The Effect of Underground Mining Footwear on Lower Limb Gait Characteristics and Perceived Comfort

by

Corey Bouwmeester

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Faculty of Graduate Studies
Laurentian University
Sudbury, Ontario, Canada

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List of Abbreviations

GRF	**Ground reaction force**
ROM	**Range of motion**
STF	**Slips, trips, and falls**

1 Introduction

For the mining sector, safety is a top priority to keep workers free from injuries, and one of the last lines of defense for these workers is the use of personal protective equipment (PPE). A key piece of the PPE used in underground mining is the safety footwear that workers wear to protect their feet, to provide steady footing underground, and to prevent their feet from getting wet. Unfortunately, the use of underground mining boots may alter a worker's gait and may increase the risk of slips, trips, and falls (STF) in the workplace. In the Ontario Mining Sector, falls accounted for 10-16% of reported lost-time injury/illness claims from 2016-2019, and resulted in an average of 15 lost-time claims per year across that time frame (Workplace Safety North, 2019; Workplace Safety North, 2018; Workplace Safety North, 2017; Workplace Safety North, 2016). As reported by Workplace Safety North (2019), the bodily reaction and exertion injuries include those injuries caused by the adverse reactions that can occur to a person's body when a trip or slip occurs but does not result in a complete fall. The bodily reaction and exertion category has been the highest reported percentage of injuries for the Ontario Mining Sector as reported by Workplace Safety North from at least 2016-2019 and of these injuries reported a portion of them are likely the result of a STF injury (Workplace Safety North, 2019; Workplace Safety North, 2018; Workplace Safety North, 2017; Workplace Safety North, 2016). STF risk is present in all industrial settings but the risk is heightened in the underground mining environment due to the low light levels and rough terrain that can include sloped, uneven, and wet surfaces (Cappellini et al., 2010; Lay et al., 2007; Wade et al., 2014). In addition to the risk of STF from the environment, underground miners are required to wear several pieces of personal protective equipment (PPE) to protect them from hazards they are exposed to on a daily basis. In terms of PPE, the specialized rubber work boot, commonly referred to as a ‘mucker’, has a metatarsal guard to prevent crush injuries to the foot and toes and a tough bottom sole to prevent punctures to the bottom of foot. However, anecdotal evidence suggests that the current design of the mucker (heavy, stiff shaft, limited ankle support, and sole inflexibility) may contribute to adverse changes in worker gait and increase risk of STF injuries (Bohm & Hosl, 2010; Chander et al., 2014; Chiou et al., 2012; Cikajlo & Matjacic, 2007; Dobson et al., 2015). There remains a lack of research focused on the effect that underground mining footwear has on worker gait characteristics and perceived comfort.

The aim of this study was to determine the impact of three commonly used underground mining boots on comfort and gait characteristics when compared to a control condition. Finding the footwear that least impacts gait characteristics should aid in limiting worker exposure to STF and injury risk. To accomplish this objective, this major paper begins with a literature review (Section 2) of STF risks in mining, gait characteristics and the influence of work boot factors on gait and comfort. In Section 3 laboratory methods used to evaluate gait and perceived comfort when wearing mining boots are presented and findings are shared in Section 4. Further discussion on relevance of this work to underground miners, work boot manufacturers, and health and safety practitioners is presented in Section 5 along with recommendations for future research and knowledge dissemination.

2 Literature Review

2.1 Underground Mining

Underground hard rock mines typically consist of a number of adits (horizontal tunnels) and shafts (vertical tunnels) that are excavated to extract ore from underground. Underground miners often walk long distances during their work-shift while performing duties such as drilling, blasting, and excavating to remove ore from underground. Common hazards in underground mines include overhead rock, high moisture levels, lack of natural lighting, stagnant air, hot working conditions, and uneven terrain (Kenny et al., 2012; McPhee, 2004). The underground mining industry attempts to control these workplace hazards by implementing technology and safety mechanisms, including: controlling the moisture levels by pumping out water pools when present, introducing light sources on every individual and piece of equipment in the mine, and venting air down into the mine corridors for air circulation and to assist in controlling temperature levels (McPhee, 2004).

Even though some conditions in underground mines can be managed, the terrain is a much harder factor to control because of constant heavy equipment movement over the terrain, pooling water, and continuous blasting and hauling of materials (Kenny et al., 2012; McPhee, 2004). Terrain in underground mines is often sloped, uneven, has stones and debris underfoot, and can be slippery, making walking precarious (Cappellini et al., 2010; Lay et al., 2007; Wade et al., 2014). In addition to traversing the difficult terrain, workers must do so with limited illumination, being cautious of nearby heavy equipment, and under the effects of mental and physical workloads (Brooke-Wavell et al., 2002; Chang et al., 2016; Fan & Smith, 2017; Wickwire et al.,2017).

2.2 Slips, Trips, and Falls

Slips, trips, and falls (STF) risk in underground mining is elevated due to poor environmental conditions (Kenny et al., 2012; McPhee, 2004). The factors that place workers at an increased risk of STF include locomotion and job duties under circumstances such as: a) fatigue (Fan & Smith, 2017; Wickwire et al.,2017), b) wet, uneven, and sloped walking surfaces (Cappellini et al., 2010; Lay et al., 2007; Wade et al., 2014), c) low light conditions (Brooke-Wavell et al., 2002; Chang et al., 2016), and d) cumbersome personal protective equipment (PPE) (Park et al., 2015; Schulze et al., 2014; Taylor et al., 2012).

2.2.1 Workplace Fatigue

Fatigue in the workplace has been linked with alertness, work-life balance, physiological factors (Fan & Smith, 2017), performance (Fan & Smith, 2017; Wickwire et al., 2017) and cognitive factors (Fan & Smith, 2017; Legault et al., 2017; Wickwire et al., 2017). Worker fatigue is highly dependent on multiple risk factors including: workload, job type, noise and vibration, low job control and support, unhealthy lifestyles, negative personalities (Fan & Smith, 2017), and shift-work (Fan & Smith, 2017; Legault et al, 2017; Wickwire et al., 2017). In addition to performance issues, fatigue in the workplace has been shown to increase accidents and errors (Fan & Smith, 2017; Wickwire et al., 2017). Due to the variability in the required job tasks for an underground miner, it is difficult to determine how fatigue impacts individuals specifically and might contribute to an increased risk of STF. However, by looking at the workplace factors that cause fatigue and those factors present for underground miners, it is reasonable to assume that there may be high levels of fatigue in this population.

2.2.2 Environmental Conditions

Walking surfaces that are uneven, sloped, and made from shifting materials put workers at risk of STF due to challenging their balance and adaptive muscular reflexes (Lay et al., 2007; Wade et al., 2014). Two studies performed by Alexander and Schwameder (2016a; 2016b) determined that compression forces are increased in the lower limb because of greater forces at the joint and by the increased use of musculature when walking on sloped surfaces. The increase in muscular and joint forces are a counter measure to maintain adequate gait movement but may result in further muscular fatigue and increased risk of lower limb injury (Alexander & Schwameder, 2016a; Alexander & Schwameder, 2016b). A similar pattern is observed when walking on slippery terrain, such as when water settles on stones or in puddles in an underground mine, the worker must incorporate adaptive balance and motor pattern techniques to maintain proper balance and locomotion, recruiting additional muscles and increasing the risk for fatigue and thus injury (Cappellini et al., 2010).

Underground miners are not only exposed to precarious terrain, they often work in conditions with high temperatures, increased humidity, (Donoghue, Sinclair, & Bates, 2000; Maurya et al., 2015a) and poor air quality (Dontala et al., 2015). There are many factors that influence the temperature inside of a mine with the two most prominent being geothermal gradient and auto compression or ventilated air (Donoghue, Sinclair, & Bates, 2000; Maurya et al., 2015a). This increase in temperature in a mine often places underground miners at risk of heat stress and exhaustion, with the incidence increasing as the depth of the mine increases (Donoghue, Sinclair, & Bates, 2000; Maurya et al., 2015a). It has been shown that heat stress reduces productivity and efficiency during work (Maurya et al., 2015b) and leads to fatigue and unhealthy physiological outcomes in workers (Donoghue, Sinclair, & Bates, 2000; Maurya et al., 2015b).

2.2.3 **Lighting**

Low light conditions hinder worker line of sight to walking surfaces and obstacles. The low light conditions present in underground mines can therefore result in reduced obstacle clearance and avoidance and increase postural sway when navigating uneven terrain (Brooke-Wavell et al., 2002; Chang et al., 2016). To increase the light levels that workers are exposed to when working and navigating underground, individuals wear a cap lamp on their safety headwear. This allows illumination to where the worker's head is pointing, although in some cases this may not be directed toward the terrain they are walking on and so obstacle clearance and avoidance still becomes a problem. When using a cap lamp on a helmet Sammarco (2012) found that the type of light that the lamp provided did not change balance measures of participants but when moving from a laboratory to an underground environment they found decreases to participant's balance. Even with the use of lights attached directly to the individual, underground miners are at increased risk of STF and other loss of balance injuries because of the lighting conditions.

2.2.4 **Personal Protective Equipment**

Personal protective equipment (PPE) keeps the worker safe from specific aspects of the working environment; however, it can decrease worker mobility and range of motion (ROM) (Park et al., 2015; Schulze et al., 2014; Taylor et al., 2012). Underground mining PPE includes but is not limited to a helmet with mounted light, reflective coveralls, metatarsal guard footwear, cut resistant gloves, eye protection, hearing protection, and communication devices. Industrial footwear specifically has been reported to alter gait and lower limb motion (Park et al., 2015; Schulze et al., 2014). Furthermore, in 2012, Taylor et al., found that footwear had a larger impact on a firefighter's physiological workload when compared to other pieces of their PPE. When considering similarities between industrial footwear and firefighting footwear it can be hypothesized that the footwear donned by underground miners would also affect worker gait.

2.3 **Gait Characteristics**

Gait is the motion of locomotion, for humans this constitutes walking and running locomotion. Gait is comprised of many different characteristics from stride length to impact forces, and measuring these factors requires many different techniques. The common way of reporting if a condition or circumstance affects gait is to determine if specific characteristics of gait are impacted. The differences in gait can either be found by comparing an individual to a population norm, to determine how the condition affects them or by comparing the individual under a condition to themselves during a control. Reporting changes or adaptations to gait can be performed by using spatiotemporal, kinematic, kinetic, and subjective variables. Using a combination or variety of the variables encompassed by the categories above allows for a larger view of the effect that different factors can have on human locomotion and any potential short and long-term impacts of the condition.

2.3.1 **Spatiotemporal**

Spatiotemporal measures are used to describe the timing associated with a specific motion, in this case walking locomotion. Spatiotemporal measures are reported as being the easiest gait analysis measures to repeat at a high level of reliability because of the gross nature of the measurement, be it either just distance or time (Benedetti et al., 2013; Meldrum et al., 2014). The common spatiotemporal variables associated with gait are walking velocity, step and stride lengths, and time spent in stance and swing phases. The spatiotemporal variables allow for a description of how an individual is progressing through a series of gait cycles or motions, the implications for their comfort and injury risk, as well as a comparison to a reference norm.

2.3.2 **Kinematics**

Kinematic variables of gait involve the measurement of the motion itself, using accelerometers, goniometers, and/or motion recording devices like video cameras. A database of normal population kinematic data has been reported in the past by Borghese (1996) and Kadaba (1989) and more recently studies have been performed to determine the inter-laboratory and inter-rater differences between kinematic gait analysis data (Benedetti et al., 2013; Meldrum et al., 2014; Wilken et al., 2012). Measuring of a normal population has shown that there are similar patterns that exist across individuals for kinematics of the lower limb even though movement patterns may vary at the individual level. Additionally, changing certain parameters of the gait movements, such as speed, gait phase timing, or external factors, can cause changes to this normal gait pattern (Borghese et al., 1996; Kadaba et al., 1989; Winter 1984). The more recent studies have found that slower and more repeatable gait movements, like a normal walking gait, can show reproducibility for kinematic gait measures to a high level of reliability and repeatability even for inter-rater reliability (Benedetti et al., 2013; Meldrum et al., 2014; Wilken et al., 2012). **Figure 1** shows the results from the study performed by Benedetti (2013), which compared seven different average joint angles from seven different laboratories illustrating a common profile. Kinematic variables include measures such as: segment or joint positions, angles, velocities, and accelerations. The major variables reported for determining condition effects on normal gait are:

1) Hip, Knee, and Ankle Joint Angles – A description of how each of the lower limb joints are moving and the ROM required at the joint to maintain normal gait patterns.

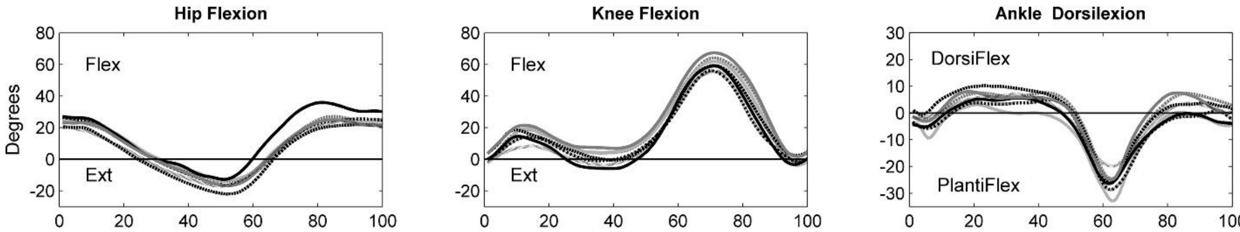

Figure 1: Walking Gait Joint Angles
Joint angles of the hip, knee, and ankle joints through a gait cycle, time is represented as a percent of the gait cycle. Data taken from 7 different laboratories. Adapted from Benedetti et al., 2013.

2.3.3 Kinetics

Kinetic variables of gait involve the measurement of the forces used to create or manipulate the motion. Kinetic variables include internal and external forces, moments, and impulses. Normal population force profiles have been reported by Kadaba and colleagues (1989) and Winter (1984) which have shown that although force patterns are variable dependent on the participant and speed of the gait there is still an underlying pattern that holds true in the normal population. Further analysis of the consistency and reliability of continued kinetic measures has shown that forces pertaining to gait are the most consistent of all kinetic measures. However, it has been noted that these measures possess less repeatability than either kinematic and spatiotemporal measures because of the highly variable way in which an individual can use force to create a similar motion (Benedetti et al., 2013; Meldrum et al., 2014; Riley et al., 2007; Wilken et al., 2012). An example of a force profile from a normal population during walking is shown in **Figure 2**, illustrating an underlying pattern that varies in magnitude and is dependent on participant. Common kinetic variables used to analyze and describe gait are:

1) Impact force - The amount of force measured during the initial contact phase of gait. Related to the heel contact velocity for walking gait.

2) Push-off force - The amount of force used to propel the subject in the direction of movement. Usually occurs during toe push-off in walking gait.
3) Force profile – A general overview of the total force pattern associated with a gait movement. This measure is usually reported as a single or double step pattern of the foot or feet in the stance phase of gait. Specific profiles are associated with different types of gait as the ground reaction forces change when we modify our movement pattern (Riley et al., 2007).

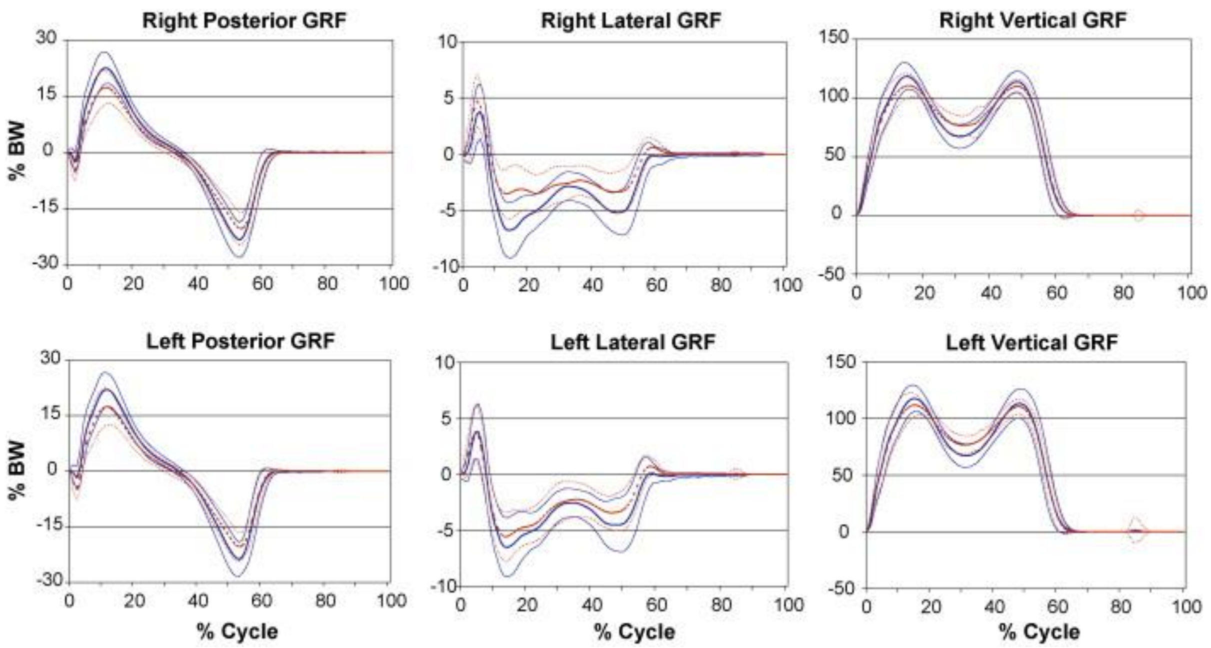

Figure 2: Normal, Healthy Population Force Profiles.
Example of normal population force profiles, the x axes are reported as a percent of the gait cycle and the y axis is reported as a percent of the body weight (%BW) of the participant broken down into right and left steps. GRF = ground reaction force. The focus of the image is on the pattern of the profiles. Adapted from Riley et al., 2007

2.3.4 **Subjective Comfort**

Participants can be asked to rate their comfort when using a device, during an experimental condition, or when performing an activity. Often reported using Likert scales of varying degrees, comfort ratings help determine whether a participant prefers one condition over another, would be willing to participate again, or aid in determining a best practice. Subjective measures allow the representation of an individual's perceived comfort score and when measured over a group they may be able to show trends in general preference towards an option. Subjective comfort and preference scores have been used in measuring underground mining populations on varying topics because they require the administration of a survey or questionnaire that can be easily implemented (Dobson et al., 2018; Dobson et al., 2017b; Sherrington et al., 2020). A study performed on underground coal miners looking at the comfort and pain ratings between the traditional "mucker"/"gumboot" style of mining footwear as opposed to the leather lace-up style found that workers reported higher comfort and support in the leather lace-up boot (Dobson et al., 2017b). Additionally, Dobson and colleagues (2018) also looked into footwear factors that coal miners perceived to be lacking in their footwear, and resultant data demonstrated that in addition to having wet feet, workers wanted improvements in ankle support, fit of the boot to their foot, and improvements in ventilation within the boot.

Overall, a combination of direct and subjective measurement systems can be utilized to gauge the comfort of footwear and influence on a person's gait pattern. Commonly measured characteristics include step and stride lengths, gait cycle timing, force profiles, peak forces, and comfort or pain ratings. Ideally, a combination of these measures can be used to gather the cumulative effect that the footwear creates on the wearer.

2.4 **Footwear Factors that Influence Gait and Comfort**

The footwear that underground mine workers in Ontario wear must adhere to the requirements of the Canadian Standards Association - CAN/CSA-Z195-14 Protective Footwear. The footwear requires sole puncture protection to prevent punctures to the foot and toes from the underside of the footwear and a Grade 1 metatarsal guard to prevent crush injuries to the foot and toes. Underground mining footwear is also designed to provide water resistance and in most cases the boot level is above the ankle to a mid-shaft level. Of the footwear available to the underground mining community there are three major types: an above ankle leather lace-up boot, a mid-shank leather lace-up boot, and a mid-shank rubber slip on boot. All three of these boot types meet the safety standards stated above but vary in factors such as: weight, shaft height, stiffness of the shaft, the footwear material, the material and flexibility of the sole, the tread design, and the mechanism by which the footwear binds to the user (laces versus slip on). For workers who spend most of their time working underground they lean towards the mid-shank high rubber boot, given their ability to prevent water getting into the boot, however, this may change in the coming years as the water-resistant properties of leather boots are becoming more prevalent (Dobson et al., 2017).

Footwear used by firefighters, military personnel, construction workers and industrial workers share similar characteristics to those used by underground mine workers. Previous research has found that the factors present in footwear used in these sectors have detrimental effects on worker locomotion, lower limb ROM, and worker comfort (Dobson et al., 2017). The influential footwear factors are the footwear material and binding type (Dobson et al., 2015; Schulze et al., 2014; Tian et al., 2015), mass (Chander et al., 2014; Chiou et al., 2012; Garner et al., 2013; Taylor et al., 2012; Turner et al., 2010), shaft height (Chander et al., 2014; Nunns et al., 2012;

Park et al., 2015; Yang et al., 2015), shaft stiffness (Bohm & Hosl, 2010; Cikajlo & Matjacic, 2007), and sole flexibility (Chiou et al, 2012; Lin et al., 2007).

2.4.1 Material and Binding Type

In industrial settings, most boots are leather with some form of metatarsal guard to prevent crush injuries to the foot and toes. Contrary to other industries, in the underground mining industry the footwear is often made of rubber to add a water-resistant characteristic. Moreover, footwear used in underground mines commonly rise to the level of the mid-shank to prevent water and debris from entering through the top of the footwear in addition to protecting impacts to the shank. Some research has been conducted to determine if there is a difference between the type of boot material and the effect on workers.

A study comparing combat boots, athletic shoes, and dress shoes found that there was an increase in stride length and decrease in ankle ROM for the combat boot compared to the other conditions (Schulze et al., 2014). This study failed to report the differences in all the characteristics of the footwear, so it remains unclear if the differences in ROM for the combat boot were due to material, weight, shaft height, or design (Schulze et al., 2014). Similarly, heavier, and stiffer oil rig work boots were found to increase ground reaction forces and time spent in stance phase when compared to a typical running shoe (Tian et al., 2015). Turner and colleagues (2010) examined boot characteristics within a firefighting population and found that there was no effect on metabolic and respiratory measures during a walking task from boot material when comparing leather to rubber boots. However, lower limb muscle activity was found to be higher with a leather lace-up boot when compared to a rubber slip-on (Dobson et al., 2015). Furthermore, the leather boot characteristic that caused the increase in muscle activity could not be distinguished from the difference of weight, shaft height, binding type, or footwear material (Dobson et al., 2015).

Another measure that is overlooked regarding footwear design and preference is that of subjective user comfort. How the wearer perceives the comfort of the footwear when they are using it has strong implications for how they will use the footwear and the potential for short and long-term pain and discomfort. Dobson and colleagues (2017) looked specifically at the boot type and how it impacted work habits, pain, and comfort for underground coal miners. The study found that there was no significant difference between the leather lace-up and gumboot (high rubber slip-on boot) in terms of reported pain and foot problems but the gumboot wearers were more likely to report their work boot fit and comfort were lower than those of the leather boot wearers.

2.4.2 **Footwear Mass**

Footwear mass is one of the variables most often reported to be the cause of footwear dependent differences in research findings. The mass of footwear has been shown to have effects on muscle activity, oxygen consumption (Frederick, 1984; Hanson, 2011; Perl, 2012), and gait characteristics (Divert, 2008). The mass of the footwear is dictated by the material that the footwear is constructed of, the design and material of the toecap, and the height and shape of the footwear. In a study by Turner and colleagues (2010), both men and women showed significant changes in metabolic and respiratory variables because of increased mass of the firefighter footwear. For a 1-kg increase in boot weight there was a 5-12% increase in metabolic and respiratory measures seen for men during a treadmill walk, while women showed lower increases of 3-4.5% (Turner et al., 2010). The differences observed between men and women was thought to be the result of greater relative weight of the additional equipment the participants wore after taking their boot weight into consideration (Turner et al., 2010). In a similar population men and women were found to maintain lead toe clearance of obstacles regardless of the weight of the footwear they were wearing but the trail toe clearance decreased by roughly 14% per 1-kg increase in footwear mass (Chiou et al., 2012). Chiou and colleagues (2012) also observed that participants adapted their obstacle clearance patterns as the footwear weight and trial duration increased. First, the firefighters decreased the distance they were placing their trail foot from the obstacle before they stepped over it, which caused reductions in toe height clearance and an increase in trip risk (Chiou et al., 2012). As an adaptive change, the firefighters also increased the lateral displacement of their leg when stepping over the obstacle, this allowed the participants to maintain adequate clearance of the obstacles even as they were fatiguing (Chiou et al., 2012). The physiological measures of this study showed a 7-9% increase in VO_2/kg for both males and females per 1-kg increase in footwear mass (Chiou et al., 2012). Chiou and colleagues (2012) hypothesized that the adaptive changes in the gait patterns may be the cause of the metabolic changes but even despite these changes there was still a decrease in trail foot toe height clearance, which places workers at greater risk of tripping. The increase in VO_2 consumption could also place the workers at increased risk of fatigue induced STF after prolonged use of the footwear.

Another study that tried to determine the physiological impact of firefighters PPE looked at each part of the PPE on a non-firefighting population with a large age range (Taylor et al., 2012). The comparison of the equipment was done by measuring the mass of each piece and the findings indicated that footwear exerted an 8.7 times higher impact than the breathing apparatus in terms of increases in metabolic and exercise demand (Taylor et al., 2012). In determining the breakdown of the PPE that firefighters wear, the footwear was found to have the largest impact on exercise tolerance and oxygen consumption reserve for the non-firefighting population

(Taylor et al., 2012). Looking specifically at the mass of firefighting footwear, a study had twelve male firefighters performed strength tests and a simulated fire stair climb while wearing either a lighter leather boot or heavier rubber boot (Garner et al., 2013). The heavier rubber boot caused greater detriment to balance and postural control after the stair climbing trials over the fatiguing trials, compared to the lighter leather boot (Garner et al., 2013). The increased mass of the rubber boot likely caused the participants to fatigue to a larger degree as shown by larger decreases in peak torque at the knee and ankle than when wearing the lighter boots (Garner et al., 2013). The observed muscular fatigue reduced the adaptive capabilities of the muscles which could have been the cause of the observed lower balance scores (Garner et al., 2013).

Trying to identify the ideal footwear in terms of balance, Chander and colleagues (2014) determined that an above ankle height boot was better for balance measures when compared to a similarly massed, low rise shoe or a similarly high boot with more mass (Chander et al., 2014). Chander's study (2014) helped to separate the effects of boot mass from boot shaft height but still could not completely differentiate the effects from one another. In a similar study, Kim et al. (2015) looked at three footwear with the same shaft height but varying masses and found that muscle activity increased for the vastus medialis as footwear mass increased. Furthermore, in an underground mining study the heavier leather lace-up boot was found to increase muscle activity of the vastus lateralis and biceps femoris when participants traversed a sloped terrain compared to the lighter rubber slip on boot (Dobson et al., 2015).

2.4.3 **Shaft Height**

Footwear shaft height has implications for the ROM at the joints that the shaft covers. In industrial settings, a higher shaft height is necessary to reduce impacts to the lower shank and ankle and is often used to improve stability of the ankle joint. In the underground mining industry, the higher boot shaft height serves the same purpose as stated for other industrial sectors and aids in preventing water from getting into the boot. These features mean the footwear used in underground mines usually rises even higher than those commonly seen in other industries. Research into the effect of a higher boot shaft has been performed and findings are inconclusive between either showing a restriction of the ankle joint causing decreased power generation and efficiency of gait (Nunns et al., 2012; Park et al., 2015); or restriction of the ankle joint preventing ankle injuries from sprains and strains (Chander et al., 2014; Yang et al., 2015). In either condition a restriction in the ankle ROM was seen as the height of the boot shaft over the joint increased.

Comparing a military boot to a traditional running shoe, the impact forces were found to be greater on the foot in the military boot and the mobility of the ankle joint was decreased (Nunns et al., 2012). The shaft height, mass, and midsole hardness were different between the two footwear conditions, so it is hard to pinpoint which factors were the cause of the increased impact forces and decreased ankle ROM (Nunns et al., 2012). Similar findings were found in a study by Park et al., 2015 comparing rubber boots worn in firefighting with running shoes, the authors found ROM at the ankle decreased and ROM at the knee and hip increased in the boot condition. A similar comparison was made when looking at the difference between two safety footwear and a control shoe regarding balance performance (Chander et al., 2014). The boot that rose above the ankle increased balance performance compared to the traditional below ankle shoe (Chander et al., 2014). The differences observed in the balance performance and ankle, knee, and hip kinematics may have been the result of the higher footwear shaft; however, with other differences present between the footwear conditions the exact cause cannot be concluded. Yang and colleagues (2015) compared two different rain boots, that varied only in their shaft height, and found that the boot with the higher boot shaft had better balance scores as the trial progressed compared to the lower shaft height boot. The hypothesized mechanism behind this finding is that as the muscles fatigued and could not adapt as quickly to a loss of balance, the higher boot shaft was able to aid in maintaining the subject's balance (Yang et al., 2015).

2.4.4 **Shaft Stiffness**

Boot shaft stiffness refers to the flexibility of the shaft of a footwear, usually only measured in footwear that rise above the level of the ankle. Several researchers have evaluated the impact of footwear shaft stiffness on gait parameters (Bohm & Hosl, 2010; Cikajlo & Matjacic, 2007). The difference in shaft stiffness between two similar types of footwear was found using an assessment of the load deformation of each footwear at different positions (Cikajlo & Matjacic, 2007). Footwear with a less stiff shaft allowed for a larger ROM at the ankle which enabled greater power generation during push-off (Cikajlo & Matjacic, 2007). The increased restriction to the joint caused by the height of the shaft is known to decrease power generation capabilities of the joint (Cikajlo & Matjacic, 2007). Cikajlo and Matjacic (2007) also reported that, despite differences in ankle ROM caused by various types of footwear with different shaft stiffness, significant differences in ROM were not observed at hip and knee joints.

A study that also examined shaft stiffness for two types of footwear determined that both the ankle ROM in the sagittal plane and the eccentric energy absorption at the ankle decreased for the footwear that had the stiffer shaft (Bohm & Hosl, 2010). Loads applied to a prosthesis while placed inside each footwear allowed for the movement of the top of the prosthetic to be measured using a motion capture system. The stiffer shaft allowed for less movement of the prosthesis when the load was applied laterally to the prosthetic. The amount of movement that each footwear allowed under the same load created a comparative measure of stiffness (Bohm &

Hosl, 2010). Although this study did not look at changes in the knee and hip ROM, the effects of the shaft stiffness on the ankle can cause compensatory actions resulting in increased co-contraction of muscles and eccentric energy absorption at the knee joint which may not appear as a change in the motion (Bohm & Hosl, 2010).

Studies that have indirectly measured shaft stiffness have compared leather and rubber footwear on a simulated mining course and discovered differences that shaft stiffness had on gait (Dobson et al., 2015). The researchers found that the leather boot caused increases in muscle activity at the knee, likely compensating for restricted ankle ROM and the inability to generate enough power at the ankle (Dobson et al., 2015). Additional effects of boot shaft stiffness or boot shaft height on gait characteristics were reported by comparing military and rubber firefighter boots to traditional running shoes (Nunns et al., 2012; Park et al., 2015). Both Nunns (2012) and Park (2015) found decreases in ankle ROM, likely the cause of restricted ankle mobility from the shaft of the footwear, which caused an observed increase in impact forces and hip and knee ROMs.

2.4.5 **Sole Flexibility and Design**

The flexibility of the sole of a footwear, which is determined by the material composition of the outsole and the design of the footwear, can impact gait. In the mining and industrial sectors, a hard sole is required to prevent punctures through the bottom of the footwear. For safety reasons a harder sole would appear to be more beneficial, but research has found that a flexible sole may have benefits for the worker (Arndt et al., 2003; Chiou et al., 2012; Hardin et al., 2004; Lin et al., 2007).

When testing the effects of two military boots, a more flexible sole was found to increase dorsal tension and may lead to increases in stress fractures (Arndt et al., 2003). In contrast Hardin and colleagues (2004) found that harder midsoles were found to cause increased flexion velocities of the lower limb joints, which may be the result of increased ground reaction forces. The increased flexion velocities would be used as a mechanism to reduce impact forces on the joints (Hardin et al., 2004), if this adaptation is not taken then injury to the joint would be possible over prolonged exposure.

Looking at the effects that sole flexibility has on muscle activity and physiological responses concluded that more flexible soles resulted in lower muscle activity responses, ground reaction forces, and discomfort ratings (Lin et al., 2007). Chiou and colleagues (2012) also observed similar findings where a 5-6% decrease in VO_2/kg was observed for boots with a more flexible sole. An increase in sole flexibility of firefighter boots was also shown to mitigate some of the detrimental metabolic effects that were elicited by the mass of the footwear (Chiou et al.,2012). In other terms, the boots with a more flexible sole allow for decreased metabolic use to achieve the same movement outcome for the subjects (Chiou et al, 2012).

2.5 **Summary and Objectives**

Underground mining boots are heavy, made of leather or rubber, rise to a mid-shank height, and have a tough, hard sole. Using the research outlined above we can see that some researchers have found different effects on wearers between types of footwear used (Dobson et al., 2017; Dobson et al., 2015; Schulze et al., 2014; Tian et al., 2015). However, the highly variable nature of the footwear conditions used in these studies means it is difficult to determine which factor was the true effector. Research has attempted to fractionalize these various factors to determine the effect of each individual factor on worker gait and comfort.

As there is an increase in the mass of the boots, we see varying detrimental effects on subjects, from increasing the muscle activity needed to complete a motion (Dobson et al., 2015; Kim et al., 2015), to altering the motion itself by increasing physiological demand (Chiou et al., 2012; Taylor et al., 2012; Turner et al., 2012), and decreasing obstacle clearance ability (Chander et al., 2014; Chiou et al., 2012; Garner et al., 2013). Regarding the effect of boot shaft height on the wearer, research has shown that boot shafts that rise above the ankle joint cause decreased mobility of the joint (Nunns et al., 2012; Park et al., 2015) but may aid in balance when the muscles become fatigued and cannot adapt as quickly (Chander et al., 2014; Yang et al., 2015). The hip and knee joints have been shown to compensate for the ankle when it has been restricted by footwear by increasing the ROM utilized at these joints (Park et al., 2015). In addition to the height of the shaft, the stiffness of the shaft may also have an impact. The results of studies performed on boot shaft stiffness have shown that as the boot shaft becomes stiffer, ROM at the ankle becomes restricted and the body adapts to these changes by increasing power generation, muscle activity, and ROM utilized at the hip and knee. (Bohm & Hosl, 2010; Cikajlo & Matjacic, 2007; Nunns et al., 2012; Park et al., 2015). Lastly, sole flexibility has implications for force profiles, ankle, knee, and hip motion, and physiological measures. A more flexible sole decreases the impact forces during gait but may increase the tension in the forefoot (Arndt et al., 2003; Hardin et al., 2004), in addition to decreasing muscle activity, decreased discomfort ratings, and improved physiological responses in a multitude of different footwear conditions (Chiou et al, 2012; Lin et al., 2007).

Past research has shown that heavy and cumbersome footwear used by firefighters and military personnel can affect gait characteristics but the effect that footwear designed specifically for underground miners remains unclear. The only studies to look directly at mining related footwear were performed in Australia on footwear specific to coal mining (Dobson et al., 2018; Dobson et al., 2017a; Dobson et al., 2017b; Dobson et al., 2015). These studies reported slight statistical differences between muscle activity, kinematic data, pain, and perceived comfort in two different mining footwear conditions, the ‘mucker’ style versus the leather lace-up boot. To the author’s knowledge no research has looked at changes to gait or perceived discomfort when wearing underground hard-rock mining footwear.

Therefore, the purpose of this research is to determine the effect of three common underground hard-rock mining boot types on lower limb gait characteristics and perceived comfort. Findings could inform risk mitigation strategies for STFs. If one of the footwear types is found to alter gait in a manner associated with increased risks of STFs the findings can be shared with boot manufacturers and mining industry health and safety professionals. Furthermore, sharing findings with workers will enable them to select a footwear type associated with greater comfort and footwear type that enables a natural gait and lower risk of STF.

3 Methodology

The study methodology was approved by the Laurentian Ethics Committee REB Number: 6012184. Participants were recruited using the script provided in **Appendix B** and informed consent was provided by all participants using the consent form in **Appendix A**. Prospective participants were then screened for their ability to participate in the study by completing the Entrance Questionnaire (**Appendix C**). The study was completed in a controlled laboratory setting to determine changes in gait parameters and perceived comfort while participants donned three underground mining boots and one control condition.

3.1 Participants

Fourteen participants between the ages of 18-65, free from any lower limb and/or back discomfort and pain in the past six months, were selected from a sample of convenience. Participants were also excluded if they had lower limb or back surgery over the past two years or a foot size smaller than a men's 5 or larger than a men's 12. Participants also completed a short questionnaire about demographics and their experience with mining related footwear. The final sample of participants included eight males and six females with an average mass of 77.75 kg (standard deviation of 9.5 kg) and average foot size of a men's 9.5 (standard deviation of 2.2) across the male and female participants.

3.2 Habituation Phase

During the habituation phase, participants completed a Body Map – Discomfort Survey (**Appendix D**) to determine if they had any noted lower body or back pain that may affect their results. The participants were also fitted with each mining boot and asked to wear each boot for 1-2 hours, over a 1-week period, to habituate to the footwear and ensure the proper size was identified, before the start of the experimental phase. After the habituation period, the participants also completed the Comfort Questionnaire (**Appendix E**) to determine a baseline comfort rating for each of the three footwear conditions and a running shoe condition.

3.3 **Experimental Phase**

Participants completed the Body Map Discomfort Survey (**Appendix D**) again on the day of testing before starting the experimental trials to ensure no musculoskeletal pain or discomfort would potentially affect the study results. During the experimental phase, each participant was randomly assigned to don each of the four footwear conditions and asked to walk at their preferred normal pace along a path that had them step on two force plates. During the walking trials, spatiotemporal, kinematic, and kinetic variables were collected. After each footwear condition trial was completed participants completed the Comfort Questionnaire (**Appendix E**) for that condition and at the end of the experiment (all footwear conditions completed), the participants completed an Exit Questionnaire (**Appendix F**) to gain an understanding of their perceived comfort and preference for each footwear condition. The study used four distinct measurement systems to collect the spatiotemporal, kinematic, kinetic, and comfort data.

Footwear Conditions

a) b) c)

Figure 3: Underground footwear conditions
a) Oliver 65-690 Leather Lace-up; b) Viking VW49 Miner 49er ; c) STC Titanium

The four footwear conditions evaluated in this study were:

1. Personal Athletic Shoe - Control
2. Oliver 65-690 Leather Lace-up - Leather Lace-up Boot (Figure 3a)
3. VW49 Viking Miner 49er - Rubber Slip-on Boot #2 (Figure 3b)
4. STC Titanium - Rubber Slip-on Boot #1 (Figure 3c)

The Control condition for this study was an athletic/running shoe that the participant provided. Participants were informed during the intake phase that they would need to provide an athletic/running shoe that they are accustomed to but that was not broken in any way. The participant would bring the Control footwear in with them the day of data collection and the principal investigator examined the shoe for any defects prior to beginning the study.

The Oliver footwear condition is a style that is commonly referred to as a leather work boot, it is made up of leather and has laces across the entire anterior face of the boot. The laces allow the boot to be adjusted to the user's preference. This type of footwear is utilized in most industrial settings, however, in this case the Oliver rises to a mid-shank level rather than just above the ankle joint. This higher rise feature allows the Oliver to be a better candidate for underground mining because debris and water cannot as easily enter through the top of the boot.

The second footwear condition is the Viking boot, this is very commonly used in underground mining and this style is often referred to as a "mucker". The Viking boot is rubber, has a very aggressive tread, is inflexible, and often oversized at the ankle, shank, and foot to allow for users to fit in large socks if necessary, for cold weather. The boot also rises to a mid-shank level to help prevent water and debris from entering the top of the boot.

The third condition is the Titanium boot, this too is a “mucker” style of footwear. The Titanium, similar to the Viking, is made of rubber and has a rather aggressive tread on the sole. In contrast to the Viking, the Titanium has an ankle guarding technology placed into it that makes the ankle and foot much tighter. The ankle guarding was put in place to help prevent ankle roll-over injuries. Additionally, the Titanium came equipped with an insulated insert so it could be used during the cold weather. Similar to the other two footwear conditions, the Titanium also rises to a mid-shank level to prevent water and debris from entering through the top of the footwear.

The footwear conditions were chosen so that some differences in common underground mining boot types could be explored. Namely, the difference between the “mucker” style (Titanium and Viking) and the leather work boot style, and the difference between the shaft stiffness by examining the differences between the loosely fitted Viking and the tighter fit Titanium boots. Variances in mass of the footwear could not be controlled without adjusting the footwear themselves. The shaft height of all of the footwear was similar in that they rose to a roughly mid-shank level, so the effect of shaft height was relatively controlled for.

3.3.1 **Data Collection**

The variables measured during this study are listed in Table 1.

Table 1: Summary of variables measured in this study and the output evaluated.

Variable	Measurement Technique	Output
Ankle, Knee, and Hip Joint Angles	Notch	The angle of the ankle, knee, and hip during any gait phase.
Impact/Landing Peak Force	Force plates	The ground reaction force from the participant’s foot as they impact the force plate.
Push-off Force	Force plates	The ground reaction force from the participant’s foot as they push

		themselves off the force plate.
Time Spent in Stance	Force plates	The duration the participant is positioned with either the left, right or both feet on the ground (single or double support)
Stride Length	Digital Video Camera	The distance between the left and right foot in the direction of propulsion when the body is in double support.
Walking Velocity	Digital Video Camera	The change in position of the subject over the period that it took place.
Toe Height Clearance	Digital Video Camera	The distance between the lowest point of the foot and the walking surface during the swing phase.

Spatiotemporal Variables

Spatiotemporal variables of Walking Velocity, Stride Length, and Toe Height Clearance were to be collected using a video camera setup with a field of view of the participant's motion along the middle portion of the walking path, with focus on the centre four steps. A GoPro camera was set up to collect a video recording of the side profile of the participant during the trails. The video recording device was set to 1080p resolution with a parallel camera lens setting. The video camera was positioned to view the participant's sagittal plane as they performed the walking trials. The camera system required a calibration standard to be positioned in the video at the same distance from the camera that the motion would take place at any time during the video. The calibration standard was a 1-meter measuring stick positioned in the middle of the large force plate at waist height during the beginning of the video. The camera was not moved from its position after its initial placement and the video was continuously recorded for every trial of an individual footwear condition. This setup resulted in four videos, one for each footwear condition, for each participant.

A piece of reflective white tape was placed onto the toe of each of the footwear conditions to use as a physical marker in the video files for computer position-based analysis. The video files were examined to determine the frame where the toe of the footwear was last in contact with the ground, this location was marked by locating the physical toe marker of the leading foot in that frame and placing a digital marker at that position. The video was advanced frame by frame placing a digital marker on the location of the tape marker, on the toe of the footwear, for each frame until the foot started to descend. The distance between the digital marker for the ground reference level frame and the digital marker for each frame was to be determined. The greatest of these distances was labelled as a maximum height the toe rose above the ground and represented an estimate of the Toe Height Clearance for that trial. Similarly, the video files of the trials were to be used to determine the Walking Velocity and Stride Length. By measuring the distance cleared across the field of view of the camera and knowing the frames per second of the video recording an approximation of the walking velocity could be determined by dividing this distance covered by the time it took. For the Stride Length, the position of the toe marker of the left and right foot could be determined and the distance between these two markers at the time of double stance, when both feet at in contract with the ground, would be used as the Stride Length. For all measures the average would be calculated across the five trials for the condition for each participant. Unfortunately, the spatiotemporal variables measured using the video camera setup could not be accurately determined in this study because of the quality of the video recordings once it was slowed down to a frame by frame analysis.

Kinematic Variables

Kinematic variables in this study were to include measures of hip, knee, and ankle joint angles. The kinematic measures were to be determined using an Inertial Measurement Unit (IMU) system that uses a coupling of accelerometers and gyroscopes to extrapolate joint angles from the data measures it collects. In this study the Notch motion sensor system (Notch Interfaces Inc., 2017) was used to collect joint angle data.

Collecting joint angle data using the Notch sensor system involved the use of a tablet and application to sync the sensors, collect the data, and replaying the motion using their avatar within the application. The Notch motion sensor system uses an IMU system to determine the orientation and positioning of the sensors relative to each other and in respect to the segment of the body it is placed onto. Calibrating the sensors to each person gives a proportional skeleton and starting angle of the subject that allows for relative joint angles to be measured throughout a dynamic movement. The Notch sensors are calibrated with the participant standing in a neutral standing position with the lower limbs straight, head looking straight ahead, and arms at the side with palms facing in towards the torso. Each trial was recorded using the Notch application and auto downloaded onto the tablet device. The trial number and condition was recorded along with the time at which the trial is completed for future data analysis. The syncing of the sensors is performed prior to each new condition as the exact positioning of the sensors relative to each other for the baseline ‘zeroing’ may have changed. This process involved ensuring all the sensors are in the correct positions, having the participant stand in the calibration stance, and confirming that all the sensors have been calibrated correctly on the application.

Notch sensors were attached to the anterior portion of the chest (on the middle of the sternum), abdomen (on the navel), at the thigh and shank at a position halfway through the segment, and the final sensor was positioned on the superior face of the footwear halfway between the toes and ankle, outlined in **Figure 4**. Placement of the marker on the foot to collect ankle angles was not possible as the sensor could not be positioned within the footwear directly on the superior aspect of the midfoot as is recommended so we positioned the foot sensor for ankle data collection on the anterior aspect at the midpoint of the footwear. The sensors were adhered to the participants using the Notch provided elastic straps, the straps were adjusted to ensure they were adequately tight on the participants but did not cause any discomfort or limit muscle movements. The sensor on the footwear was adhered using double sided tape and a Velcro strip to allow for removal of the sensor, should it need to be recalibrated or charged, but ensuring the placement of the sensor was maintained at a constant location on the footwear.

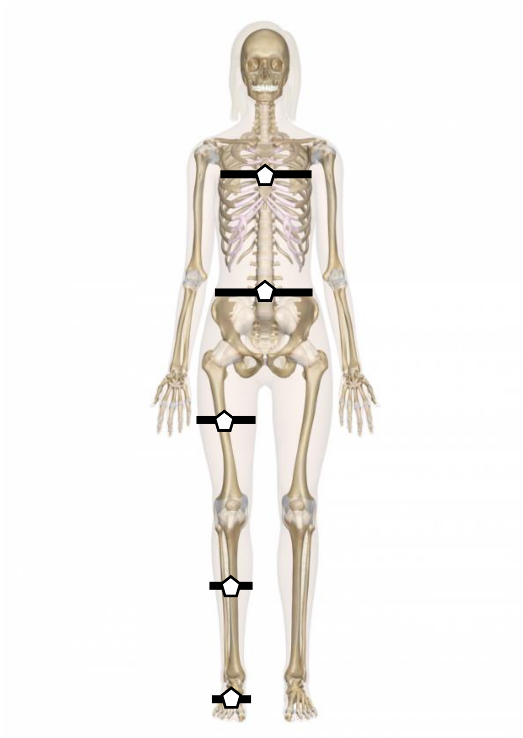

Figure 4: **Notch sensor placement**
Anterior aspect of sternum, anterior aspect of abdomen, anterior aspect of thigh halfway between the knee and hip, anterior aspect of shank halfway between the knee and ankle, and the superior aspect of footwear halfway between the toe and ankle.

Kinetic Variables

Kinetic variables were measured using force plates to collect ground reaction forces as participants completed walking trials along the pathway. The force plates used in this study were two AMTI force plates (AMTI BP400600 and AMTI BP12001200) to collect ground reaction forces in all three planes (vertical, fore-aft, mediolateral directions) for each participant throughout the trails. The trials were recorded for 10 second intervals on the force plate at a collection rate of 250Hz. The force plates were mounted into the floor so the walking path for the trials was designed to have the participant land with their right foot fully on the first force plate and the subsequent left foot and next right step landing on the second larger force plate. However, because the placement of the two force plates relative to each other and the varying length of participant's step lengths not all participants were able to have a fully collected force profile on both force plates. Focus was placed on ensuring that the right foot was placed squarely in the centre of the first force plate to gather the most accurate data for that initial landing and push off.

Additionally, the Time Spent in Stance was collected through the force profiles from the force plates by using the collection frequency of the force plate and the number of collected data points that made up of the force profile. A MATLAB code was used to determine the number of collected data points by using a cut off of a minimum of 10 newtons of force in the vertical ground reaction force measure as the threshold to determine when to start and stop the force profile. The force profiles determined using this window of datasets were also collected and graphed for further analysis in all three of the planes.

Perceived Comfort

Perceived comfort was measured using subjective questionnaires completed by the participants at the end of the data collection phase for each individual footwear condition. The Comfort Questionnaire (**Appendix E**) was completed four times (Control, Oliver, Titanium, Viking) for each participant. As can be identified in **Appendix E**, the Comfort measure was a question as to the subjective perceived comfort of the footwear. The Mobility was pertaining to the perceived mobility allowed at the ankle. The Ankle Stability was the perceived feeling of stability at the ankle. The Exertion was how hard did you feel it was to use the footwear for walking. Lastly, the subjective rating was how would you rate this footwear if you had to wear it for an 8-hour workday. All questions were to be made relative to a traditional comfortable athletic shoe that the participant had provided for use in the study. Additionally, users were asked, in Question 6 of the Comfort Questionnaire, to list any reasons for why they put the scores they did. They could choose to include as much information as they wish.

3.3.2 **Setup and Procedures**

All walking trials for a single participant were completed in one session. When participants arrived in the lab, they completed a baseline discomfort survey, they were fitted with the Notch motion sensors, and the video camera was placed into the correct position. The participant was weighed using a scale and the participant provided the investigator with the running/athletic shoes they brought with them to act as the control condition. The shoes were examined for any excessive damage or wear before being fitted with the necessary adhesion tools that allowed for the proper placement of the Notch motion sensor on the footwear. The participant then donned the control footwear and completed practice passes along the walkway and a “Start” marker was placed and moved into a position that allowed for the consistent and correct placement of the foot steps onto the force plates for data collection. Once the participant was able to consistently land with the correct foot placements onto the force plates by starting at the “Start” marker while walking at a preferred pace and looking forward then the “Start” marker was left alone for the remaining duration of the study and used as the starting point for all of the experimental trials. The participants then donned the footwear that was randomly assigned to be their first condition. The Notch motion sensor system was calibrated to the participant and three to five practice trials were performed in the footwear condition before data collection commenced to ensure proper foot placement would still be maintained in the current footwear condition.

3.3.3 Experiment Protocol

The laboratory walkway scenario consisted of the participant performing gait trials over the walkway while measurements were collected of the participant under each of the four footwear conditions. Examples of the footwear impact and push offs are shown in **Figure 5**, **Figure 6**, and **Figure 7**, and the walkway design is outlined in **Figure 8**.

Figure 5: Oliver footwear condition small force plate impact (left) and push off (right)

Figure 6: Titanium footwear condition small force plate impact (left) and push off (right)

Figure 7: Viking footwear condition small force plate impact (left) and push off (right)

The steps performed throughout the experiment are outlined below. These steps describe the process that was used for one full footwear condition data collection, which consisted of trials until five successful trials were collected:

Step 1: The participant was positioned to take two full gait cycles, four strides, before landing with the right foot onto the first smaller force plate then stepping forward and landing the left foot onto the second larger force plate then the right foot onto the second portion of the large force plate. The participant continued for four more steps after the third step on the force plates. The total stepping pattern was (Right-Left-R-L-**R-L-R**-L-R-L-R) with the bolded letters being the steps onto the force plates, as outlined in **Figure 8**. Participants performed three to five warm-up trials to practice getting their foot placement correct and re-familiarization with the footwear condition before data collection trials were performed.

Step 2: The testing trails were recorded using the force plates, video recording, and Notch systems. Five successful trials were completed for each footwear condition. A successful trial was one where the steps landed completely on the correct force plates, the participant's gaze was straight forward and not looking down at their feet, and the participant's walking gait was "normal" with no lunging or enlarged steps to reach the force plates as evaluated by the investigator subjectively.

Step 3: Once the participant had successfully completed the data collection phase, the devices were paused and the participant was given 10 minutes to complete the Comfort Questionnaire (**Appendix E**), providing information about the comfort and usability of the footwear they were wearing.

Step 4: After completion of the questionnaire the participant had completed the experiment for that footwear condition, and they changed into the next footwear condition. The condition order was randomized for each participant.

The participant would then complete the second footwear condition using the steps and procedures outlined above. The participant continued to perform the experimental procedures until all four of the footwear conditions were completed. Once all conditions were successfully completed the equipment was removed from the participant. The participant then completed the Exit Questionnaire (**Appendix F**) after all the trials for all of the conditions were completed and the footwear was returned to the researchers.

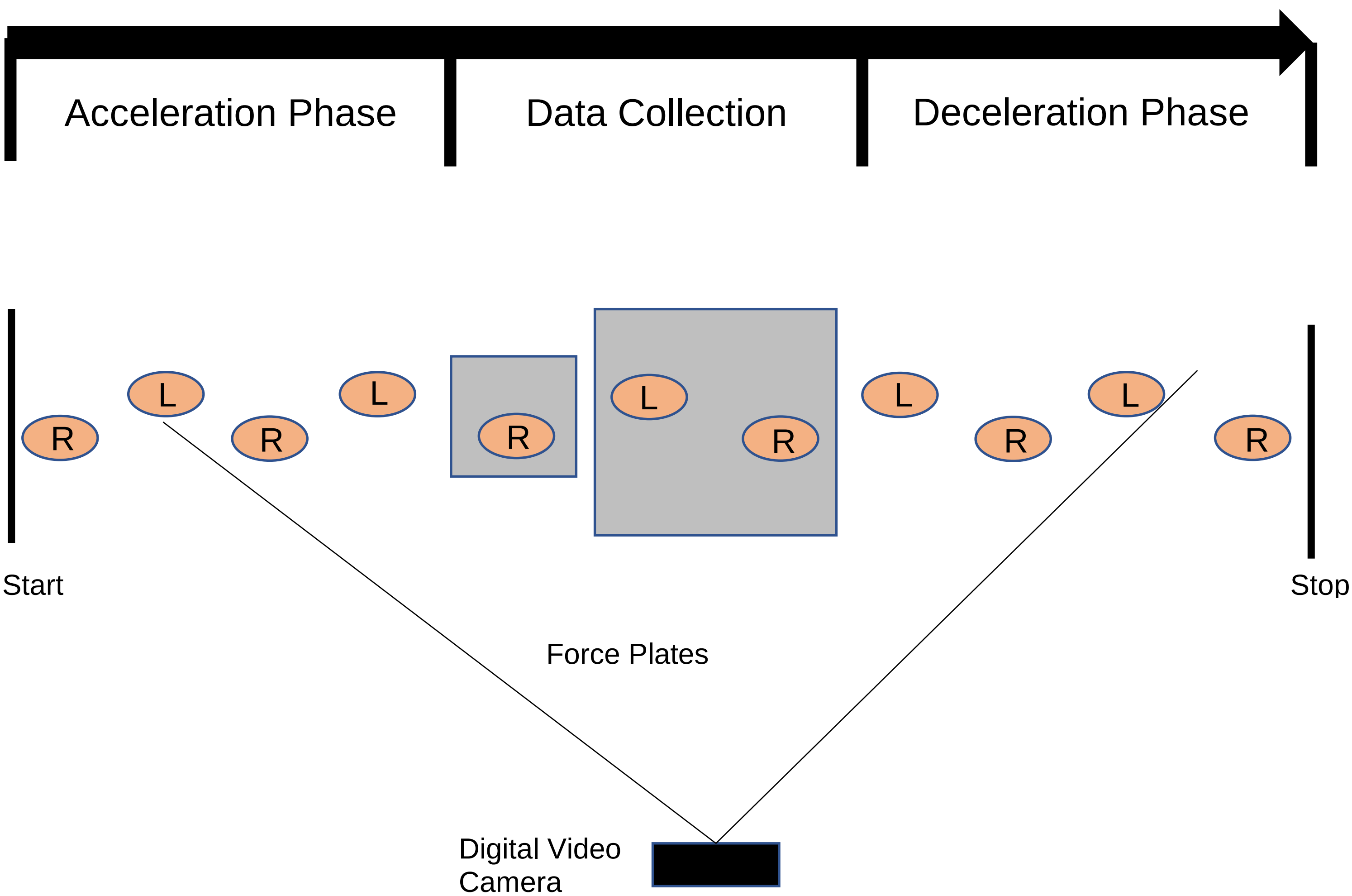

Figure 8: Laboratory walkway setup

Two force plates positioned in the middle of the walkway and the digital video camera positioned on the right side of the walkway to view the sagittal plane of the participant as they completed the walking trial. Marker was placed at the start location to create relatively repeatable step locations onto the force plates, dependent on the participant, as outlined. R = right foot placement, L = left foot placement. Exact distance between the steps was individual dependent.

The data collected from the experiment provided descriptive data of the lower limb motion for each of the four footwear conditions under controlled laboratory settings and subjective comfort and preference of the participants for the mining boots when compared to the same walking trials completed in the control condition.

4 Study Outcomes

This study looked to utilize both objective and subjective measures of gait function and discomfort for novel participants with a variety of underground mining footwear conditions. To start, during intake and pre-experimental surveys it was determined that there was no notable levels of pain/discomfort for any participant at the time of the Habituation Phase or during the Experimental Phase. Two participants wore orthotics; however, they were removable orthotics, so they were able to be fitted into the footwear conditions, so these participants were included in the study. The results from these two participants mirrored those of the other participants so their results were included.

4.1 Results

4.1.1 Comfort

The results from the Comfort Questionnaire for each footwear condition, recorded immediately after each trial, are summarized in **Table 2** and outlined below.

Regarding the mining footwear conditions specifically, participants' rated comfort highest for the Oliver footwear, then the Titanium and the Viking. Mobility at the ankle was rated as the lowest in the Titanium and reading the written responses, it often came forward that participants found the ankle to be very tight and restrictive in this footwear. Along the same line, the Ankle Stability was rated low for the Viking, which participants often claimed was too loose at the ankle and calf. For the Titanium, participants reported low Mobility scores but high Stability scores. The Oliver had a different set of results as participants perceived the footwear to have both high Mobility and Stability. In terms of exertion, all the boots caused marked increases in perceived exertion when compared to the control footwear, and this was likely because of the increased mass of the mining footwear compared to the athletic shoes. Lastly, from observing the overall Subjective Rating scores from all the participants, the Oliver was the preferred mining footwear, with Titanium after that, and then the Viking coming in as the least preferred. Overall, the Oliver was deemed to be more comfortable, require less exertion, and be both more mobile and stable at the ankle when compared to the other mining boots for most participants (**Table 2**).

Table 2: Median subjective ratings of footwear comfort, mobility, ankle stability and exertion levels associated with wear after the completion of each footwear condition
Rating system is 1-9 scale. 1 represents low rating in that category, 9 represents high rating in that category. Exertion was measured as perceived exertion with high rating being high levels of exertion needed to use the boot. Subjective rating was determined as the potential rating a participant would give if worn over an eight-hour workday.

Variable	Footwear Condition			
	Control	Oliver	Titanium	Viking
Comfort	9	7	5	4.5
Mobility	8.5	6	4.5	6
Ankle Stability	7.5	7	6.5	4
Exertion	1	4	5	6
Subjective Rating	8.5	7	5	3

Participants recorded a comfort rating after all the footwear conditions had been used by completing the Exit Questionnaire, the results are displayed in **Table 3**. The results of the Exit Questionnaire supported those found in the individual condition Comfort Questionnaires reported in **Table 2**. The Oliver was ranked as the footwear of preference, followed by the Titanium, then the Viking. Moreover, the Oliver received the highest rating for Comfort, Mobility, and Ankle Stability, and received the lowest rating for Exertion in the Exit Questionnaire, mirroring the results from the Comfort Questionnaires. Additionally, the questionnaire asked for a Subjective Preference score similar to the Comfort Questionnaire, however, it provided a fourth option that participants could put a score of ‘4’, which meant they would not want to wear that footwear under any circumstance if given the choice. Six of the participants chose a rating of ‘4’ for the Viking, five participants gave it a score of ‘3’, and the remaining three had put the Viking at a score of ‘2’. This meant that a reported a median score of ‘3’ was achieved, but almost half of our participants would never wear these boots if given the choice. When the Viking did receive a score of ‘2’ it was because that participant put the Titanium at a score of ‘3’ because of the immobility/tightness at the ankle that it produced. The Oliver was rated as a ‘1’ for all participants expect for one, this individual gave the Titanium a ‘1’ because they preferred the tightness around the ankle.

Table 3: Median subjective ratings of footwear comfort, mobility, ankle stability and exertion levels associated with wear after the completion of all trials and all footwear conditions

Rating system is 1-9 scale. 1 represents low rating in that category, 9 represents high rating in that category. Exertion was measured as perceived exertion with high rating being high levels of exertion needed to use the boot. Subjective preference was the ranking of the footwear conditions, 1 being would choose to wear first, and 3 being would choose to wear last.

Variable	Footwear Condition		
	Oliver	Titanium	Viking
Comfort	8	4.5	3
Mobility	7	4	4.5
Ankle Stability	7.5	7	2.5
Exertion	2	6	7.25
Subjective Preference	1	2	3

4.1.2 **Kinetic Data**

The peak forces at the heel strike and toe off were determined using an average of measured heel strike peak forces and measured push off peak forces from both of the force plates. The peak forces were determined by running the force datasets through a MATLAB code that determined the peak force at the heel strike and the toe off phases of the force profile measured during the trials. The trial peak forces were then averaged across the participant for that condition, then the participants' condition averages were compiled and averaged again. This resulted in a condition average for the 1^{st} heel strike, 1^{st} toe off, 2^{nd} heel strike, and 2^{nd} toe off peak forces across all participants. The 1^{st} and 2^{nd} heel strike peak forces were then averaged together and the 1^{st} and 2^{nd} toe off peak forces were averaged together. The final values reported would be the average heel strike peak force and the average toe off peak force across all participants for that condition.

The results of the kinetic data measures are shown in **Table 4** below. The notable findings from the force plate measurements are that the Viking condition resulted in the greatest forces when taking both the Heel Strike and Toe Off peak force averages, although the Viking did not have the highest average for both of those measures. The Oliver and Titanium conditions both had greater then 5 Newtons of difference between average Heel Strike Peak Impact Force and average Toe Off Peak Push Off Force. Both the Oliver and Titanium had lower scores than the Control for the Average Heel Strike Force but then higher values for the Toe Off Force. The Control condition had the least difference between the two average scores with a 0.4-unit difference between the two scores. The last measure is the difference seen in Time Spent in Stance; this measure increases respectively from Control to Oliver to Titanium to Viking. As outlined earlier, the Time Spent in Stance is an indirect measure of the speed of the participant during the trial.

Table 4: Experimental Phase: Force plate results
Force values are reported in units of percent of body weight, this means that for each participant their body weight force was used as a reference value to compare the measured forces against. Example: a participant with body mass of 70kg has a body weight force of 686.7 Newtons, their measured forces were then divided by this body weight force to determine the peak force as a percent of their body weight. This technique allows for individuals to be compared to one another for peak forces as the values become relative to the individual, controlling for variability in individuals' masses.

Footwear		Control	Oliver	Titanium	Viking
Heel Strike Peak Impact Force (Percent of Body Weight)	**Average**	**117.5**	**114.8**	**114.5**	**122.5**
	Standard Deviation	9.8	9.8	9.0	10.9
	Highest	142.5	139.8	141.1	150.0
	Lowest	104.3	102.9	101.2	104.7
	Number of Impact Force Data Points	138	138	138	136
Toe Off Peak Push Off Force (Percent of Body Weight)	**Average**	**117.9**	**121.3**	**119.6**	**120.7**
	Standard Deviation	13.2	17.3	15.3	16.1
	Highest	145.3	175.1	155.3	150.0
	Lowest	94.4	91.3	93.1	91.2
	Number of Push-off Force Data Points	124	119	129	128
Time Spent in Stance (Seconds)		**0.69526**	**0.70571**	**0.72041**	**0.73254**

In addition to the reported values from the kinetic measures of the force plates, the representation of the force profile through the movement on the force plate was collected. The major details that were present in all of the participants' force profiles are that the vertical ground reaction forces, as shown in **Figure 9,** remain relatively the same across the conditions for the same participant. The force profiles in the fore-aft direction (Fy), the direction of motion across the pathway, and the medial/lateral direction (Fx) show that the mining boot conditions vary slightly from the Control condition (**Figure 10** and **Figure 11** respectively). Namely, a difference can be seen in the initial peak on the force profiles for the mining boots when compared to the Control condition. The differences are noted as the jutted and pointed peaks in the mining boots while the Control condition contains smoother curves at these peaks. These sharp peaks are more easily visible in the fore-aft and mediolateral directions for the Titanium and Viking conditions then for the Oliver condition, as shown in **Figures 9, 10, and 11**.

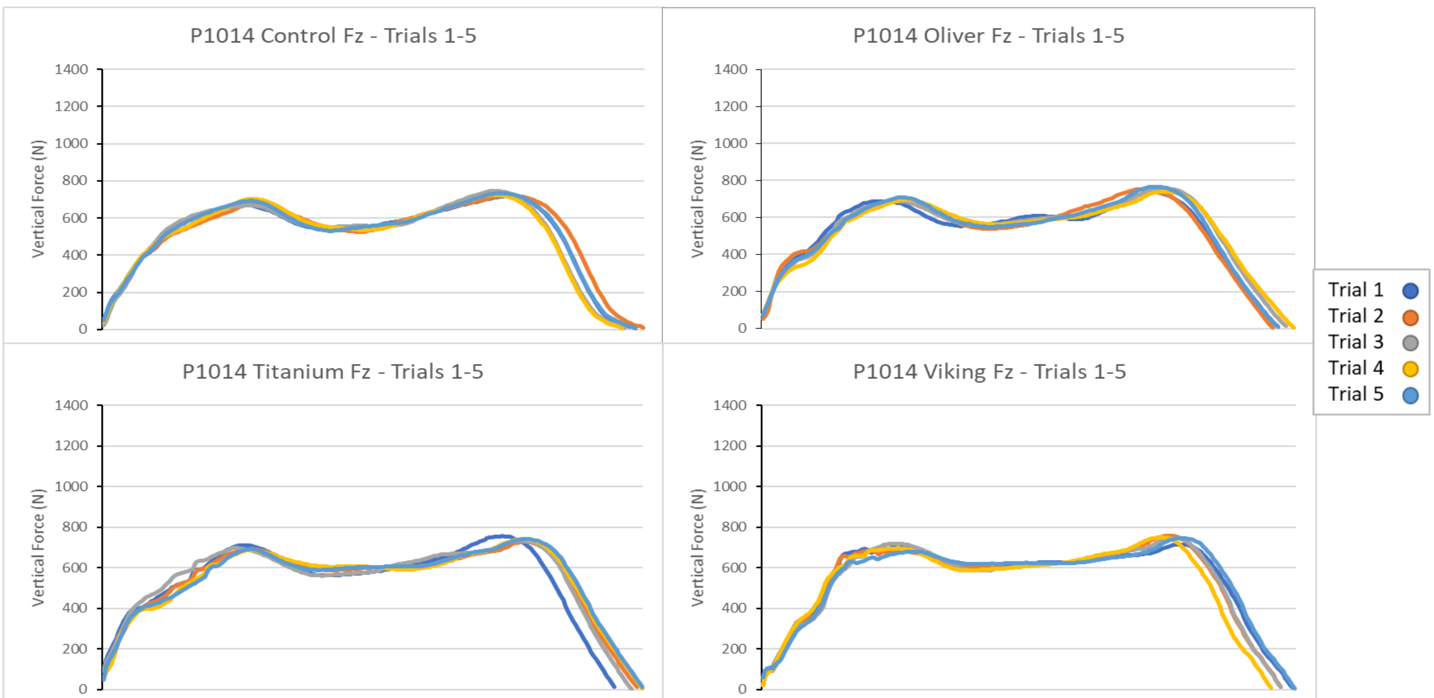

Figure 9: Vertical ground reaction forces of participant 14
Fz = Vertical Ground Reaction Force, P1014 = Participant 14, the five trials measured for each condition are displayed. The force profile shown in each chart is of the right foot impacting the first of the force plates. The y-axis is measured in Newtons of force in the vertical direction (+ = vertically up) by the x-axis which is as time progresses. Due to participants being able to choose their own Walking Velocity the x-axis is not shown as there is slight differences in the time taken for the force profile based on the participant and the footwear condition. The profile starts and ends when a 10 Newton force threshold was passed.
The first peak in the profile is peak force measured during the heel strike. The second peak in the profile is the Toe Off Peak Push Off Force. The dip between the two forces represents the loading phase of the gait cycle where participants are moving their weight from their hindfoot to forefoot.

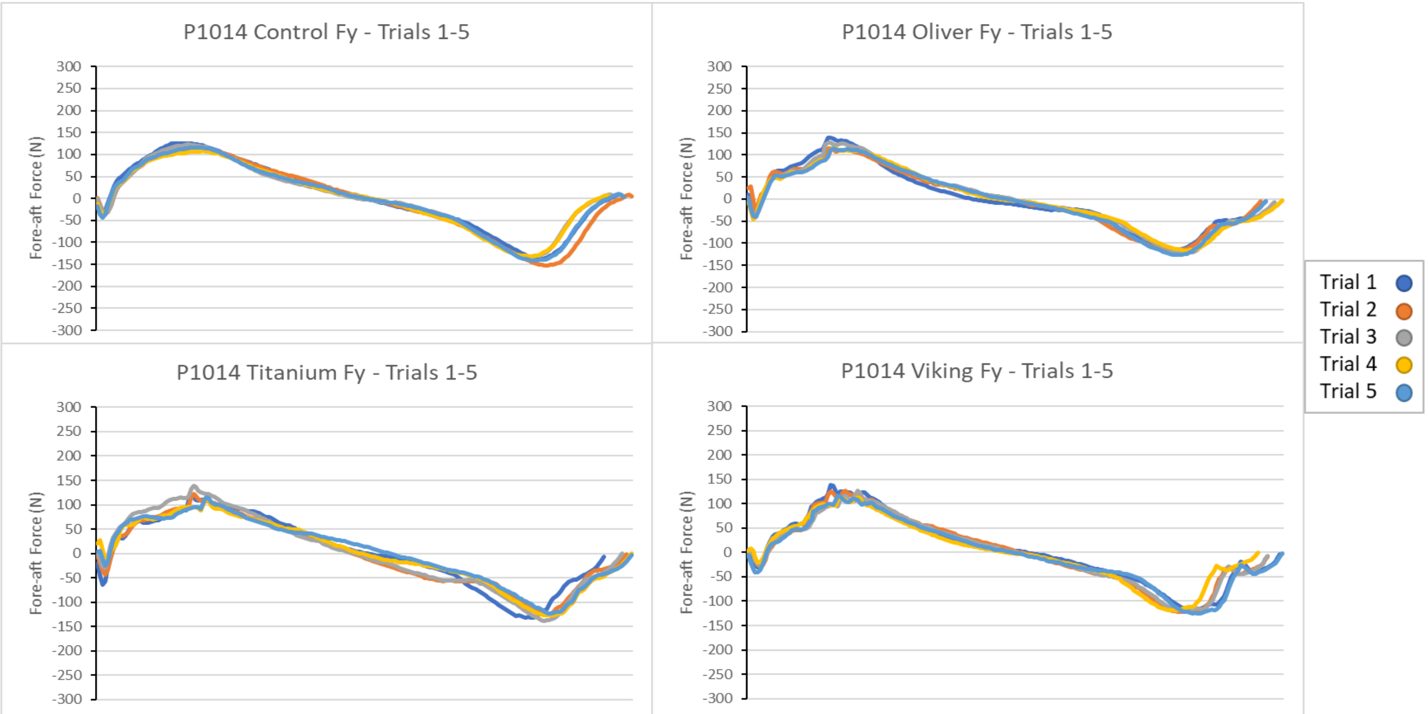

Figure 10: Fore-aft ground reaction forces of Participant 14

Fx = Fore-aft forces are along the direction of forward and backward motion on the pathway, P1014 = Participant 14, the five trials measured for each condition are displayed. The force profile shown in each chart is of the right foot impacting the first of the force plates. The y-axis is measured in Newtons of force in the fore-aft direction (+ = force pushing forward into the plate, - = force pushing back into the plate relative to the direction of motion) by the x-axis which is as time progresses. Due to participants being able to choose their own Walking Velocity the x-axis is not shown as there is slight differences in the time taken for the force profile based on the participant and the footwear condition. For the Fore-aft direction the force profile starts and stops based on the time frame determined by the force threshold for the vertical ground reaction forces. This meant the fore-aft force data were pulled for the same time window as the vertical force data.

The fore-aft data of the right foot starts with the foot impacting the force plate with the hindfoot. This is shown with the force pushing into the force plate in the same direction as the forward motion and the force plate pushing back against that force towards the heel of the foot. This initial force is shown as the positive values on the charts and the first peak of the curves. The slope of the curves going from positive values through represents the foot coming down to be fully planted onto the force plate as the participant moves into the midstance phase of gait. This midstance phase is shown with the zero fore-aft force (y-axis) in the middle of the curves. As the curve transitions to negative values, on the second half of the curve, this is the result of the hindfoot coming off of the force plate and the forefoot starting to apply force backwards into the force plate to propel the individual forward in the direction of motion. The net result of the motion is positive forces increasing and coming to a peak positive force then decreasing through zero into negative forces that increase in the negative direction until a peak negative force is *reached then decreasing until the force no longer is present as the foot completely leaves the force plate.*

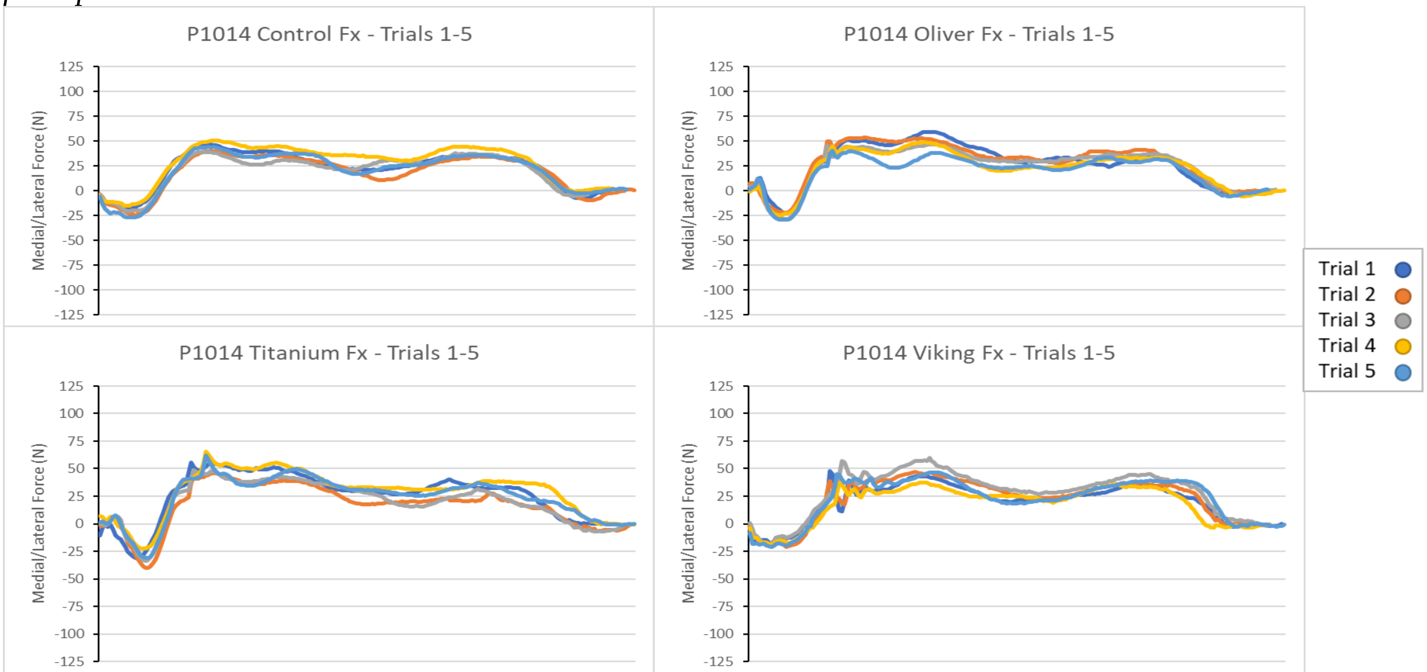

Figure 11: Medial/Lateral Ground Reaction Forces of Participant 14

Fy = Medial/Lateral forces perpendicular to the direction of forward and backward motion on the pathway, P1014 = Participant 14, the five trials measured for each condition are displayed. The force profile shown in each chart is of the right foot impacting the first of the force plates. The y-axis is measured in Newtons of force in the vertical direction (+ = medial, - = lateral) by the x-axis which is as time progresses. Due to participants being able to choose their own Walking Velocity the x-axis is not shown as there is slight differences in the time taken for the force profile based on the participant and the footwear condition. For the Medial/Lateral direction the force profile starts and stops based on the time frame determined by the force threshold for the vertical ground reaction forces. This meant the mediolateral force data were pulled for the same time window as the vertical force data.

The medial/lateral force data of the right foot starts with the heel strike of the hindfoot onto the force plate and transitioning to the foot fully flat on the force plate and then ending with the forefoot pushing off of the plate. Most of the force is kept in the medial direction to keep the individual balanced on the one leg as the pushing off force from the last step creates momentum forward but also towards the opposite side of the body. For example, the push off of the left foot creates medial force relative to the left side so that the right foot can be brought forward, and weight distributed onto that right foot. As the right foot is placed there is a relative lateral force from the left foot medial push off force so the right foot/leg must create a medial force throughout its stance to first overcome the relative lateral force and to create a net medial force back towards the left side for the next foot placement.

4.2 Implications

The purpose of this research was to determine the effect of three common underground hard-rock mining boots on lower limb gait characteristics and perceived comfort. A combination of kinetic data and subjective discomfort survey questions were collected to represent the effect of, and preference for, the three major types of underground mining footwear options when compared to an athletic/running shoe that acted as the control for the experiment. The goal of the study was to bring together an objective/direct measurement of the gait characteristics of novel underground mining boot wearers while also gauging subjective rating and preference of these boots. Comfort ratings and user preference can give us an understanding of which boots individuals will choose to wear while using the direct kinetic measures, we can gain an understanding of how each boot affects the user's movements. If a single boot condition is shown to both have little impact on the user's kinetic variables of gait and is perceived to be comfortable then there may be an indication that use of that footwear for workers in industry should also be beneficial.

The data collected from the objective and subjective measures show a general trend that the Oliver was the preferred boot by the vast majority of the participants and altered the gait characteristics to a low degree when compared to the other two mining boots. We will first discuss the direct measurement data from the force plates and then compliment these results with the subjective ratings and scores that participants provided. Implications of this study for workers, industry partners, and footwear manufacturers are outlined at the end of this section, and a brief outline of the limitations of the study are included.

Regarding the force plate data that were collected, there appeared to be a consistent gait force profile across participants. In terms of differences seen between the footwear conditions, we can first see the measure of the average Time Spent in Stance (**Table 4**), as measured by the force plate, appears to be dependent on the footwear condition. For this study, the Time Spent in Stance is used as an indirect measure of the walking velocity of the participant. As presented in **Table 4**, the Control had the least amount of Time Spent in Stance, followed by the Oliver, Titanium, and last, the Viking. The hypothesis for this outcome is that user preference of the footwear condition resulted in a quicker walking pace. Namely, participants are believed to have the fastest walking velocity in the Control condition because it is the most comfortable and habituated footwear of all the conditions to the participant. Using this logic, it can be hypothesized that the Viking is therefore the least preferred/comfortable footwear condition because it had the lowest relative walking velocity. From this change in walking velocity we should expect to see increases in impact and push off forces, however this was not the case as noted in **Table 4**.

A metronome could have been used to control the cadence of the participants' trials, however, when controlling step timing there can arise a problem with participants altering their gait without them being aware of it as it is being influenced by an outside source. We believe that the allowance of participants to adjust and control their own cadence during the trials and conditions gave us an indirect measure of their preference/comfort of the condition without them reporting it.

The Time in Stance variable values show that there is approximately a 5% increase in time spent in stance from the Control measure to the Viking boot which can be deemed reasonable for the control versus any individual boot. However, there is also an approximately 3.8% increase in this time just from the Oliver to the Viking. We can then cross reference these indirect preference/comfort scores to our subjectively reported measures from the surveys and questionnaires (**Table 2** and **Table 3**) to determine if participants' subjective views of the conditions lined up with the more objective inference. When compiling these two sources of preference/comfort information it can be observed that the Control condition was the preferred footwear, which of course was predicted. Of the underground mining footwear conditions specifically, the Oliver was placed as the boot of preference according to the Comfort Questionnaire, Exit Questionnaire, and the inferred comfort measure of the lowest Time Spent in Stance measure. Conversely, the Viking footwear had the lowest preference across all the Questionnaires and had an average higher Time Spent in Stance measure. The Titanium footwear tended to land in the middle of the three boot conditions for most users in terms of subjective preference and from the indirect walking velocity measure. These results show that the participants on average choose to walk slower when given heavier footwear compared to a running shoe and that the perceived comfort or actual design of the footwear, Oliver versus Viking, may impact the chosen walking speed as well.

Since there was no restriction placed on cadence or walking velocity during the trials, preference and comfort of the user was allowed to manifest itself within the force plate data. The average Heel Strike Peak Impact Force and average Toe Off Peak Push Off Force should have been lower for the Control condition versus the other conditions because the mining footwear had more mass than the participant's chosen athletic footwear. The measured average peak forces were not seen to follow this expected trend and instead resulted in only the Viking boot being higher than the Control in both peak force measures. These increased forces seen for the Viking boot, even when walking velocity was taken into account, could mean that the user is at an increased STF risk when compared to the other footwear conditions. The increased forces could create a disadvantageous adherence of the footwear sole to the surface, especially in wet or uneven situations often seen within the underground mining environment. The change in the adherence between the two objects/surfaces could create an ideal circumstance for a STF injury to occur (Cappellini et al., 2010; Lay et al., 2007; Wade et al., 2014). In addition to this increase in STF risk, an increase in impact and push off force required when using the footwear, as seen with the Viking boot, could mean that there would be increased muscular fatigue to compensate to keep the gait characteristics within the normal range of the user. If these muscular adjustments are required for prolonged periods of time then fatigue may result, which is likely to occur during the 8+ hour shifts that mining industries utilize, and lead to an increase in workplace error and injuries, including STF incidents ((Fan & Smith, 2017; Wickwire et al., 2017).

Another use of the force plate collected data were to view the general force plate profile that was created in all three of the measured planes: vertical (Fz), fore-aft (Fy), medial/lateral (Fx). The directional measures differed for each participant as the gait cycle and timing are specific to an individual, however, the general pattern remains constant across individuals given they have no underlying gait altering condition. The force profiles similarly mirrored those reported in a past study reporting force profiles in all three planes (Ray et al., 2007). In terms of the force profiles, as reported above in the Results section, Participant 14's force profiles are displayed as representative profiles because they subjectively (as determined by the principal investigator) had the least extreme variations in all planes, so the profiles show the most conservative differences between the conditions. All the participants' individual force profiles are included in **Appendix G** for reference. Each graph displays all the trials for a condition, each trial labelled as a specific colour as outlined in the legend, each condition contained five trials, however as stated previously, some participants were only able to be reported on for four trials.

As displayed in **Figure 9**, **Figure 10**, and **Figure 11**, the Control force profile maintains a relatively smooth curve throughout all three of the planes of motion. In contrast, all of the mining footwear conditions, more so with the two “mucker” style boots (Titanium and Viking), have distinct points and sharpness to the profiles. It is hypothesized that the changes to the force profiles is the result of the rigidity of the sole of the footwear, toe heavy nature of the footwear, and/or the change to the ankle joint motion when wearing these footwear conditions. In all of the possible explanations for these it is noted that although not directly measured, we would likely see increases in muscular activation to try to control the impact motion to keep the foot and ankle in control. Over prolonged periods, these adaptations to the musculature could lead to increases in worker fatigue and put them at a higher risk of injury. In addition, the peaks in the fore-aft and medial/lateral force profiles could lead to an increase in slip propensity similar to the mechanism for an increase in peak impact vertical forces outlined above, causing an increase in STF risk. As previously stated, the risk for a slip related injury increases in underground mining because of the environment and conditions the worker is working in, so trying to reduce the effect that their footwear has on this risk is important from an ergonomics stand point (Cappellini et al., 2010; Lay et al., 2007; Wade et al., 2014).

The results of the preference and perceived comfort of the underground mining footwear conditions, shown in **Table 2** and **Table 3**, lines up with our predicted outcomes and are supported by the participant’s written responses from the Questionnaires. Specifically, participants often claimed that the Oliver was the nicest and most comfortable of the underground boots because it was laced the whole length of the boot so participants were able to tighten the footwear as they deemed appropriate for their own comfort. The next highest rated mining footwear was the Titanium, the main finding from the written results for this footwear condition was that participants either found benefit with the ankle lock technology that the Titanium used or they found this additional resource to be very cumbersome. Interestingly, the tightness at the ankle in the Titanium boots was advertised as a beneficial feature of the footwear because in underground mining environments it is relatively easy to roll your ankle given the uneven terrain. Given that the design of the Titanium was made specifically for underground and surface mining this feature could provide many benefits to reduce lower limb musculoskeletal injuries given the nature of the environment and walking surfaces that the mining population encounters. Therefore, it may be appropriate to assume that a mining population may find more benefit with this footwear than our novel population.

Lastly, the written responses found on the Questionnaires for the Viking boot tended to be negative in nature. Most participants reported discomfort and a dislike of this footwear because of the loose fit at the ankle and shank, general heaviness of the boot, and it being described as toe heavy when compared to the other two boots. Overall, the participants reported using the Viking boot to be very cumbersome and that is the reasoning for roughly half of the individuals reporting that they would never want to wear this footwear again if given the chance. Similar to the Titanium, the Viking boot is designed specifically for underground and surface mines, so the high rise nature and the material from which it is designed it meant to keep the user’s feet dry in wet conditions.

Overall, in comparing the three mining boots to one another it can be reported that the novel users preferred the Oliver footwear over the other two options, the Viking and Titanium boots. The main reason appears to be because the Oliver was easy to adjust to the user's preferred fit and tightness and it was reported to feel less cumbersome in terms of flexibility and lighter weighted material it was made with. The Viking and Titanium tended to be reported as heavier and more cumbersome, in addition, the Viking was reported as too loose and the Titanium too tight. With this in mind the Oliver was deemed to be the most comfortable for the participants of this study. It is predicted by the investigators that the preference for the Oliver is because it more closely mimics their normal footwear when compared to the more traditional "mucker" style of underground mining footwear.

Although the Oliver may appear to be the preferred footwear among our novel study group we must keep in mind that the Oliver is constructed of a leather material, although the manufacturers state it is highly water resistant, it would be appropriate to state that the rubber outer material of the Viking and Titanium should still offer a greater water resistant ability. In the underground mining environment workers often care about keeping their feet dry as a top priority even if that means increasing their risk of musculoskeletal disorders or discomfort. Since this study was performed on a representative group of the general population, with little to no experience with the "mucker" style of footwear, it cannot be inferred that the underground mining work force would identically mirror these results. A further study should be conducted to determine the comfort and benefit of these specific mining boots on the specific mining population if possible.

The study presented here has implications for a few different stake holders. First, the frontline underground mining worker can use the research presented in this study to help make more informed decisions about which footwear/boot they utilize when working. As the study has shown, opting for a better adhering boot, that allows for an adjustable fit should reduce overall user discomfort and possibly reduce the risk of injury to the worker. Changing to a leather lace-up boot similar to the Oliver would be the recommendation to the worker from this study, however, it should be noted that given the variety of working conditions and environments present underground, a change to using a leather boot may not be feasible for every worker. If a worker has to stand or walk through puddles constantly throughout a work shift, then a more water-resistant boot may be deemed more appropriate for their circumstance. Overall, the worker must take the information provided here within into their own workplace to determine if the recommendation of the Oliver (or other similar high leather lace-up boot) is feasible for them.

The second group to benefit from the research that took place should be the mining industry. Although the direct measurement data were limited for this study, there is still implications that there may be increases in fatigue and STF risk when using boots like the Viking as opposed to those more like the Oliver. Taking these recommendations into consideration there could be an economic and moral benefit for employers and the industry to encourage their workers to switch over to a leather lace-up style of footwear moving forward. In addition, with the results provided here, there is a possible benefit for the mining industry to push for innovation on footwear/boot design to allow for a better constructed boot that impacts user locomotion to a reduced degree.

Lastly, the study provides an outline to the footwear/boot manufacturing industry by showing that a more comfortable, adjustable boot, like the Oliver, is preferred by users. However, knowing the environment that underground mining workers are exposed to is often wet, there are some changes that could be made to improve potential worker compliance with these boots.

Namely, the leather lace-up boot or similar style will need to be adapted, if possible, to be waterproof. Additional changes to user comfort may be possible for the “mucker” style of boot, by adjusting the sole and shaft flexibility, but this is cautioned as changes to these features may cause adverse changes to gait characteristics and thus negatively impact workers. Future research or testing should be performed if this is the case.

If this study can be reproduced there are several future directions that should be explored. First, administering a similar study to a mining specific population would allow for a greater benefit for understanding how the footwear impacts and is received by the population in which they will be used. Secondly, a future study could look to explore a walking pathway or terrain that more closely mimics that of the underground mining surfaces to assist in determining how users felt with the footwear conditions on the traditional uneven and wet surfaces. Ideally, future studies could evaluate gait from miners working in underground mines. Within this context, adaptations would need to be made to collect the direct measures in this field-based environment. Force plates require computer based systems and electronics which are not easily implemented into field settings, however, the Notch motion sensor system has been advertised and used in previous research in the field based setting with some accuracy to measure joint angles. The use of the Notch motion sensors system could potentially provide the missing piece to allow for researchers to collect accurate and meaningful kinematic data in the field-based setting and should be explored in the future. Lastly, as discussed, a potentially large impact could be the role of muscle and physical fatigue of the boot wearer from the additional weight and stiffness of the mining boots. Additional research could be performed to look at the effect of the three different mining boots on user fatigue levels measured within the laboratory setting and the implications this would have for the mine workers.

4.3 Limiting Factors

During data collection and analysis there were several limitations that resulted in an incomplete data set. The measures that were unable to be collected or reported on are outlined below:

1) The Video recording system used during the experimental phase of the study originally appeared to be of high enough resolution to capture video data adequate to measure spatiotemporal variables for the lower limb. However, during the analysis phase, the video resolution during playback was found to be not high enough quality for lower limb markers to be digitized accurately, therefore, the variables Stride Length, Walking Velocity, and Toe Height Clearance were not determined or explored.

2) The Notch system was cumbersome to use during the data collection phase because each trial required roughly 2 minutes of download time after the individual trial was completed. If there was an attempt to let multiple trials take place then download the resulting data onto the application, this would result in the application crashing and complete loss of the data. This problem was discovered during the first round of data collection, so the study design was adapted to include time in between each individual trial to allow for the download phase. Additionally, during the experimental phase the Notch motion sensor system would often become uncalibrated which required a new calibration to be completed. Again, this was able to be resolved by ensuring the application was running properly before, during, and after each trial took place and if the system became uncalibrated then a recalibration was performed, and the trial was recompleted. For many participants this resulted in a large number of discarded trials and so they completed closer to eight or ten total trials to collect the five successful trial limit.

3) A second limiting factor that presented itself with the Notch motion sensor system was not made apparent until the data analysis phase. During analysis of the datasets it was noted that the large majority of kinematic data collected from the Notch system either became completely corrupted after storage or were corrupted in small but analytically relevant ways. Namely, the corruption problems resulted in very noticeable differences in the measured joint angle data that could not have physically taken place during the trials. These corrupted datasets included widely fluctuating drift and joint angles that flipped measurement signs (example flexion flipped to extension), among other disturbances to the data. The overall implication from these data corruptions meant that there were very few useable data files for most joints, and zero fully complete datasets for any participant or condition. The result was that the kinematic data were not reported for any participant or condition, therefore, the effect of the footwear conditions on joint angles could not be discussed in this study.

In total, the limiting factors that arose namely during the data analysis phase meant that there was no reportable data for Joint Angles, Stride Length, Walking Velocity, or Toe Height Clearance.

4.4 **Conclusion**

In conclusion, this study looked to uncover more information and data regarding direct and subjective measures of gait characteristics and perceived comfort for three distinct underground mining boots. The study utilized a novel general population and tested within a laboratory setting with three commonly used underground mining boots. The measurements obtained during the study could indicate a potential increase in slips, trips, and falls risk due to the cumbersome nature of the mining boots and the hypothesized increase in muscular fatigue that could manifest from a worker's use of these boots. Two types for rubber mucker boots and one leather lace-up boot was evaluated in the study. The leather lace-up boot was found to have the least impact on the user's force profiles and forces and was preferred by our novel participants for their comfort and usability. By using these adjustable, lighter weight boots there may be the potential to decrease the incidence of worker fatigue, worker discomfort, and slips, trips, and falls related injuries in their workplace. In addition, the information gathered here supports the need for future studies to be conducted specifically looking to include implementing similar research directly with underground mine workers and measurement within the underground mine setting.

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Appendix A: Consent Form

Consent Form

"The Effect of Underground Mining Footwear on Lower Limb Gait Characteristics"

I, ____________________________________, am interested in participating in the study **"The Effect of Underground Mining Footwear on Lower Limb Gait Characteristics"** lead by Corey Bouwmeester, Masters in Human Kinetics (MHK) student, under the supervision of Dr. Tammy Eger, REB File Number 6012184. The proposed study is to determine the effect that underground mining footwear has on the lower limb motion.

I understand that I am ineligible to participate if I have had a lower limb and/or back injury in the past 6 months or if I wear orthotics.

If I agree to participate, I will be asked to complete a short questionnaire to determine height, weight, age, shoe size and past experience with safety footwear. I understand that the testing for this experiment will take place over the course of one day for upwards of 3 hours with a maximum of 2 hours of light physical activity (walking).

I understand I will be given three pairs of underground mining footwear provided to me by the Principal Investigator and I am expected to bring in one pair of my own athletic/running shoes the day of testing. Once the testing day has been completed I understand that I must return all three of the underground mining footwear provided to me by the researchers. I understand that I will be video recorded using a motion analysis camera and software, have 8 small sensors attached to my lower body and abdomen with adjustable straps, and step upon a series of force plates.

I understand that I will be required to complete a series of walks across the "Laboratory Walkway" under four footwear conditions. The walks will require me to perform trials where I step my left and right foot onto the corresponding force plates. I will be given practice trials until I can complete the proper foot placement in a repeatable manner. I will complete five successful measurement trials under each of the four footwear conditions. The trials for each footwear condition will involve upwards of 20 minutes of walking and I will be given 10 minutes between each condition where I will complete a comfort questionnaire about the footwear and rest before the next footwear condition. I understand that the experiment will take place over a 3-hour period on one testing day.

If I agree to participate, I understand that double sided tape and medical grade tape will be used to attach equipment sensors to my body. I have been informed that in rare circumstances a participant may develop a rash or allergic reaction to the tape. The rash

will likely fade in 24 hours, however, should the rash last longer I am advised that I should seek medical attention. If at any time I am itchy I can withdraw from the study.
My participation is strictly voluntary, and I can withdraw from the study or refuse to participate at any time during the study without any penalty. I have been informed that only members of the research team will have access to the data collected. All data recorded will remain strictly confidential and my individual results will not be posted. All collected data will be coded with a subject number and stored in a locked filing cabinet or password protected computer that only members of the research team can access. I understand that there is no direct benefit to me for participating in this study.

There are two copies of this consent form, one which I keep and one that the researcher will keep.

If I have any questions or concerns about the study or about being a participant I can contact the lead researcher, Professor Tammy Eger:
Email: teger@laurentian.ca
Phone: 705-675-1151 ext 1005

If I have any questions or concerns surrounding the ethical conduct of the study I may contact the Research Ethics Officer, Laurentian University Research Office, telephone: 705-675-1151 ext 3213, 2436 or toll free at 1-800-461-4030 or through email: ethics@laurentian.ca

I agree to participate in this study.

Participant Signature: ______________________________ Date: ________________________

Witness Signature: _________________________________ Date: ________________________

Thank you for your participation.

Appendix B: Recruitment Script

Recruitment Script

Hello, my name is Corey Bouwmeester, I am a Masters student with the Centre for Research in Occupational Safety and Health (CROSH) at Laurentian University in the Department of Human Kinetics. I am working on my thesis project titled "The Effect of Underground Mining Footwear on Lower Limb Gait Characteristics". My thesis supervisor is Professor Tammy Eger, Research Chair of CROSH.

In the underground mining industry, a large portion of injury claims are the result of slips, trips, and falls. Past research has studied the effect of various footwear on slip, trip, and fall risk but research into specifically underground mining footwear remains unknown. By studying the effect that underground mining safety footwear has on worker lower limb motion and comfort we can determine how the footwear affects slip, trip, and fall risk.

This research is looking to recruit participants between 18-65 years of age to participate in this study. Participants will be asked to come into the undergraduate laboratory in the School of Human Kinetics to complete the experiment.

Experiment: Participants are required to complete upwards of 2 hours of light physical activity (walking) in a laboratory setting while wearing underground mining footwear. Each footwear condition will involve 20-30 minutes of walking followed by a 20-minute rest period during which participants will complete a short questionnaire about their comfort with the footwear. The full testing experiment time will be less than 3 hours on one day. In the experiment the participant will have 8 small "Notch" accelerometers placed onto their chest and lower body that will measure the joint angles of their lower limb, they will be recorded by a Microsoft Kinect camera to determine their lower limb and postural motion as they walk across the walkway, and they will be recorded by an additional video camera to determine their foot clearance. The walkway has two force plates embedded in the ground and participants will land with their left and right foot upon on the corresponding force plates. The participants will complete multiple passes of the walkway under each footwear condition.

The study is restricted to participants between the ages of 18-65 with no lower limb and/or back injuries in the past 6 months and do not wear orthotics.

There is no immediate benefit to you as a participant in this study. You are able to withdraw from the study at anytime without penalty.

If you are interested in participating in this study, please contact lead researcher Corey Bouwmeester at cbouwmeester@laurentian.ca or in person at CROSH in the Department of Human Kinetics at Laurentian University.

Thank you for your consideration.

Appendix C: Entrance Questionnaire

ID # (investigator to complete):

Answer the following questions to the best of your knowledge.

Name: Date of Birth:

Gender:

Height: Weight: Shoe Size:

Email:

Would you like to be made aware of the results of the study?

Yes No

Have you had a musculoskeletal injury to the lower limb and/or back in the past 6 months?

Yes No

Have you had surgery on your lower limb or back in the past 2 years?

Yes No

Do you wear orthotics or have you been diagnosed with a foot condition by a medical professional?

Yes No

How often would you say you have worn safety footwear in the past year (metatarsal or toe cap containing footwear with a stiffened sole to prevent punctures)? Circle daily if you wear safety footwear in your workplace.

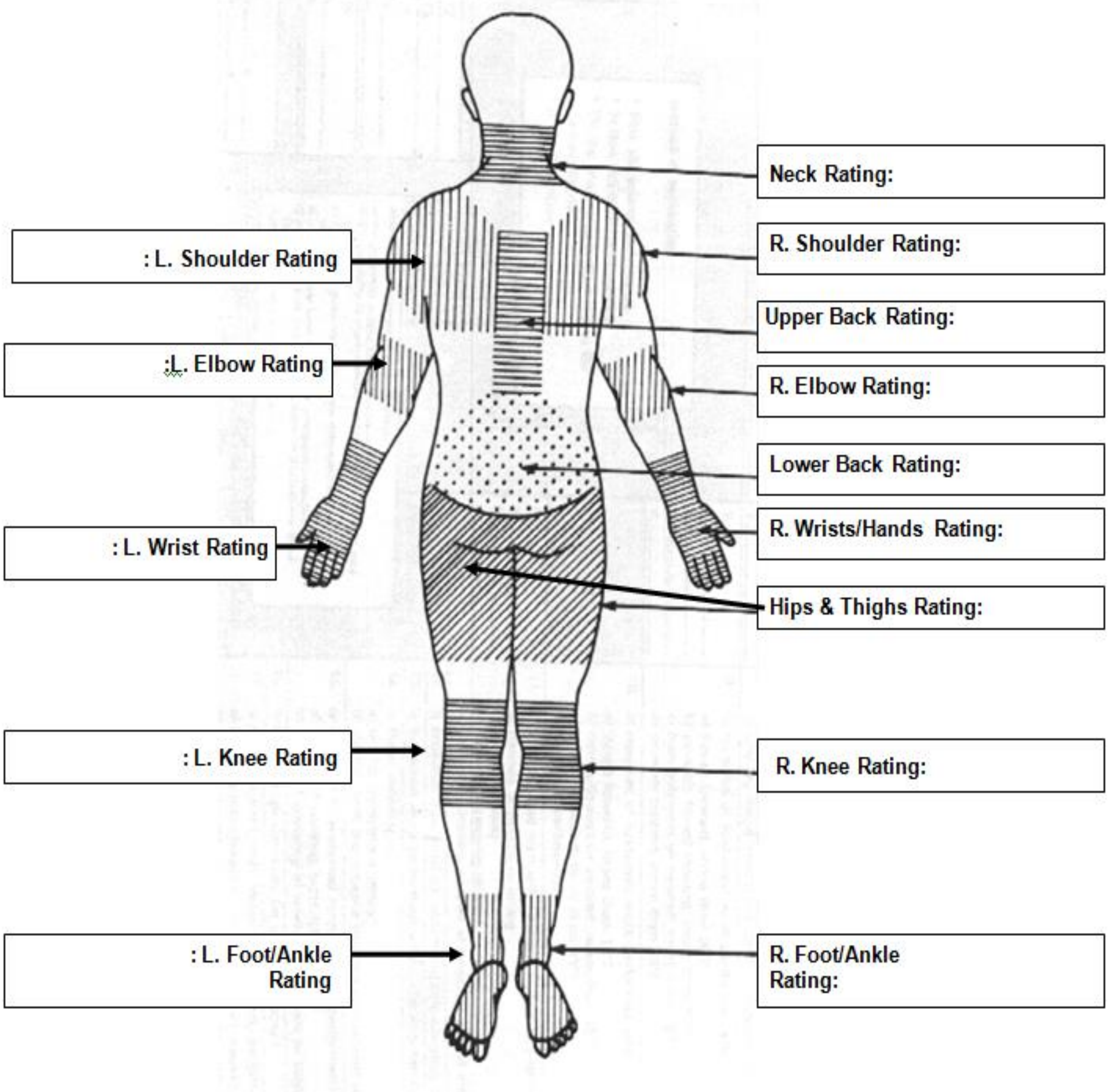
Never	Haven't worn safety footwear in the past
Rarely	Less than 1 time a month
Sometimes	More than 1 time a month but less than once a week
Often	More than once a week but less than 3 days a week
Daily	4 or more days a week

Appendix D: Discomfort Survey Date:________________

The body has been divided into fourteen different regions (right). For each body region please indicate if you have had any trouble (**ache, pain, numbness or discomfort**) in the region in the last 2-weeks. If you have had trouble in the area in the last 2-weeks rate the severity of the trouble, at the worst episode that you felt.

Rating Score

1 = mild ache, pain, numbness or discomfort
2 = moderate ache, pain, numbness or discomfort
3 = severe ache, pain, numbness or discomfort
4 = very, very severe ache, pain, numbness or discomfort



Appendix E: Footwear Comfort Questionnaire **Name:__________________**

Footwear Condition: _______________
Date and Time:_________________

The below questions should be about the current footwear compared to a typical running shoe. 1 is lowest and 9 is highest.

1) **How would you rate the overall comfort of this footwear?**

1 2 3 4 5 6 7 8 9

2) **How would you rate the mobility of this footwear at the ankle?**

1 2 3 4 5 6 7 8 9

3) **How stable did your ankle feel in this footwear when walking the course?**

1 2 3 4 5 6 7 8 9

4) **How would you rate your perceived exertion over the course of the experiment when using this footwear?**

1 2 3 4 5 6 7 8 9

5) **Overall how would you rate this footwear if you had to use it daily for upwards of 8 hours?**

1 2 3 4 5 6 7 8 9

6) **Why did you choose the rating you gave for question 5?**

____

____

____

____

____

Appendix F: Exit Questionnaire **Participant #__________**

Date: ________________

Oliver **Titanium** **Viking**

Overall Preference:
If you had to choose a boot to wear for an 8-hour working shift which would you select?

Rank: **1st Choice ____**

2nd Choice ____

3rd Choice ____

Never Choose to Wear ____________________________________

Why?

____

____

____

If you could redesign the boot what changes would you make and why?

____

____

____

Exit Questionnaire: Part 2

Put the letter for the rating you would give the boot when comparing them to one another. 1 being the WORST and 9 being the BEST. You can rate them anywhere along the scale, please rate each footwear for each characteristic.

Oliver- A

Titanium - B

Viking - C

	WORST								BEST
Comfort	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Mobility	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Stability	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Exertion	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	WORST								**BEST**

Thank you for your participation in this study

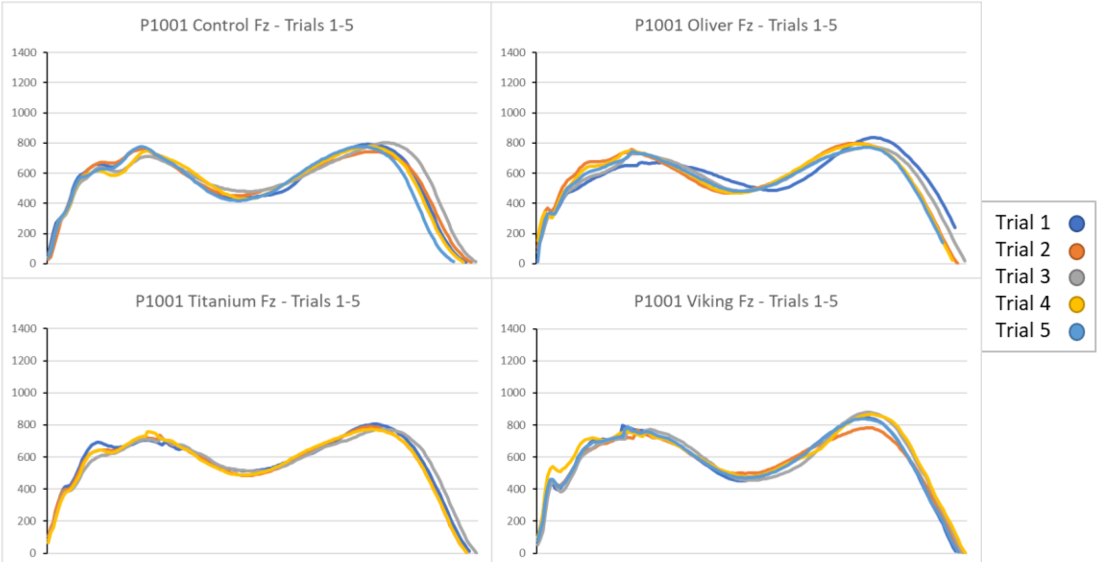
Appendix G: Data Sets

Participant	Control				
	Heel Strike Peak Force (FBW)			**Toe Off Peak Force (FBW)**	
	Average 1st Heel Strike Peak Impact (FBW) by Participant	Average 2nd Heel Strike Peak Impact (FBW) by Participant		Average 1st Toe Off Peak Impact (FBW) by Participant	Average 2nd Toe Off Peak Impact (FBW) by Participant
1001	1.136621612	1.090472367		1.175497248	1.05888639
1002	1.093653173	1.130021007		1.189364946	1.13758156
1004	1.105484823	1.133388954		1.142964653	1.325147814
1005	1.182875662	1.177730197		1.139402761	1.164902194
1006	1.367959167	1.254429111		1.170724165	
1007	1.425348403	1.384095433		1.225308019	1.453481721
1008	1.266176437	1.235826125		1.299443728	1.259376198
1009	1.187196513	1.25668796		0.961839075	1.39649366
1010	1.174171881	1.152463676		1.340771316	
1011	1.111972906	1.048876358		1.126026693	1.075383561
1012	1.119280825	1.073509195		1.128141491	1.164832575
1013	1.109901617	1.097188571		0.943692585	1.113858473
1014	1.043296398	1.118767125		1.056674691	1.031221023
1016	1.233569848	1.192603585		1.388846326	
	Sample Size	28		**Sample Size**	25
	Avg Peak Force	**1.175127462**		**Avg Peak Force**	**1.178794515**
	STD of Peak Force	0.098318655		**STD of Peak Force**	0.131753991

Participant	Oliver				
	Heel Strike Peak Force (FBW)			**Toe Off Peak Force (FBW)**	
	Average 1st Heel Strike Peak Impact (FBW) by Participant	Average 2nd Heel Strike Peak Impact (FBW) by Participant		Average 1st Toe Off Peak Impact (FBW) by Participant	Average 2nd Toe Off Peak Impact (FBW) by Participant
1001	1.102731689	1.061568672		1.200923847	
1002	1.035370317	1.132063277		1.018507256	1.265180221
1004	1.136440364	1.102275329		1.227189074	1.155806695
1005	1.22857708	1.180025228		1.20083313	1.200550032
1006	1.300971675	1.233723566		1.176193582	
1007	1.398550942	1.360243215		1.200039352	1.75084881
1008	1.264171557	1.27064422		1.34012968	1.154164534
1009	1.117850068	1.149899322		1.003574328	1.409771156
1010	1.103092433	1.181855708		1.352399876	
1011	1.112455714	1.078436853		1.187036605	1.073198276
1012	1.103720445	1.082872399		1.138854912	
1013	1.06848881	1.028820299		0.912527331	1.309430328
1014	1.063398332	1.073539646		1.006101956	1.105804968
1016	1.052355131	1.119749104		1.31095076	1.421242286
	Sample Size	28		**Sample Size**	24
	Avg Peak Force	**1.147996121**		**Avg Peak Force**	**1.213385791**
	STD of Peak Force	0.097916221		**STD of Peak Force**	0.173137462

Participant	Titanium				
	Heel Strike Peak Force (FBW)			Toe Off Peak Force (FBW)	
	Average 1st Heel Strike Peak Impact (FBW) by Participant	Average 2nd Heel Strike Peak Impact (FBW) by Participant		Average 1st Toe Off Peak Impact (FBW) by Participant	Average 2nd Toe Off Peak Impact (FBW) by Participant
1001	1.101515422	1.144848992		1.184946226	1.552718067
1002	1.012301113	1.095784311		1.112460286	1.076588592
1004	1.119136544	1.118613984		1.172865298	1.391198302
1005	1.133658525	1.128643332		0.982788496	1.139099364
1006	1.279712978	1.225966521		1.220521338	
1007	1.411494915	1.319533456		1.122413861	1.088306614
1008	1.221498432	1.199445281		1.338131187	1.219544794
1009	1.170512694	1.184713603		0.953051639	1.311574494
1010	1.158756779	1.170859332		1.356563476	
1011	1.114231651	1.084866428		1.161024373	1.080570794
1012	1.093901255	1.061201253		1.153113618	1.284129074
1013	1.057605546	1.018078086		0.930713655	1.257424961
1014	1.063584242	1.052778256		1.006342695	1.232665521
1016	1.195737395	1.133450493		1.381830968	1.394558386
	Sample Size	28		**Sample Size**	26
	Avg Peak Force	**1.145443958**		**Avg Peak Force**	**1.196351772**
	STD of Peak Force	0.089762839		**STD of Peak Force**	0.152583974

Participant	Viking				
	Heel Strike Peak Force (FBW)			Toe Off Peak Force (FBW)	
	Average 1st Heel Strike Peak Impact (FBW) by Participant	Average 2nd Heel Strike Peak Impact (FBW) by Participant		Average 1st Toe Off Peak Impact (FBW) by Participant	Average 2nd Toe Off Peak Impact (FBW) by Participant
1001	1.174297589	1.163512332		1.273357266	1.045809252
1002	1.17862197	1.164047098		0.911546284	1.374926613
1004	1.192937253	1.220955106		1.223518955	1.158654429
1005	1.175287481	1.181334155		0.992639807	1.234776097
1006	1.346779571	1.275733776		1.115958598	1.498549062
1007	1.499899893	1.422038813		1.199515028	1.250624593
1008	1.356661151	1.329629375		1.339128982	1.290855133
1009	1.278584553	1.339297324		0.987394352	1.427336557
1010	1.189472617	1.234800955		1.364969629	
1011	1.246324872	1.138725945		1.182124619	1.226838822
1012	1.106600097	1.071023906		1.066842675	1.312599803
1013	1.171204287	1.107674554		0.964161895	1.266347332
1014	1.047353204	1.079751304		0.95173131	1.301076308
1016	1.327304154	1.281181707		1.411865074	
	Sample Size	28		**Sample Size**	26
	Avg Peak Force	**1.225036966**		**Avg Peak Force**	**1.206659557**
	STD of Peak Force	0.109472865		**STD of Peak Force**	0.160867253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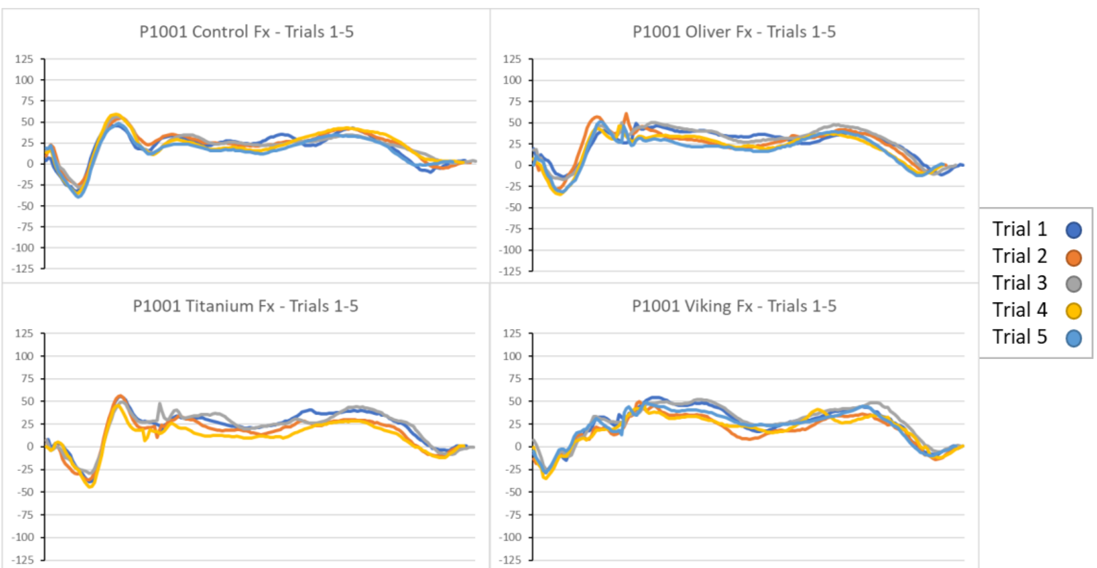
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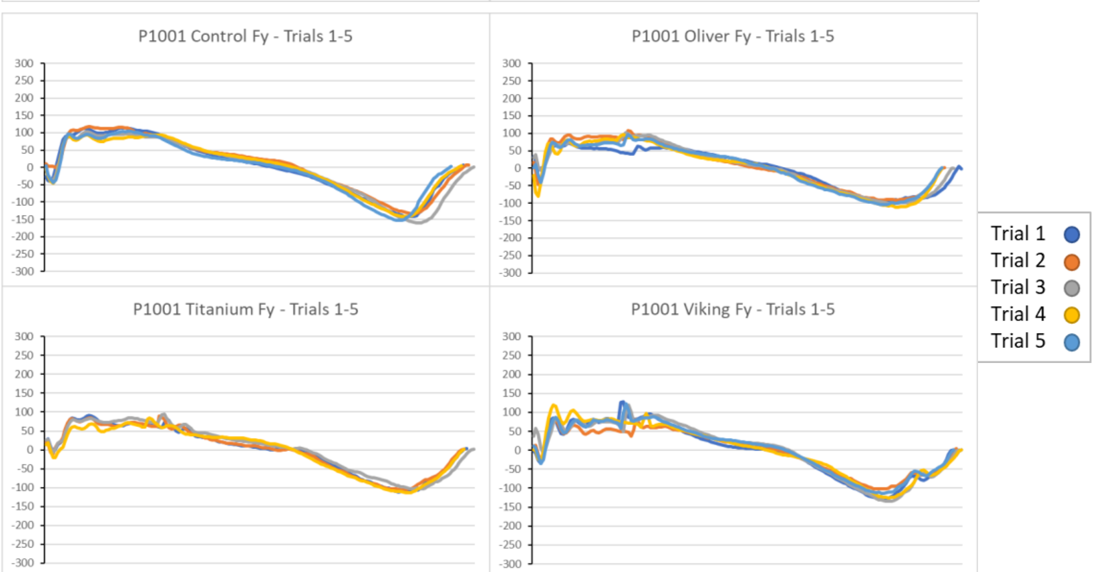
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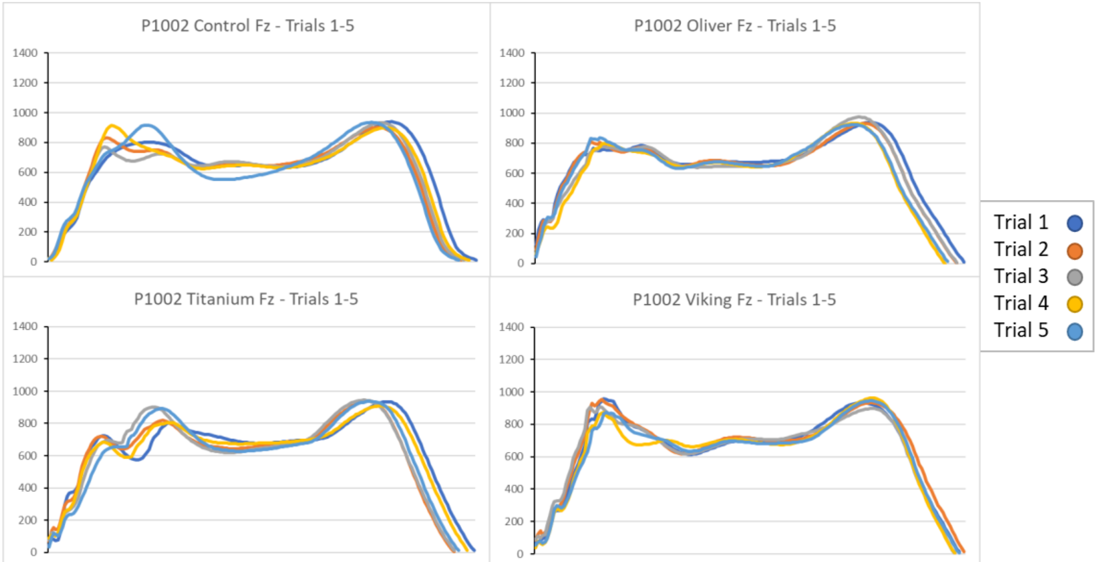
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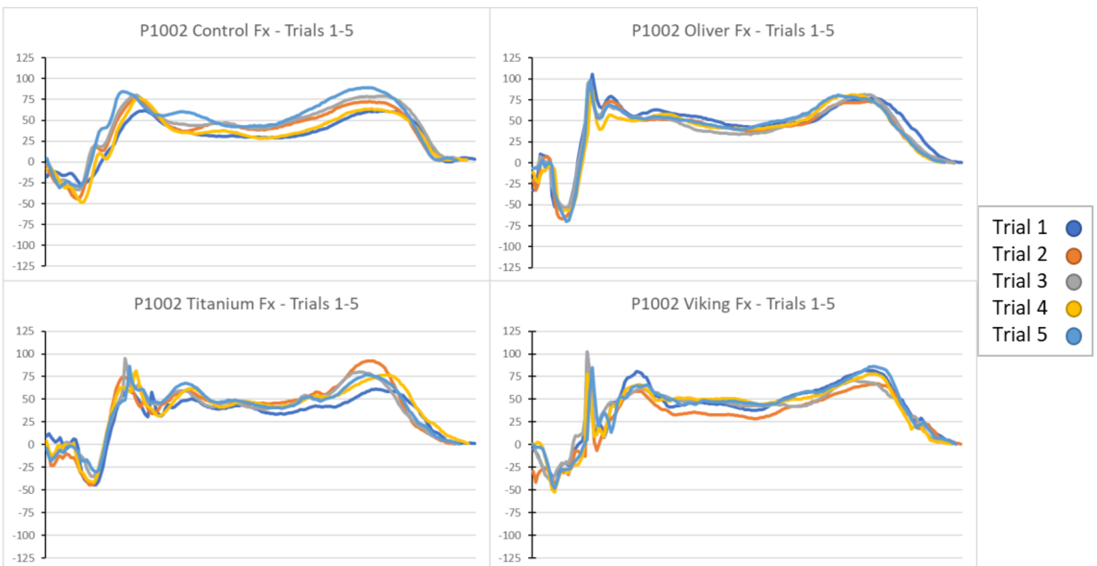
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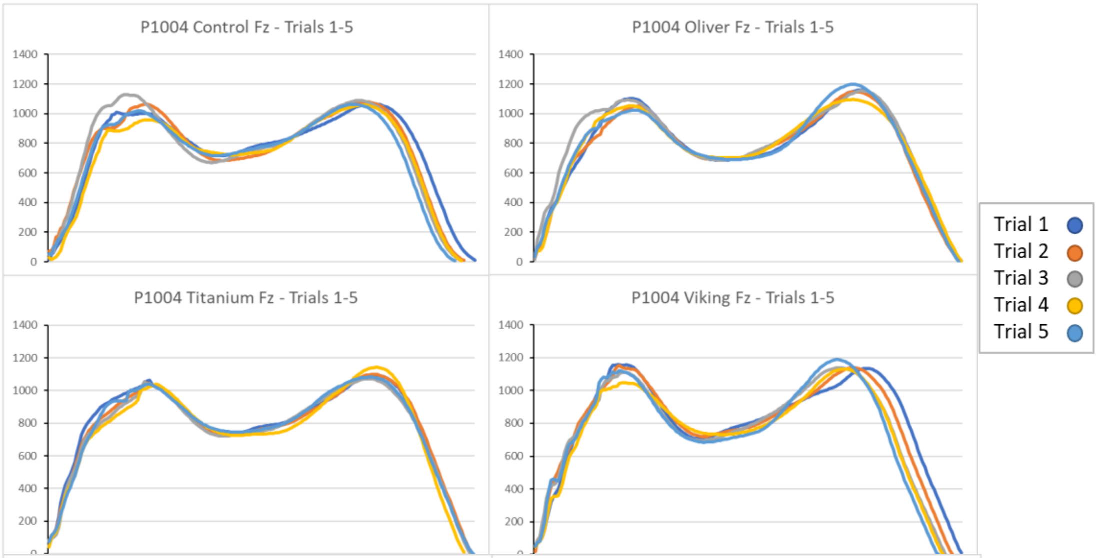
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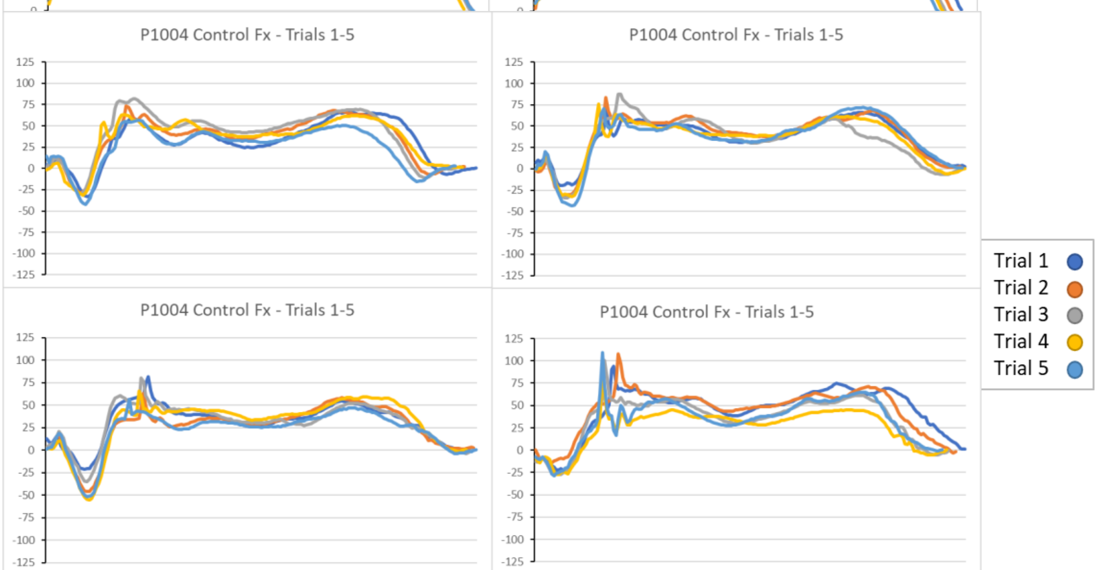
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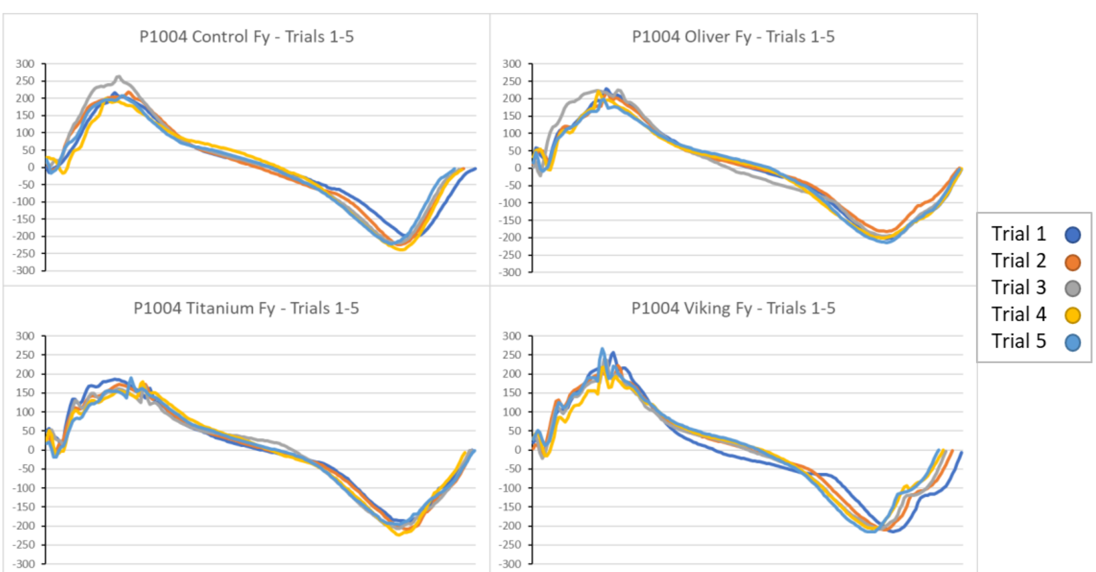
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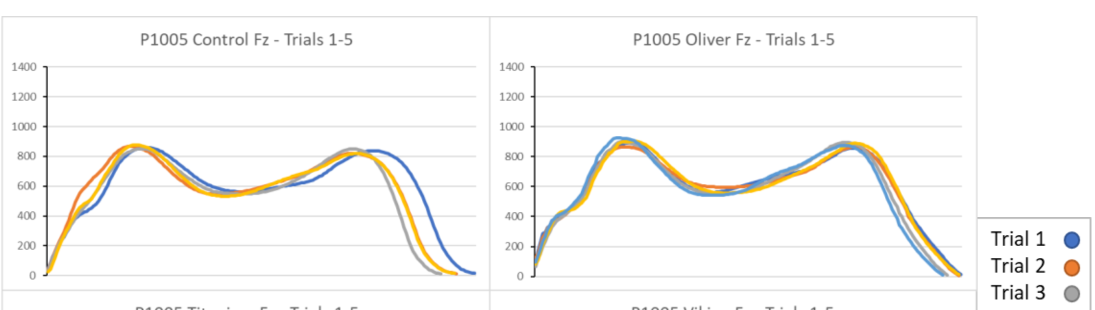
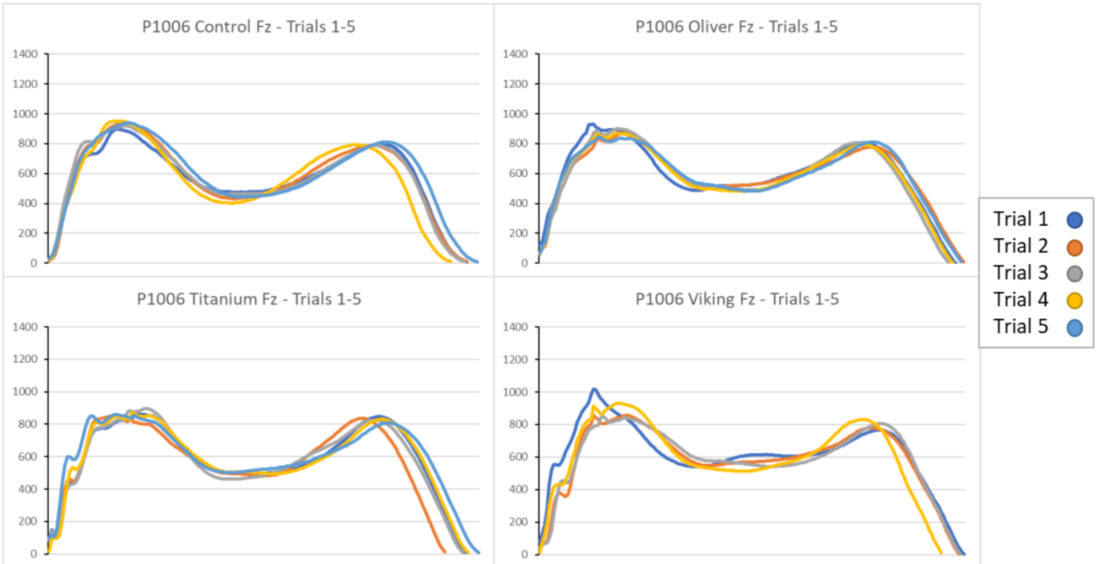
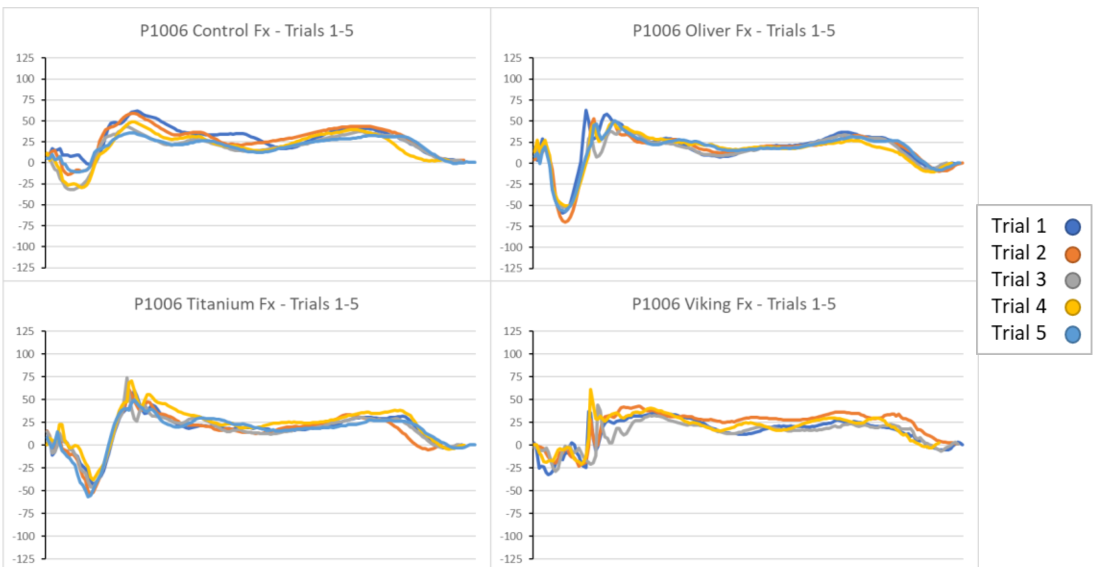
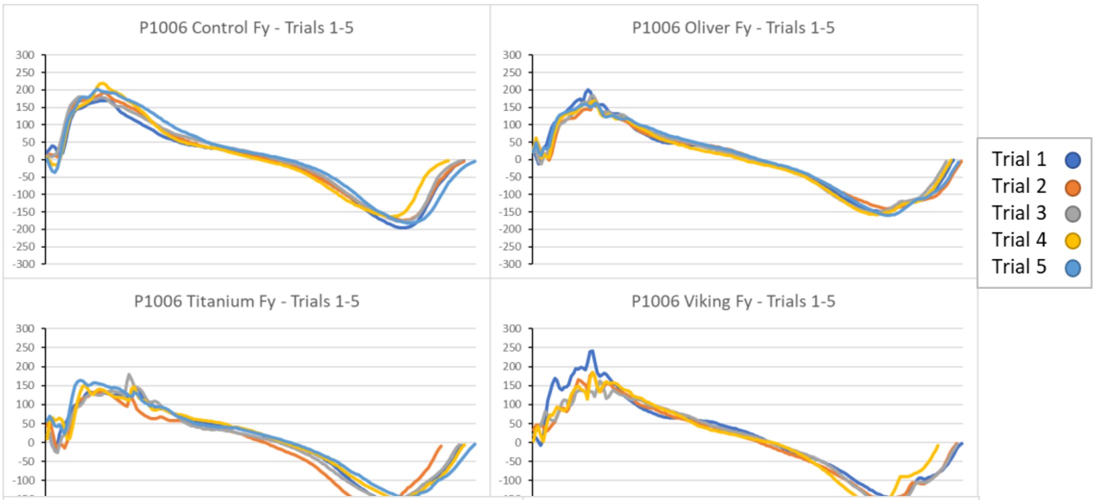
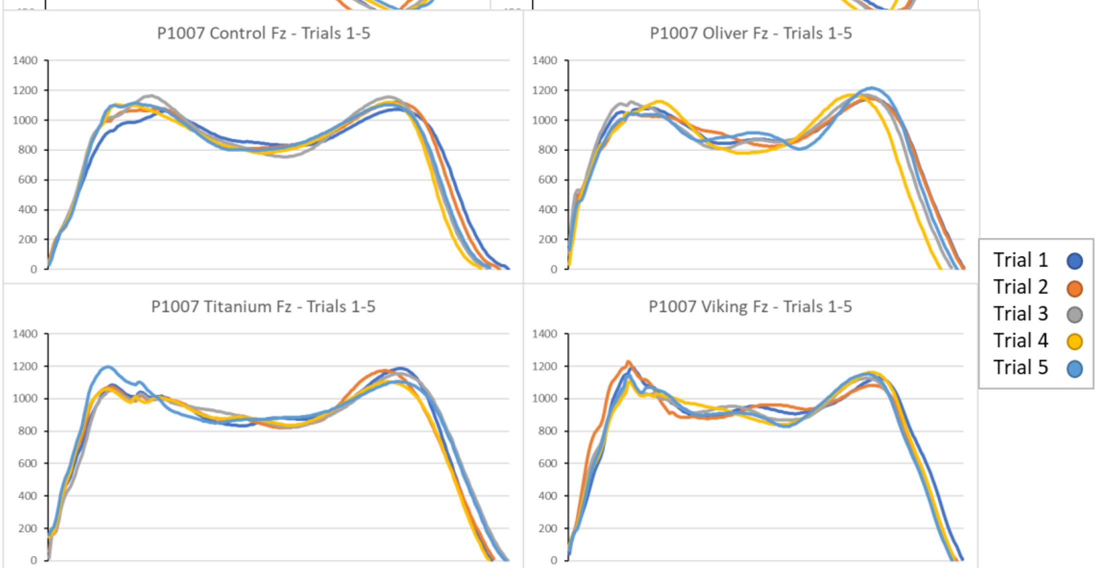
Trial 4
Trial 5

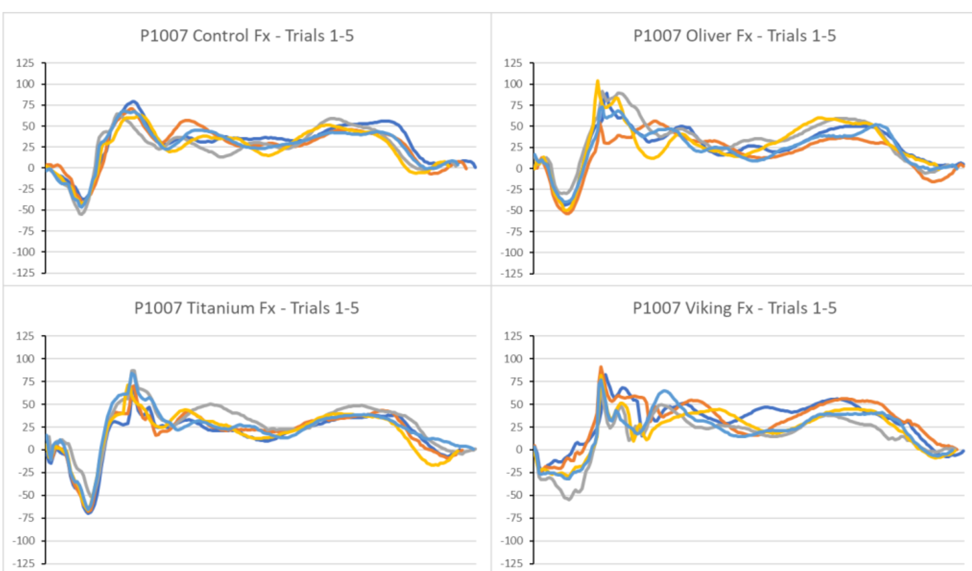

P1005 Control Fz - Trials 1-5
1400
1200
1000
800
600
400
200
0
P1005 Oliver Fz - Trials 1-5
1400
1200
1000
800
600
400
200
0
Trial 1
Trial 2
Trial 3

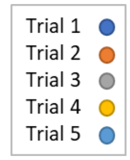

P1006 Control Fz - Trials 1-5
P1006 Oliver Fz - Trials 1-5
P1006 Titanium Fz - Trials 1-5
P1006 Viking Fz - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

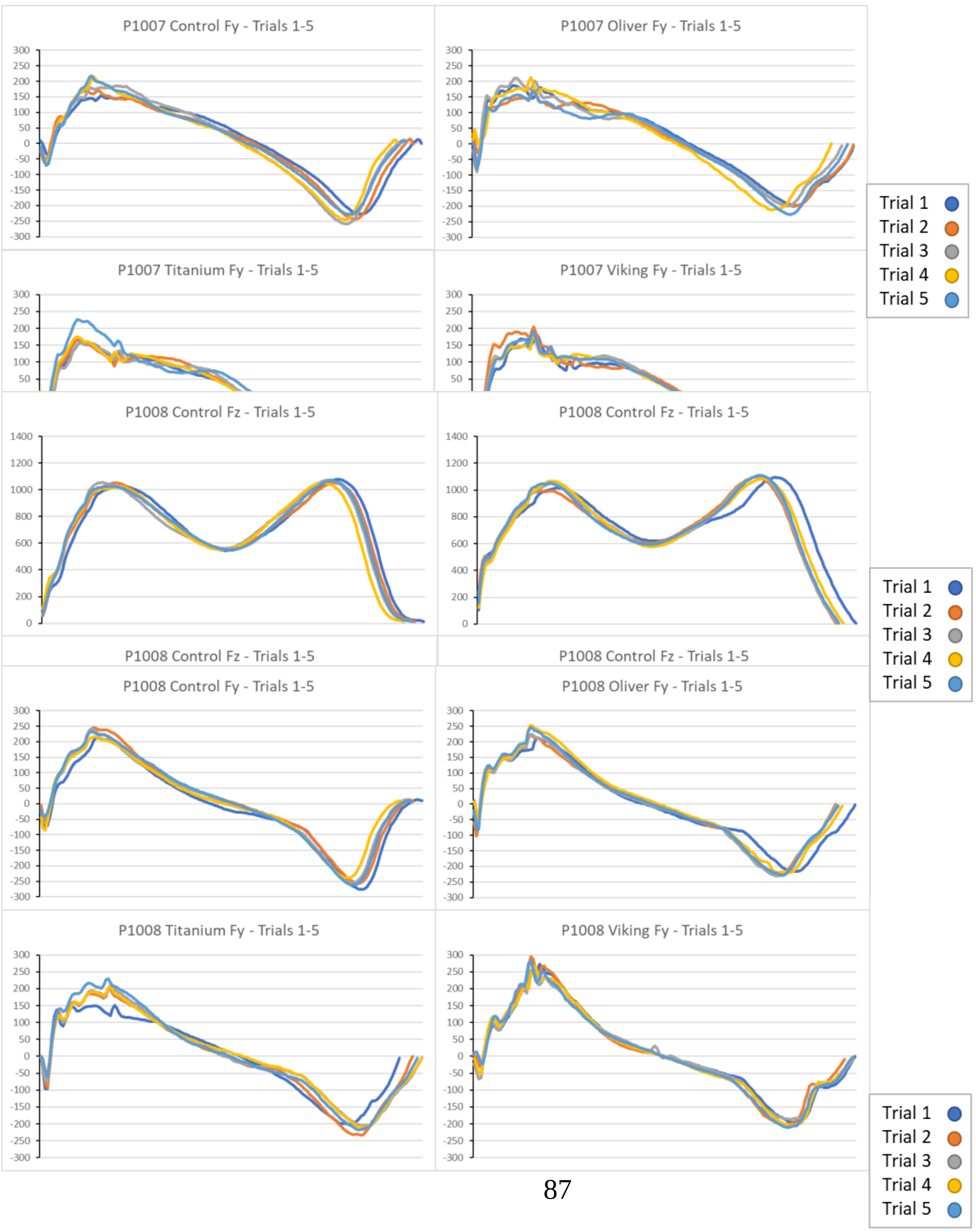

P1006 Control Fx - Trials 1-5
P1006 Oliver Fx - Trials 1-5
P1006 Titanium Fx - Trials 1-5
P1006 Viking Fx - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

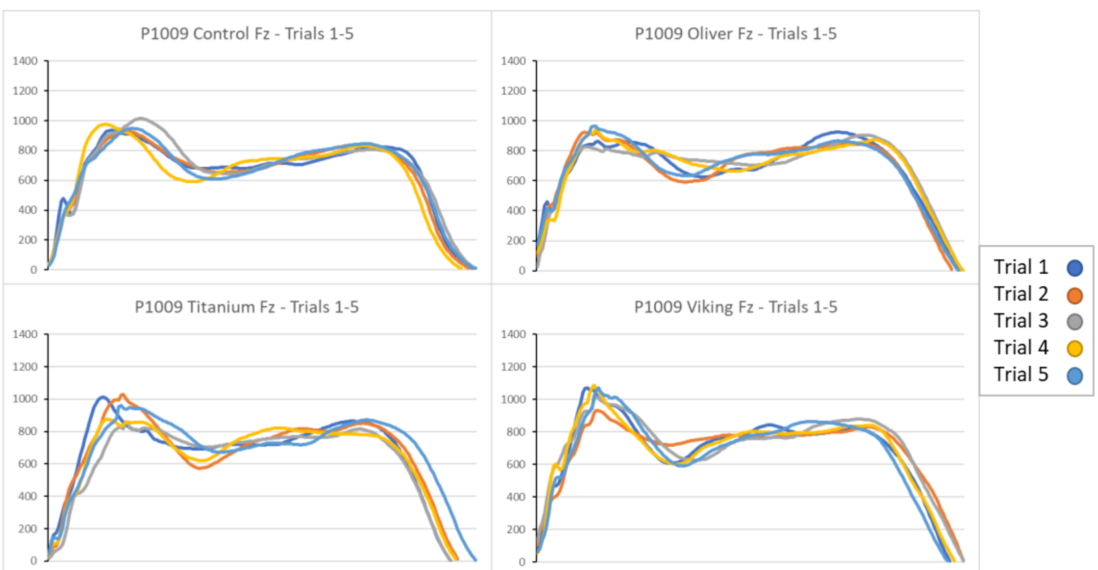

P1006 Control Fy - Trials 1-5
P1006 Oliver Fy - Trials 1-5
P1006 Titanium Fy - Trials 1-5
P1006 Viking Fy - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5


P1007 Control Fz - Trials 1-5
P1007 Oliver Fz - Trials 1-5
P1007 Titanium Fz - Trials 1-5
P1007 Viking Fz - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

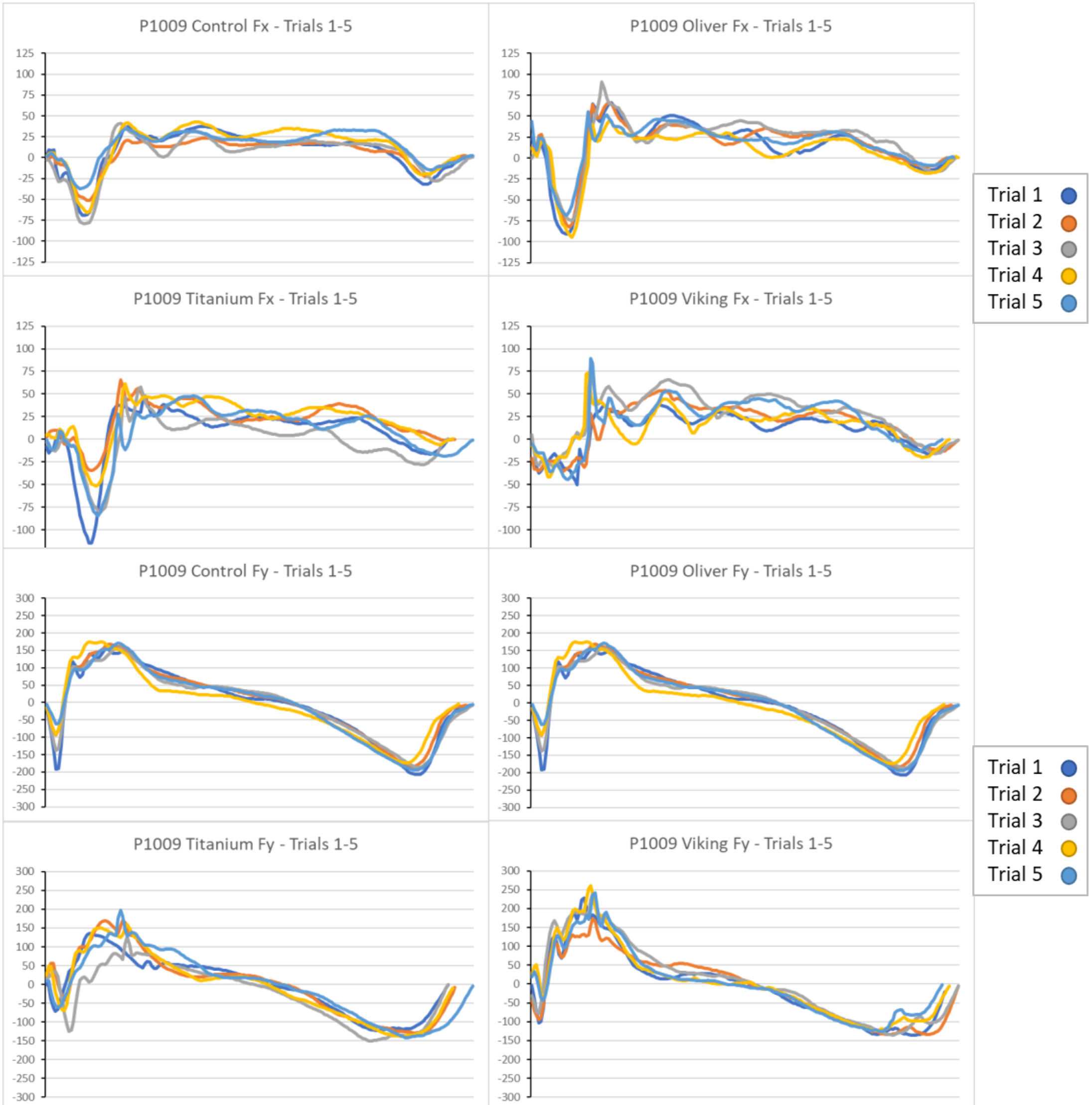

P1007 Control Fx - Trials 1-5
P1007 Oliver Fx - Trials 1-5
P1007 Titanium Fx - Trials 1-5
P1007 Viking Fx - Trials 1-5

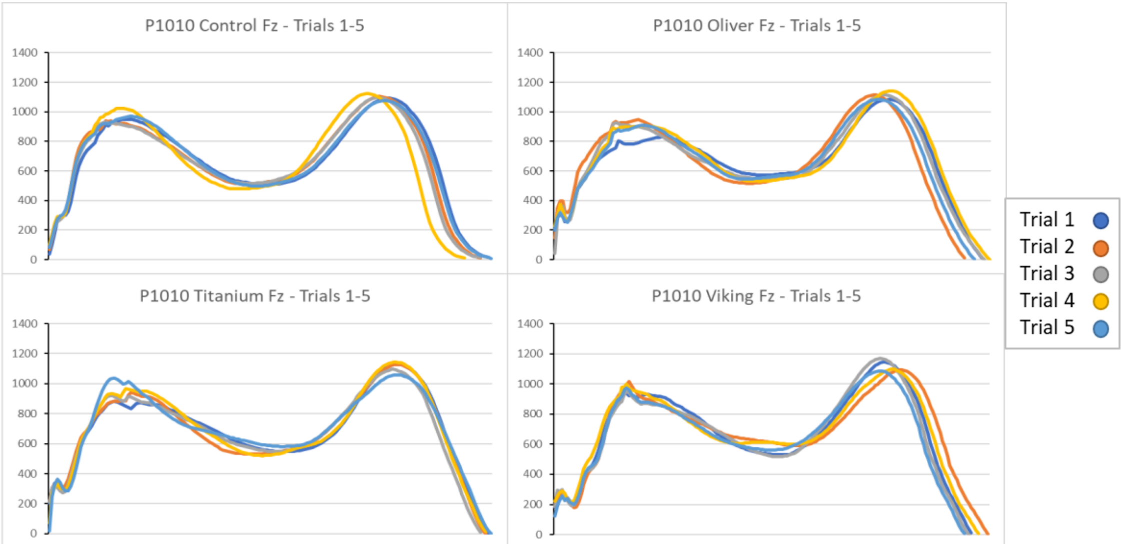

Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

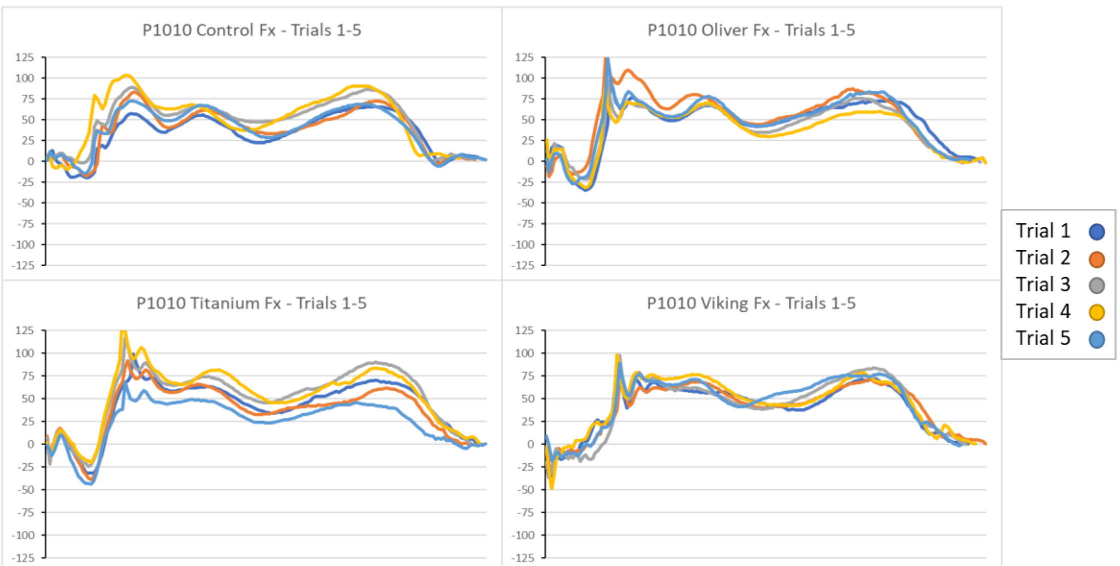

P1007 Control Fy - Trials 1-5
P1007 Oliver Fy - Trials 1-5
P1007 Titanium Fy - Trials 1-5
P1007 Viking Fy - Trials 1-5
P1008 Control Fz - Trials 1-5
P1008 Control Fz - Trials 1-5
P1008 Control Fz - Trials 1-5
P1008 Control Fz - Trials 1-5
P1008 Control Fy - Trials 1-5
P1008 Oliver Fy - Trials 1-5
P1008 Titanium Fy - Trials 1-5
P1008 Viking Fy - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

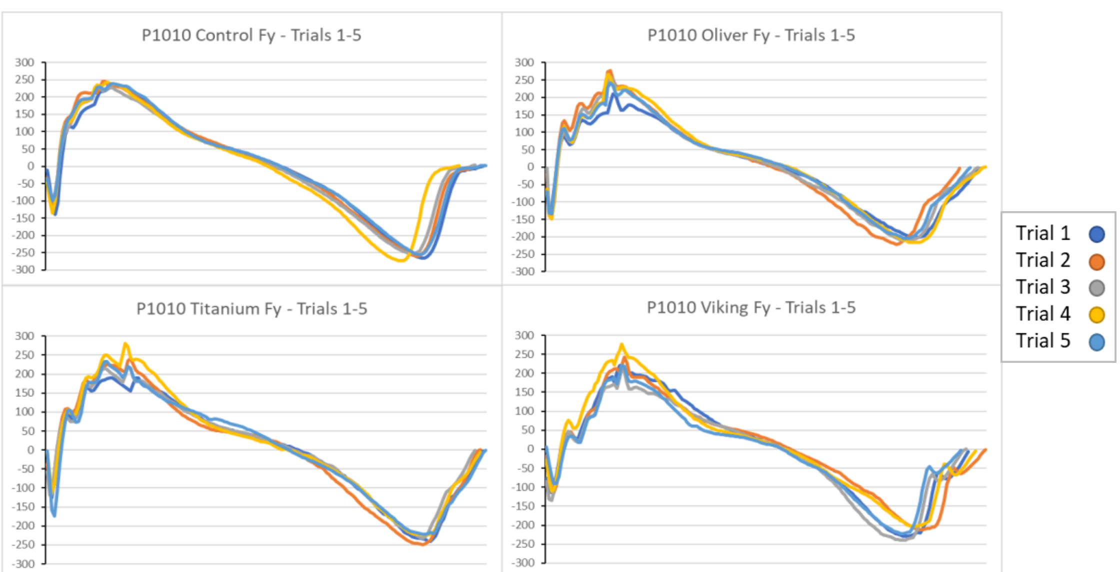


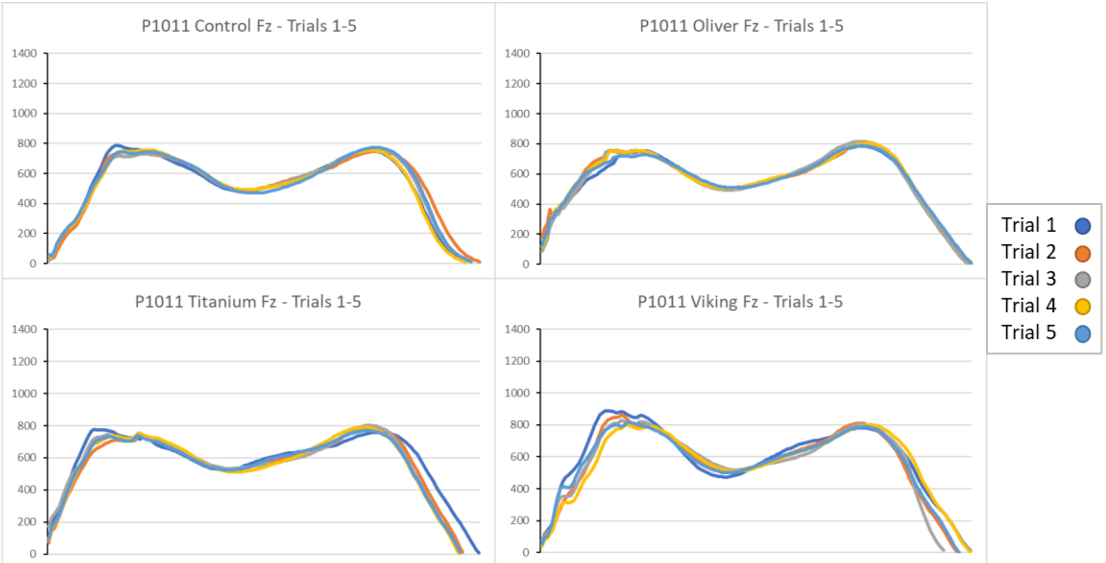
P1009 Control Fz - Trials 1-5
P1009 Oliver Fz - Trials 1-5
P1009 Titanium Fz - Trials 1-5
P1009 Viking Fz - Trials 1-5
1400
1200
1000
800
600
400
200
0
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

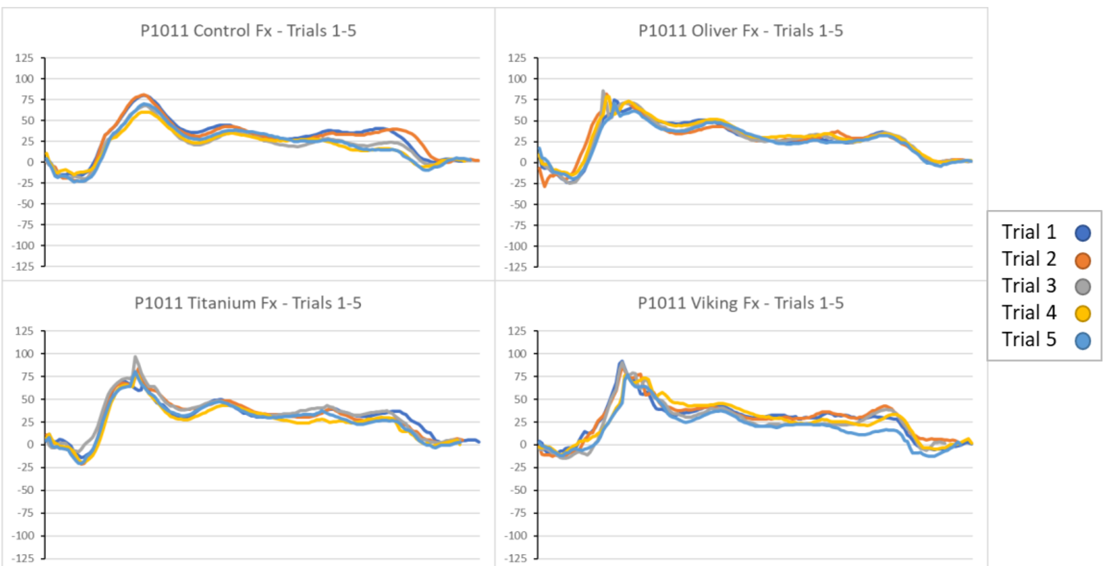

P1009 Control Fx - Trials 1-5
P1009 Oliver Fx - Trials 1-5
P1009 Titanium Fx - Trials 1-5
P1009 Viking Fx - Trials 1-5
P1009 Control Fy - Trials 1-5
P1009 Oliver Fy - Trials 1-5
P1009 Titanium Fy - Trials 1-5
P1009 Viking Fy - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

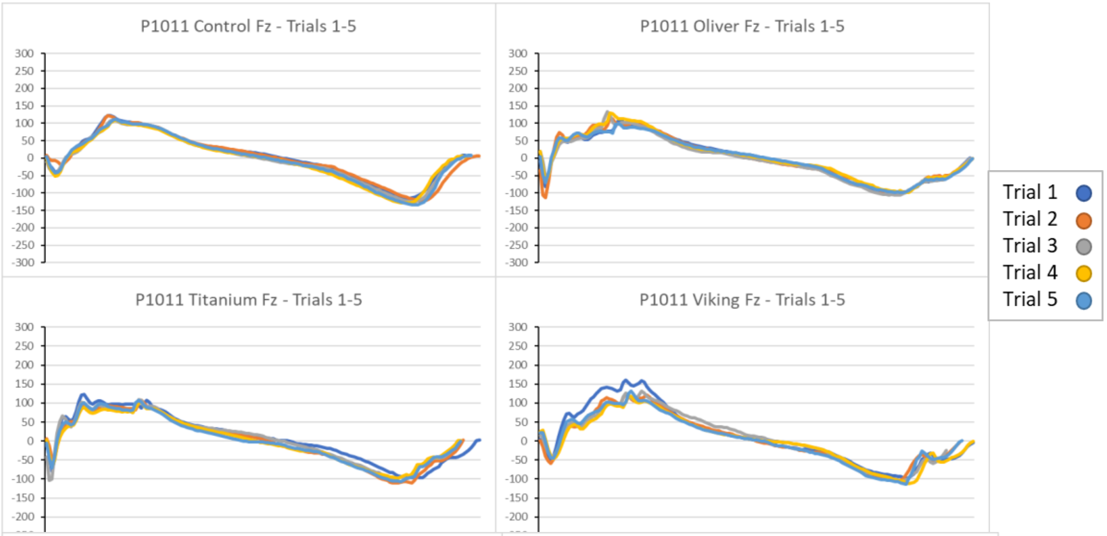

P1010 Control Fz - Trials 1-5
P1010 Oliver Fz - Trials 1-5
P1010 Titanium Fz - Trials 1-5
P1010 Viking Fz - Trials 1-5
1400
1200
1000
800
600
400
200
0
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

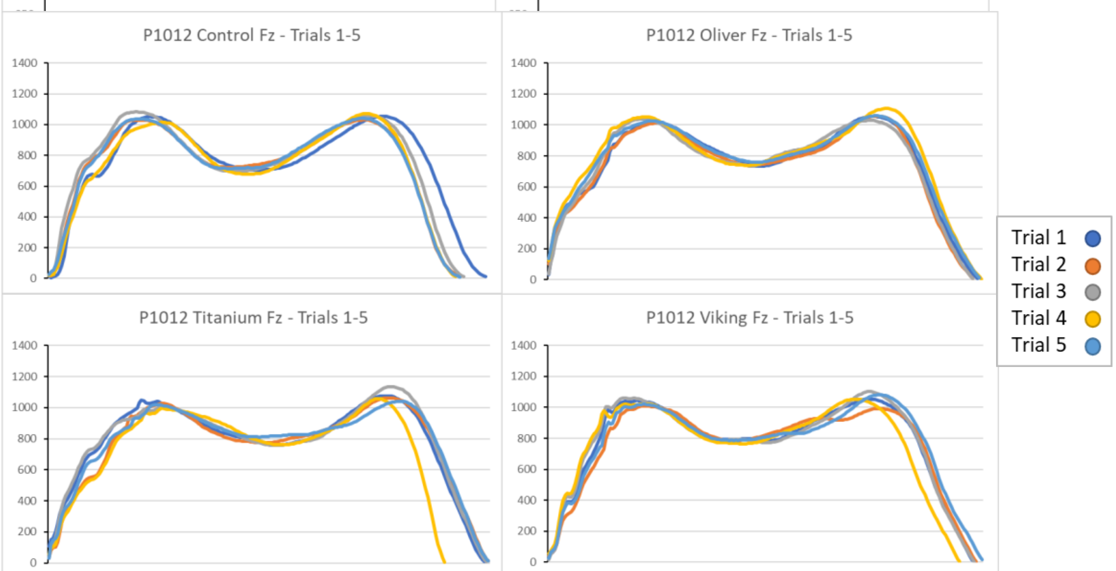

P1010 Control Fx - Trials 1-5
P1010 Oliver Fx - Trials 1-5
P1010 Titanium Fx - Trials 1-5
P1010 Viking Fx - Trials 1-5
125
100
75
50
25
0
-25
-50
-75
-100
-125
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

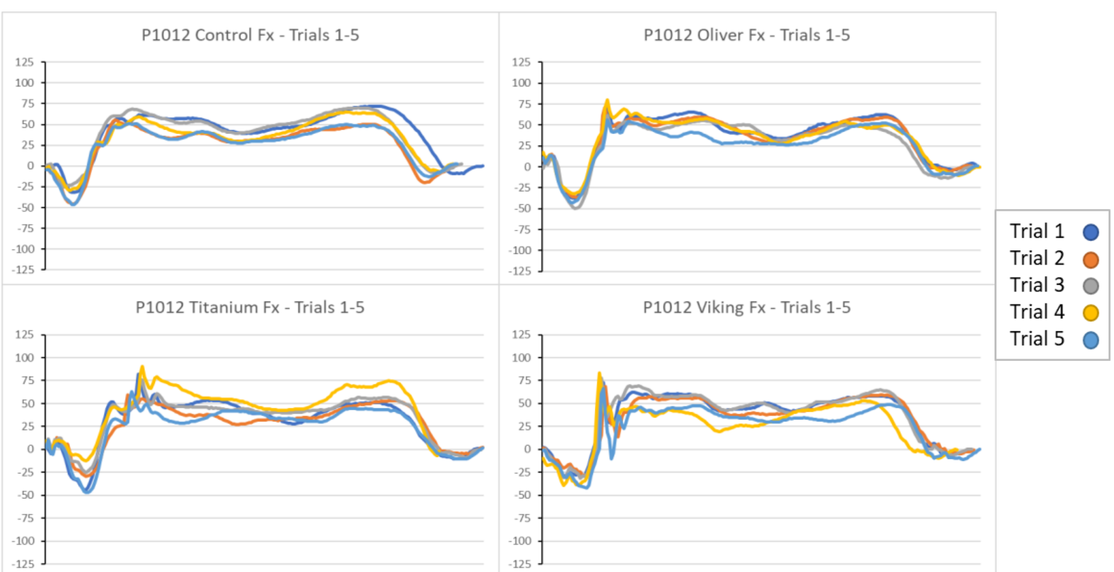

P1010 Control Fy - Trials 1-5
P1010 Oliver Fy - Trials 1-5
P1010 Titanium Fy - Trials 1-5
P1010 Viking Fy - Trials 1-5
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

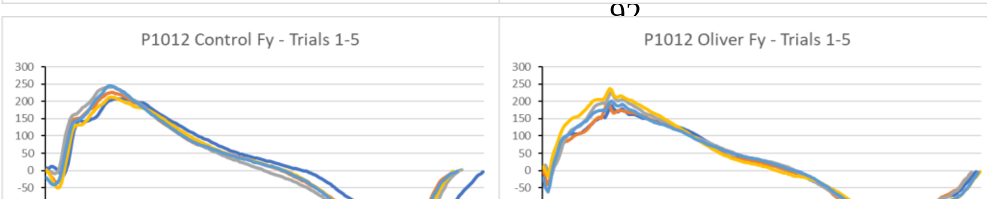

P1011 Control Fz - Trials 1-5
P1011 Oliver Fz - Trials 1-5
P1011 Titanium Fz - Trials 1-5
P1011 Viking Fz - Trials 1-5
1400
1200
1000
800
600
400
200
0
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

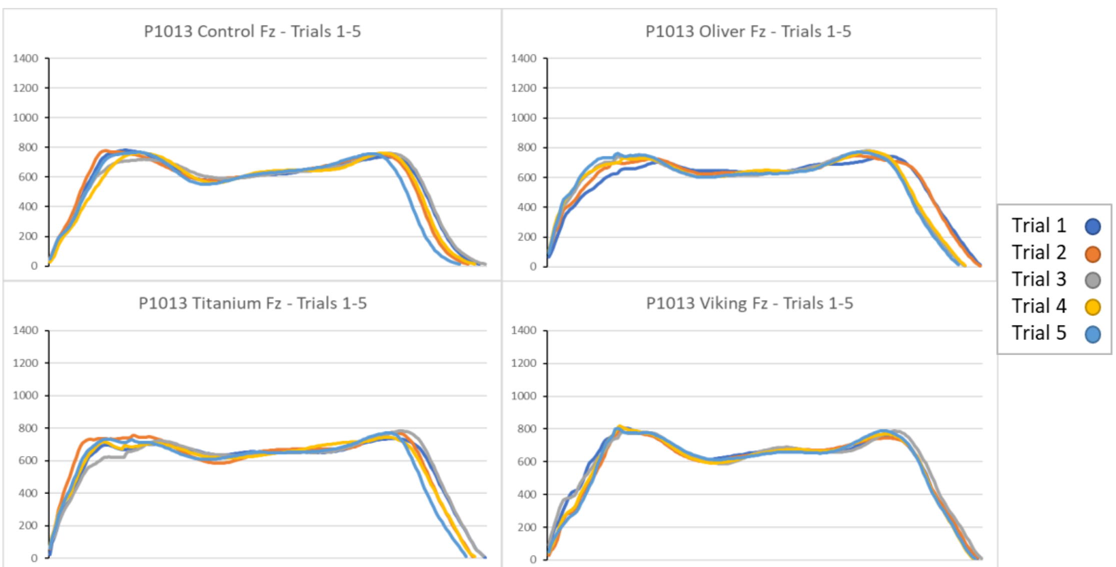

P1011 Control Fx - Trials 1-5
P1011 Oliver Fx - Trials 1-5
P1011 Titanium Fx - Trials 1-5
P1011 Viking Fx - Trials 1-5
125
100
75
50
25
0
-25
-50
-75
-100
-125
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

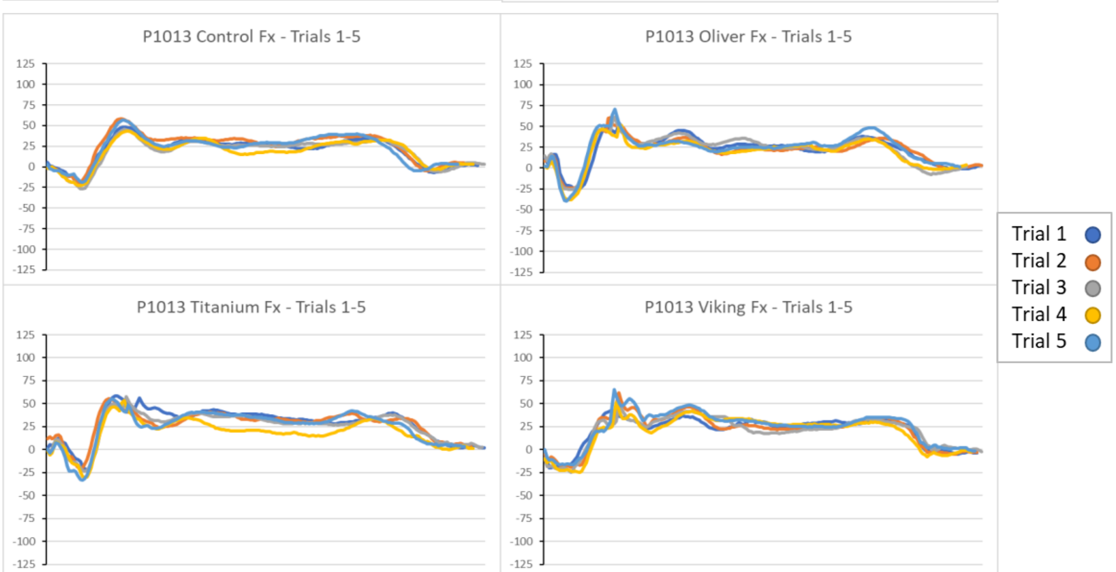

P1011 Control Fz - Trials 1-5
P1011 Oliver Fz - Trials 1-5
P1011 Titanium Fz - Trials 1-5
P1011 Viking Fz - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

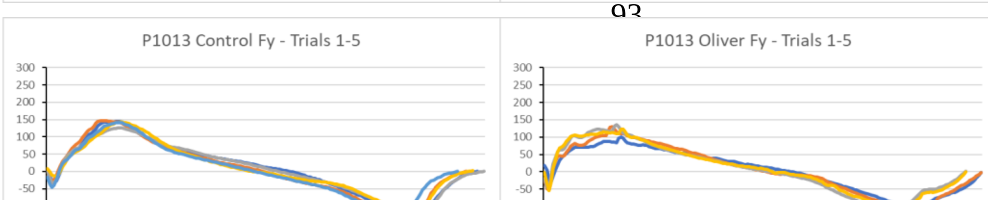

P1012 Control Fz - Trials 1-5
P1012 Oliver Fz - Trials 1-5
P1012 Titanium Fz - Trials 1-5
P1012 Viking Fz - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

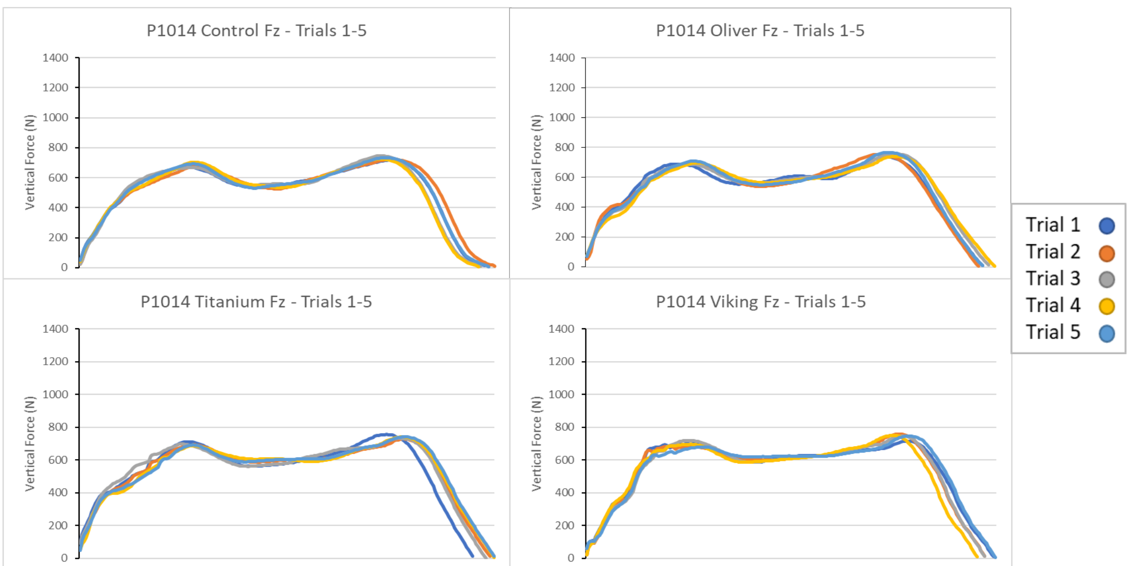

P1012 Control Fx - Trials 1-5
P1012 Oliver Fx - Trials 1-5
P1012 Titanium Fx - Trials 1-5
P1012 Viking Fx - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

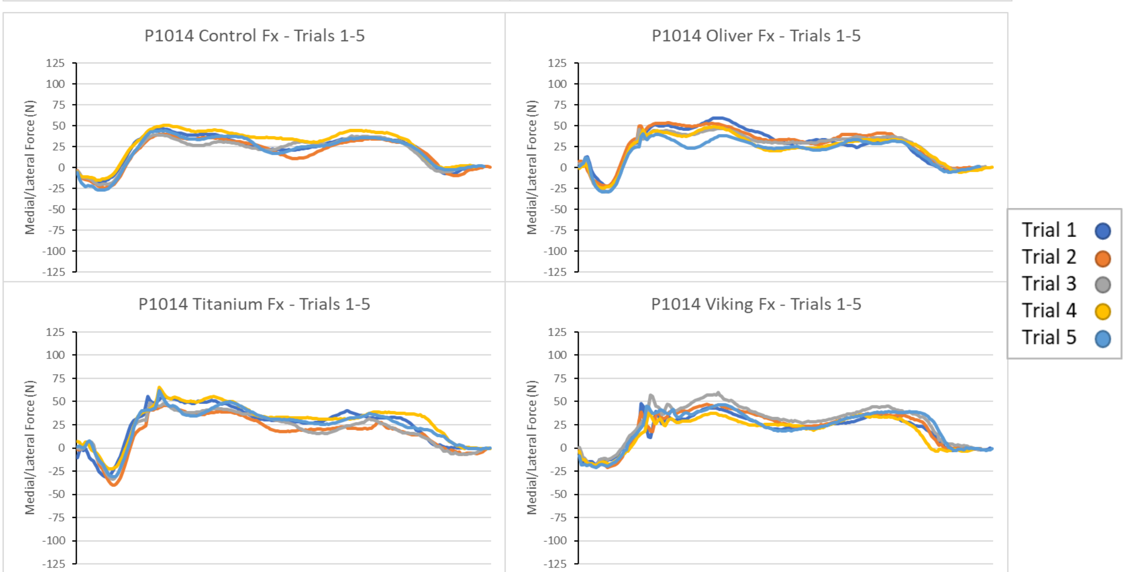

P1012 Control Fy - Trials 1-5
P1012 Oliver Fy - Trials 1-5

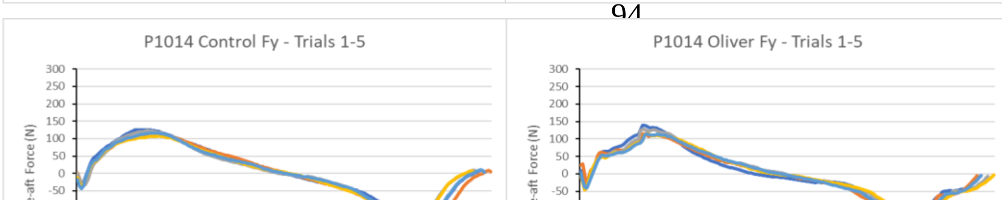

P1013 Control Fz - Trials 1-5
P1013 Oliver Fz - Trials 1-5
P1013 Titanium Fz - Trials 1-5
P1013 Viking Fz - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

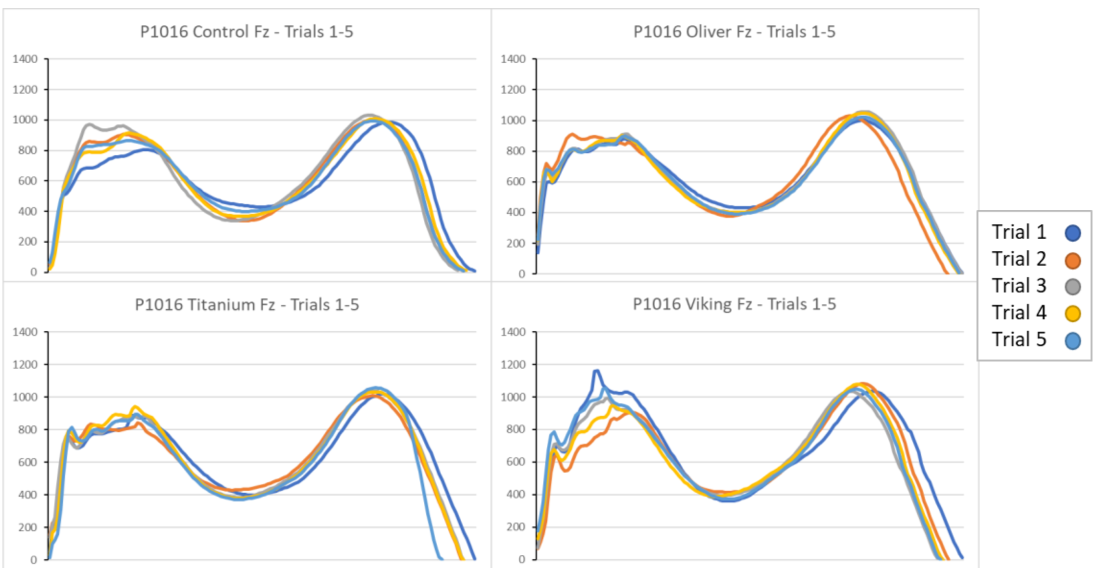

P1013 Control Fx - Trials 1-5
P1013 Oliver Fx - Trials 1-5
P1013 Titanium Fx - Trials 1-5
P1013 Viking Fx - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5

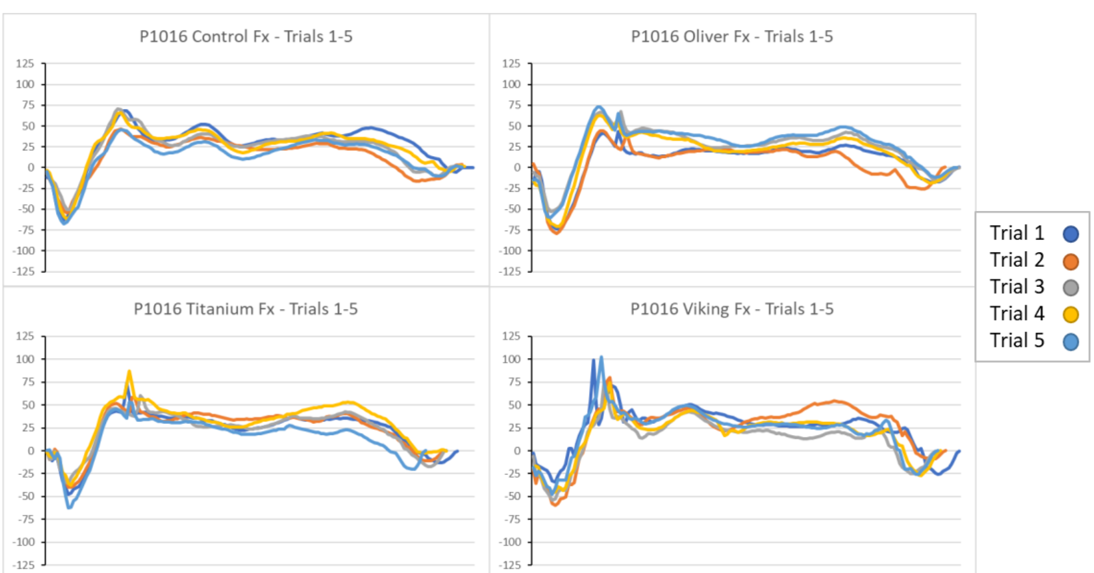

P1013 Control Fy - Trials 1-5
P1013 Oliver Fy - Trials 1-5

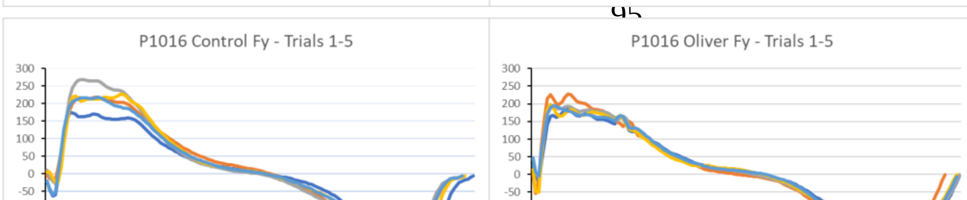

P1014 Control Fz - Trials 1-5
P1014 Oliver Fz - Trials 1-5
P1014 Titanium Fz - Trials 1-5
P1014 Viking Fz - Trials 1-5
Vertical Force (N)
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5


P1014 Control Fx - Trials 1-5
P1014 Oliver Fx - Trials 1-5
P1014 Titanium Fx - Trials 1-5
P1014 Viking Fx - Trials 1-5
Medial/Lateral Force (N)
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5


P1014 Control Fy - Trials 1-5
P1014 Oliver Fy - Trials 1-5


P1016 Control Fz - Trials 1-5
P1016 Oliver Fz - Trials 1-5
P1016 Titanium Fz - Trials 1-5
P1016 Viking Fz - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5


P1016 Control Fx - Trials 1-5
P1016 Oliver Fx - Trials 1-5
P1016 Titanium Fx - Trials 1-5
P1016 Viking Fx - Trials 1-5
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5


P1016 Control Fy - Trials 1-5
P1016 Oliver Fy - Trials 1-5