tool use for various tool and task related conditions. The study required the setup of a test rig with a simulated handle of the tool. The ergonomic impact was assessed by measuring the torques associated with different tightening strategies, as well as measuring the angular displacement of the tool handle. By varying the joint stiffness and workplace orientation, the complexity of the task was varied and thus quantified. Measurements of muscle activity during each tightening procedure provided a quantification of the physiological impact on the operator. By combining the measurements on the operator with subjective assessment of perceived exertion and discomfort, a more holistic perspective on the tightening procedure was obtained.

The results obtained from the study stressed the negative impact on the operator which the Quick Step tightening strategy on medium hard joints implies, regardless of workspace orientation. The Turbo Tight and Tensor Pulse tightening strategies turned out to generate the lowest reaction torques and handle deflections, regardless of joint stiffness and workspace orientation. The findings from the muscle activity measurements in combination with the subjective evaluation methods further confirmed the mildness of the Turbo Tight and Tensor Pulse strategies. Moreover, horizontal workspace resulted in lower tool handle deflection compared to vertical workspace for all tightening strategies and joint stiffnesses.

Sammanfattning

Många antällda på monteringsband exponeras ofta för ergonomiskt ofördelaktiga arbetsuppgifter och arbetsförhållanden. De handhållna monteringsverktyg som används genrerar ofta reaktionskrafter som i många fall kan orsaka en känsla av obehag eller ge upphov till mer bestående hälsobesvär. De kraftfulla och repetetiva arbetsuppgifterna som montering många gånger innebär kan bana väg för förluster i arbetskraftskapacitet, vilket i sin tur kan leda till stora förluster i produktivitet och produktkvalitet. En paraplyterm för de många åkommor och besvär som kan uppstå som ett resultat av användandet av handhållna monteringsverktyg är ’förslitningsskador’ (Cumulative Trauma Disorders på engelska).

Målsättningen för denhär studien har varit att undersöka de ergonomiska effekter som användandet av handhållna monteringsverktyg innebär vid olika vektygs- och arbetsuppgiftsrelaterade parametrar. Studien genomfördes med hjälp av en test rig där ett simulerat verktygshandtag utnyttjades. Den ergonomiska effekten på användaren undersöktes genom mätningar av uppnådda reaktions moment och handtags vinklar associerade med olika åtdragningsstrategier, styvhet av förband samt orientering av arbetsyta. Genom att mäta muskelaktiviteten i underarmen hos testpersonerna erhölls en kvantifiering av den fysiologiska effekten på testpersonerna. Mätningarna av vinkel, moment och muskelaktivitet kombinerades med subjektiva skattningsmetoder för att på så sätt kunna erhålla ett mer holistiskt perspektiv på åtdragningarna och deras effekt på människan.

Resultaten från studien underströk de negativa effekterna av åtdragning med Quick Step strategin på medium hårda förband, oavsett orientering av arbetsytan. Turbo Tight och Tensor Pulse strategierna genererade de lägsta reaktions momenten och handtags deflektionerna. Resultaten från muskelsaktivitetsmätningarna och de subjektiva skattningsmetoderna bekräftade den relativa mildheten hos Tensor Pulse och Turbo Tight strategierna. Dessutom påvisades att åtdragningar som sker på en horisontell arbetsyta resulterade i lägre handtagsdeflektion jämfört med åtdragningar på en vertikal arbetsyta, oavsett åtdragningsstrategi och styvhet hos förband.

Acknowledgements

This master thesis project has been an application of the knowledges and skills that I have gained throughout my engineering education. However, several persons have been involved and blown wind beneath my wings throughout the course of the project.

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Finally, I owe a big thanks to the people who have participated as test persons in the experiments. Your participation has been a fundamental requirement for making this project possible.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 General

Throughout the years, people have used many different methods and tools for manufacturing products - spanning from the early uses of hammers and wrenches which rely on forces generated by the operator, i.e. the person handling the tool, to today's wide use of power tools which are powered by external energy sources such as air or electricity.

As industries today develop more complex products, it puts a greater demand on the various tools and methods required to produce them. The increasingly high complexity means that the industries today need to rely on more secure and accurate assembly tools. One such industry is the automobile industry, in which it is estimated that power tools constitute 75% of the tools used in a manufacturing plant (1). The introduction of power tools within assembly lines has in many ways been a great benefit to the industries, where improvements in terms of productivity, security and product quality have been achieved. Although automation is nowadays used for overcoming many of the forceful and advanced tasks involved in assembly, the need for manpower is still significant.

The difference in energy sources between manual tools and power tools inevitably implies a different ergonomic impact on the operator. When handling manual tools, the operator can alter the force generation and so the force output is limited to the strength and capacity of the operator. The shift in force generation from manual tools to power tools unburdens the operator in many ways while at the same time achieving force magnitudes which are difficult or impossible for a human operator to exert, thanks to the use of external power sources. (2) However, this shift in power source does in many cases imply that the magnitude of forces and torques generated by the tool is beyond the limit to which the operator can counteract without being prone to injury.

J. Lin et al. have in multiple studies attempted to investigate the effects of power tool use on the human operator. Different approaches have been taken in order to evaluate various ergonomic aspects associated with power tool use. The results from the studies show that there are clear correlations between power tool use and quantified muscle force exertions, as well as perceived operator discomfort. (3) (4) Moreover, S. Mukherji has quantified the ergonomic impact of different power tool settings by means of a mechanical simulation of a human hand-arm system (3). Another study was conducted by S. Oh and R. Radwin where the operators' ability to stabilize a power tool during different work conditions was investigated. (1)

1.2 Thesis Objectives

Within the field of power tool ergonomics, there are today no well-established methods for prediction of how power tool use affects the operator. It is therefore of great interest to develop a method which accurately estimates the forces present during tool operation and the impact on the operator which they imply. The development of such a method will require extensive research, and several studies throughout the years have paved the way for the continued work towards a thorough ergonomic impact prediction method. This thesis work will function as an addition to the work towards reaching that goal. Moreover, the understanding of how different fastening strategies affect the operator is also limited and thus needs to be further explored. (3)

The main objectives of the work conducted throughout this master thesis was to contribute with the following:

- Determining reaction forces, handle displacement and muscular activity associated with pistol grip power tool use.
- Increase knowledge on the potential ergonomic impact which pistol grip tool operation has on the operator.
- Increase understanding of the combination between workspace orientation, fastening strategy and joint stiffness.

1.2.1 Goals

The ultimate outcome of the study intended to result in a compilation of which combinations of tool and task related parameters that have the least and most negative impact on the operators from an ergonomic point of view. The anticipation is to contribute to a more general understanding of power tool use and its effect on the operator.

1.2.2 Limitations

- Only pistol grip tools will be included in the study.
- Only one target torque (8 Nm) will be used throughout the experiments. This is mainly due to the limited time scope of the project, hence the choice of an intermediate value.
- The ‘Two Step’ fastening strategy is excluded from the study due to its similarities with the ‘Quick Step’ strategy. Moreover, Quick Step is a more common choice of tightening strategy for the specific tool model included in the study.

1.3 The gain from ergonomics

The value of ergonomically designed products and work places extends far beyond solely the operators' health. Great improvements can be achieved in terms of product quality and productivity while at the same time contributing to cost, resource and time savings within organizations when increased attention is given to ergonomics.

In Figure 1, impact of ergonomics on different levels of an organization can be seen. Impact on production level refers to process and production times as well as potential loss of time due to rework of mistakes caused by poor ergonomics. Workforce level refers to the health aspect of the workers, and the possible loss of performance or even inability to work due to for example musculoskeletal disorders as a result of poor ergonomics in the working environment. Finally, the impact of ergonomics on a business level is reflected by the quality and productivity which in turn can be regarded as a summary of all factors in the chain. (4)

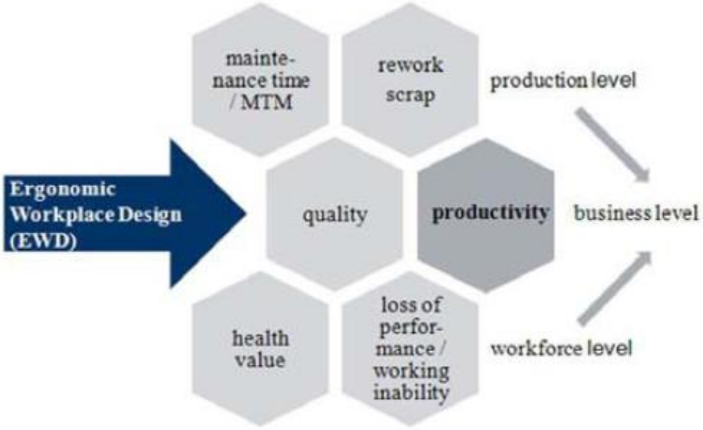


Figure 1. Parameters affected by ergonomics. (4)

It has been roughly estimated that large companies have costs related to poor ergonomics in the range of 10-100 million USD per year. Moreover, it is estimated that one case of Carpal Tunnel Syndrome which is a common health related consequence of frequent power tool use (explained in chapter 2.4.4) costs approximately 10-30 thousand USD to treat. These costs are regarded as direct costs while costs related to loss in productivity and product quality are regarded as indirect costs. (5)

Former car manufacturer SAAB has reported that the risk of quality failure is 3 times higher for tasks which are considered to be ergonomically demanding and that 40% of quality failures are caused by poor ergonomics. Moreover, it has been observed that improved ergonomics has led to improvements in terms of product quality at the motor assembly department at Volvo. (6)

2 Background

2.1 Tool types

Handheld power tools require an external source of energy in order to produce an output. The most commonly used energy sources for this purpose are compressed air supply, i.e. pneumatic power tools, and direct current, i.e. electrical power tools. Pneumatic systems have been widely used for a long time in many manufacturing industries. Such tools normally incorporate a mechanical clutch which will cut off the air supply once the appropriate torque has been reached, i.e. when the fastener, for example a nut, has been fully tightened.

In modern day, the use of electrical power tools has become significantly more widespread and these tools differ from the pneumatic tools in more ways than just their energy supply. The electricity can be delivered either through a cable or through an attached battery. One of the main advantages of electrical power tools is the possibility of connecting the tool to a computer controller, thus allowing for communication with the tool. Through the controller, multiple parameters such as tool speed, target torque and tightening algorithms can be adjusted, allowing for precise control of the torques achieved. The controller also provides real-time feedback in terms of actual torque and angle achieved by displaying these values on the controller screen. In addition, due to the absence of an attached cable, the electrical battery driven tools allow for a more flexible use, for example in settings where electricity or air supply is not readily available or in settings where a cordless tool is preferred. On the other hand, the battery adds a substantial weight to the tool. (7)

Power tools can also be categorized according to the shape of their handle. The decision on tool type based on handle shape should be in accordance with the direction in which force will be exerted. The ultimate goal is to choose a tool which assures that the operator maintains a straight back, vertically hanging upper arms and a straight wrist. For tightening on vertical surfaces, the use of a pistol grip tool is preferred, while tightening on horizontal surfaces is best achieved with an in-line or right angle shaped tool handle. The three tool handle configurations can be seen in Figure 2.

Pistol grip tools and in-line tools are normally associated with lower torque tasks while right angle tools are used for tasks involving high torques. Right angle tools have substantially longer handles, thus functioning as a lever so that the operator can counteract the torque generated with two hands. The ideal tool handle would absorb as much of the reaction force as possible, as opposed to the operator doing so. (8)

Figure 2. The three most common tool shape configurations: In-line tools (left), pistol grip tool (upper right) and right-angle tool (lower right). (9)

2.2 Tool operation and tightening

A tightening procedure refers to the joining of two components together and corresponds to torque as a function of time. The tightening is initiated once the operator presses the tool trigger, which in turn causes the spindle head in the tool to rotate. The fastener, for example a threaded bolt, initially rotates freely and the time during which it is doing so is called 'run-down'. When the fastener stops rotating freely and comes in contact with its mate, i.e. the other joint member, a buildup of resistance known as 'snug' begins.

The fastener initially brings the joint members into tight contact, and thereafter continues to draw the parts together until they form a solid joint. From the point at which the joint becomes solid, the continued drawing of the fastener leads to torque generation, and this is the instant at which reaction forces are produced. The torque buildup and hence reaction force increases in a linear fashion until target torque is reached. This then corresponds to the clamp force in the joint, which in fact is the target of interest, and is represented in Figure 3. Due to difficulties in measuring the clamp force which in fact is the target of interest, one instead measures the torque. (11)

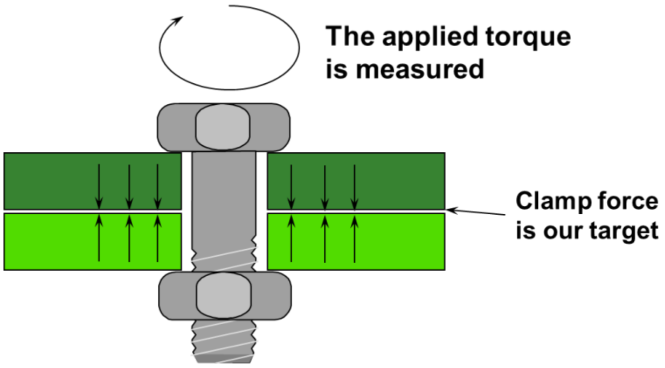


Figure 3. Due to difficulties in measuring the clamp force which in fact is the target of interest, one instead measures the torque. (10)

Not all of the energy from the applied torque is transferred to the clamp force, as a large fraction of the torque is instead converted to friction, both in the fastener head and in the threads of the fastener, as seen in Figure 4. Fractions of the applied torque that contribute to clamp force and friction.

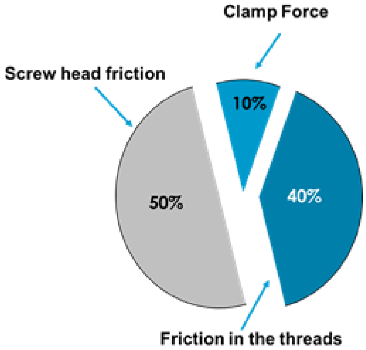


Figure 4. Fractions of the applied torque that contribute to clamp force and friction. (10)

The fastener undergoes different types of loading, among which is tensile loading, referring to the load acting along the axis of the bolt. The force which clamps the two joint members together is then proportional to the tensile load which acts on the fastener. The stability of the clamping is dependent on external forces that may act on the fastened joint members, where an external force which is larger than the clamping force will cause the joint to come apart. (12)

The operator supports the tool by holding it throughout the fastening procedure. When the torque of the fastener reaches its final value, the conserved energy transmits to the operator who now has to limit the displacement of the tool handle by exerting a force in the opposite direction of the tool movement in order to retain her/his posture and balance. The purpose of limiting the displacement of the tool handle is also related to the quality of the fastening, where the absence of counteraction may imply that the joint has not been sufficiently fastened. If the magnitude of the force exceeds the capability of the operator, her/his hand and arm is suddenly pulled away in the direction of the torque generated by the tool. (13)

2.2.1 Tightening Strategies

One way of contributing to the development of ergonomically correct power tools is by altering the method with which the tool reaches its target torque during a tightening procedure. In electrical tools, this is possible by programming the tools with algorithms called tightening strategies, which calculate and regulate the energy levels required to reach a sufficient and reliable nut or bolt fastening. Once the target torque is reached, the motor shuts off instantly and the tightening is thereby completed. (14) Different tightening strategies are utilized depending on application and a variety of strategies developed by Atlas Copco are presented hereafter.

The different tightening strategies can be categorized as direct driven tightening and highly dynamic torque tightening. A 'Two Step' strategy is a direct driven strategy, and the tightening is achieved through dividing the tool speed in two separate steps with a short halt in between (approximately 50 ms). The pause allows for joint relaxation, i.e. properties of the joint which result in the loss of desired clamping force over time after tightening. During the first section of the strategy, tool speed is high, while the second section makes use of a lower tool speed. The total duration of a Two Step strategy normally last from 0.5 – 1 second.

Another direct driven fastening strategy is the 'Quick Step' strategy which resembles the Two Step strategy. The main difference is the absence of pause between the shift from high to low tool speed. In Figure 5 and Figure 6, the torque profile over time (at the joint) can be seen for both medium hard and hard joints respectively.

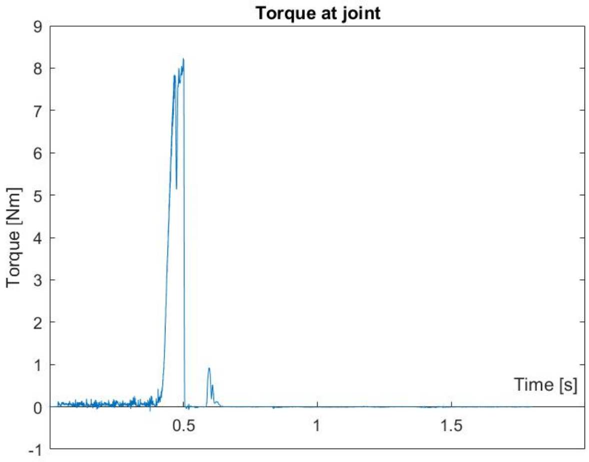


Figure 5. Torque profile of Quick Step on medium hard joint.

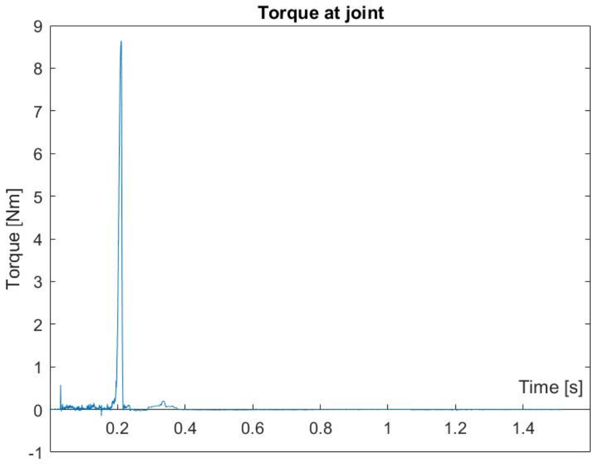


Figure 6. Torque profile of Quick Step on hard joint.

'Turbo Tight' is one of the highly dynamic fastening strategies and is characterized by its ability of achieving the fastening rapidly. This, in combination with the fact that the inertia of the tool is intended to absorb great portions of the reaction force, is what makes this particular fastening strategy beneficial from an ergonomic point of view. Turbo Tight takes the joint into consideration by dynamically reading the joint stiffness throughout the fastening procedure. The energy needed to reach target torque is continuously regulated by the algorithm and thereby allows for accurate tool speed in order to achieve sufficient fastening. In Figure 7 and Figure 8, the torque profile over time can be seen for both medium hard and hard joints respectively.

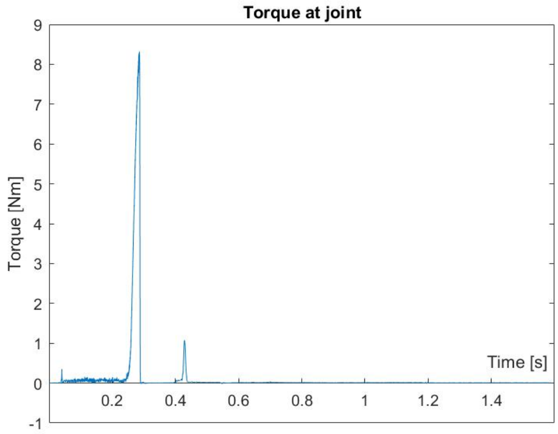


Figure 7. Torque profile of Turbo Tight on medium hard joint.

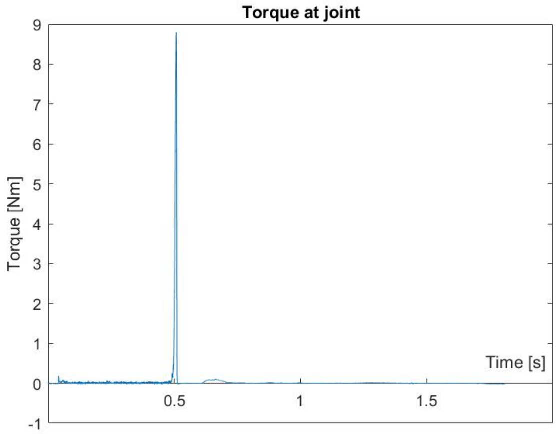


Figure 8. Torque profile of Turbo Tight on hard joint.

‘Tensor Pulse’ is yet another highly dynamic strategy and can be described as a strategy which makes it possible for non-impact tools (impact tools produce high torque output in a pulsed sequence) to produce a pulse-like output for tightening. The typical (i.e. recommended) number of pulses for this strategy is ~ 10 pulses for one tightening cycle. Tensor Pulse allows for low reaction forces but produces significant amounts of vibration. In Figure 9 and Figure 10, the torque profile over time (at the joint) can be seen for both medium hard and hard joints respectively. From the image, it can be distinguished that the pulse strategy has a significantly longer temporal duration compared to the previously mentioned tightening strategies. (15)

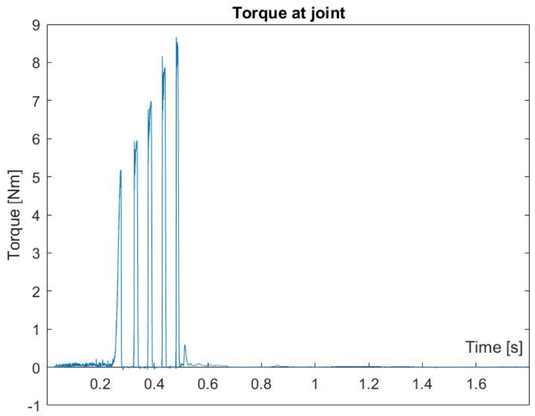


Figure 9. Torque profile of Tensor Pulse on medium hard joint.

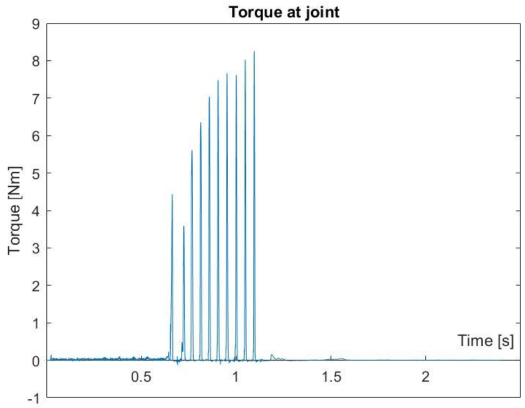


Figure 10. Torque profile of Tensor Pulse on hard joint.

2.2.2 Stopping Mechanism

When the fastening comes to an end and target torque is reached, the tool needs to shut off in order to fully complete the tightening cycle. Just as sudden load can be harmful to the operator, the same concern is relevant to sudden release of load which is the case as the tool shuts off. The operator now no longer needs to counteract the reaction torque which is present during torque buildup, and so there is a rapid transition from high tension and muscle force exertion in one direction to sudden relaxation of muscles. This could result in a jerk motion of the operators' arm. Therefore, some power tool manufacturers have developed an add-on algorithm to the fastening strategies to mitigate this effect. The stopping mechanism developed by Atlas Copco is called 'Soft Stop'.

The basics of the Soft Stop feature is based on the deceleration of the tool motor upon sensing of the target torque. An electrical current is added which helps to ramp down the load in a controlled fashion, as opposed to a sudden release. The Soft Stop is normally set to last for 50-350 milliseconds, thus prolonging the total procedure.

The purpose of the Soft Stop feature is not merely to gain ergonomic benefit. The sudden shock that arises from a sudden stop of a tightening cycle may be unfavorable to the joints, hence the beneficial use of Soft Stop. (16)

2.2.3 Joint Stiffness

Another component which affects the displacement of the handle, and thus the reaction force transmitted to the operator, is the joint. The stiffness of the joint (in combination with other factors such as tool speed and shut off method) determines the rate of torque buildup and is defined as the amount of angular displacement per 10 Nm torque. The scale of joint stiffness ranges from hard to soft, where a tightening angle of less than 60° for reaching target torque implies a hard joint, whereas joints that reach their final torque after 700° are considered to be soft joints. Joint with intermediate angle displacement values are referred to as medium soft or medium hard joints. Since the torque buildup reaches its final value rather quickly in hard joints, the displacement in the joint is relatively small, as opposed to soft joints where torque buildup is quite slow (may last up to 0.5 seconds), thus leading to a larger displacement in the joint. Soft joints will thereby deliver a higher reaction force to the operator. From an ergonomic point of view, hard joints are advantageous to the operator. However, hard joints tend to lose their clamping force much faster than softer joints when exposed to external load changes, thus being less reliable in terms of mechanical durability. (5) (8)

2.3 Reaction Torque & Feed Force

The forces generated by the tool are not only applied to the joint to be fastened, although that would be the ideal case. The operator, being the 'component' at the distal end of the tool, i.e. the tool handle, is likewise subjected to the forces generated by the tool as well as the weight of the tool.

One of these forces is a counteraction to the feed force which the operator must apply in order to push the tool towards the work piece. The feed force acts along the longitudinal axis of pistol grip and in-line tools, and perpendicular to the longitudinal axis of right angle tools.

Another force which is greatly associated with tool operation is reaction force/reaction torque. A tightening of a joint, as mentioned earlier, is achieved by the rotation of a spindle in the tool. When the fastener stops rotating as it reaches final torque, the energy from the rotation of the spindle must be conserved as the procedure stops according to the law of conservation of energy. This excess energy will therefore transmit to the handle of the tool which in turn is in contact with the operator and is thereby channelized to the hand-arm system of the operator as seen in Figure 11.

The forces that are required for the operator to sufficiently support the tool are affected by the weight and length of the tool, center of gravity of the tool, and air hose or battery attachment. The reaction forces/torques to which the operator is exposed are related to the torque output and the length of the tool handle. (5)

Figure 11. Motion of wrist when exposed to reaction torque during pistol grip power tool use. (5)

The temporal duration of the reaction force is also a factor which affects the user and is defined as the time required for total torque buildup as well as the time until the tool is turned off. The duration of the reaction force affects the displacement of the tool handle, and thus operator discomfort. In cases where the tool does not turn off until the operator releases the trigger, for example when operating stall tools, reaction torque is greater due to the fact that the time until the operator releases the trigger may last up to several seconds. In electrical tools, a shut off mechanism is automated and so the tool immediately shuts off when target torque is reached or when the stopping mechanism is terminated. The reaction time is considered to be short if the duration is less than 0.5 seconds, and long when above 2 seconds. (11)

2.4 Pistol Grip Tool Operation & Workspace Orientation

Different motions and muscles are activated depending on the tool shape and orientation of force exertion when performing a task involving power tool use. The feed force required during tool operation with a pistol grip tool on a vertical surface is limited to the operators' capability to push the tool in a forward direction. Furthermore, parameters such as height and distance of the task also have a significant effect on the operators' ability to perform the task. Using a pistol grip tool at shoulder height causes greater bending of the wrist as compared to the same operation at elbow height. Moreover, using a pistol grip tool for tightening causes the forearm and wrist of the operators to undergo an axial rotation as torque builds up. The forearm has limits in pronation and supination and so the reaction torque originating from the tool should not cause the forearm to exceed those limits. Tool operation on a vertical plane also implies a downward pulling gravitational effect on the tool, and thus requires addition support from the operator to keep the tool in the correct distance from the floor.

When performing power tool operation on a horizontal plane, the dynamics of the operation changes. The downward pulling gravitational effect on the tool is now reduced due to the changed orientation of the tool and due to the naturally occurring support from the tool bit engaged in the socket. (5)

2.5 Power Tool Ergonomics

When operating handheld power tools such as nutrunners, drills and screwdrivers, various factors interact and contribute to both the quality of the fastening as well as the impact on the operator. These factors can be divided into the following categories:

- **Tool related parameters.** These refer to the design and capacity of the tool as well as various settings of the tool, for example choice of fastening strategy, tool type and target torque.

- **Task related parameters.** These are related to the complexity of the task and can potentially have a large ergonomic impact. Examples of task related parameters are workspace orientation, stiffness of the joint to be fastened and work piece height or distance.

- **Operator related parameters.** These factors are purely dependent on various aspects of the operator, for example muscle mass and strength (which in turn affects the hand and arm stiffness of the operator), previous experience of tool use, age, overall health etc.

The overall ergonomics of a power tool is generally related to handle design, external load (feed force and reaction force), tool weight, temperature, shock reaction, vibration, noise and dust & oil.

The main risk factors regarding the man-machine interaction relevant to power tools are repetitive tasks, high force exertions and awkward or static postures, and the combination of them is what constitutes the greatest risk to the operator. (5)

The repeated and prolonged use which power tool handling often implies is a cause not only for discomfort to the user, but also several injuries and diseases. These injuries are collectively referred to as Cumulative Trauma Disorders (CTD), and include injuries associated with the musculoskeletal system as well as the nervous system, mainly in the upper extremities and in the back. The resulting response to the injuries may in turn cause abnormalities in tendons and connective tissue, muscle tear, ligament disorders, inflammation of the bursae (fluid filled sacs acting as a cushion between bone and tendons), or nerve compression.

The development of CTD does generally not occur when one is exposed to the abovementioned factors for a short and limited period of time. Musculoskeletal and nervous damages have a slow progression and may first become chronic in the absence of sufficient rest and recovery. (17)

2.5.1 Skeletal Muscle Anatomy

The human skeletal muscles are constituted of muscle fibers bundled together in so called fascicles or motor units, as seen in Figure 12. The motor units are separated by the perimysium which is composed of connective tissue fibers, and the muscle fibers within the bundles are in turn separated by the endomysium. The outermost layer of the muscle is the epimysium. The epimysium, perimysium and endomysium merge together at the end of the muscle to form the tendon, thus attaching the muscle to bone. This leads to a pulling motion of the bone once the skeletal muscle contracts.

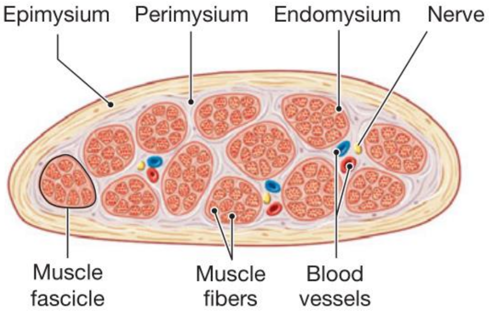


Figure 12. Cross section of a skeletal muscle with associated components. (18)

Nerve fibers conduct electrical impulses from the central nervous system to the muscle fibers, causing the muscle fiber to contract. During contraction, electrical impulse waves known as action potentials travel towards the endings of the muscle fiber. These action potentials are in turn caused by a rapid potential difference which occurs between the inside and outside of the muscle cell walls.

One contraction can be added to another if a new impulse reaches the muscle before the duration of the contraction has ended, thus resulting in one prolonged contraction. A high number of muscle fibers that undergo contraction in combination with impulses reaching the motor unit with a short time interval between each impulse result in a greater force output.

Muscle contractions can be categorized as follows:

- Isotonic contractions: The length of the muscle changes as tension rises. There are two types of isotonic contractions:
    i) Concentric contraction – occurs when the tension of the muscle exceeds the load and the muscle thereby shortens.
    ii) Eccentric contraction – occurs when the tension of the muscle is less than the load applied. The muscle is thereby elongated due to the contraction of an antagonist muscle or gravity.
- Isometric contractions: The developed tension in the muscle does not exceed the magnitude of the load, and so the length of the muscle as a whole does not change.

Contraction of muscle fibers consumes energy from the reserves and releases heat. If the contraction reaches its peak levels, lactic acid is generated. Muscle contractions which exceed certain levels of maximum contraction ability may hinder the blood flow through that muscle. This implies a decreased oxygen supply to muscles, thus being an anaerobic metabolism. As a result, waste products such as acidic metabolites are gathered in the muscle. The accumulation of acidic metabolites can in turn affect the concentration of sodium, calcium and potassium as well reducing the conduction speed in the muscle fibers. As the concentration of the various elements in the muscle changes, so does the pH (normally toward a lower pH level), which can lead to alterations of the enzyme activities. (18)

Muscle fibers are categorized as either slow twitch or fast twitch. Governed by factors such as genetics, human muscles are constituted of a mixture of slow and fast twitch fibers. Slow twitch fibers are more fatigue resistant and are responsible for supporting endurance demanding tasks, while fast twitch fibers are activated when requiring an explosive effort and thus generate a rapid muscle contraction. Force generated by fast twitch muscle fibers typically lasts for a short period of time, in contrast to the stamina provided by the slow twitch muscle fibers. (19)

2.5.2 Human Response to Stimuli

Humans respond to mechanical stimuli by using the body’s natural motor skills. One definition of the term ‘motor skills’ is “the ability to use the correct muscles with the exact force necessary to perform the desired response with proper sequence and timing”. The time required to respond to a stimulus is called reaction time and is governed by a number of factors. Among those are the following;

- **Complexity of stimulus**. A more complex stimulus requires more processing of information, and will thus increase the reaction time.
- **Recognition and expectation of stimulus.** Reacting to a stimulus to which one has reacted before will decrease the reaction time. This is related to the ‘memory’ of the muscles. Moreover, reacting to an expected stimulus, such as a runner waiting for the start signal, will also decrease the reaction time.
- **State of the operator.** Several factors, such as fatigue, age and temperature, can affect our ability to detect, process, and thereby respond to a stimulus. In addition, the operators’ alcohol and drug or medicine consumption can affect the reaction time. (20)

2.5.3 Repetitive motion

Repetition is the temporal aspect of the task. Repetition is defined as the number of exertions per unit time. Muscle fatigue and potential damage of soft tissue due to fatigue are closely linked to repetition of an activity. Tasks that involve high force exertion in combination with high repetition frequency are the ones that pose the highest risk for tissue disorders.

When soft tissue is exposed to mechanical load, the response mechanisms occur at both cellular and matrix levels. If the response and recovery time is sufficient, the tissue will adapt and thereby be prepared for the next applied load. In the case where the response and recovery time are not sufficient, the repetitive load will cause degeneration of the tissue and require a prolonged repairing process. A high-repetition movement is in itself not necessarily harmful, given that the applied force is modest. The same is true for exposure to high force exertions, where a few repetitions of the exertion actually could benefit and strengthen the muscles, tendons and ligaments. However, in order for this to occur, it is required that sufficient amount of rest is allowed between the exposures, or else the risk of fatigue induced injuries could increase.

When healthy tissue is exposed to loading and repetition, microscopic tears are formed in the affected tissues. As the loading continues, these tears expand with a rate that depends on the magnitude of the load as well as the number of repetitions. The tears are a breakdown of the tissue. Naturally occurring growth factor could either enhance or interfere with the response to mechanical load. If an excessive amount of load is applied, it results in the production of degrading enzymes that will initially activate stored growth hormone, but eventually degrade the matrix and promote the production of inflammatory mediators. Furthermore, exposure to transverse compressive load stimulates the production of fibrocartilage in the tendons.

Exposing ligaments and tendons to repetitive loading can result in the development of either adaption to that motion/load or pathology. This type of repetitiveness can lead to increased vascularization, edema, fibrosis and inflammatory cell infiltration in the paratendon (the sheath surrounding the tendons). Due to lack of rest, the paratendon will also experience a shortage of lubrication, thus increasing the friction towards the tendons and thereby resulting in pain. This causes inflammation of the tendons which in turn begin to pinch neighboring nerves. Various symptoms may arise, such as numbness, tingling or hypersensitivity to touch. (21)

Another aspect is the speed of muscle contraction. The tendons can be damaged by highly repetitive motions due to repeated stretching and elongation. Fast muscle contractions are required when carrying out repetitive tasks, and the muscle capacity required to produce force diminishes with an increase in contraction speed. This implies that the muscle contraction becomes less efficient and demands longer recovery time, as the number of repetitions escalate. (22)

2.5.4 Carpal Tunnel Syndrome

The carpal tunnel serves as a passage from the hand to the wrist and mainly contains ligaments, bones and tendons. The median nerve which provides several fingers of the hand with sensation passes through the tunnel as seen in Figure 13.

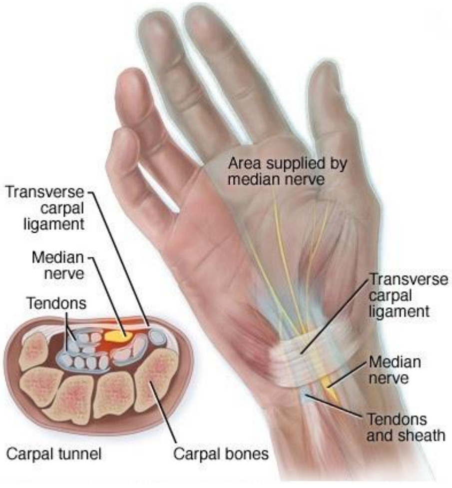


Figure 13. Cross-section of the wrist (left) and frontal view of the hand & wrist (right). (23)

Carpal tunnel syndrome is defined as a set of symptoms resulting from median nerve compression in the wrists and is the most commonly occurring chronic peripheral nerve compression disease. The median nerve is located under the transverse carpal ligament in the carpal tunnel and can be exposed to mechanical compression which in turn may lead to ischemia and impairment of the median nerve. Classical symptoms of carpal tunnel syndrome are pain, numbness, a tingling sensation and burning in the distribution of the median nerve.

During prolonged and repetitive power tool use, the risk of carpal tunnel syndrome increases, particularly if the hand and wrist position is greatly deviating from its neutral position. The pressure in the carpal tunnel normally ranges from 2-10 mmHg. External forces applied to the area or drastic changes in wrist position for a long period of time can lead to changes in pressure in the carpal tunnel, thus being a cause for nerve entrapment. By choosing the appropriate tool handle design for the task, the risk of carpal tunnel syndrome can be reduced. Vibration is another contributing factor to the occurrence of carpal tunnel syndrome, where prolonged exposure to high levels of vibration has been associated with compression of the carpal tunnel. (24)

2.5.5 Electromyography

Measurement of muscular activity is normally achieved through electromyography, EMG. Electrical activity in the muscles is a resultant from muscle contraction, and the signal is registered through electrodes. By using two electrodes on the muscle, the potential difference is measured between two points on the muscle, i.e. the voltage. A greater number of activated muscle fibers imply a higher force generation which in turn is reflected by higher EMG amplitudes. Standard values for EMG amplitudes measured with surface electrodes range from 50 μV – 200 μV. The EMG signals are affected by various factors such as for example muscle temperature (which rises during muscle work), eccentric or concentric muscle work, resistive properties of the skin and amount of subcutaneous fat.

The most common types of electrodes used are surface electrodes (electrode patches adhered to the skin) and needle electrodes (fine wire electrodes inserted into the muscle). The electrodes register the action potentials of the muscle motor units which trigger a contraction of the muscle.

The recorded EMG signal amplitudes are normalized in order to facilitate comparisons between muscles and subjects etc. One common way of doing so is by comparing the EMG signals to the maximum voluntary contraction of the muscle, MVC. MVC is a general measure for muscular strength and is related to the voluntary activation on muscles. General limits during occupational tasks are recommended not to exceed 70% MVC, and for highly repetitive tasks the corresponding level should be 10-15% MVC.

It is however sometimes difficult to demand the test persons in an EMG study to perform maximum voluntary muscle contraction. Therefore, another reference measure is often introduced, namely reference voluntary contraction, RVC, which is a submaximal muscle contraction. The RVC is measured prior to the tests and can be obtained in a number of ways. One common method is by letting the test persons perform a contraction of the muscle of interest without any applied load, thus functioning as a voluntary reference contraction level.

A typical EMG measurement session commonly used in ergonomic studies is conducted by applying pairs of surface electrodes to the muscles of interest as well as a ground electrode to for example the back of the hand. The collected EMG signal is then amplified and filtered for noise attenuation, and finally transmitted to an Analog to Digital converter before the signal can be processed in a computer. (5) (25)

2.5.6 Subjective Rating & Body Map

While quantification of physiological effects, i.e. direct measurements on the body, is of great interest to research, the operators' subjective perception of discomfort as a result of tool operation could be used as a benchmark for the potential ergonomic impact. Subjective ratings can be considered an indirect measurement and can be used to correlate the objective tool and task related parameters with the ergonomic impact on the operator. Subjective rating methods allow for rapid and easy implementation, and do generally not require advanced skills and training as is often the case when using direct measurement methods, for example EMG. (26)

Ergonomists and other professionals employ subjective ratings of for example perceived discomfort or perceived force exertion for the assessment of ergonomic impact in various applications. One established tool for such an assessment is the Borg CR10 scale (Category-Ratio scale) which is a zero to ten scale, where 0 represents the lowest perception of the matter of interest (for example 'No discomfort at all'), and 10 represents the highest (for example 'Extreme discomfort'). The test persons is asked to subjectively rate the amount of for example discomfort she or he perceives during a given task. (27)

Another way of gathering data regarding the perceived discomfort of the operator is by asking the test person to point out where, spatially, on a map of the body such as in Figure 14, that the discomfort is perceived. The so called 'Body Map' is divided into anatomical regions where symptoms tend to accumulate and which are distinguishable from each other. The use of Body Map provides a very simple yet effective way of evaluating how the task of interest directly impacts the operator and gives a more holistic perspective of the subjective perception of the task. (28)

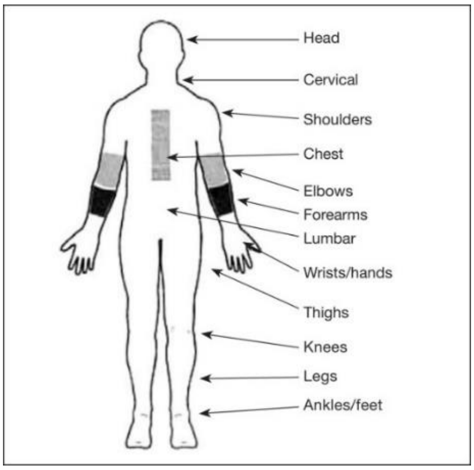


Figure 14. Body Map with anchored anatomical regions. (28)

2.5.7 Reaction Torque Impulse

The area under the torque - time curve is known as impulse, and is normally considered to begin at a certain percentage of the target torque. The reaction torque alone is not always a sufficient measure when performing ergonomic investigations, since it unlike the impulse does not take into account the torque levels in combination with their duration. (29)

2.5.8 Energy Transfer to Hand/Arm System

One way of studying the ergonomic impact on the hand arm system of the tool operator is by investigating the absorbed or transferred mechanical energy in the hand and arm. The rate at which energy is dissipated in hand and arm is an indication of the magnitude of damage done to the body part of interest. By studying the transferred energy, one can assess the biological impact in a more holistic way compared to studying for example the acceleration to which the hand and arm is exposed.

The human body can be regarded as an elastic system, capable of storing both potential energy and kinetic energy. When the tissues undergo motion, kinetic energy is stored, while storing of potential energy arises during the relative compression and extension of tissues. The relative motion of both soft and hard tissue when for example an impulse is applied is believed to cause the absorption of energy, i.e. mostly heat, and if the motion is too powerful it is likely that damages or changes will occur in the area.

The power, i.e. energy per unit time, arising from the motion and thus interacting with the hand and arm is the scalar product of the torque, τ [Nm], and the angular velocity, ω [rpm], as seen in Equation 1.

$$\mathbf{P} = \boldsymbol{\tau}\ [\mathrm{Nm}] \times \boldsymbol{\omega}\ [\mathrm{rpm}] \qquad [\mathrm{Watt}]$$

Equation 1. Power.

Power is as mentioned earlier the rate at which work is done, which in turn is an indication of the amount of expended energy in Joules. By integrating power with respect to the angular velocity, the work performed is obtained, as seen in Equation 2. To perform X Joules of work, X Joules of energy has to be expended. (30)

$$\mathbf{W} = \int \boldsymbol{\tau} \times \boldsymbol{\omega}\ d\omega \qquad [\mathrm{Joule}]$$

Equation 2. Work.

3 State of the Art Review

Various experiments and studies have been carried out by other researchers for the assessment of the ergonomic impact on the operator which power tool use in many cases implies. The development of an accurate prediction model requires a solid method for measurement of the various forces and other ergonomic factors involved in tool operation, as well as a profound evaluation of their physiological effect on the user. Hereafter follows a presentation of state-of-the-art which is relevant to and contributes to this thesis work and the development of the methods used throughout the project. The sections of this chapter are organized by model type, i.e. assessment of tool operation impact through mechanical simulations, assessment of tool operation impact by analytical/mathematical means, and assessment of tool operation impact by measurements of muscle activity and subjective ratings of discomfort.

3.1 Simulation Models

The ergonomic impact of electrical power tool use on operators has been assessed by S. Mukherji by mechanical means through the setup of a stationary test rig. The design of the rig was based on a dynamic model of the arm developed by J. Lin and R. Radwin (31), and included a simulated hand-arm system, a right angle tool and a joint assembly. The study investigated four independent input factors, namely fastening strategy, stopping mechanism, joint stiffness and arm mass & stiffness. The output from the test setup was the reaction force and deflection of the simulated arm as a function of time. In order to evaluate the impact of the input factors from an ergonomic stand point, they were compared to four assessment criteria, namely torque impulse, deflection, reaction torque and latency impulse. Three tightening strategies were used in the study by S. Mukherji.

Three fastening strategies were used in the experiments - ‘Two Stage’ (fast tool speed at beginning of tightening followed by a short pause before accelerating with a lower tool speed towards the end of the tightening), ‘Manual Down Shift’ (fast tool speed at beginning of tightening and slower tool speed towards end of tightening), ‘Adaptive Tightening Control’ (ATC) (the torque rate is continuously sensed by the tool and dynamically changes tool speed thereafter).

Torque impulse was as defined by ISO 6544, the integral of the reaction torque curve plotted as a function of time, above a certain percentage of the target torque (set to 10% in ISO 6544). The torque impulse reflects the magnitude of the torque as well as the temporal duration. In the study by S. Mukherji the torque impulse was measured at seven different threshold values, i.e. 0%, 20%, 45%, 50%, 60%, 70% and 75% of target torque.

The second criteria, deflection, referred to the tool handle displacement and was in the study by S. Mukherji considered to be representative of the jerk motion to which the operator is exposed to during tool operation.

The latency impulse was in the study by S. Mukherji defined as the reaction torque plotted over time when subtracting the section of the curve whose duration was equal to the EMG latency for the particular joint.

S. Mukherji utilized a simulated hand-arm system which was a mechanical analog to a human operator and took both arm mass and arm stiffness into consideration since these factors reflect the muscle force output as well as controlling of movement and retaining of posture. The arm mass was represented by a mass box, i.e. an aluminum box with slots in which steel plates could be inserted to add up to the desired mass, and the stiffness was represented by an air cylinder. By varying the air pressure and air volume in the cylinder through the use of a piston, stiffness of the air spring, and thus the 'arm', was altered.

The results from the study by S. Mukherji show that the Two Stage fastening strategy was least beneficial from an ergonomic point of view when compared to the predefined criteria. Both higher torque and latency impulse was observed when utilizing the Two Stage strategy. No statistically significant results were obtained from the Manual Down Shift and ATC in terms of their impact on the torque and latency impulse criteria. The cause for this was speculated to be due to the low variety in joint stiffness (the stiffness of all three joint types used in the experiments where categorized as 'medium' according to the ISO 5393 standard).

Moreover, the stopping mechanism was by S. Mukherji observed to cause a higher latency and torque impulse (except for torque impulses above 70%), and this was true for all three fastening strategies used in his experiment. This was explained by stating that the stopping mechanism implies a longer duration of the fastening cycle. On the other hand, the experiment managed to show that the soft stop feature had the benefit of reducing both reaction torque and handle deflection.

The variations of the arm mass and arm stiffness turned out to mainly affect the deflection criterion, regardless of fastening strategy, joint stiffness and soft stop feature. Low MK level (levels of arm mass and stiffness defined as the arm mass times arm stiffness, kg * N/m) would result in a high deflection, and so the results of S. Mukherji's study were consistent with the theory which states that a weak arm would allow for a greater deflection than a strong arm. Among the fastening strategies, the Two Stage strategy was the one that resulted in the highest deflection (for low MK level).

Since the test rig in S. Mukherji's experiments was merely a simulation of a human hand-arm system, the deflection curves from his experiments were compared to corresponding curves from experiments in which the deflection response from human operators was measured. All main parameters were held identical to the ones used in the test rig. The human operator deflection curves showed substantially greater deflection magnitudes compared to the ones resulting from the rig. One important observation that was made in the human operator test was the operators' use of the whole body in order to counteract the reaction torque, and not only her/his hand and arm.

The test rig is limited in that respect due to its lacking ability to consider other elements of the human body when handling power tools. Yet another limitation of the study was, as mentioned by the author himself, the low range of joint stiffness used in the experiments. Moreover, the study only involves a right angle tool configuration, and so the results may not be completely applicable to other tool types, hence the need to further investigate the ergonomic effect of other tool configurations. (3)

3.2 Analytical Models

Two analytical models were presented by J. Lin et al for the prediction of forces and torques involved in power tool operation. The study took into account three different handle configurations, i.e. pistol-grip, right-angle and in-line tools.

In the study, the authors present a static force model through which estimations can be made on the handle forces needed to support a pneumatic nutrunner when tightening a fastener with constant torque. The model emphasized tool geometry, tool mass, orientation in space, feed force, torque buildup and stall torque. The static forces and moment equilibrium conditions were established in an equation system, and the resulting handle forces were thereby represented in a matrix. One main benchmark for the model was the assumption that the tool is in static equilibrium when the sum of all forces acting on the system is zero. This included all various forces (**F**) and torques (**M**) around the origin point (defined in a Cartesian coordinate system around the tool as the end of the tool bit/socket) and torques generated by the tool spindle ($\mathbf{M_G}$). With these conditions, an equation system of three vectors was derived. The variables are stated in Table 1.

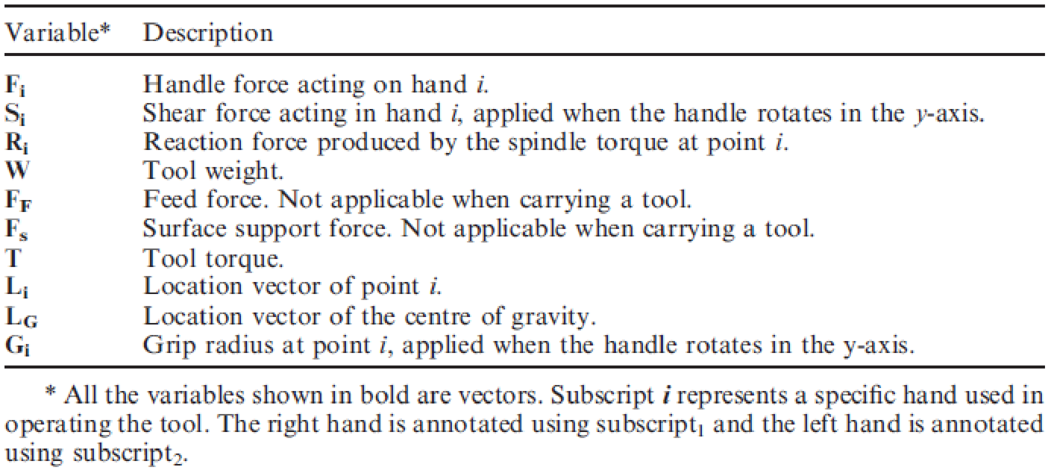
$$\Sigma\mathbf{F_i} + \Sigma\mathbf{R_i} + \mathbf{W} + \mathbf{F_F} + \mathbf{F_S} = 0 \qquad (\Sigma\mathbf{F} = 0)$$

$$\Sigma\,(\mathbf{F_i} + \mathbf{R_i}) \times \mathbf{L_i} + \mathbf{W} \times \mathbf{L_G} = 0 \qquad (\Sigma\mathbf{M} = 0)$$

$$\Sigma\mathbf{S_i} \times \mathbf{G_i} + \mathbf{T} = 0 \qquad (\Sigma\mathbf{M_G} = 0)$$

Equation 3. Static forces and moment equilibrium conditions.

Table 1. Variables used in static force model. (32)



Variable*	Description
$\mathbf{F_i}$	Handle force acting on hand *i*.
$\mathbf{S_i}$	Shear force acting in hand *i*, applied when the handle rotates in the *y*-axis.
$\mathbf{R_i}$	Reaction force produced by the spindle torque at point *i*.
$\mathbf{W}$	Tool weight.
$\mathbf{F_F}$	Feed force. Not applicable when carrying a tool.
$\mathbf{F_s}$	Surface support force. Not applicable when carrying a tool.
$\mathbf{T}$	Tool torque.
$\mathbf{L_i}$	Location vector of point *i*.
$\mathbf{L_G}$	Location vector of the centre of gravity.
$\mathbf{G_i}$	Grip radius at point *i*, applied when the handle rotates in the y-axis.

* All the variables shown in bold are vectors. Subscript ***i*** represents a specific hand used in operating the tool. The right hand is annotated using subscript$_1$ and the left hand is annotated using subscript$_2$.

The static force model required certain assumptions before the equation system could be solved. One such example was in the case of two-handed use of a right angle tool, where one counteracts the reaction torque by force exertion with both hands. The model presented by J. Lin et al. assumes an equal force exertion by both hands, which may not in fact be an accurate assumption.

Another limitation of the static force model was its inability to account for the dynamic nature of torque buildup in power tool operation. This implies that the components of reaction torque which may have a significant impact on handle force and handle displacement (and thereby ergonomic impact on the operator), such as torque buildup time, amplitude and shut-off mechanism, may not be properly represented in the model, hence the need for a complementary dynamic force model.

Therefore, the authors have also presented a dynamic force model in order to provide a more complete representation of the various forces acting during tool operation. The dynamic model describes torque buildup dependent on the joint stiffness and is based on the following differential equation, Equation 4.

$$T(t) = T_{max} + (-T_{max} + T_0)e^{-\frac{(T_t - T_0)S_0}{\theta_t T_{max}}t}.$$

Equation 4. Torque described according to J. Lin et al's dynamic model.

Where T(t) is torque delivered to the spindle of the tool, T_{max} is the maximum torque output of the motor, T_0 is the rundown torque, S_0 is the free running speed, and θ_t is the target angle.

By dividing the equation with the distance between the hand and the spindle, the force experienced by the hand can be obtained. Note that the dynamic model described in the study by J. Lin et al was intended for pneumatically driven power tools.

A regression analysis was conducted by J. Lin et al in order to compare the model predictions to actual measurements. For medium-soft joints, the average regression error of the dynamic model was 6.6% (SD = 5.4%). The corresponding value for the static model was 6.7% (SD = 6.4%). For hard joints, the average regression error of the dynamic model was 5.2% (SD = 5.3%). The corresponding value for the static model when fastening hard joints was 3.6% (SD = 3.2%). (32)

The study conducted by J. Lin et al. was based on experiments on pneumatic tools, and may therefore not allow for analog application on electrical tools. Furthermore, the models presented by the authors did not account for the capacity of the operator, but rather task and tool related variables.

3.3 Physiological Effect Based Models

Measuring physiological effects of power tool use on a human operator in not as intuitive as measurements of the various tool and task parameters. Physiological measurements can be based on several completely disassociated criteria, hence the wide spread approaches to determining the effects on the operator. A variety of those approaches will be presented in the following section.

A study was conducted by S. Kihlberg et al. in which the operators' subjective ratings of discomfort from power tool operation were investigated. The study involved 38 experienced assembly line workers and the tools involved were pneumatic right angle tools with different pre-set spindle torques, 50 and 75 Nm, and shut-off mechanisms, 'fast' 'slow' and 'delayed'. The test persons in the study performed tool operation and where asked to rate the experienced discomfort from the task according to a 20 point Borg scale, where a score of zero implied 'no discomfort at all', and twenty implied 'almost unbearable'. Moreover, the subjects were asked the yes-or-no question "Would you accept to work a whole working day with a tool that gives a reaction force like this?" in order to assess the acceptability of the task.

The reaction forces in the study by S. Kihlberg et al. were normalized by converting them to a non-dimensional value through division with the operator's body mass in Newton. The measurements of the force output were divided into 14 force classes, spanning from 0.025 to 0.375 normalized units.

The results from S. Kihlberg et al's study demonstrated a clear correlation between mean discomfort ratings and handle displacement as well as reaction force during tool operation. 50 % of the test persons accepted a normalized reaction force of up to 0.1. In terms of acceptable handle displacement, about 50 % of the test persons accepted a handle displacement of up to 6 cm. None of the test persons accepted a discomfort rating of 9 (very light discomfort) or higher when performing a tool operation task and the relationship between percentage of acceptance and discomfort rating was nearly linear up to that point. 50 % of the test persons accepted a discomfort rating of 5. These figures were used by the authors to conclude the maximum reaction force, handle displacement and discomfort rating allowed in order to reach 50 % acceptability. (33)

Another approach to the evaluation of physiological effects on the operator as a result of power tool use is by measurement of muscular activity through EMG. A study by J. Lin et al. was conducted where the authors improved a previous experiment (34). The novelty of the new study was the incorporation of EMG for measurement of muscular activity. The objectives of the study were to measure grip force, tool handle displacement and muscular activity in upper limbs when using pneumatic power tools on either horizontal or vertical work space orientations.

Input factors of the experiment consisted of experience of operator, working height, working distance, tool type and joint stiffness. Both working height and distance were set to values which were within the range of normal working conditions, and joint stiffness was varied between hard and soft. The tool height parameter relevant to pistol grip tools was defined as 30 cm above/below elbow height. Pairs of EMG surface electrodes were placed at the right forearm flexor, forearm extensor, biceps branchii and upper trapezius for the measurement of muscular activity in those muscle groups.

The soft joint resulted in higher muscular demand as reflected by the integrated EMG measurements, compared to the hard joint during the torque buildup phase of the tightening cycle. However, during the rundown phase of the cycle, the mean rms EMG signal at the forearm flexor was higher for hard joints compared to soft joints. The authors explained this by referring to a study by Armstrong et al. (35) who stated that the operators have a tendency to ‘program’ the required effort when anticipating the upcoming task right after they press the tool trigger. As earlier known, hard joints allow for shorter torque buildup times as compared to soft joints, hence the higher muscular activity during rundown, according to J. Lin et al.

The experiments by J. Lin et al. also showed that experienced operators would allow for a smaller angular displacement compared to inexperienced ones. Operator experience also seemed to have a relationship with the magnitude of the EMG signal, where more experienced operators showed a greater forearm extensor EMG activity. This was speculated to be a result of the operators’ knowledge of how to adjust hand/arm stiffness in order to counteract the forces arising from a tightening procedure. Furthermore, an increase in working height from elbow height minus 30 cm to elbow height minus 10 cm resulted in higher average EMG signal for the trapezius muscle group, i.e. an increase from 30 % RVC to 72 % RVC. (36)

4 Method

4.1 Participants

11 test persons (10 males and 1 female) participated in the study, of which none had previous assembly working experience. The gender distribution was not intentional, but rather a result of the availability of potential test persons at the company office. The obtained data was not evaluated with respect to gender.

Only measurements for 10 of the participants were included in the data processing due to technical difficulties during measurements with one of the test persons. Test trials were carried out for each participant prior to the actual measurements in order for them to get accustomed to the fastening procedures. Written informed consent was collected for all participants before initiating the measurements. The informed consent form can be seen in Appendix 3.

4.2 Experiments

An electrical pistol grip nutrunner, Atlas Copco model SRB 25 - TP 2.1 with a lash, was used in the project, as seen in Figure 15.

Figure 15. The electrical pistol grip nutrunner used in the experiments.

The experiments were divided into sets of fastening procedures. Each set consisted of 6 individual tightenings for each unique combination of input parameters within a span of 60 seconds, i.e. one tightening every 10 seconds during one minute for each combination. An audio alarm would notify the test person when a new tightening was to be initiated, i.e. every 10 seconds. 2 minutes of rest was allowed in between each set of tightenings. In total, each test person performed 12 different combinations of input parameters, i.e. 12 sets of tightening. The combinations can be seen in Table 2. The frequency of tightenings per minute and rest time was decided upon in accordance with normal work pace at the Ford St. Thomas Assembly Plant. (7)

Table 2. The twelve sets of tightenings, i.e. combinations of input parameters.

Set Nr.	Fastening Strategy	Target Torque	Joint Stiffness	Workspace Orientation
1	Quick Step	8 Nm	Medium	Vertical
2	Quick Step	8 Nm	Hard	Vertical
3	Tensor Pulse	8 Nm	Medium	Vertical
4	Tensor Pulse	8 Nm	Hard	Vertical
5	Turbo Tight	8 Nm	Medium	Vertical
6	Turbo Tight	8 Nm	Hard	Vertical
7	Quick Step	8 Nm	Medium	Horizontal
8	Quick Step	8 Nm	Hard	Horizontal
9	Tensor Pulse	8 Nm	Medium	Horizontal
10	Tensor Pulse	8 Nm	Hard	Horizontal
11	Turbo Tight	8 Nm	Medium	Horizontal
12	Turbo Tight	8 Nm	Hard	Horizontal

Two levels of joint stiffness were used in the study – one joint requiring 20° of rotation to be fastened (hard joint), and the other requiring about 120° to be fastened (medium hard joint). The joints used in the experiments consisted of Belleville spring washers, i.e. disc springs, as seen in Figure 16.

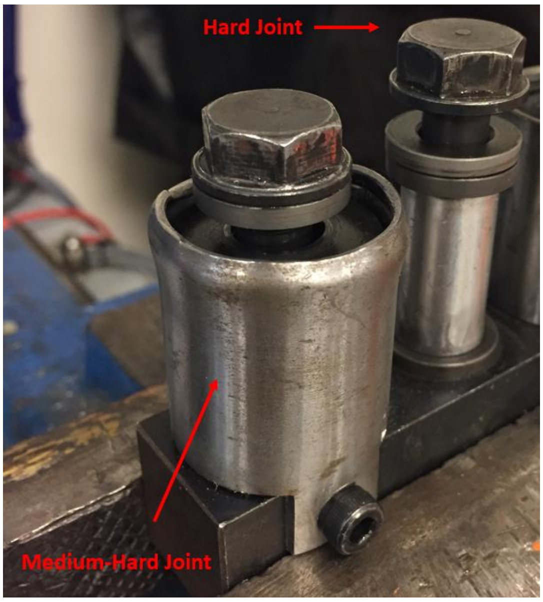


Figure 16. The two joint stiffnesses used in the experiments.

Three different fastening strategies were investigated in the experiments, namely Turbo Tight, Quick Step and Tensor Pulse. The torque to be reached in all tightenings was set to 8 Nm.

The direction of the work station was varied between horizontal and vertical for each combination of fastening strategy, target torque and joint stiffness. The direction of force exertion was perpendicular to the orientation of the workspace, meaning that for example a horizontal workspace required force exertion in a vertical direction.

4.2.1 Torque and Angle outputs

The following output parameters were collected with sensors connected to the tool during the experiments:

- Actual angle of tightening at joint [degrees]
- Actual torque at joint [Nm]
- Angular displacement of tool handle [degrees]
- Reaction torque at tool handle [Nm]

Data for angles and torques was collected using inline and encoder sensors attached to both the interface between the joint and the tool head and the interface between the end of the tool and the simulated tool handle. By connecting the sensors to a software called DEWESoft, the obtained data was stored. Examples of reaction torque and handle deflection curves can be seen in Figure 17 and Figure 18 respectively, where it can be observed that the reaction torque and handle deflection occur in directions opposite to each other. The full experimental setup can be seen in Figure 20 and Figure 19.

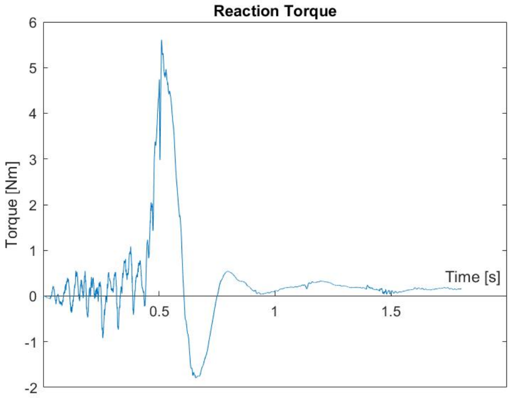


Figure 17. Reaction torque as a function of time.

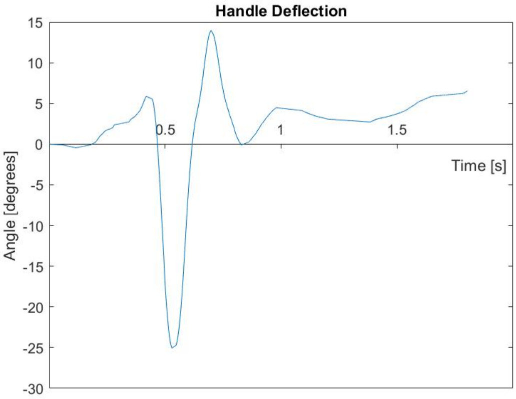


Figure 18. Handle deflection as a function of time.

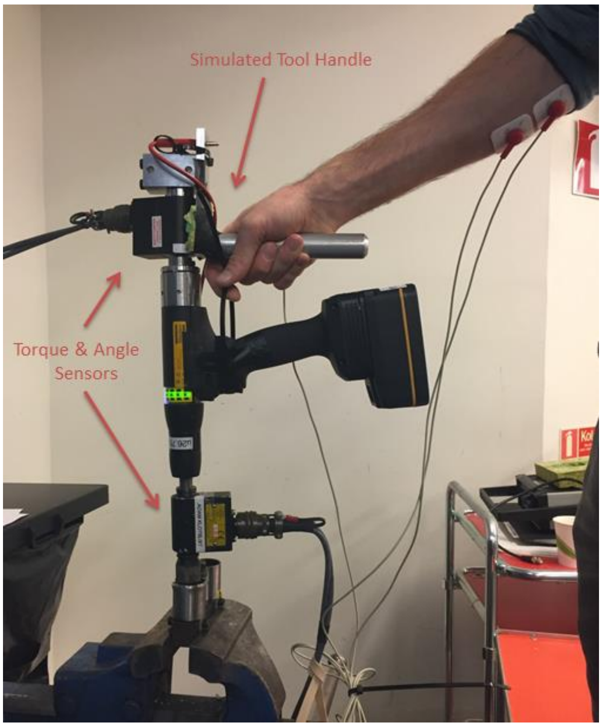


Figure 19. The complete experiment setup with joints, sensors, simulated tool handle and EMG electrodes (horizontal workspace).

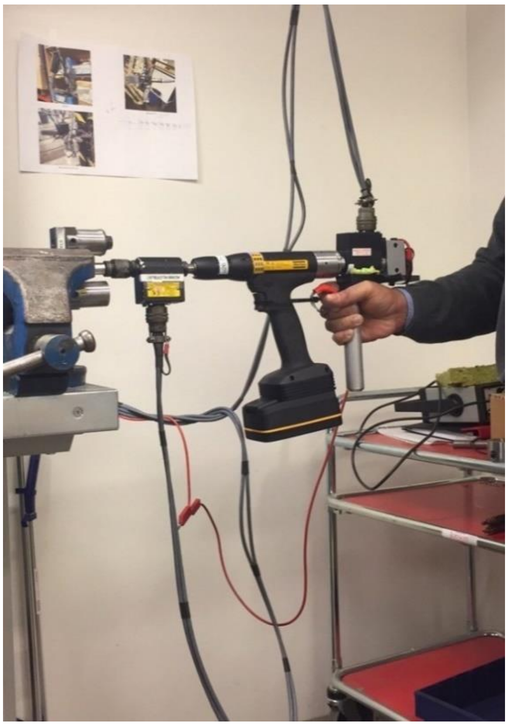


Figure 20. The experiment setup with joints, sensors and simulated tool handle (vertical workspace).

4.2.2 Electromyography

One pair of bipolar surface electrodes was placed on the forearm flexor carpi ulnaris muscle (as seen in Figure 19) for collection of muscle activity signals, and one ground electrode was placed on the back of the hand. Prior to the EMG measurements, the test persons were asked to perform minimal and maximal voluntary muscle contraction for a few seconds in order to calibrate the EMG device. Muscle activity was recorded during each 1-minute set of tightenings. In between each individual tightening, the test persons were asked to bring as little effort to the flexor carpi ulnaris muscle as possible in order not to register muscle activity from in between the tightenings.

4.2.3 Subjective Rating of Discomfort & Body Map

A Borg CR10 scale was used for the evaluation of subjective rating of perceived discomfort after each set, as seen in Figure 22. (37)

The body map seen in Figure 21 was used to further investigate the perceived discomfort for each tightening set. After each set the participants were asked to mark out on the body map where on the body that the main perception of discomfort was perceived.

Subjective Rating of Perceived Discomfort

0	None
1	Very Weak
2	Weak
3	Moderate
4	Somewhat Strong
5	Strong
6	
7	Very Strong
8	
9	
10	Unbearable
•	Maximal

Figure 22. The Borg CR10 scale used for subjective evaluation of perceived discomfort (37)

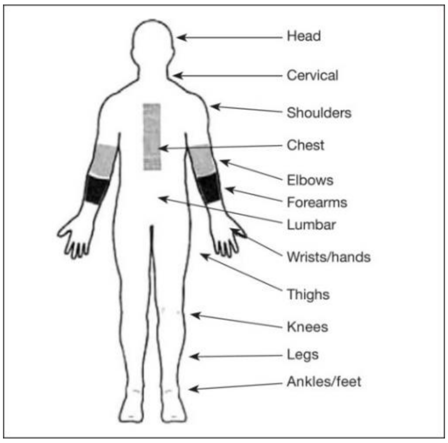


Figure 21. The body map used for evaluation of location of perceived discomfort. (28)

During the 2-minute rest interval in between each set of tightening, the experimenter altered all the necessary parameters for the next set of tightening as well as unfastening the joint. The joint was unfastened with another tool so that the participants were only exposed to fatigue arising from fastening and not unfastening of the joints. In real assembly work stations, unfastening is considered a rare procedure and is due to the sudden release of load accompanied by its own negative impact on the operator from an ergonomic point of view. (38)

4.3 Data Processing

Once data for all categories of output parameters (angles, torques, EMG measurements, subjective ratings and body maps) had been collected for all test persons throughout the experiments, the data was processed as described in the following sections.

4.3.1 Handle Deflection & Reaction torque

The torque and angle graphs were exported from DEWESoft to MATLAB where they were further processed. The script used to analyze the graphs is attached in Appendix 4. The values of interest when analyzing the graphs in MATLAB were:

- Angular displacement of tool handle [degrees] – three deflection metrics were used:
  i) Maximum deflection in negative direction
  ii) Maximum deflection in positive direction
  iii) Maximum deflection range, i.e. the absolute sum of the two aforementioned values

- Reaction torque at tool handle [Nm] - three torque metrics were used to evaluate the reaction torque curves:
  i) Maximum reaction torque in negative direction
  ii) Maximum reaction torque in positive direction
  iii) Max reaction torque range, i.e. the absolute sum of the two aforementioned values

- Impulse [Nms] – The integral of torque over time was calculated by using the trapezoidal method in MATLAB. Impulse was investigated at the following sites:
  i) The impulse arising at the tool handle, i.e. the impulse affecting the hand/arm of the operator
  ii) The impulse arising at the joint site

- Power [Watt] – Defined as reaction torque multiplied by reaction speed. Reaction speed was converted from RPM to rad/s by multiplying with $2\pi/60$. For the power curves, both the reaction torque and the reaction speed were low pass filtered by 400 Hz due to heavy noise in the reaction speed signal.

- Work [J] – By integrating the power-time curve, the work performed was obtained.

The obtained curves for the various torques and angles were analyzed for certain portions of the graphs. The lower time limit was set to the time at which snug was initiated, i.e. when torque at the joint reached 2 Nm, and the upper limit was set to 0,8 seconds after the initiation of snug.

The abovementioned values were collected for each tightening, i.e. 6 tightenings per set. Each test person performed 12 sets as mentioned earlier. With 10 participants included in the tests, a total of 6*12*10 = 720 tightenings were analyzed.

In this study, data was only recorded for each tightening procedure and not for the resting time in between tightenings and was thus not considered in the data processing.

4.3.2 Electromyography

The collected EMG signals were analyzed in the associated software program named Tension. The graphs were visually analyzed, and maximum, minimum and mean values were manually read from the graphs for each 1-minute set of tightenings. It was not possible to compare the EMG curves directly to the torque and angle curves since the obtained EMG files were not compatible with MATLAB or any program other than Tension.

4.3.3 Subjective Rating of Discomfort & Body Map

The subjective rating of perceived discomfort was compared both between test persons for the 12 sets of tightenings as well as comparing how the discomfort was perceived between the 12 combinations of parameters, and a minimum, maximum and mean level across all 10 participants was calculated. As goes for the body map, the location at which the main discomfort was perceived was marked with a rectangle representing the area at which the discomfort was perceived. The rectangles for each tests subject were added together, thus overlapping each other to visualize the distribution of the location of perceived discomfort between test persons.

4.3.4 Statistical Analysis

For each of the output parameters handle angle (min, max and range), reaction torque (min, max and range), impulse (at handle and joint), work and CR10 scale, the mean values and associated standard deviations across all 10 participants were gathered in one table. A similar table was created where the means were converted to ranks, and where they were ranked in relation to the other values within their category of output parameter across the 12 sets. This facilitated the comparison between the output parameters since the differences in units (degrees, Nm, Nms, Joule, CR10 Scale) now could be omitted.

Descriptive statistics was used to clarify the findings from the tables, where the sets with the highest and lowest values (mean value or rank) were highlighted.

Statistical tests were performed to further evaluate the significance of the results and the difference between the 12 combinations of tool- and task related parameters. Analysis was performed on the ranking table in order to statistically differentiate between the rankings of the 12 sets. The non-parametric Friedman test was performed on the tables covering the results from all 10 test persons for the output parameters handle angle range, reaction torque range, impulse at handle, and work. By doing so one could determine if the means were statistically significantly different from each other. The Friedman test is based on Equation 5.

$$\left[\frac{12}{nk(k+1)}\sum_{i=1}^{k} R_i^2\right] - 3n(k+1)$$

Equation 5. Q- value calculated during Friedman test.

Where k is the number of sets and n is the number of observations, i.e. test persons, per set. R_i^2 is the sum of squares across the 12 sets. (39)

The results from equation 5 provides the Q-value (also known as Chi-Square value). The Q-value is further compared to the alfa value found in Chi-Square Distribution Table corresponding to the degrees of freedom and significance level.

A two-way Analysis of Variance (ANOVA) with replications (significance level of 5%) was performed in Microsoft Excel for the evaluation of statistical difference between vertical workspace and horizontal workspace. Mean values for sets number 1-6 (vertical workspace) were in the test compared to mean values for sets number 7-12 (horizontal workspace). The output parameters investigated in the test were Handle Angle Range, Reaction Torque Range, Impulse at Handle, Work and Borg CR10 Scale.

5 Results

The Quick Step strategy on medium hard joints, i.e. set number one and seven, generated very high reaction torques and handle displacements. Therefore, due to ethical reasons, the participants were allowed to limit the high handle displacement by supporting the tool battery with the left hand (thus having both hands involved when operating the tool). However, it was made sure that at least one of the six tightenings throughout the two sets with the Quick Step strategy on medium hard joints was performed without the support of the left hand on the battery. In that way, data could be collected for the high reaction force output without exposing the participants to unnecessary harm throughout the experiments. The tightening (out of the six tightenings for each set) chosen for statistical evaluation was the one in which the participants did not support the tool battery with the left hand, i.e. the tightening in which data for the high reaction torque was captured.

The 12 sets have been named according to their abbreviations for tightening strategy, joint stiffness and workspace orientation for the sake of clarity, where for example set 1 will be noted as ‘QS, M, V’ (**Q**uick **S**tep, **M**edium joint stiffness, **V**ertical workspace).

5.1 Handle Deflection & Reaction Torque

Min, max and range values for each individual tightening were extracted both for the handle deflection and for the reaction torque.

The data of handle deflection (min, max and range) for all 10 test persons can be seen in Appendix 1, in Table 12, Table 13 and Table 14 respectively. In Appendix 1, the data for reaction torque (min, max and range) for all 10 test persons can be seen in Table 15, Table 16 and Table 17 respectively.

Graphical representations of the handle deflection range and reaction torque range can be seen in Appendix 7.

The mean values across all 10 participants of handle deflection and reaction torques can be seen in Table 3 and Table 4 respectively.

Table 3. Mean handle angles across all 10 participants.

Set Nr	Handle Angle [degrees]		
	min	max	range
1 (QS,M,V)	-47.01	10.69	57.69
2 (QS,H,V)	-16.76	8.79	25.55
3 (TP,M,V)	-21.66	6.61	28.27
4 (TP,H,V)	-11.18	2.46	13.64
5 (TT,M,V)	-24.35	10.95	35.3
6 (TT,H,V)	-7.69	5.89	13.59
7 (QS,M,H)	-49.8	5.97	55.77
8 (QS,H,H)	-6.67	5.51	12.18
9 (TP,M,H)	-15.96	2.19	18.15
10 (TP,H,H)	-7.01	1.38	8.39
11 (TT,M,H)	-12.45	6.5	18.95
12 (TT,H,H)	-2.86	6.41	10.01

Table 4. Mean reaction torques across all 10 participants.

Set Nr	Reaction Torque [Nm]		
	min	max	range
1 (QS,M,V)	-2.91	5.7	8.61
2 (QS,H,V)	-1.25	1.86	3.11
3 (TP,M,V)	-0.82	4.87	5.69
4 (TP,H,V)	-1.3	3.18	4.48
5 (TT,M,V)	-1.03	1.67	2.71
6 (TT,H,V)	-1.63	1.44	3.07
7 (QS,M,H)	-2.95	7.58	10.53
8 (QS,H,H)	-0.99	1.76	2.75
9 (TP,M,H)	-0.87	4.39	5.26
10 (TP,H,H)	-0.74	3.55	4.28
11 (TT,M,H)	-1.09	1.98	3.08
12 (TT,H,H)	-1.27	1.54	2.82

5.2 Impulse & Work

The data of impulse at the joint and at the tool handle for all 10 test persons can be seen in Appendix 1, Table 18 and Table 19 respectively. The data of the work performed for all 10 test persons can be seen in Appendix 1, Table 20.

Graphical representations of the impulse can be seen in Appendix 7.

The mean values of impulse and work across all 10 participants can be seen in Table 6 and Table 5 respectively.

Table 6. Mean impulse across all 10 participants.

	Impulse [Nms]	
Set Nr	**handle**	**joint**
1 (QS,M,V)	1.06	0.58
2 (QS,H,V)	0.27	0.15
3 (TP,M,V)	0.45	0.4
4 (TP,H,V)	0.33	0.35
5 (TT,M,V)	0.3	0.17
6 (TT,H,V)	0.15	0.07
7 (QS,M,H)	1.23	0.63
8 (QS,H,H)	0.23	0.1
9 (TP,M,H)	0.48	0.37
10 (TP,H,H)	0.38	0.33
11 (TT,M,H)	0.35	0.16
12 (TT,H,H)	0.17	0.07

Table 5. Mean work across all 10 participants.

Set Nr	Work [J]
1 (QS,M,V)	10.45
2 (QS,H,V)	3.37
3 (TP,M,V)	3.56
4 (TP,H,V)	1.88
5 (TT,M,V)	4.18
6 (TT,H,V)	1.81
7 (QS,M,H)	10.78
8 (QS,H,H)	1.61
9 (TP,M,H)	2.24
10 (TP,H,H)	1.31
11 (TT,M,H)	2.31
12 (TT,H,H)	1.07

- Set number 1 and 7, i.e. Quick Step on medium hard joints generated the highest impulse at the handle, 1.06 Nms and 1.23 Nms respectively. They also generated the highest impulses at the joint, 0.58 Nms and 0.63 Nms.
- Set number 1 and 7, i.e. Quick Step on medium hard joints (vertical and horizontal workspace) generated the highest work performed, 10.55 Joules and 10.78 Joules respectively.
- Set number 6 and 12, i.e. Turbo Tight on hard joints (vertical and horizontal workspace) generated the lowest impulse at the handle, 0.15 Nms and 0.17 Nms respectively. They also generated the lowest impulses at the joint, 0.07 Nms for both sets.
- Set number 10 (Tensor Pulse on hard joints) and set number 12 (Turbo Tight on hard joints) generated the lowest work performed, i.e. 1.31 Joules and 1.07 Joules respectively.

5.3 Electromyography

The collected data from the EMG could not be included in the average and statistical evaluations in the study due to incomplete obtained data for the muscle activity. Technical issues with the EMG device limited the amount of muscle activity data that could be collected, and thus left significant gaps in the collected data. Measurements of muscle activity have therefore not been collected for all test persons and for all sets.

Muscle activity from one test person is presented in Figures 23-25, and represents muscle activity profiles during the six tightenings for the three tightening strategies and the two joint stiffnesses on vertical workspace, i.e. sets 1-6. A table of the values can be seen in Appendix 5.

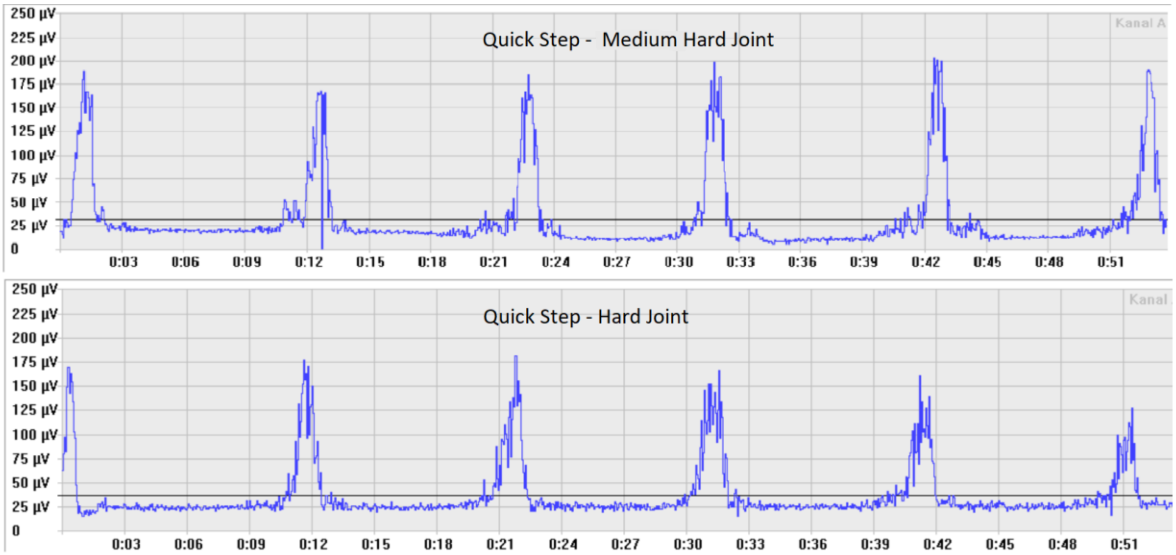
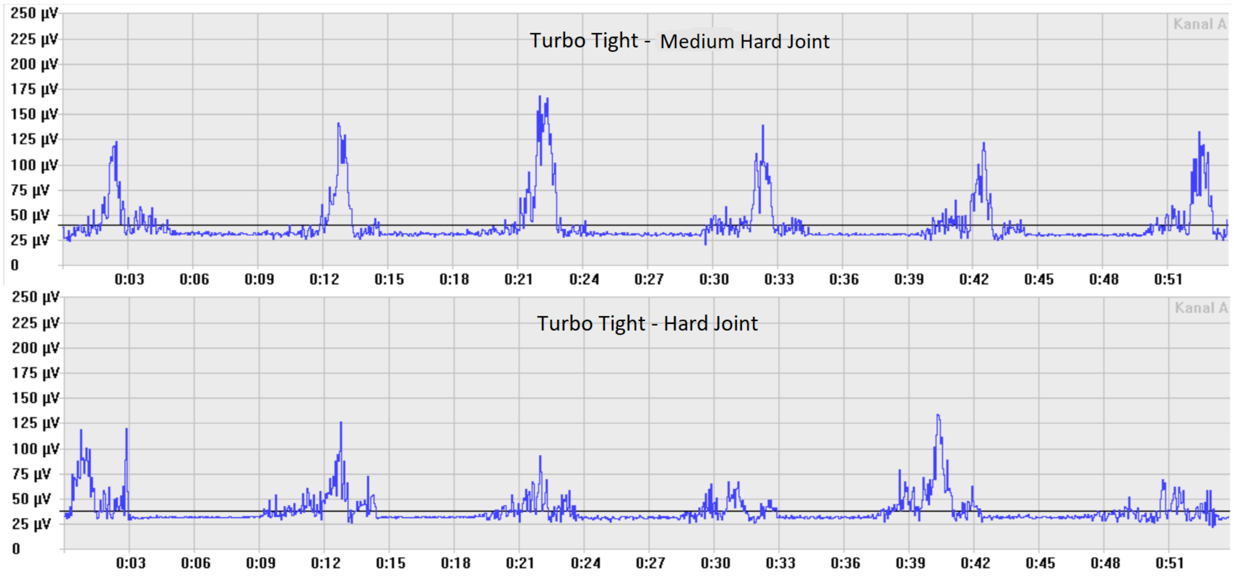


Figure 23. EMG profiles for the Quick Step strategy on medium hard joint (upper) and hard joint (lower).

It can be observed that tightening on medium hard joints with the Quick Step strategy produced higher EMG amplitudes compared tightening with the same strategy on hard joints.

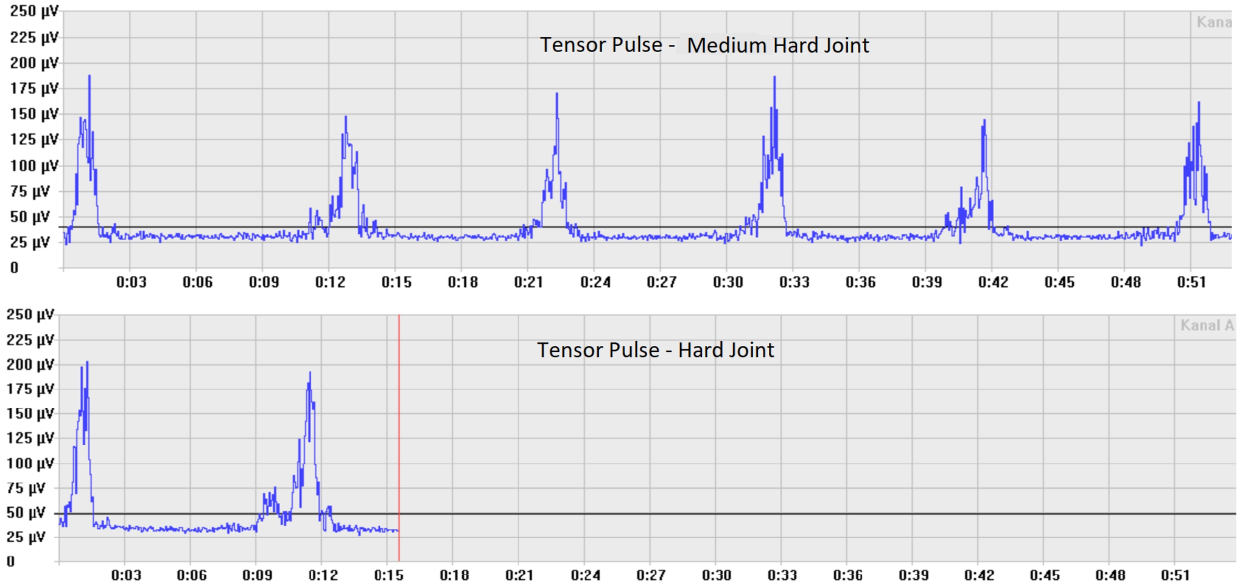
- Average EMG amplitude for tightening with Quick Step on medium hard joint: 188 µV
- Average EMG amplitude for tightening with Quick Step on hard joint: 164 µV


Turbo Tight - Medium Hard Joint

Turbo Tight - Hard Joint

Figure 24. EMG profiles for the Turbo Tight strategy on medium hard joint (upper) and hard joint (lower).

- Average EMG amplitude for tightening with Turbo Tight on medium hard joint: 137 µV
- Average EMG amplitude for tightening with Turbo Tight on hard joint: 102 µV


Tensor Pulse - Medium Hard Joint

Tensor Pulse - Hard Joint

Figure 25. EMG profiles for the Tensor Pulse strategy on medium hard joint (upper) and hard joint (lower).

- Average EMG amplitude for tightening with Tensor Pulse on medium hard joint: 167 µV
- Average EMG amplitude for tightening with Tensor Pulse on hard joint: 196 µV

As seen in Figure 25, muscle activity was not registered for all six tightenings for Tensor Pulse on the hard joint due to technical issues with the EMG device.

5.4 Subjective Rating of Discomfort

The subjective ratings of discomfort according to the Borg CR10 scale can be seen in Table 7, with minimum, maximum and mean ratings for each set across the 10 participants presented. The average values are also presented in a graph in Appendix 6.

Table 7. Subjective ratings of perceived discomfort for each test person and combination, i.e. set, of tool- and task related parameters.

	Test Person Nr.												
Set Nr.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Min**	**Max**	**Average**
1 (QS,M,V)	2	2	1	3	6	2	3	3	1	5	1	6	2.8
2 (QS,H,V)	2	3	0	2	2	0	1	3	2	2	0	3	1.7
3 (TP,M,V)	3	3	0	3	3	0	1	3	2	3	0	3	2.1
4 (TP,H,V)	2	3	1	1	2	1	0	3	3	3	0	3	1.9
5 (TT,M,V)	2	3	1	3	4	0	0	3	2	2	0	4	2
6 (TT,H,V)	2	3	1	1	1	0	0	2	3	1	0	3	1.4
7 (QS,M,H)	2	4	1	4	6	3	3	3	4	7	1	7	3.7
8 (QS,H,H)	1	3	0	2	2	2	2	3	3	2	0	3	2
9 (TP,M,H)	2	2	1	3	4	1	1	3	3	4	1	4	2.4
10 (TP,H,H)	1	3	1	2	3	1	0	2	3	3	0	3	1.9
11 (TT,M,H)	1	3	2	3	4	1	1	2	4	3	1	4	2.4
12 (TT, H,H)	1	1	1	2	2	0	0	2	2	2	0	2	1.3

- Set number 1 and 7, i.e. Quick Step on medium hard joints, vertical and horizontal direction, resulted in the highest average subjective rating of discomfort, 2.8 and 3.7 respectively.
- Set number 6 and 12, i.e. Turbo Tight on hard joints, vertical and horizontal direction, resulted in the lowest average subjective rating of discomfort, 1.4 and 1.3 respectively.

5.5 Body Map

The locations of perceived effort were marked on body maps by the participants for each of the 12 sets. Body maps for the 12 sets are presented in Appendix 2, Figure 26 - 37 with marks (represented as rectangles) gathered from all 10 participants on each body map.

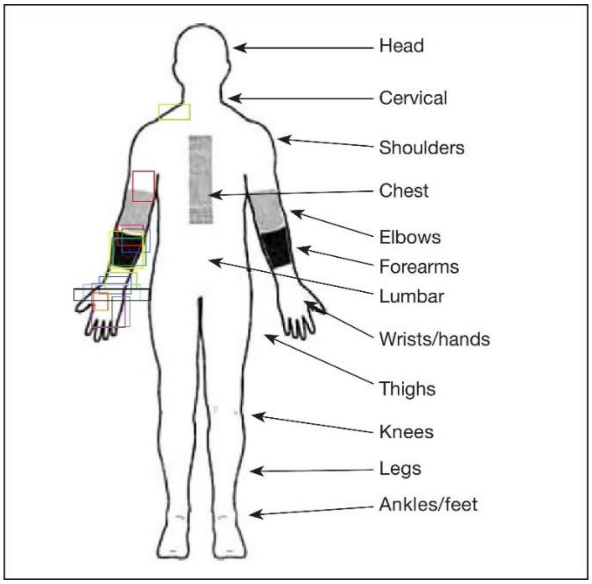


Figure 26. Body map from set nr. 6, Turbo Tight, hard joint, vertical workspace.

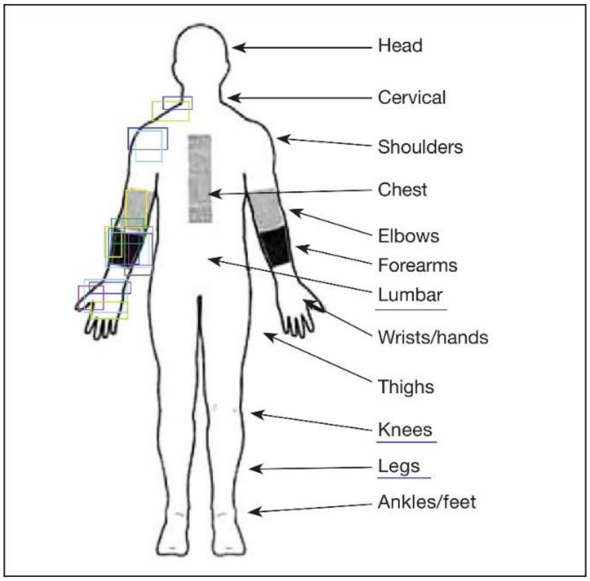


Figure 27. Body map from set nr. 12, Turbo Tight, hard joint, horizontal workspace.

From the body map in Figure 27, it can be noted that by the time the test persons reached set number 12, i.e. at the end of the experiment, the total locations of perceived discomfort had branched out and thus covered a larger area, ranging all the way from the hand up to the neck. When compared to the body maps in the beginning of the experiments, for example set number 6 (Figure 26) which consisted of the very same tightening strategy and joint stiffness, it can be noted that the perceived discomfort is represented as more centered around the hand and forearm, as opposed to the overlapping areas of perceived discomfort towards the end of the experiments which span all the way up to the neck and shoulder area.

5.6 Gathered Mean values of output parameters

The values from each output category, i.e. values from Table 11 to 19 in Appendix 1 were used to calculate the average value for all 12 sets of input parameters across the 10 participants, thus enabling representation of all categories of output parameters gathered in one table, see Table 8.

The output categories are Handle Angle (min, max and range), Reaction Torque (min, max and range) Impulse (at handle and joint), Work, and Subjective Rating of discomfort according to the Borg CR10 scale.

Table 8. Mean values and standard deviation (in parenthesis) of the 10 participants for each category of output parameter. The values are represented for all 12 sets of input parameters. Tightening strategy and joint stiffness (medium hard or hard) associated with each set is noted next to the set number.

	Handle Angle [degrees]			**Reaction Torque [Nm]**			**Impulse [Nms]**		**Work [J]**	**CR10**
Set Nr.	**min**	**max**	**range**	**min**	**max**	**range**	**handle**	**joint**		
1 (QS,M)	-47.01(±25)	10.69(±9)	57.69(±25)	-2.91 (±2)	5.7 (±2)	8.61 (±2)	1.06 (±0)	0.58 (±0)	10.45 (±3)	2.8 (±2)
2 (QS,H)	-16.76 (±9)	8.79 (±6)	25.55(±14)	-1.25 (±0)	1.86 (±1)	3.11 (±0)	0.27 (±0)	0.15 (±0)	3.37 (±2)	1.7 (±1)
3 (TP,M)	-21.66(±11)	6.61 (±9)	28.27 (±8)	-0.82 (±0)	4.87 (±1)	5.69 (±1)	0.45 (±0)	0.40 (±0)	3.56 (±1)	2.1 (±1)
4 (TP,H)	-11.18 (±6)	2.46 (±3)	13.64 (±5)	-1.30 (±0)	3.18 (±0)	4.48 (±0)	0.33 (±0)	0.35 (±0)	1.88 (±1)	1.9 (±1)
5 (TT,M)	-24.35 (±6)	10.95(±4)	35.30 (±6)	-1.03 (±0)	1.67 (±0)	2.71 (±0)	0.30 (±0)	0.17 (±0)	4.18 (±1)	2 (±1)
6 (TT,H)	-7.69 (±5)	5.89 (±4)	13.59 (±5)	-1.63 (±0)	1.44 (±0)	3.07 (±0)	0.15 (±0)	0.07 (±0)	1.81 (±1)	1.4 (±1)
7 (QS,M)	-49.8 (±20)	5.97 (±8)	55.77(±17)	-2.95 (±1)	7.58 (±1)	10.53 (±2)	1.23 (±0)	0.63 (±0)	10.78 (±3)	3.7 (±2)
8 (QS,H)	-6.67 (±4)	5.51 (±6)	12.18 (±4)	-0.99 (±0)	1.76 (±1)	2.75 (±0)	0.23 (±0)	0.10 (±0)	1.61 (±1)	2 (±1)
9 (TP,M)	-15.96 (±9)	2.19 (±5)	18.15 (±9)	-0.87 (±0)	4.39 (±1)	5.26 (±1)	0.48 (±0)	0.37 (±0)	2.24 (±1)	2.4 (±1)
10 (TP,H)	-7.01 (±4)	1.38 (±3)	8.39 (±4)	-0.74 (±0)	3.55 (±1)	4.28 (±1)	0.38 (±0)	0.33 (±0)	1.31 (±0)	1.9 (±1)
11 (TT,M)	-12.45 (±2)	6.50 (±4)	18.95 (±5)	-1.09 (±0)	1.98 (±0)	3.08 (±0)	0.35 (±0)	0.16 (±0)	2.31 (±1)	2.4 (±1)
12 (TT,H)	-2.86 (±3)	6.41 (±3)	10.01 (±3)	-1.27 (±0)	1.54 (±0)	2.82 (±0)	0.17 (±0)	0.07 (±0)	1.07 (±0)	1.3 (±1)

From Table 8 one can observe the following:

- Sets number 1 and 7, i.e. Quick Step on medium hard joints (vertical and horizontal workspace), generated the two highest values in all categories of output parameters
- The lowest work performed, 1.07 Joules, was achieved by set number 12, i.e. Turbo Tight on hard joint.
- Sets number 7-12, i.e. horizontal work space, all generated lower handle angle range compared to sets 1-6, i.e. vertical workspace.

5.7 Rankings of output parameters

The mean values from Table 8 (section 4.6) were converted to ranks within their associated category, i.e. column. This means that for example the values across the 12 sets in the category 'handle deflection range' were compared to each other and thus ranked in relation to each other. A ranking value of 1 indicates the lowest mean value, while a ranking value of 12 indicates the highest mean value in each category of output parameters. The ranks can be seen in Table 9.

Table 9. Mean values from Table 8 (section 5.6) converted to ranks, ranging 1 to 12. The sets with the lowest and highest ranks within each category are represented at the bottom of the graph. Note that they do not represent lowest and highest rank, but rather which of the 12 sets that is associated with the lowest and highest rank within each column. Tightening strategy and joint stiffness (medium hard or hard) associated with each set is noted next to the set number.

	Handle Angle			**Reaction Torque**			**Impulse**		**Work**	**CR10**
Set Nr.	**min**	**max**	**range**	**min**	**max**	**range**	**handle**	**joint**		
1 (QS,M)	11	11	12	11	11	11	11	11	11	11
2 (QS,H)	8	10	8	7	5	6	4	4	8	3
3 (TP,M)	9	9	9	2	10	10	9	10	9	8
4 (TP,H)	5	3	5	9	7	8	6	8	5	5
5 (TT,M)	10	12	10	5	3	1	5	6	10	5
6 (TT,H)	4	5	4	10	1	4	1	1	4	2
7 (QS,M)	12	6	11	12	12	12	12	12	12	12
8 (QS,H)	2	4	3	4	4	2	3	3	3	5
9 (TP,M)	7	2	6	3	9	9	10	9	6	9
10 (TP,H)	3	1	1	1	8	7	8	7	2	4
11 (TT,M)	6	8	7	6	6	5	7	5	7	9
12 (TT,H)	1	7	2	8	2	3	2	1	1	1
Lowest set	**12**	**10**	**10**	**10**	**6**	**5**	**6**	**12**	**12**	**12**
Highest set	**7**	**5**	**1**	**7**	**7**	**7**	**7**	**7**	**7**	**7**

5.8 Statistical Analysis

The values from Table 7 (Borg CR10 values), Table 14 (Handle Angle Range), Table 17 (Reaction Torque Range), Table 18 (Impulse at joint), Table 19 (Impulse at handle) and Table 20 (Work) were analyzed in Microsoft Excel by conducting the non-parametric Friedman tests in order to test whether there is a significant difference in ranking between the sets with a significance level of 5%. The values were converted to ranks, and Q-values were calculated according to Equation 5. The p-values were obtained from the CHISQ.DIST(Q,df) function in Microsoft Excel. The degrees of freedom (df) were number of sets minus one, i.e. 12 - 1 = 11.

The p- and Q-values can be seen in Table 10. A Q-value larger than the alpha found in the Chi Square Distribution table, i.e. 19.675, indicates that the null hypothesis, i.e. that there is no significant difference between the means of the 12 sets, can be rejected.

Table 10. Q- and p-values for the output parameters handle angle range, reaction torque range, impulse at handle, work and CR10 scale.

	Handle Angle Range	Reaction Torque Range	Impulse at Handle	Work	CR10
Q-value	90.169	95.031	92.062	90.692	20.912
p-value	6.970E-15	7.766E-16	2.971E-15	5.508E-15	1.063E-02

Q-values for all output categories are larger than 19.675, meaning that there is a statistically significant difference between the 12 sets for the handle angle range, reaction torque range, impulse at handle, work and CR10 rating.

The two-way ANOVA with replications (significance level of 5%) for the evaluation of statistical difference between vertical workspace orientation and horizontal workspace orientation can be seen in Table 11. The output parameters investigated in the test were Handle Angle Range, Reaction Torque Range, Impulse at Handle, Work and Borg CR10 Scale.

Table 11. Two-way ANOVA with replications for the workspace orientation evaluation.

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F-critical*
Rows (orientation)	2.227227	1	2.227227	0.03667	0.848914	4.03431
Columns (output)	4631.974	4	1157.993	19.06581	1.41E-09	2.557179
Interaction	319.391	4	79.84776	1.314656	0.277364	2.557179
Within	3036.832	50	60.73664			
Total	7990.424	59				

The conclusions that can be drawn from the ANOVA are the following:

- The p-value for the rows (workspace orientation) = 0.849 > 0.05, so we can not reject the null hypothesis and thus conclude, with a 95% confidence, that there is no statistic difference between the workspace orientations.
- The p-value for the interaction = 0.277 > 0.05 and thus conclude that there are no significant differences in the interaction between workspace orientation and output categories.

6 Discussion

The purpose of this study was to evaluate the ergonomic impact on the user when performing nut/bolt tightenings with an electrical pistol grip nutrunner. Depending on the demands of the task, settings of the power tool and human related factors, the ergonomic impact on the user can differ. To investigate these differences, tool and task related parameters were altered in order to reach a conclusion of least and most negative combination of tool- and task related parameters from an ergonomic standpoint. By combining both objective and subjective means of measuring, a more complete image of the ergonomic impact on the user could be formed. This was one of the main contributions and strengths of the methodology designed throughout this project, where the different approaches could together either point toward one conclusion, thus giving the results greater substance, or contradict each other, thereby paving way for new questions regarding the topic. The findings from this study highlighted which combinations of fastening strategy and joint stiffness that were considered as most and least negative in terms of ergonomic impact on the user. This obtained information could be used in future product development projects, where the gained knowledge could play a more central role in the product development. The current study can be regarded as a roadmap for further studies of similar nature, where certain improvements and developments of the current methodology could potentially result in a solid methodology for ergonomic evaluation of nutrunner power tools.

The structure of this chapter is as follows: Each subchapter is divided according to output category, i.e. reaction torques and handle deflections, electromyography and subjective assessments. The subchapters are initiated with a discussion on the chosen method and then followed by an evaluation of the results.

None of the participants in this study had previous experience from for example assembly work, and so the results were analyzed with respect to this. It is possible that experienced power tool users would have generated different results by for example reacting to the resulting torques and handle deflections differently.

6.1 Reaction Torques and Handle Deflections

As mentioned earlier in this report, and as demonstrated by the torque and angle measurements, the Quick Step strategy on medium hard joints, i.e. set nr 1 and 7, generated very high reaction torques and tool handle displacements. The test persons were therefore allowed, by the experimenter, to limit the displacement of the tool handle by supporting the battery with their left hand. Therefore, the 'true' reaction angle and torque of that particular fastening strategy on hard joints was not measured throughout all six tightenings for sets 1 and 7, and so there was a tradeoff between research ethics and collected data. However, it was made sure that at least one of the six tightenings throughout the two sets with the Quick Step strategy on hard joints was performed without the support of the left hand on the battery. In that way, data could be collected for the high reaction force output without exposing the participants to unnecessary harm throughout the experiments. When performing tightenings with torques above certain levels, many manufacturers recommend the operator to support the tool with two hands as described above in order to reduce the discomfort and potential harm. However, this may not always be possible when tightening nuts and bolt at locations which are difficult for the operator to reach, for example in cavities of automobiles. Moreover, the purpose of performing multiple tightenings over a one-minute span was for the participants to experience a fatigue buildup, thus imitating 'real' working conditions. The intention of this study was not to evaluate for example changes in handle deflection or reaction torque over time or as a result of fatigue. Although those factors may in themselves be of interest to investigate, they were not part of the scope of this study.

The statistical evaluation was performed on only one of the six tightenings per set. This is due to the aforementioned issue, where only one of the tightenings captured the high reaction torque and handle deflection of the Quick Step strategy on medium hard joints. The variations between the output parameters throughout the six tightenings was so low that the inclusion of the other five tightenings would not have significantly affected the outcome of the study. For example, the handle angle range did not differ significantly between the six tightenings and this was true for all sets, all test persons and all output parameters.

The deflection of the tool handle (handle angle range) was smaller for all horizontal sets (set nr. 7-12) in comparison with their corresponding set on vertical workspace (set nr. 1-6). This is favorable from an ergonomic point of view since high tool handle displacements are greatly associated with both injury and discomfort. One possible explanation to the lower handle deflections when performing tightenings on horizontal workspace is the position of the operator in relation to the tool. When working on the horizontal workspace, the operators in this study were nearly hovering over the tool and joint, thereby applying some of her/his bodyweight to the tool. Moreover, when performing tightening on a horizontal workspace, the tool was in this study held closer to the body than when performing tightening on the vertical workspace, where the tool was held at a greater distance from the body. The proximity to the body when operating the tool on the horizontal workspace is likely to have allowed for the test persons to have higher control over the tool, thus enabling the test persons to limit the displacement of the tool handle at greater extent.

Although the peak reaction force in positive and negative direction gives an indication of the torque magnitudes involved during a tightening procedure, the impulse could be considered a more suitable measurement of ergonomic impact since it takes the duration of the tightening into account – a factor that affects the overall ergonomic impact on the user. (8) Instead of considering a momentary instance as one would when observing only peak reaction torques, the impulse gives an indication of torque levels and their variations over time, thus providing a more comprehensive understanding of how the reaction torque throughout a tightening affects the human body. The duration of the tightening in combination with the torque levels present during that time can be directly related to the buildup of fatigue. As fatigue builds up in the muscles, a higher number of motor units in the muscles are recruited in order to maintain the force output which the task demands. (40)

Set number 1 (Quick Step, medium hard joint, vertical workspace) and set number 7 (Quick Step, medium hard joint, horizontal workspace), generated the highest mean reaction torques (8.61 and 10.53 Nm respectively). The implications for the muscles and tendons as a result of the high reaction torques and handle deflections generated by the Quick Step strategy (particularly on medium hard joints) are the following: the time at which the deflection of the handle angle starts going below zero, i.e. moving in the opposite direction of the reaction torque in positive direction, an extension of the tendons is initiated. This translates to the instance at which the operator starts feeling a jerk motion of her/his arm, and eccentric muscle work (elongation of the muscles) is thereby initiated. Once the reaction torque reverses towards the negative direction, the handle angle starts moving in positive direction, and the muscle work is now instead switched over to concentric work (muscle shortening).

The sudden switch from eccentric to concentric muscle work at such high force magnitudes stresses the ergonomically disadvantageous features of the sets. As mentioned earlier, fatigue implies that a higher number of motor units are recruited. It is believed that some motor units are rarely recruited during normal levels of loading. Therefore, the tendon fascicles (bundles of dense connective tissue) associated with muscle fibers of these rarely used motor units have not been exposed to the same extent of loading compared to some other fascicles within the tendon. (41) Due to this smaller amount of total loading, the conclusion is thereby that these tendon fascicles are weaker and thus more prone to injury in the event of sudden loading.

6.2 Electromyography

The EMG device was not able to act as the desired complement to this study due to severe technical issues. The choice of including the incomplete EMG measurements as a part of the results of the study was for the sake of the presentation of the *differences* between EMG amplitudes associated with the combination of fastening strategies and joint stiffness. Although statistical conclusions could not be drawn from the available EMG measurement data, distinguishable differences were observed in the EMG curves of the different fastening strategies. Muscle activity, as reflected by the EMG curves, could potentially have high interindividual differences, and it is not expected that EMG measurements on different individuals would result in similar EMG peak amplitudes. The amplitudes are strongly related to factors such as muscle fiber activation pattern, muscle tone, anatomical structure of the individual etc. However, the *differences* in EMG peaks between the various fastening strategies is not expected to differ drastically between individuals. For example, it is not expected that the Turbo Tight strategy on hard joints (which was experienced as requiring low muscle exertion) would on average result in higher EMG peaks than the Quick Step strategy on medium hard joints (which was experienced as requiring high muscle exertion). The presented EMG values in study can therefore be argued to be partly representative of the *differences* in EMG values between the different fastening strategy/joint stiffness combinations. It is however clear that extensive and proper EMG measurements are necessary for a full understanding of muscle exertions related to power tool use.

The Quick Step fastening strategy on medium hard joints presented the highest mean EMG amplitude across the six tightenings (188 µV), while the Turbo Tight strategy on hard joints presented the lowest mean EMG amplitude over six tightenings (102 µV). The Tensor Pulse strategy on hard joints resulted in average of 196 µV but was only averaged over two tightenings since the EMG device unexpectedly shut off after that. The duration of the Tensor Pulse strategy on hard joints was longer than the other strategies, with approximately 10 pulses to reach target torque of 8 Nm. Despite the high EMG amplitude, the Tensor Pulse Strategy on hard joints received a mean subjective rating of discomfort of 1.9 on the Borg CR10 scale, which corresponds to the anchored word ‘Weak’. Therefore, although the data available for muscle activity is limited, it can be hypothesized that a high muscular activity peak does not necessarily imply high perceived discomfort. This could possibly be explained by the following paragraph.

The Tensor Pulse strategy, being a pulsating tightening strategy, produces higher levels of vibration compared to the other tightening strategies. When muscles are exposed to vibration, the tonic vibration reflex is initiated, and so the muscles start to contract. A muscle exposed to vibration undergoes a reduction of tactility – the ability to feel pressure or pain. It is well established that tactility affects the amount of force that can be exerted by a muscle when holding or manipulating an object. The reduction in tactility implies that the force required in repetitive tasks is increased, since the sensation in the muscles is decreased, thus leading to an increased risk of chronic tendon and nerve disorders. (42) This could explain the low perceived discomfort when performing tightening with the Tensor Pulse strategy, despite the relatively high muscular activity.

Since the fastening on the hard joint was achieved with a higher number of pulses compared to the fastening on medium hard joints, the duration of the tightening, and thus impact on the operator, was greater.

No correlation was seen between EMG amplitude over time, i.e. changes in muscle activity due to fatigue throughout the tasks were not distinguishable from the EMG graphs. Although observation of changes in muscle activity over time throughout each set was not included in the scope of this study, it may be interesting to further explore how muscle activity changes over time as fatigue builds up in the muscles. There are studies that indicate that muscle activity increases with time due to a higher number of recruited muscle fibers as fatigue builds up. This in turn leads to increases in EMG amplitudes. (40) This was observed in set number 1 (Quick Step, medium hard joint, vertical workspace) and set number 7 (Quick Step, medium hard joint, horizontal workspace), which generated high EMG amplitudes (188 µV and 164 µV). Therefore, it can be speculated that the use of the Quick Step strategy leads to a higher number of recruited motor units in the muscle. One study suggests that as the amount of recruited motor units increases (as a result of fatigue), the fluctuations in force output increases. (43) This indicates an instability which arises in muscles and the operator is thereby increasingly prone to injury.

6.3 Subjective Assesments

The use of a rating scale, in this case a Borg CR10 scale, requires the participant to have a reference in order to accurately rate the perceived discomfort. The optimal case would have been if the participants would rate the 12 different sets in relation to each other, but this was not always the case.

The experimental setup used in this study was rather unsophisticated due to the simulated tool handle, the quite large sensors attached to both the head of the tool to the simulated handle, and the extension of the tool trigger by using a cable tie. This added substantial weight to the tool as well as manipulating the center of gravity of the tool, and did therefore not accurately represent the true ‘feeling’ of operating the actual tool. The actual tool handle and trigger are ergonomically designed, while the simulated tool handle was simply a metal rod. Therefore, these factors may have affected the outcome of the subjective ratings, and was clearly demonstrated on the body maps, where several test persons had highlighted the fingers as a location of discomfort arising from the 'cable tie' trigger. This would most likely not have been the case if the actual tool handle and trigger would have been used.

Each participant performed 72 tightenings during an approximate of 45 minutes per participant. The participants did therefore inevitably experience a buildup of fatigue over time, thus possibly having an effect on both the subjective and objective measurement methods. A gradient of increasing subjective ratings on the Borg CR10 scale throughout the 12 sets was expected, but was not captured in the study. The phenomena might be more clearly demonstrated at more intensive work pace or over a longer duration of work. The results from the body maps do however highlight the increase of fatigue. The last body map, i.e. body map for set nr 12, shows an extension of locations of perceived discomfort, ranging from the forearm up to the shoulders and the neck. The body map for set nr 12 shows a larger number of overlapping rectangles at the shoulder and neck area, thus implying that an increased number of test persons perceived discomfort at the site at the end of the experiments. The distribution of perceived discomfort at the final set (Turbo Tight, hard joint, horizontal workspace) does therefore not necessarily represent the discomfort associated with the particular combination of tightening strategy, joint stiffness and workspace orientation. This can be stated with confidence, since the other measurement methods in this study clearly point toward the gentleness of set nr 12. It can therefore be concluded that the effect of time during tightening causes the discomfort to branch out toward adjacent muscles, in this case toward the right shoulder and neck.

One way of eliminating the gradient of fatigue which biases the subjective assessments would have been to randomize the order of the sets for each test person. Thereby, the outcome of the subjective assessments could more clearly be anchored to the characteristics of each set as opposed to fatigue buildup.

Set number 1 (Quick Step, medium hard joint, vertical workspace) and set number 7 (Quick Step, medium hard joint, horizontal workspace), resulted in the highest mean subjective ratings (2.8 and 3.7 respectively). As discussed earlier in this chapter, the two sets produced the highest mean reaction torques and handle deflections. The correlation between the high ratings (in comparison to the other sets) and high handle deflections and reaction torques is in consensus with findings from other studies which demonstrated that large handle displacements were accompanied by high subjective ratings of discomfort. (44)

7 Conclusion

The goal of this study was to determine which combinations of tool and task related parameters that were the most and least ergonomically disadvantageous. As goes for the most ergonomically disadvantageous combination, all of the measurement methods pointed toward the ergonomically unfavorable characteristics of the Quick Step tightening strategy on medium hard joints, regardless of workspace orientation, i.e. set number 1 and 7.

In terms of least ergonomically disadvantageous combination of tool and task related parameters, the results from the various measurement methods were not as aligned. The subjective ratings were the lowest for set number 6 and 12, i.e. Turbo Tight on hard joints (vertical and horizontal workspace respectively), while handle deflection was lowest for set number 10 (Tensor Pulse, hard joint, horizontal workspace) and set number 12 (Turbo Tight, hard joint, horizontal workspace). Set number 10 and 12 also resulted in the lowest work performed.

From the study, the following can be concluded:

- The Quick Step tightening strategy on medium hard joints was demonstrated by all measurement method to be the most ergonomically disadvantageous combination of tightening strategy and joint stiffness.
- The Turbo Tight and Tensor Pulse tightening strategies on hard joints were suggested to be the least ergonomically disadvantageous combinations of tightening strategy and joint stiffness.
- The Tensor Pulse tightening strategy on hard joints produced high muscular activity (196 µV) but rather low subjective ratings (ranked as the 5th most discomforting set out of the 12 sets). This was speculated to be due to the reduction of tactility and ability to feel pain due to the high vibration generation from the pulsating strategy, while for the same reason causing the operator to exerting more muscular force.
- The effect of workspace orientation was shown to be statistically insignificant. However, when performing tightening on a horizontal workspace, the range of handle deflection was lower compared to tightenings performed on a vertical workspace. This was true for all tightening strategies and joint stiffnesses when compared with respect to workspace orientation. A low range of handle deflection is considered to be less ergonomically disadvantageous.

- The methodology developed throughout this study can be used as a roadmap for future studies of the ergonomic impact from nutrunner power tools. By refining and adjusting certain parts of the current methodology, power tools can further be evaluated from an ergonomic perspective and thus developed for minimal harmful impact on the tool user.

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Appendix 1 – Tables of Torques, Angles, Impulse & Work

Handle Angle Min. [degrees]

Table 12. Peak handle deflection in negative direction. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	-29.36	-9.85	-39.77	-27.46	-86.13	-86.52	-42.15	-61.74	-52.40	-34.64
2 (QS,H,V)	-7.32	-10.01	-15.25	-11.58	-14.96	-13.48	-28.61	-37.58	-16.20	-12.57
3 (TP,M,V)	-8.63	-14.28	-12.37	-21.80	-28.35	-19.12	-46.49	-17.80	-20.22	-27.50
4 (TP,H,V)	-6.16	-9.69	-9.05	-9.56	-15.54	-6.58	-24.68	-11.63	-14.81	-4.11
5 (TT,M,V)	-12.10	-30.28	-26.88	-22.22	-24.57	-32.40	-29.20	-20.82	-24.86	-20.20
6 (TT,H,V)	-2.34	-5.75	-1.67	-9.45	-3.23	-7.40	-14.66	-14.23	-8.48	-9.67
7 (QS,M,H)	-36.37	-36.30	-41.32	-30.39	-54.41	-45.13	-87.59	-80.53	-50.57	-35.40
8 (QS,H,H)	-5.20	-3.04	-8.95	-8.01	-9.86	-3.52	-14.98	-7.74	-2.36	-3.03
9 (TP,M,H)	-8.72	-5.27	-16.25	-21.03	-20.04	-34.46	-10.44	-23.96	-5.41	-14.04
10 (TP,H,H)	0.10	-3.49	-6.66	-13.12	-6.81	-7.86	-7.17	-10.37	-12.56	-2.10
11 (TT,M,H)	-12.66	-9.66	-13.59	-15.47	-15.82	-10.05	-8.49	-13.66	-13.39	-11.69
12 (TT,H,H)	-4.42	-1.91	-8.25	-2.37	-0.50	-4.85	-4.33	-5.71	1.76	1.94

Handle Angle Max. [degrees]

Table 13. Peak handle deflection in positive direction. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	0.88	27.70	6.88	8.91	3.17	17.20	11.99	19.47	1.86	8.79
2 (QS,H,V)	9.07	14.24	3.73	3.89	6.49	5.15	16.04	19.38	6.31	3.60
3 (TP,M,V)	8.60	14.55	6.97	0.35	11.74	9.01	-9.22	20.18	7.21	-3.24
4 (TP,H,V)	4.74	6.55	-0.25	-0.07	2.39	6.46	-1.86	1.52	1.49	3.65
5 (TT,M,V)	15.32	11.91	5.12	6.26	10.59	12.60	12.99	10.83	7.14	16.72
6 (TT,H,V)	9.62	7.26	0.83	3.21	13.30	7.02	3.27	7.22	5.23	1.94
7 (QS,M,H)	5.47	9.41	0.16	4.41	5.41	3.39	0.66	-7.74	15.88	22.61
8 (QS,H,H)	12.03	9.34	-1.56	1.13	2.09	15.25	-3.46	4.22	5.73	10.33
9 (TP,M,H)	4.29	11.25	2.39	-0.63	6.68	4.22	-1.29	-9.19	1.74	2.42
10 (TP,H,H)	4.32	3.31	-0.67	1.12	3.04	-3.27	-1.71	0.53	1.50	5.64
11 (TT,M,H)	10.90	11.09	2.58	3.87	9.14	10.71	1.00	7.08	0.32	8.35
12 (TT,H,H)	4.72	6.53	3.00	3.23	9.35	6.42	4.11	5.54	6.68	14.56

Handle Angle Range [degrees]

Table 14. Absolute sum of max and min handle deflection. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	30.24	37.55	46.64	36.37	89.30	103.72	54.14	81.21	54.26	43.43
2 (QS,H,V)	16.39	24.26	18.99	15.47	21.45	18.64	44.65	56.96	22.50	16.18
3 (TP,M,V)	17.23	28.83	19.34	22.15	40.09	28.13	37.27	37.98	27.43	24.26
4 (TP,H,V)	10.90	16.24	8.79	9.49	17.93	13.03	22.82	13.15	16.30	7.76
5 (TT,M,V)	27.42	42.19	32.00	28.48	35.16	45.00	42.19	31.64	32.00	36.92
6 (TT,H,V)	11.96	13.01	2.50	12.66	16.52	14.42	17.93	21.45	13.71	11.61
7 (QS,M,H)	41.84	45.70	41.49	34.80	59.82	48.52	88.25	72.79	66.45	58.01
8 (QS,H,H)	17.23	12.38	7.39	9.14	11.96	18.77	11.51	11.95	8.09	13.36
9 (TP,M,H)	13.01	16.53	18.63	20.40	26.72	38.67	9.15	14.77	7.15	16.45
10 (TP,H,H)	4.22	6.80	5.99	14.23	9.85	4.59	5.47	10.90	14.07	7.74
11 (TT,M,H)	23.56	20.74	16.17	19.34	24.96	20.76	9.50	20.75	13.71	20.04
12 (TT,H,H)	9.14	8.44	11.25	5.60	9.85	11.26	8.44	11.25	8.44	16.50

Reaction Torque Min. [Nm]

Table 15. Peak reaction torque in negative direction. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	-2.79	-0.49	-4.34	-8.22	-2.58	-3.10	-0.69	-0.59	-3.79	-2.55
2 (QS,H,V)	-1.01	-1.07	-1.32	-1.33	-1.58	-2.03	-0.45	-0.69	-1.32	-1.70
3 (TP,M,V)	-0.91	-1.23	-0.85	-0.96	-0.58	-0.68	-0.81	-0.60	-0.77	-0.80
4 (TP,H,V)	-0.89	-1.60	-1.17	-0.77	-1.78	-1.28	-1.58	-1.35	-1.30	-1.29
5 (TT,M,V)	-1.05	-1.52	-0.77	-0.87	-0.70	-1.56	-1.50	-0.77	-0.73	-0.88
6 (TT,H,V)	-1.44	-1.78	-0.86	-0.73	-1.97	-2.17	-1.64	-1.83	-1.72	-2.15
7 (QS,M,H)	-3.05	-4.08	-1.79	-2.07	-3.44	-2.86	-1.30	-2.75	-3.83	-4.33
8 (QS,H,H)	-0.83	-1.37	-0.93	-0.41	-1.68	-0.92	-1.52	-0.72	-0.53	-1.04
9 (TP,M,H)	-0.80	-1.09	-0.69	-0.70	-1.07	-1.02	-0.79	-0.93	-1.01	-0.64
10 (TP,H,H)	-0.88	-0.87	-0.63	-0.83	-0.77	-0.50	-0.82	-0.77	-0.67	-0.62
11 (TT,M,H)	-1.29	-1.83	-1.21	-0.68	-1.09	-1.30	-0.65	-0.78	-1.15	-1.00
12 (TT,H,H)	-1.21	-0.93	-1.95	-1.69	-1.36	-1.44	-0.87	-1.30	-0.99	-0.98

Reaction Torque Max. [Nm]

Table 16. Peak reaction torque in positive direction. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	6.49	9.88	6.94	4.21	4.34	5.04	4.87	5.29	4.29	5.65
2 (QS,H,V)	2.01	1.55	1.29	1.76	1.47	1.30	3.34	2.76	1.17	1.99
3 (TP,M,V)	5.27	5.19	4.28	4.66	5.05	5.36	3.83	4.94	5.62	4.51
4 (TP,H,V)	3.18	3.40	3.24	3.25	3.22	3.39	3.14	2.43	3.73	2.82
5 (TT,M,V)	1.91	1.32	1.61	1.69	2.01	1.32	0.94	1.75	2.18	1.96
6 (TT,H,V)	1.39	1.83	1.77	1.58	1.04	1.07	0.98	1.75	1.94	1.04
7 (QS,M,H)	7.16	7.39	8.61	5.34	6.71	8.17	7.61	7.30	8.72	8.81
8 (QS,H,H)	2.48	1.57	1.62	2.08	1.68	1.56	0.73	1.38	2.31	2.15
9 (TP,M,H)	4.75	4.69	4.77	4.92	2.88	5.05	3.60	5.38	3.15	4.71
10 (TP,H,H)	2.78	3.79	3.08	3.27	3.69	3.22	3.04	3.94	5.20	3.47
11 (TT,M,H)	2.47	2.02	2.00	1.68	1.75	2.08	1.42	1.99	2.07	2.34
12 (TT,H,H)	2.24	1.62	1.08	1.45	2.04	1.53	1.25	1.53	1.48	1.20

Reaction Torque Range [Nm]

Table 17. Absolute sum of max and min reaction torque. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	9.28	10.37	11.28	12.43	6.92	8.14	5.55	5.89	8.07	8.20
2 (QS,H,V)	3.01	2.62	2.60	3.09	3.06	3.32	3.78	3.44	2.49	3.69
3 (TP,M,V)	6.19	6.42	5.13	5.62	5.64	6.04	4.65	5.55	6.39	5.31
4 (TP,H,V)	4.08	5.00	4.40	4.02	5.00	4.67	4.72	3.78	5.03	4.11
5 (TT,M,V)	2.96	2.84	2.39	2.55	2.72	2.88	2.44	2.52	2.91	2.84
6 (TT,H,V)	2.83	3.61	2.63	2.31	3.01	3.24	2.62	3.58	3.66	3.19
7 (QS,M,H)	10.21	11.47	10.39	7.42	10.15	11.03	8.91	10.05	12.55	13.15
8 (QS,H,H)	3.30	2.95	2.56	2.49	3.36	2.48	2.25	2.11	2.84	3.19
9 (TP,M,H)	5.55	5.79	5.46	5.62	3.95	6.07	4.39	6.30	4.17	5.35
10 (TP,H,H)	3.67	4.67	3.71	4.10	4.46	3.72	3.85	4.71	5.88	4.09
11 (TT,M,H)	3.75	3.85	3.21	2.36	2.85	3.37	2.07	2.77	3.22	3.35
12 (TT,H,H)	3.46	2.55	3.04	3.15	3.40	2.96	2.12	2.83	2.47	2.19

Impulse at joint [Nms]

Table 18. Impulse arising at the joint for the various sets. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	0.66	0.66	0.50	0.40	0.71	0.69	0.62	0.68	0.50	0.39
2 (QS,H,V)	0.11	0.11	0.10	0.09	0.10	0.09	0.33	0.34	0.11	0.10
3 (TP,M,V)	0.41	0.40	0.41	0.38	0.40	0.40	0.40	0.39	0.38	0.38
4 (TP,H,V)	0.36	0.36	0.37	0.17	0.33	0.29	0.33	0.55	0.31	0.48
5 (TT,M,V)	0.17	0.17	0.17	0.16	0.16	0.16	0.16	0.17	0.17	0.16
6 (TT,H,V)	0.07	0.08	0.03	0.07	0.08	0.07	0.07	0.07	0.09	0.08
7 (QS,M,H)	0.52	0.55	0.71	0.68	0.49	0.61	0.75	0.71	0.69	0.60
8 (QS,H,H)	0.11	0.09	0.11	0.10	0.09	0.10	0.09	0.11	0.12	0.10
9 (TP,M,H)	0.41	0.40	0.39	0.38	0.16	0.41	0.41	0.39	0.32	0.47
10 (TP,H,H)	0.25	0.44	0.37	0.31	0.29	0.55	0.26	0.23	0.39	0.21
11 (TT,M,H)	0.15	0.16	0.16	0.15	0.16	0.16	0.16	0.18	0.15	0.16
12 (TT,H,H)	0.08	0.07	0.08	0.03	0.07	0.08	0.07	0.07	0.07	0.10

Impulse at handle [Nms]

Table 19. Impulse arising at the tool handle for the various sets. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	1.12	1.33	1.49	1.00	0.97	1.19	0.62	0.48	1.13	1.25
2 (QS,H,V)	0.39	0.42	0.21	0.15	0.21	0.17	0.34	0.37	0.21	0.22
3 (TP,M,V)	0.53	0.48	0.44	0.46	0.46	0.47	0.33	0.43	0.47	0.44
4 (TP,H,V)	0.35	0.53	0.32	0.20	0.32	0.25	0.27	0.30	0.29	0.48
5 (TT,M,V)	0.43	0.40	0.28	0.25	0.31	0.28	0.18	0.24	0.29	0.31
6 (TT,H,V)	0.27	0.29	0.09	0.12	0.13	0.11	0.11	0.11	0.15	0.14
7 (QS,M,H)	1.00	1.25	1.18	1.49	1.08	1.26	1.11	1.12	1.36	1.45
8 (QS,H,H)	0.31	0.25	0.13	0.21	0.21	0.28	0.11	0.21	0.22	0.33
9 (TP,M,H)	0.55	0.53	0.61	0.50	0.35	0.55	0.18	0.54	0.34	0.61
10 (TP,H,H)	0.32	0.52	0.33	0.35	0.35	0.51	0.25	0.35	0.49	0.38
11 (TT,M,H)	0.35	0.48	0.34	0.29	0.33	0.37	0.24	0.30	0.39	0.40
12 (TT,H,H)	0.18	0.19	0.10	0.12	0.21	0.21	0.18	0.16	0.17	0.15

Work [Joule]

Table 20. Work performed during tightening for each set and test person. Tightening strategy (Quick Step, Tensor Pulse, Turbo Tight), joint stiffness (Medium hard or Hard) and workspace orientation (Vertical or Horizontal) associated with each set is noted next to the set number.

	Test Person Nr.									
Set Nr.	1	2	3	4	5	6	7	8	9	10
1 (QS,M,V)	8.56	8.65	9.92	7.73	13.87	16.28	7.62	13.46	9.52	8.91
2 (QS,H,V)	2.15	2.85	2.15	1.95	2.57	2.15	5.52	8.95	2.83	2.58
3 (TP,M,V)	2.72	3.47	2.62	3.40	4.82	3.52	4.17	4.30	3.58	3.00
4 (TP,H,V)	1.69	2.52	1.15	1.56	1.89	1.61	2.90	1.79	2.27	1.45
5 (TT,M,V)	2.89	4.51	4.07	3.56	4.30	5.52	4.67	3.60	4.29	4.43
6 (TT,H,V)	1.43	1.48	0.63	1.57	2.60	1.77	2.44	2.55	1.93	1.64
7 (QS,M,H)	9.48	7.75	8.56	9.91	10.09	8.76	16.53	14.08	11.99	10.61
8 (QS,H,H)	3.01	1.43	1.10	1.42	1.46	2.05	1.32	1.28	1.44	1.62
9 (TP,M,H)	2.07	1.79	2.34	2.64	2.39	4.69	1.34	2.09	0.93	2.14
10 (TP,H,H)	0.88	1.42	1.25	1.55	1.36	1.35	0.92	1.34	2.01	1.02
11 (TT,M,H)	3.66	2.77	2.17	2.25	2.48	1.97	1.29	2.37	1.81	2.34
12 (TT,H,H)	1.29	1.01	1.38	0.78	0.92	1.76	0.77	1.20	0.55	0.99

Appendix 2 – Body Maps

Body Maps for all 12 sets with gathered results from each participant on each body map.

Each participant is represented by a color as follows:

☐ Test Person 1 ☐ Test Person 2 ☐ Test Person 3 ☐ Test Person 4 ☐ Test Person 5
☐ Test Person 6 ☐ Test Person 7 ☐ Test Person 8 ☐ Test Person 9 ☐ Test Person 10

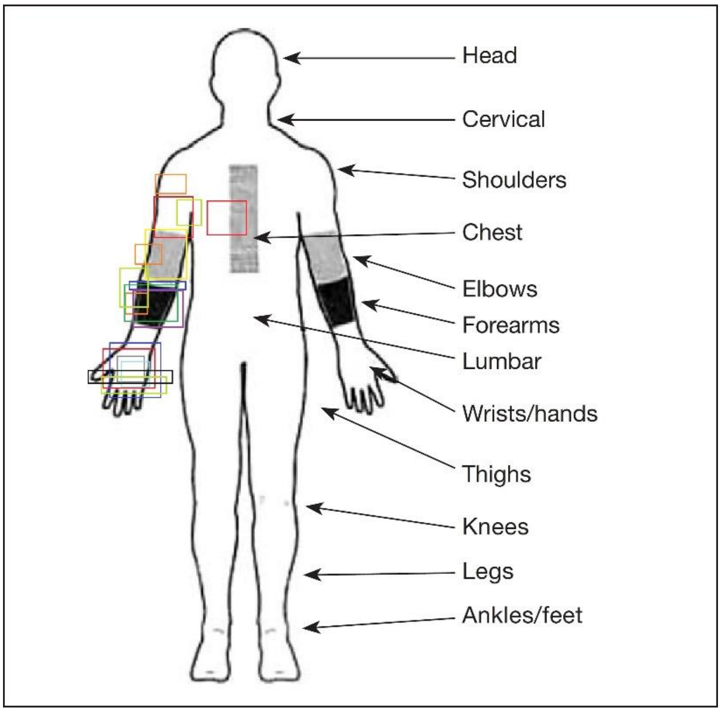


Figure 28. Set nr. 1 (QS,M,V)

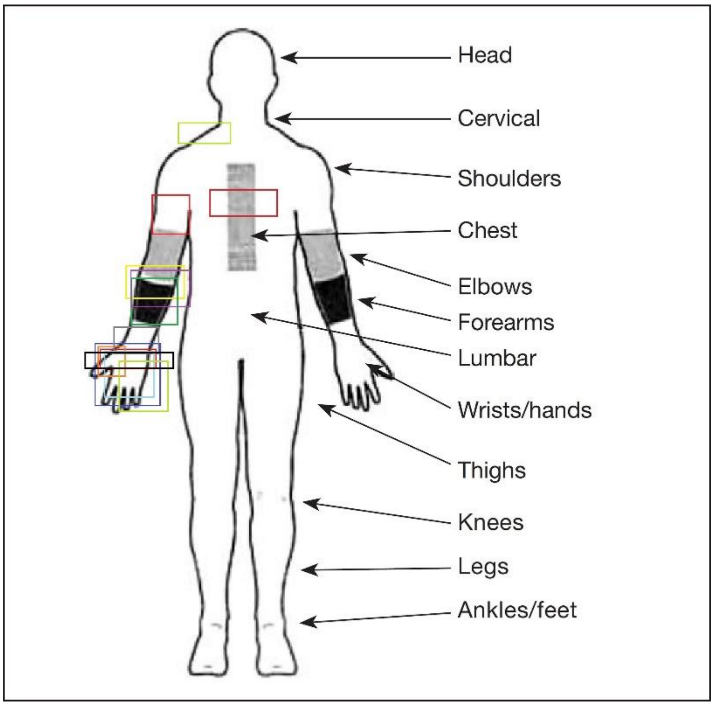


Figure 29. Set nr. 2 (QS,H,V)

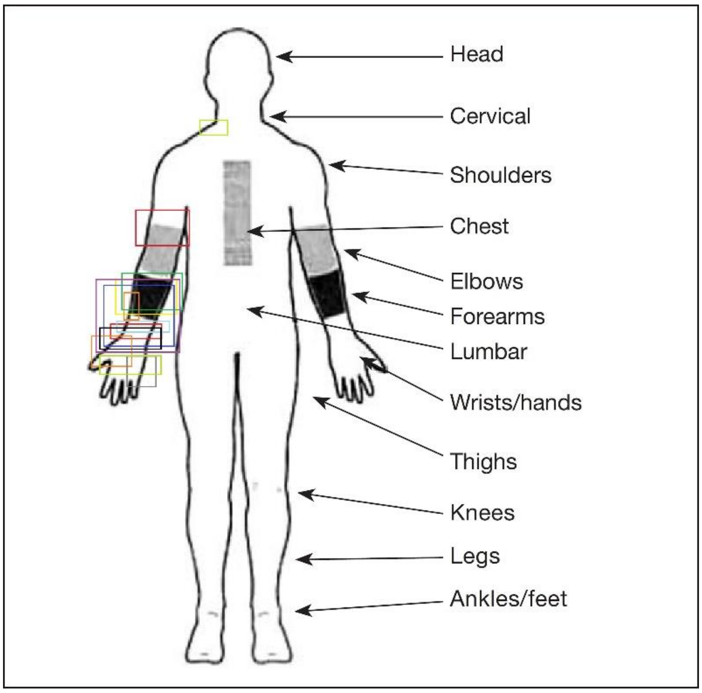


Figure 30. Set nr. 3 (TP,M,V)

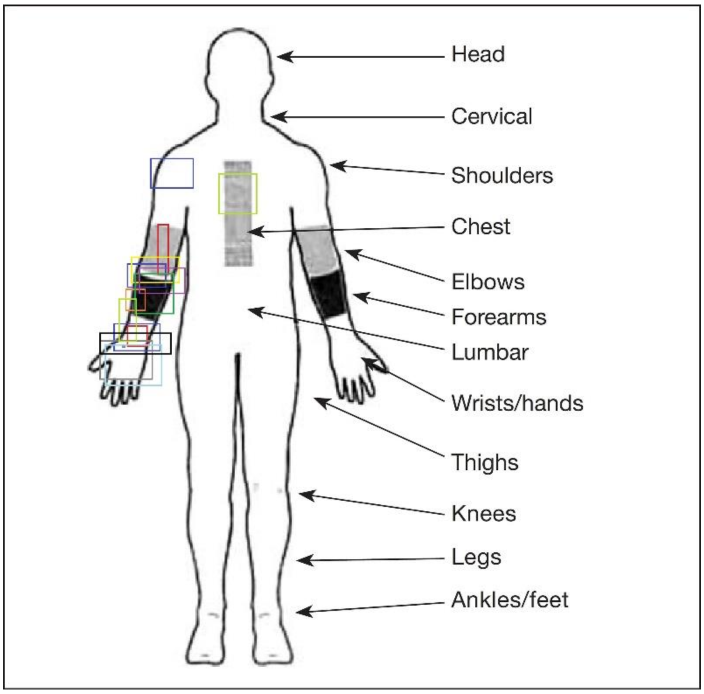


Figure 31. Set nr. 4 (TP,H,V)

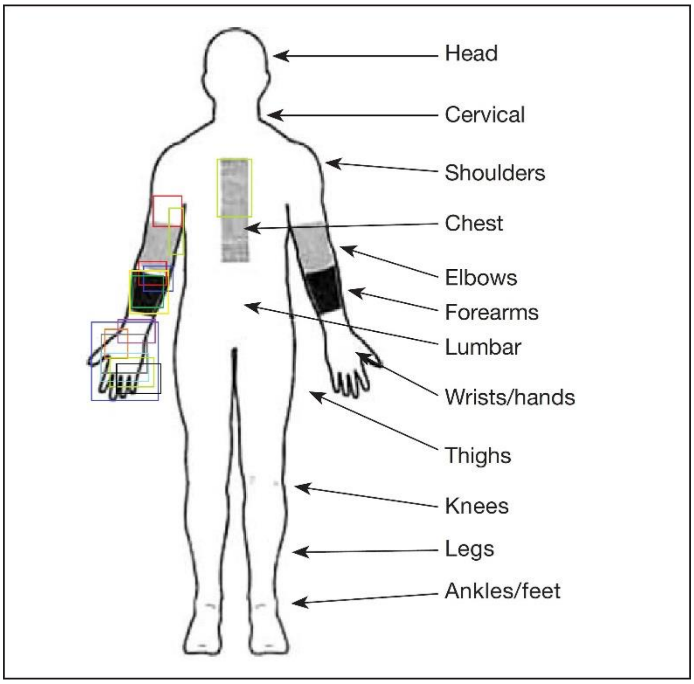


Figure 32. Set nr. 5 (TT,M,V)

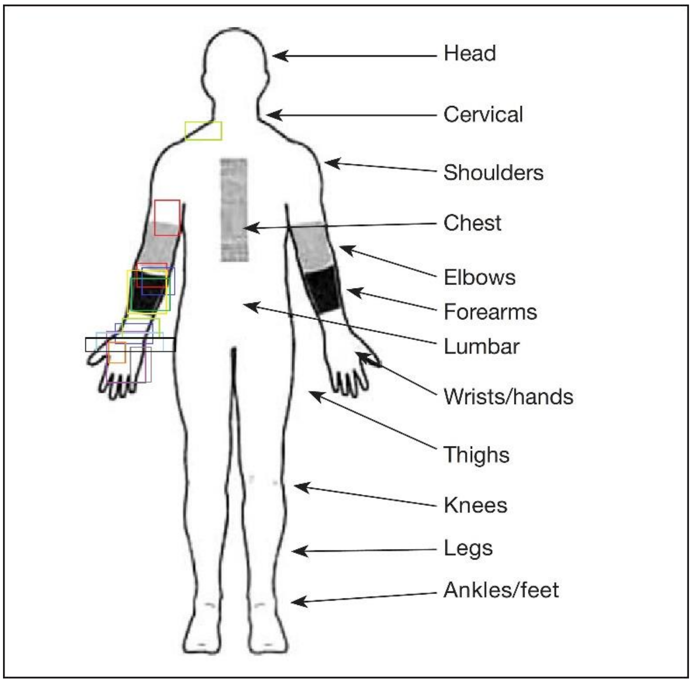


Figure 33. Set nr. 6 (TT,H,V)

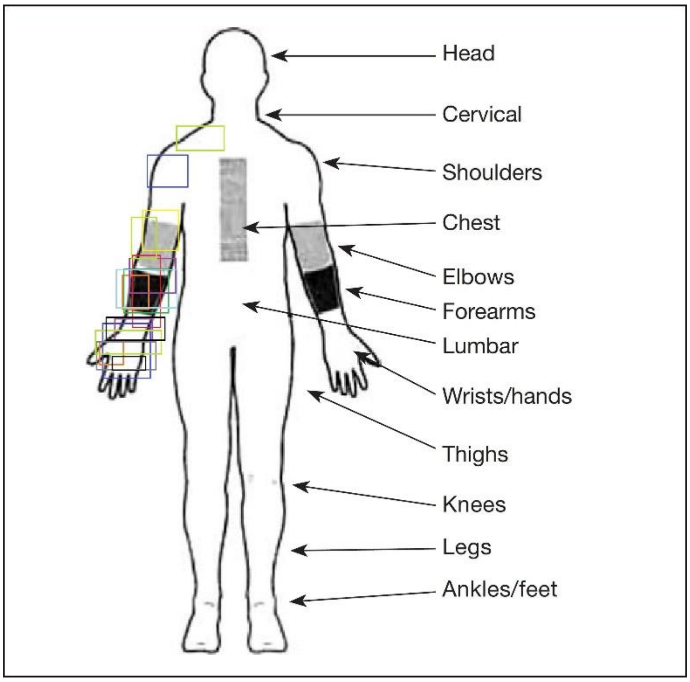


Figure 34. Set nr. 7 (QS,M,H)

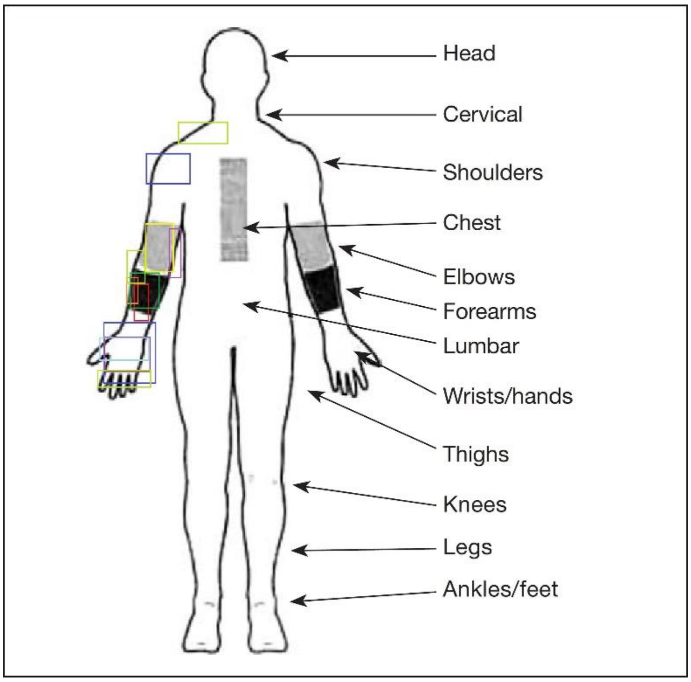


Figure 35. Set nr. 8 (QS,H,H)

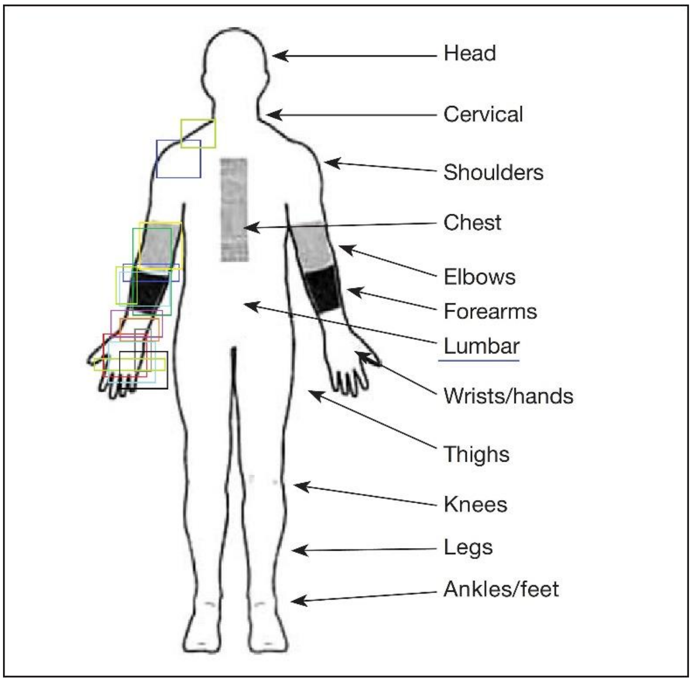


Figure 36. Set nr. 9 (TP,M,H)

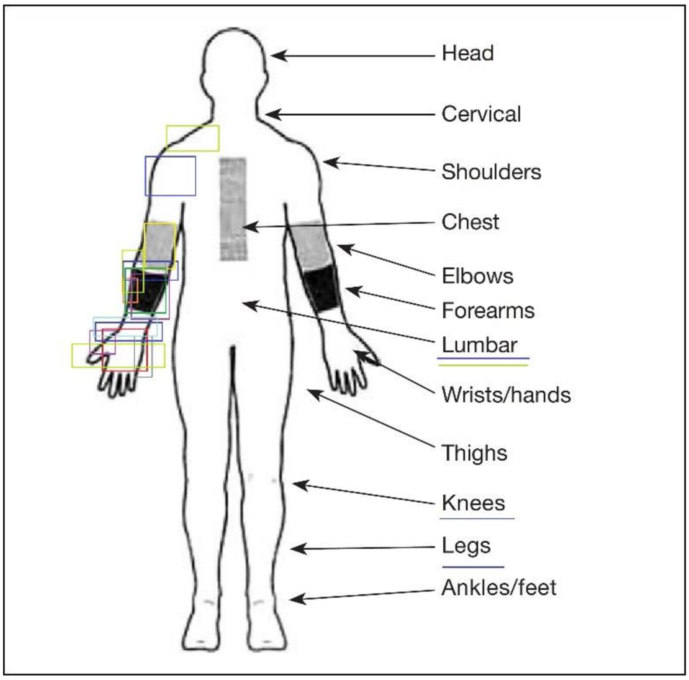


Figure 37. Set nr. 10 (TP,H,H)

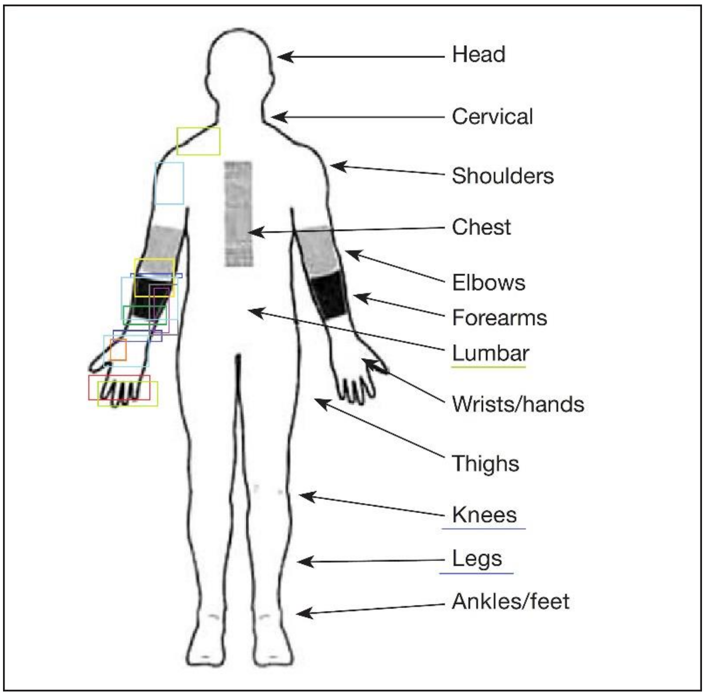


Figure 38. Set nr. 11 (TT,M,H)

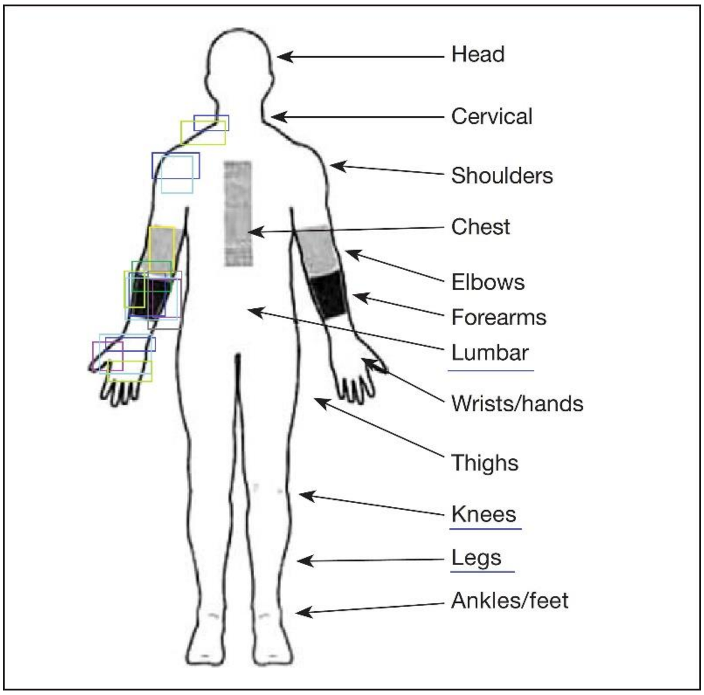


Figure 39. Set nr. 12 (TT,H,H)

Appendix 3 – Informed Consent Form

In order to assess the ergonomic impact as a result of electrical pistol grip power tool use, the undersigned hereby consents to voluntarily participate in the experiments which are a part of a master thesis study.

Explanation of tests:

The test person will perform 6 simulated nut tightenings per minute during 12 minutes with a pistol grip tool. In between each 1-minute set, 2 minutes of rest will be allowed. Each set of tightenings consists of a unique combination of task and tool related parameters. During each set, EMG signals will be collected from the test persons' forearm for measurement of muscle activity. After each set, the test person will be asked to subjectively rate their perceived discomfort on a 1 to 10 scale as well as pointing out the location of perceived discomfort on a body map.

Purpose of research:

The results from the study is intended to provide a guidance on which combination of tool and task related parameters that has the least negative impact on the user from an ergonomic point of view.

Potential risks:

The nature of the experiments may lead to moderate discomfort in the wrist joints as well as muscle fatigue in the hand/arm system due to the occurrence of reaction forces and prolonged tool use.

Withdrawal of participation:

The test person is allowed to at any time of the study withdraw her/his consent and terminate her/his participation without prejudice.

______________________________	______________________________
Test Persons' Signature	*Researchers' Signature*
______________________________	
Date	

Appendix 4 – MATLAB Script

The following MATLAB script was run on all individual tightenings and provided handle deflection angle (min, max and range), reaction torque (min, max and range), impulse (at joint and handle), and the work exerted.

```
clc;
close all;


%%Tigtening Angle

figure(1)
plot(Data1_time_Formula_27_AngleTigh,Data1_Formula_27_AngleTightenin -
Data1_Formula_27_AngleTightenin(1,1)) %offset to start at origin
title('Tightening Angle')
xlabel('Time')
ylabel('Angle [degrees]')

ax = gca;
ax.XAxisLocation = 'origin';
ax.YAxisLocation = 'origin';

% %Torque at joint
figure(2)
plot(Data1_time_Inline_torque,Data1_Inline_torque -
Data1_Inline_torque(1,1)) %offset to start at origin
title('Torque at joint')
xlabel('Time [s]')
ylabel('Torque [Nm]')

ax = gca;
ax.XAxisLocation = 'origin';
ax.YAxisLocation = 'origin';

%Snug, 2 Nm, lower limit for integration
snug1_index = find(Data1_Inline_torque - Data1_Inline_torque(1,1) >
2,1,'first');

%The time at which snug initiates
SnugTime1=Data1_time_IIR_filter_51_Reacti(snug1_index);

%0.8 sec after snug, upper limit for integration
snugPlus1_index1 =
find(Data1_time_IIR_filter_51_Reacti>SnugTime1+0.8,1,'first');

%Impulse at joint
joint_impulse1 =
trapz(Data1_time_Inline_torque(snug1_index:snugPlus1_index1),abs(Data1
```

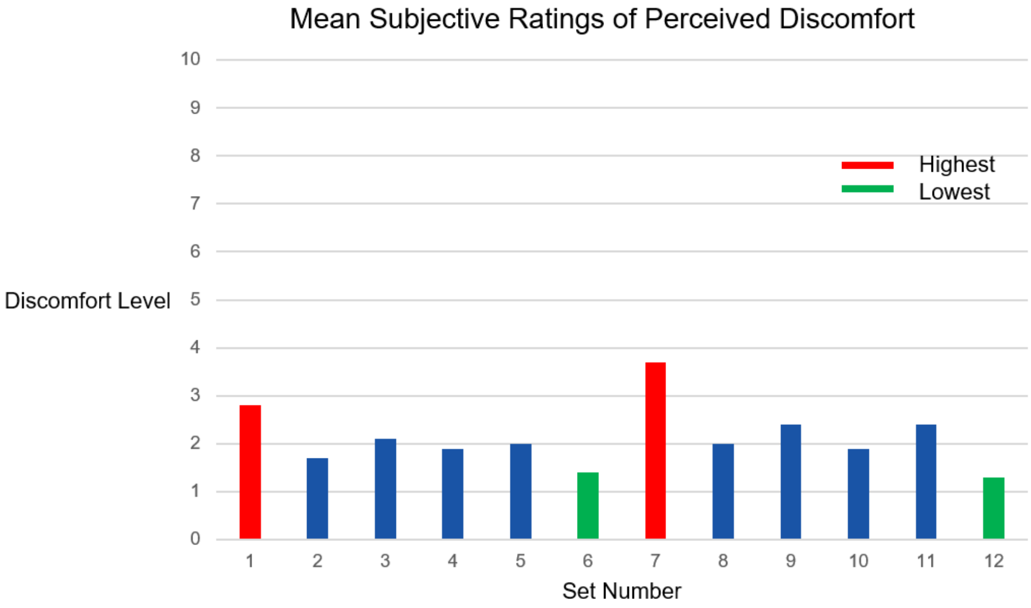
```
_Inline_torque(snug1_index:snugPlus1_index1) -
Data1_Inline_torque(1,1)));

%Reaction Angle
figure(3)
plot(Data1_time_ReactionAngle , Data1_ReactionAngle -
Data1_ReactionAngle(1,1))  %offset to start at origin

title('Handle Deflection')
xlabel('Time [s]')
ylabel('Angle [degrees]')

ax = gca;
ax.XAxisLocation = 'origin';
ax.YAxisLocation = 'origin';

maxReactionAngle1 =
max(Data1_ReactionAngle(snug1_index:snugPlus1_index1) -
Data1_ReactionAngle(1,1));
minReactionAngle1 =
min(Data1_ReactionAngle(snug1_index:snugPlus1_index1) -
Data1_ReactionAngle(1,1));
rangeReactionAngle1 = maxReactionAngle1 + abs(minReactionAngle1);

%Reaction Torque
figure(4)
plot(Data1_time_IIR_filter_51_Reacti , Data1_IIR_filter_51_Reaction_To
- Data1_IIR_filter_51_Reaction_To(1,1))  %offset to start at origin

title('Reaction Torque')
xlabel('Time [s]')
ylabel('Torque [Nm]')

ax = gca;
ax.XAxisLocation = 'origin';
ax.YAxisLocation = 'origin';

maxReactionTorque1 =
max(Data1_IIR_filter_51_Reaction_To(snug1_index:snugPlus1_index1) -
Data1_IIR_filter_51_Reaction_To(1,1));

minReactionTorque1 =
min(Data1_IIR_filter_51_Reaction_To(snug1_index:snugPlus1_index1) -
Data1_IIR_filter_51_Reaction_To(1,1));

rangeReactionTorque1 = maxReactionTorque1 + abs(minReactionTorque1);

%Impulse at handle
reaction_impulse1 =
trapz(Data1_time_IIR_filter_51_Reacti(snug1_index:snugPlus1_index1) ,
abs(Data1_IIR_filter_51_Reaction_To(snug1_index:snugPlus1_index1) -
Data1_IIR_filter_51_Reaction_To(1,1)));
```

```
%%Reaction Power
figure(5)
plot(Data1_time_ReactionPower , Data1_ReactionPower
Data1_ReactionPower(1,1))

title('Reaction Power')
xlabel('Time [s]')
ylabel('Power [Watt]')

ax = gca;
ax.XAxisLocation = 'origin';
ax.YAxisLocation = 'origin';

work1 = trapz(Data1_time_ReactionPower(snug1_index:snugPlus1_index1) ,
abs(Data1_ReactionPower(snug1_index:snugPlus1_index1) -
Data1_ReactionPower(1,1)));

%Table with all output parameters
Table1 = table(minReactionAngle1, maxReactionAngle1,
rangeReactionAngle1,minReactionTorque1, maxReactionTorque1,
rangeReactionTorque1,reaction_impulse1, joint_impulse1,work1)
```

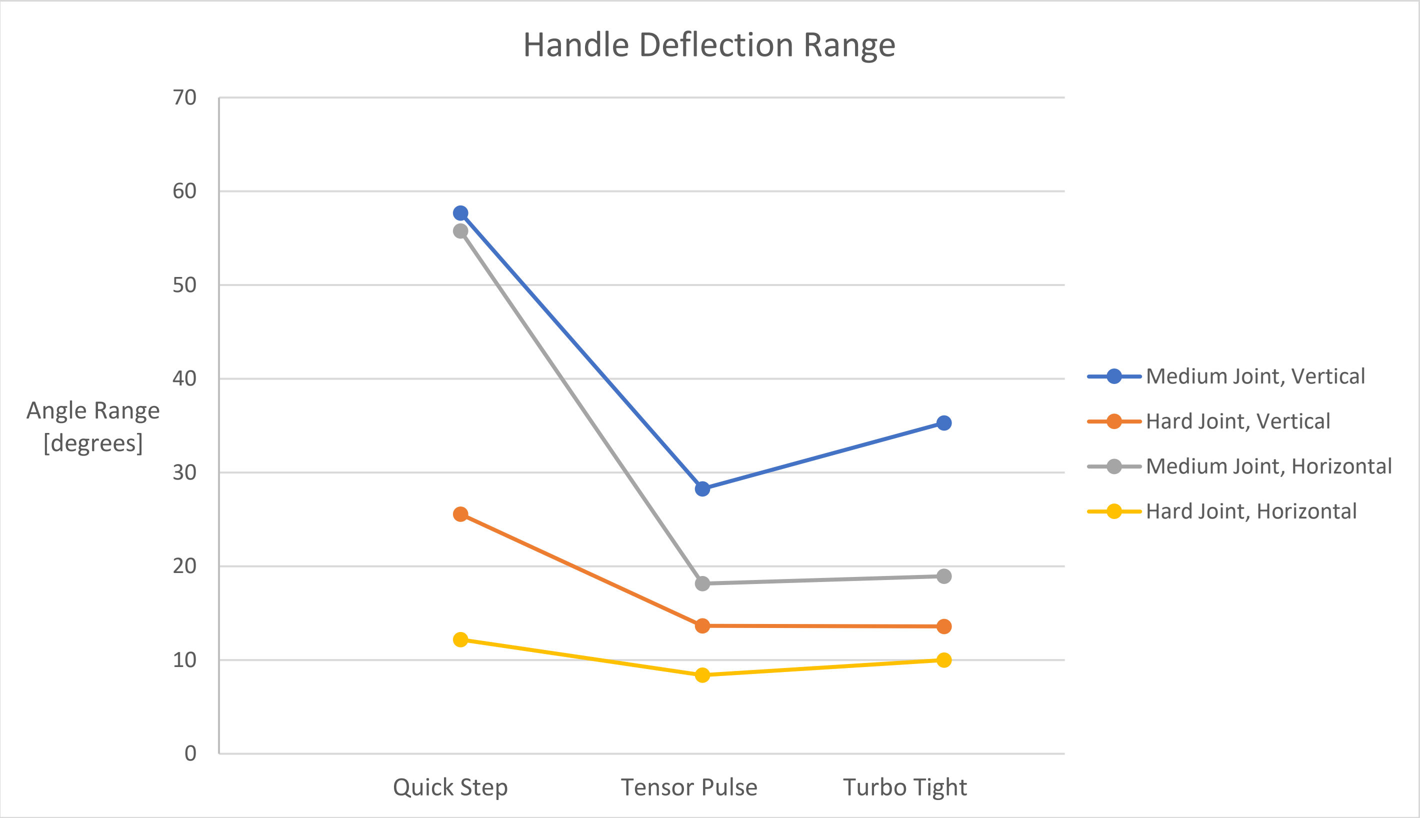
Appendix 5 – EMG values

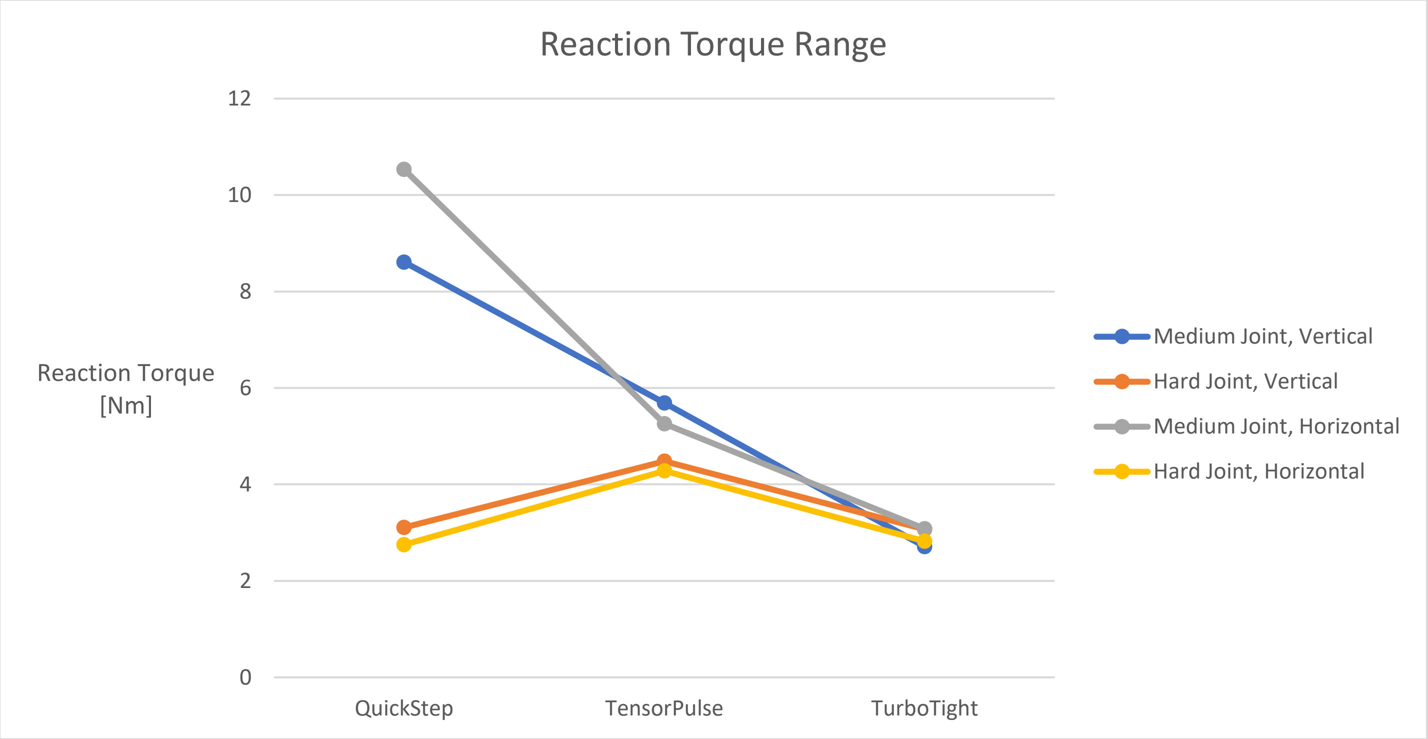
Tightening Strategy	Joint Stiffness	EMG Amplitude [µV]
Quick Step	Medium Hard	188 µV
Quick Step	Hard	164 µV
Tensor Pulse	Medium Hard	162 µV
Tensor Pulse	Hard	**196 µV**
Turbo Tight	Medium Hard	137 µV
Turbo Tight	Hard	**102 µV**

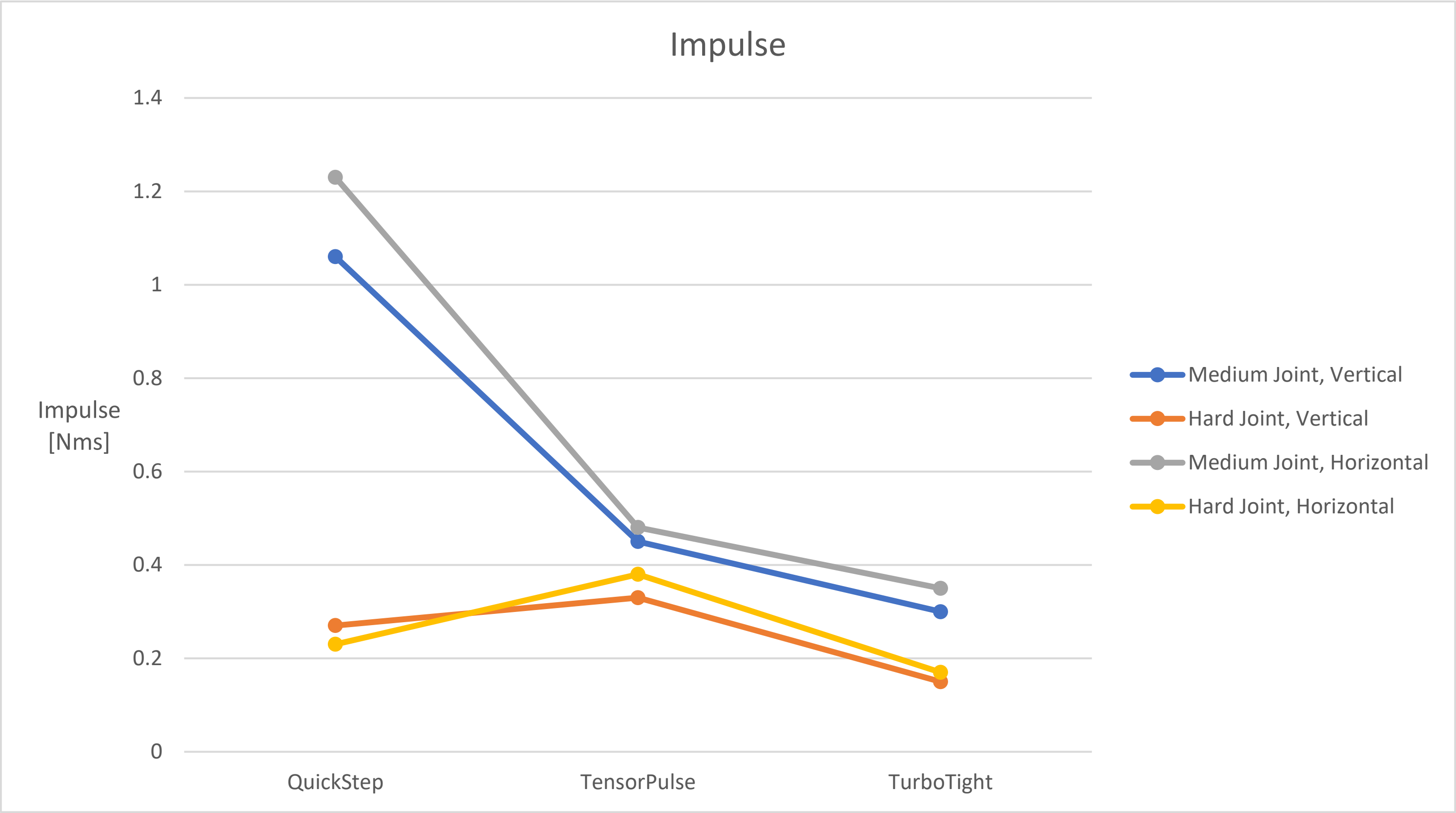
Appendix 6 – Subjective Ratings of Discomfort



Appendix 7 – Graphs of Handle Angle, Reaction Torque & Impulse






Impulse
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Impulse [Nms]
QuickStep
TensorPulse
TurboTight
Medium Joint, Vertical
Hard Joint, Vertical
Medium Joint, Horizontal
Hard Joint, Horizontal

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