An examination of glove attributes and their respective contributions to force decrement and increased effort in power grip at maximal and submaximal levels

by

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Abstract

Gloved work has been shown to increase the effort required to perform manual tasks. In power grip tasks, these differences have been observed as reductions in strength and increases in muscular effort. Decreases in force output have been attributed to a number of factors, including loss of tactile sensitivity, glove flexibility or suppleness, thickness, changes in hand geometry, and friction at the glove-object interface. Glove research has rarely quantified glove attributes, and often compared gloves of varying material and physical properties. This research had the unique opportunity to control for a number of these properties by using three sets of identical gloves (powerline maintainers' insulating rubber gloves), differing only in thickness.

Administering the Von Frey Hair Test indicated that the gloves did indeed decrease tactile sensitivity. This research showed that increasing glove thickness led to large decreases in maximum power grip force. Small changes in hand geometry, such as increased interdigital space or grip span, affected force output. In the same hand posture, participants increased their grip force with increasing glove thickness for the object lifting task but were able to maintain a fixed submaximal force with visual feedback. The decrease in tactile sensitivity is a likely cause of this difference.

Muscular activity was affected by wearing the gloves while performing manual tasks. Inconsistent responses of muscular activation were seen in gloved maximum grip effort, while overall increases in electromyographic activity were recorded for tasks at submaximal levels when wearing gloves.

Interdigital spacing had different effects on maximal and submaximal tasks. For maximum effort power grip, interdigital spacing decreased force output by as much as 10%, with no significant changes in muscle activation. For submaximal tasks, no significant differences were seen in muscular activity or in force output. The overall force capability of the gloved user is hindered by changes in interdigital spacing at near maximal effort, but does not appear to be for tasks requiring lower grip force, such as the lifting task which required roughly 20%MVC.

Overall, the effect of wearing these gloves on the users, the powerline maintainers, is a substantially increased effort to work. This research contributes to a greater understanding of why and how gloves inhibit performance.

Acknowledgements

Undoubtedly, the love and support of my family has been the most critical in helping me achieve my goals and comforting me through small defeats. Thank you for your unwavering encouragement and guidance, even with most of a country between us.

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Chapter 1: Introduction

Upper-extremity work-related musculoskeletal disorders have a considerable prevalence in the workplace and have been shown to be highly associated with high repetition and forcefulness of manual work (for example, Bernard, 1997; Hagberg et al., 1995; National Research Council, 2001). Many workplaces require the use of gloves for protective purposes, and these gloves are as varied as the jobs in which they are used. Regardless of the type of glove required, gloved work increases the amount of muscular effort required when performing manual tasks (Sudhakar, Schoenmarklin, Lavender, & Marras, 1988).

Reduction in strength has also been widely recognized as one of the most common consequences of wearing gloves, with grip strength decrements ranging from 5% to 30% for maximal efforts (Hertzberg, 1955; Lyman & Groth, 1958; Rock, Mikat, & Foster, 2001; Wang, Bishu, & Rodgers, 1987). Such effects have been explored less with tasks of submaximal effort, where the reduction in force transmission and increase in muscular activity is not seen as clearly.

Sudhakar et al. (1988) examined EMG activity in reference to force output and found that the same level of muscle activation produced different grip strengths across glove types. The muscle force is obviously being generated, but is not being transmitted to the object. The question thus arises, what is attenuating the force exerted and which attributes of the gloves are responsible? If such attributes are identified, it will have implications for the design and selection of gloves for the workplace.

Though many studies have attempted to explore the functional consequences of wearing gloves with manual work, none have systematically examined glove attributes. Though thickness has oft been cited as a reason for force decrement and increased muscular effort while gripping, it may not be glove thickness in itself, but rather consequences attributable to an increase in thickness. Such repercussions could include an increase in interdigital spacing or a decrease in tactile sensitivity. In fact, it is rare in the literature to quantify glove attributes; arbitrary gloves are often compared to bare hand performance. As well, most studies have not had the opportunity to examine a series of such similar gloves as proposed in this research, and particularly not at this magnitude of glove thickness, where elemental attributes can be more easily isolated. In essence, it is difficult to draw comparisons between studies using gloves of different sizes, materials, and shapes, where analogous characteristics have not been appropriately isolated.

The purpose of this research is to attempt to parse the constituent attributes of gloves and these attributes' contribution to the force decrement and increased effort seen in gripping tasks while wearing gloves. Using electromyography of seven forearm muscles and grip force profiles from power grip, this research proposed to examine the level of muscular activity and corresponding force data for six tasks under a number of conditions. Four glove conditions (barehanded and three thicknesses of insulating rubber gloves) and a variety of manipulative tasks were employed to assist with identification of attributes responsible for force loss and increased muscular activity in prehensile actions.

In order to determine if particular attributes or consequences of wearing gloves while performing manual tasks could be isolated, and to predict their effect on force output and muscular activity, this research had a number of objectives:

- To determine if increasing glove thickness corresponds to
    - decreasing maximal power grip force capabilities, and by how much;
    - increases in peak and stable holding phase grip forces during a lifting task;
    - increases in muscular activity levels for submaximal effort tasks.
- To discover if standardizing the hand posture, by changing the grip span to compensate for glove thickness, improves maximum force output.
- To investigate if and how changes in hand geometry in the form of interdigital spacing contributes to force decrement and changes in muscular activity in both maximal and submaximal effort tasks.
- To determine if increases in glove thickness reduce tactile sensitivity, and if so, if this attribute is associated with higher than normal grip forces.

Chapter 2: Literature Review

Glove attributes and types

A number of glove types and glove attributes have been examined in the literature. Batra et al. (1994) identified four characteristics of gloves that could be used to predict gloved performance. These included thickness, tenacity (friction), snugness, and suppleness. Other studies have used the same attributes to predict maximum grip and grasp forces (Bishu, Batra, Cochran, & Riley, 1987). Groth & Lyman (1958) provided support for the importance of considering friction as a variable capable of affecting manual performance while wearing gloves, while the coefficient of friction was identified as the best variable of the four in predicting decrements of strength (Batra et al., 1994). Thickness was also distinguished as an important attribute in the Batra et al. study, but did not show to have an effect on strength in the grasping task. It was postulated that the biomechanical differences between the grip and the grasp postures (i.e. the grip posture required more finger flexion) was responsible for the insignificant effect for grasping. It is more likely that the insignificance occurred due to the fact that the differing glove thicknesses did not arise from gloves of the same type or material. Though the identification of these attributes was a good attempt at explaining why gloves cause performance decrements, the attributes were not controlled and interfered with any conclusions about their individual effect on gloved performance.

Many different types of gloves have been assessed in the literature. These have included cotton gloves (Kinoshita, 1999), leather gloves (Tsaousidis & Freivalds, 1998), work gloves (Fleming, Jansen, & Hasson, 1997), surgical gloves

(Kinoshita, 1999; Nelson & Mital, 1995; R. H. Shih, Vasarhelyi, Dubrowski, & Carnahan, 2001), hazardous materials gloves (Bensel, 1993), and extra-vehicular activity (space) gloves (Bishu, Kim, & Klute, 1995; Buhman, Cherry, Bronkema-Orr, & Bishu, 2000; Korona & Akin, 2002; Roy, O'Hara, & Briganti, 1990). On many occasions, gloves of differing types were compared with each other (Cochran, Albin, Bishu, & Riley, 1986; Kinoshita, 1999; Lyman & Groth, 1958; Mital, Kuo, & Faard, 1994; Rock et al., 2001; Y. C. Shih & Wang, 1997) or one or more gloves of the same or differing types were layered (Bradley, 1969a; Hallbeck & McMullin, 1993). Though this may provide an overall comment on the ability of a particular glove to compromise its action, it does not systematically elucidate why.

In summary, glove attributes have been defined in the literature but never comprehensively examined for important potential consequences on grip force for each attribute.

Gloves and dexterity

There are many performance tests used to evaluate manual dexterity with and without the use of gloves (Muralidhar & Bishu, 1994). Performance and dexterity decline when wearing gloves, however, this seems to depend on the nature of the task. Bradley (1969a) examined controls (switch, vertical and horizontal lever, knob, and push button) with various types and combinations of gloves and determined that the physical characteristics of the both the glove and control contribute to task success (or lack of it). For example, when wearing double gloves, “the operator may reach to, and operate, the toggle switch with great speed and semi-ballistic movement without fear of injury to his hand”. This would decrease the time taken to complete the task, but obviate any need for fine precision. With validated dexterity tasks, performance time is found to increase with increasing glove thickness (Bensel, 1993), but certain characteristics (such as correct glove sizing and suppleness and increased friction between the glove-object interface) were able to mitigate the results on performance time (Bradley, 1969b; Chen, Cochran, Bishu, & Riley, 1989). The detrimental effect of gloves on manual dexterity may be due to their interference with hand movement, which has been noted in the abduction/adduction and supination/pronation ranges of motion (Bellingar & Slocum, 1993).

Though gloves have a distinct effect on manual dexterity, an examination of this nature will not be conducted for the purposes of this research.

In summary, dexterity and performance suffers when wearing gloves.

Gloves and tactility

Tactility has been shown to deteriorate while wearing gloves. Various measures of this decrement have been used, such as detecting changes in surface texture (Nelson & Mital, 1995), the Von Frey hair test (R. H. Shih et al., 2001), two-point discrimination (R. H. Shih et al., 2001), among other hand function tests (Muralidhar & Bishu, 1994). Further considerations in the loss of tactile sensitivity are discussed with respect to grip forces and grip force profiles in a further section.

In summary, tactility declines when wearing gloves.

Gloves and maximal effort

It has been widely reported that wearing gloves decreases effective power grip strength by 5-30% (Cochran et al., 1986; Kovacs, Splittstoesser, Maronitis, & Marras, 2002; Lyman & Groth, 1958; Sudhakar et al., 1988; Tsaousidis & Freivalds, 1998). Though the gloves range in type and function, even a simple cotton glove has been shown to significantly reduce maximal grip force by 7.3% (Cochran et al., 1986) to 26% (Wang et al., 1987). Conversely, for torquing activities, it has been shown that wearing gloves increases the amount of torque produced with a maximal effort (Cochran, Batra, Bishu, & Riley, 1988; Riley, Cochran, & Schanbacher, 1985), with maximum torque exertion increasing by 3%-41%, depending on the frictional condition and shape and size of the handle (Y. C. Shih & Wang, 1997). However, these increases are likely due to the increase in friction between the hand-object interface while wearing gloves alone, as grasp force is inversely related to the size of the coefficient of friction of this interface (Bronkema-Orr & Bishu, 1996; Groth & Lyman, 1958).

Factors commonly cited as responsible for reducing force output while wearing gloves include glove thickness, changes in the geometry of the hand, snugness of fit of the glove, loss of tactile sensitivity, and the frictional characteristics of the hand-object interface. The three latter factors are discussed in another section of this review. Poorly fitting gloves, whether they are too small or too large, affect all aspects of glove use and are a detriment to performance (Bradley, 1969b; Hallbeck & McMullin, 1993; Kovacs et al., 2002; Muralidhar & Bishu, 1994). The fit of gloves is not always controlled in the reported studies, and it often cited as a potential confounder of results (Batra et al., 1994). Increasing glove thickness has also been shown to be a determinant for decreases in strength (Nelson & Mital, 1995).

The effective strength reduction described previously is paired with the observation that for a given grip force, the muscular effort required to produce that grip force is greater when wearing gloves, and this effect is magnified with increasing glove thicknesses. Correspondingly, during a maximal voluntary effort where muscular activity is at a maximum, it has been shown that the force output decreases as glove thickness increases (Sudhakar et al., 1988).

Though this effect is seen with purely gripping activities, it has been shown that there is no significant muscular activity increase during torquing activities (Mital et al., 1994). This too may be attributable to the frictional characteristics described in the previous section.

In summary, wearing gloves reduces the capacity for exerting force in gripping tasks.

Submaximal efforts while wearing gloves

The majority of the research examining force loss and increased muscular activity levels arises from investigations using maximum grip forces only. As much gloved work in the workplace does not involve maximal exertions, it seems reasonable that research investigating the consequences of donning gloves should consider tasks of submaximal effort. As would be expected, investigations using *maximal* contractions across many glove types have shown no difference in muscular activity during these exertions, only a decrease in force output, indicating that material properties of the gloves are not interfering with EMG activity, just force transmission (Kovacs et al., 2002). Therefore, it is very important to consider sub-maximal efforts in glove evaluation to determine the magnitude of decrement (if any) when such differences would actually be discernable. However, published evidence on the effect of gloves on grip or grasp force is marginal at submaximal exertions (Bishu, Bronkema, Garcia, Klute, & Rajulu, 1994; Buhman et al., 2000). This may be due to unbalanced comparisons between gloves of widely differing characteristics.

In summary, donning gloves requires increased muscular effort for gripping tasks, though the effect of gloves on submaximal gripping tasks has been understudied and current results indicate that the glove effect is marginal at best.

Posture and grip strength

A variety of postural factors affect maximal grip strength. These include forearm and wrist postures, as well as grip size and finger spacing, with any deviation from a neutral position contributing to a decrement in force output. Looking solely at wrist posture in the flexion/extension plane, maximal grip strength is greater in extension (Hallbeck & McMullin, 1993; Hansen & Hallbeck, 1996; O'Driscoll et al., 1992). Another investigation reported a decrement in postures deviating from neutral, but with no significant difference between flexion and extension deviations (Jung & Hallbeck, 2002). Mogk & Keir (2003b) examined the effects of various postures on forearm loading and found no difference between the extension and neutral wrist grip forces. In a study investigating forearm position, Richards et al. (1996) found significant differences between maximum force output in forearm pronation and supination as compared to a neutral posture, keeping the wrist in a standard position.

Grip span alters the MVC potential of a power grip, with too small or too large a span negatively affecting the maximal force as compared to an optimal distance with the highest MVC output (Petrofsky, Williams, Kamen, & Lind, 1980).

The fact that gloves change the geometry of the hand is also a factor to be considered. Primarily this change is seen in the form of increased interdigital spacing, with losses of grip strength varying from 12% to 26% reported in spacing ranging from 3-10 mm (Hallbeck, Muralidhar, & Balachandran, 1994; Hansen & Hallbeck, 1996). Therefore, even small changes in thickness will have significant effects on the ability to produce grip force by means of changed hand geometry alone. Conversely, the geometry of the new posture itself, such as when the fingers are more widely spaced, force ineffective lines of action.

In summary, potential grip strength is dictated by posture, with changes in posture being reflected by changes in muscle length and the consequent inability to produce maximal force under suboptimal conditions.

EMG

EMG is a useful tool for evaluating muscle activity during a given task, however, its use and interpretation can be subject to error if proper precautions are not followed. For example, movement of the forearm during a task may alter the placement of the EMG electrode over the muscle being measured, or may cause changes in muscle length altering the EMG-force relationship (Duque, Masset, & Malchaire, 1995). The forearm muscles are relatively small and tightly organized, making EMG crosstalk a concern. It has been reported that the magnitude of common signal between adjacent electrode pairs over the extensors has reached nearly 50%, while neighbouring electrode pairs over the flexors approached 60% (Mogk & Keir, 2003a). As well, individual differences are rampant and normalization must occur before any inter-subject comparisons or mean data can be formulated.

Since it has been shown that manual gloved work increases the amount of muscular activity required, it is should be expected that the onset of fatigue arises sooner than similar barehanded work. Efforts to quantify fatigue in gloved work have employed an analysis of median frequency (Fleming et al., 1997; Roy et al., 1990), subjective ratings (Roy et al., 1990), time to fatigue (Fleming et al., 1997), and other EMG fatigue indices (Lariviere et al., 2004). Though these methods are certainly useful in other venues, this biomechanical assessment will not be examining the measures of fatigue, as evidence has been provided that relative muscle activation indices are more suitable than fatigue indices for detecting the effects of glove (Lariviere et al., 2004). However, some conclusions drawn from fatigue research provide good context for examination of muscular activity, such that is has been shown that forearm extensors are more sensitive to exertions made during gripping activities than flexors (Hagg & Milerad, 1997; Lariviere et al., 2004). Extensors also reflect grip posture better than the flexors (Lariviere et al., 2004), particularly at low levels of force (Mogk & Keir, 2003b).

In summary, EMG can be a good indicator of the amount of effort being exerted during a task. However, care must be taken to reduce error wherever possible to avoid high variability and low validity of results.

Maximal voluntary efforts and terminology

To match an attempt at standardizing terminology in the literature (Mathiassen, Winkel, & Hagg, 1995), the electromyographic result of these contractions is referred to as maximal voluntary electrical activation (MVE), while the corresponding force output is maximal voluntary contraction (MVC). As Figure 1 illustrates, normalizing submaximal muscular efforts in the EMG domain have been termed reference voluntary electrical activation (RVE) and are expressed as a percentage of electrical activity obtained during a reference voluntary contraction (RVC). This study, however, will mainly make use of the MVC/MVE terminology as the normalization process will be referent to maximal efforts. To obtain the MVE for each muscle, ensure the effort is directed in accordance with muscle function to maximize activation for each muscle being measured, or if looking at maximal force output, that the participant is in an optimal posture for doing so. Either of these efforts should not be held for too long, as fatigue related changes have been seen within 15 seconds (as cited in Mathiassen et al., 1995). When measuring maximum force output, it is typical to perform three trials and take the highest value, provided each effort is sustained for no more than five seconds and the participants are allowed to choose their rate of force production (DeLuca, 1997).

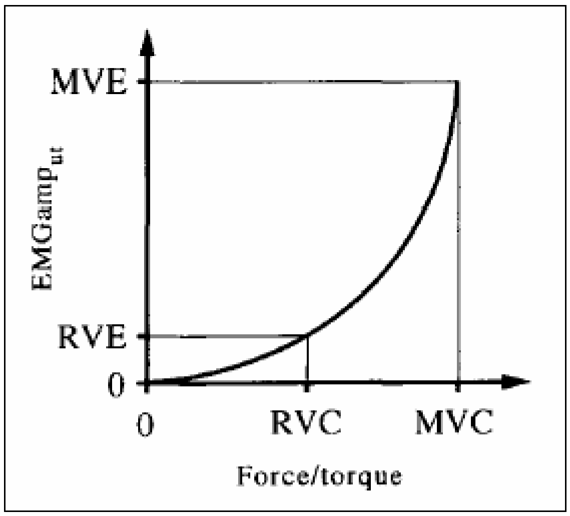


Figure 1. Terminology in the normalization of EMG amplitude. From Mathiassen et al., 1995.

In summary, when used properly, MVC is a useful tool for normalization of muscular activity and force output and enables comparisons between participants.

Grip force profiles: normal vs. digital anaesthesia conditions

Load force and grip force comprise the primary components of a lifting task analysis. Load force, the vertical lifting force, and grip force, the force exerted on an object by the hands or fingers, are coordinated in parallel under normal conditions to generate the most efficient grip/load force ratio (Flanagan & Wing, 1997; Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991; Monzee, Lamarre, & Smith, 2003; Nowak & Hermsdorfer, 2003; Westling & Johansson, 1984). Under normal conditions, the grip force will exceed the load force just enough to prevent slippage of the object being held. Literature in the realm of motor control describes a multitude of information which can be derived from these force profiles, however, for the purposes of this research, only a few aspects will be considered. A typical force profile is shown in Figure 2. There is characteristically a momentary overshoot of grip force before this force settles into a static grip. The magnitude of these peak and stationary forces can be compared across conditions and used to quantify detriments to grip force. As well, rate of force increases and how smoothly this increase occurs can be examined.

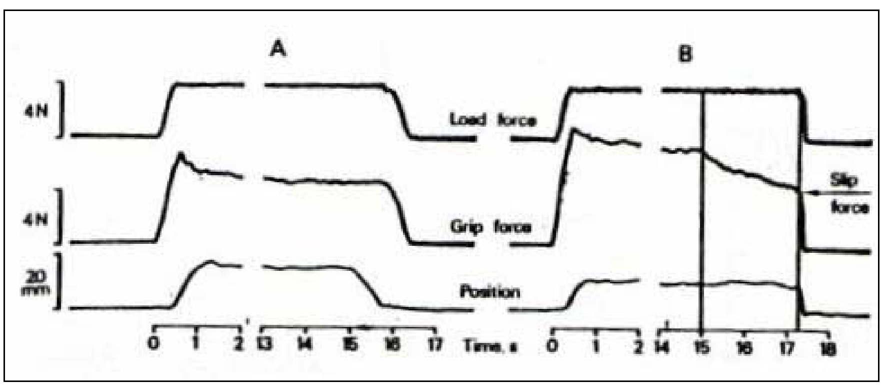


Figure 2. Typical grip and load force profiles (seen here for a pinch grip). A lift and replace trial is seen in (A), while in (B) the participant drops the object by letting it slowly slip from the fingers. From Westling & Johansson (1984).

Slip force (seen on graph B in Figure 2) is typically denoted as the grip force value at the exact moment a load held in the hand begins to slip (Westling & Johansson, 1984), and is influenced by the frictional characteristics of the hand-object interface. Westling & Johansson (1984) outlined some conclusions regarding factors which influence the control of force during a precision grip:

- Static grip force on an object held in the air is approximately proportional to the weight of the object.
- Load force and slip force are approximately proportional, with a ratio between these two forces represented by the coefficient of friction.
- Surface friction, and not texture, influences the modulation of grip forces (see also Cadoret & Smith, 1996; Monzee et al., 2003).
- Under normal conditions, grip force is highly correlated with load force, while under local anaesthesia these forces are unrelated.
- Digital anaesthesia causes an increase in grip force exerted on an object. This has also been reported by Monzee et al. (2003), where, depending on the coefficient of friction of the hand-object interface, grip force under anaesthetic during the static phase increased 1.46-4.57 times the grip force seen with intact sensory input (see Figure 3).

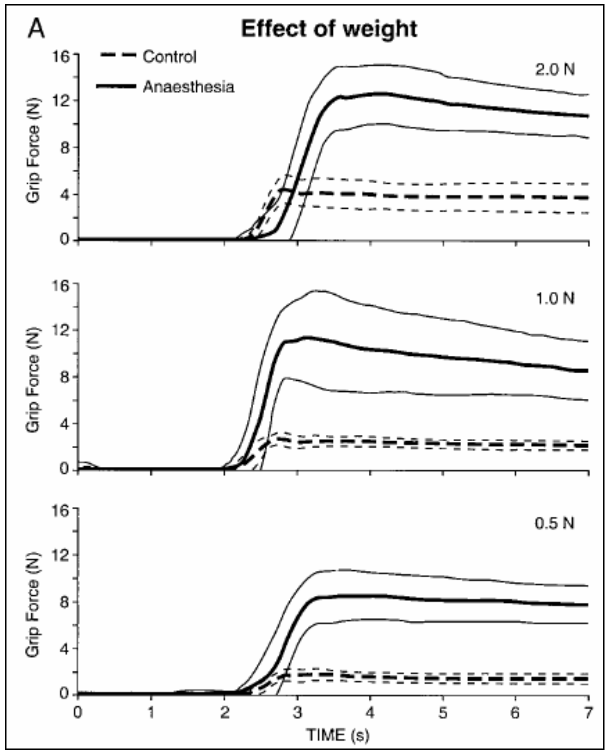


Figure 3. Effect of digital anaesthesia on the manipulation of 3 different resistive forces simulating object weight for a single subject, with the mean grip force ± SD for 20 trials. From Monzee et al. (2003).

Friction, for the purposes of this discussion, will be defined as the minimal force needed to initiate or maintain sliding of a given weight on a particular surface and is calculated using the formula $\mu = F/W$, where μ is the coefficient of friction, F is the tangential (grip) force needed to initiate movement, and W is the normal (load) force (Cadoret & Smith, 1996). Similar calculations are presented elsewhere in the literature (Monzee et al., 2003; R. H. Shih et al., 2001; Westling & Johansson, 1984). The magnitude of the coefficient of friction affects the force required to maintain a grip on an object. Figure 4 demonstrates the differing grip forces required to lift and hold an object of the same weight, but with different frictional characteristics. In this figure, the hatched line (±SD) represents the mean grip force for 20 trials with cutaneous sensation intact, and the thick line (±SD) represents the mean grip force after digital anaesthesia. Digital anaesthesia amplifies the amount of force exerted on the same objects, with a larger margin of error for the more “slippery” (metal) condition. The information presented here regarding digital anaesthesia derives from precision grip research, as much of the research undertaken in this area uses this type of grip.

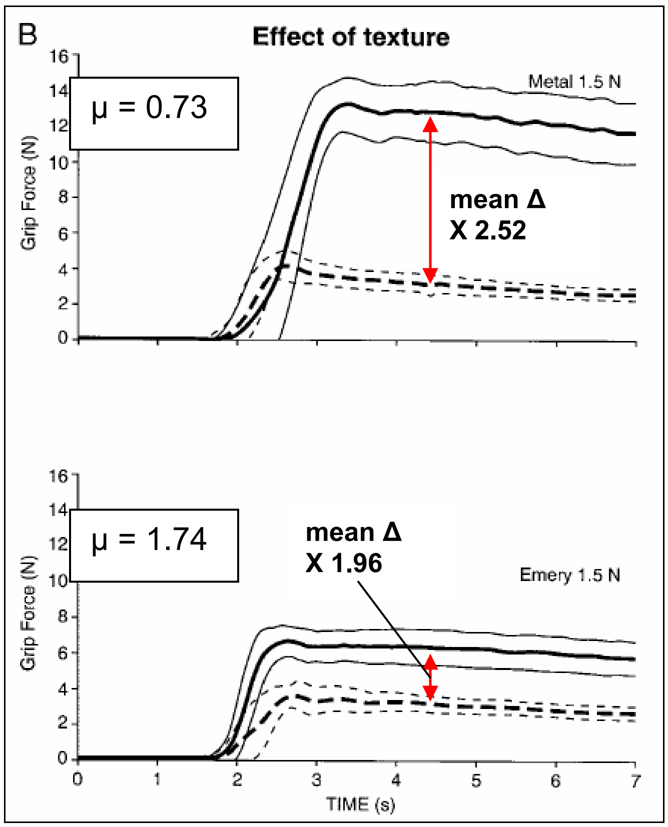


Figure 4. Effect of digital anaesthesia on the manipulation of two conditions of surface friction for a single subject. From Monzee et al., (2003).

With gloved tasks, it has been shown that grip forces increase with increasing glove thickness as demonstrated by Shih et al. (2001) while wearing 1, 2, or 3 surgical gloves (see Figure 5). Thus, the increased muscular effort seen in glove use may be directly attributable to an impairment of tactile sensitivity.

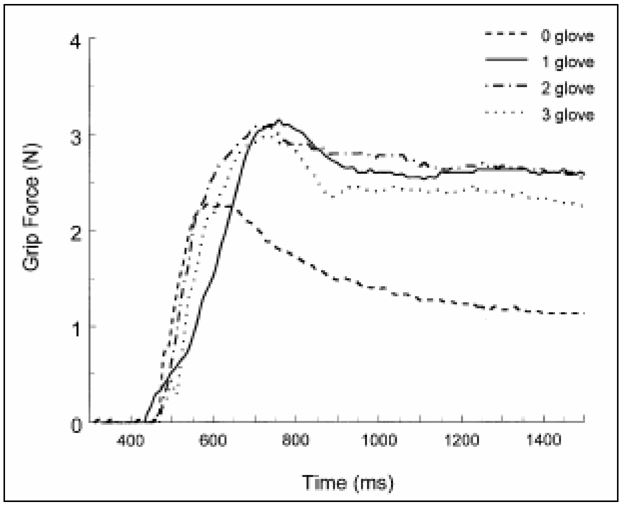


Figure 5. Typical grip force curves for a participant wearing 0, 1, 2, or 3 surgical gloves. From Shih et al., (2001).

In summary, grip and load force profiles provide insight into the effects of interference with sensory feedback in lifting tasks. Gloves interfere with the skin mechanoreceptors of the fingertips' role in providing sensory feedback when manipulating an object. This lack of tactile sensitivity is manifested in the use of higher than necessary grip forces.

Chapter 3: Methodology

Participants

Ten male and ten female participants were recruited from the university population, and were required to be free from upper extremity injury, pain, or discomfort. Each participant reviewed and signed a consent form detailing the experimental protocol as approved by the ethics committee of the University of Waterloo Office of Research.

Apparatus and Materials

A schematic of the experimental set-up can be found in Appendix A.

Force dynamometers

Maximal voluntary contraction (MVC) and maximum effort trials (MVE) were performed with an instrumented grip dynamometer (MIE Medical Research, UK). This dynamometer recorded the grip force, and was adjusted to a power grip span corresponding to each participant's anthropometrics, such that the thumb and tip of the index finger lightly touched in a barehanded relaxed grip. A geometrically similar dynamometer (MIE Medical Research, UK) instrumented to record grip forces was used for the remainder of the trials with non-maximal efforts, as pictured in Figure 6. This dynamometer was supported and placed on an adjustable platform so that all subjects performed the tasks with a uniform posture. The grip force from this dynamometer was amplified (MIE amplifier, Medical Research Ltd.) and low pass filtered at 20 Hz (Krohn-Hite, filter model 3550). The grip force on the MVC dynamometer was amplified with a LVDT amplifier (Daytronic, Model 3230P).

Figure 6. Picture of the instrumented grip force dynamometer.

EMG system

Surface EMG was collected with custom-built electrodes (input impedance: $10^{10}\ \Omega$, bandwidth: 25-550 Hz) for seven forearm muscles described in the protocol section. All EMG data was collected in raw form at 1024 Hz, differentially amplified, and processed post-collection.

Glove types

Powerline maintainers' rubber insulating gloves (Salisbury, Skokie, IL) were used for this investigation, incorporating three different classes (0, 2, and 4), as well as a barehanded condition. Each class is graded according to its voltage rating, and as such, the higher the voltage rating, the thicker the glove. The thicknesses of the Class 0, 2, and 4 gloves range from 0.51-1.02 mm, 1.27-2.29 mm, and 2.54-3.56 mm, respectively (ASTM International, 2002). The gloves are also available in a variety of sizes, therefore, participants wore properly fitted gloves for the experimentation. By using these specific rubber gloves, the unique opportunity existed to evaluate individually certain attributes of the gloves while controlling for others. For example, the gloves are identical in material, shape, and size but differ in thickness across the glove classes. Also, as the gloves are manufactured to a regulated safety standard (ASTM International, 2002), their attributes will not differ significantly between gloves. The Type I gloves are made from a high-grade *cis*-1,4-polyisoprene rubber compound of natural or synthetic origin, properly vulcanized. Table 1 provides some further properties of the gloves being tested.

Table 1. Glove properties. From ASTM Standard D 120-02 (2002).

Property	Type I
Tensile strength, min, Die C, MPa (psi)	17.2 (2500)
Tensile stress at 200 %, max, MPa (psi)	2.1 (300)
Ultimate elongation, min, %	600
Tension set, max at 400, %	25
Tear resistance, min, kN/m (lbf/in.)	21 (120)
Puncture resistance, min, kN/m (lbf/in.)	18 (100)
Hardness, max, shore A	47

Protocol

Tasks

Other than the maximal voluntary exertions, the order of the tasks were randomized to control for any learning or practice effects. Participants also had the opportunity to manipulate the dynamometer before the start of each glove condition to familiarize themselves with the feel of the new glove. Furthermore, glove conditions were blocked so that all tasks were completed with one glove (or barehanded, or with interdigital spacing) before moving to the next condition.

During the trials, the participants' posture was standardized. Participants sat comfortably on a chair adjusted to their anthropometry, such that their knees were at a 90 degree angle with their upper legs parallel to the floor and they rested their forearms on the armrest with their elbows bent at 90 degrees. Participants were reminded to keep their forearms parallel to their legs throughout the experiment. The forearm and wrist positioning was akin to that of a handshake posture, mid-pronation. The platform on which the grip dynamometer sat was adjusted according to this forearm height, such that the gripping surface was aligned with a neutral wrist posture.

This experiment was carried out in two separate testing sessions. Sessions are described below as Protocol 1 and Protocol 2, with Protocol 1 lasting roughly three hours and Protocol 2 lasting approximately one hour. Whether participants completed Protocol 1 or Protocol 2 first was randomized. Participants were fitted with an appropriately-sized glove. This was accomplished by measuring the circumference of the participant's palm just below the base of the fingers and passing through the thumb crotch. This measurement, in inches, corresponds to the appropriate glove size. To help control the internal environment of the glove, a thin cotton glove was worn underneath the rubber glove. The gloves were also worn solely for the duration of each trial and removed during the time in between. A series of tasks were completed under the four glove conditions, as well as three conditions of interdigital spacing. Appendix C offers a schematic of the testing tasks and trials. Each task was performed five times, and recorded for five seconds, with the exception of the MAX task, which was completed three times for each glove condition.

EMG

Electromyographic activity was recorded from seven (7) forearm muscle sites: flexor digitorum superficialis (FDS), flexor pollicis longus (FPL), flexor carpi radialis (FCR), flexor carpi ulnaris (FCU), extensor carpi radialis (ECR), extensor carpi ulnaris (ECU), and extensor digitorum (ED). These muscles were chosen as representative of hand demand during the experimental tasks as well as for ease of electrode placement (Koppelaar & Wells, 2005) under the insulating rubber gloves. Standard electrode placement and skin preparation was followed as outlined in the literature (Basmajian, 1979; Delagi, Perotto, Iazzetti, & Morrison, 1975; Zipp, 1982). The EMG electrode placements are illustrated in Figure 7.

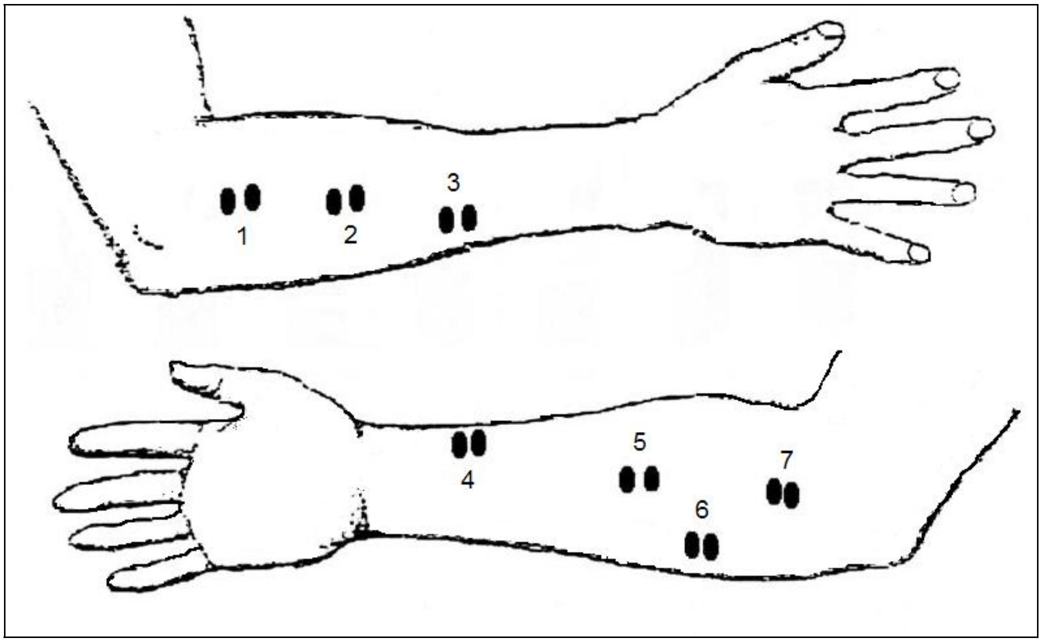


Figure 7. Electrode placement sites for extensor carpi radialis (1), extensor digitorum (2), extensor carpi ulnaris (3), flexor pollicis longus (4), flexor digitorum superficialis (5), flexor carpi ulnaris (6), and flexor carpi radialis (7).

Anthropometric measurements

Select dimensions of the participants' hands were recorded and used to quantify the fit of the rubber insulating gloves. These measurements included palm circumference, palm length, knuckle thickness, finger length, hand length, and greatest hand circumference. Palm circumference, in inches, was used to select the correctly sized glove for each participant.

Von Frey hair test

A Von Frey hair test was administered for each of the gloved conditions. This test is a measure of force sensitivity, where participants report if they feel a series of hairs of increasing diameter pressed into the skin of the fingertip (Semmes, Weinstein, & Ghert, 1960). As the diameter of the hairs increase, so does the amount of force needed to bend them (see Figure 8). In this experiment, the Von Frey hair test was administered to the bare hand and the 3 glove classes. The number corresponding to the first hair felt by the participant was recorded and compared across glove conditions.

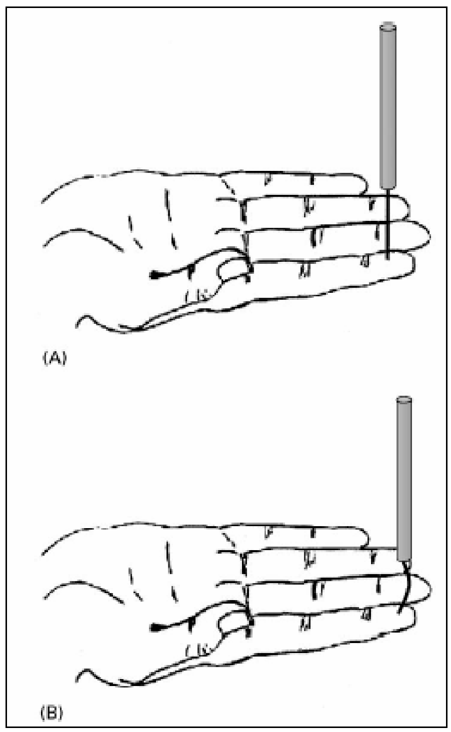


Figure 8. Administration of the Von Frey hair test (from Shih et al., 2001).

Perceived exertion

Participants were asked for a self-reported effort for each of the tasks. A 100-point rating scale with ratio properties (CR100) was used (Borg & Borg, 2002). The scale is shown in Appendix C.

Protocol 1

Protocol 1 comprised of the following tasks, recording EMG and grip force throughout.

MVE [MVE]

Maximal voluntary electrical activations (MVE) were performed by each participant in various postures to ensure a maximum contraction had been elicited for each muscle recorded. For example, the flexor carpi radialis MVE was obtained by attempting to isometrically flex and radially deviate the wrist against resistance during gripping. In total, 6 wrist postures and three maximum grip contractions per condition were undertaken to find an absolute maximum voluntary muscle activation per muscle. The MVE for each muscle was used to normalize the muscular activity data obtained in the remaining trials. Muscle activation levels (EMG amplitude) are expressed in %MVE.

Maximum effort [MAX]

In each glove condition, participants were instructed and verbally encouraged to attain a maximal effort for grip strength by ramping their effort up to a maximum and holding it there briefly. These recordings were made in the standardized experiment posture using the grip dynamometer to determine the maximum grip force for each participant in each glove and task condition. Participants performed each maximum effort three times, taking the largest value as the MVC (DeLuca, 1997). A minimum rest period of 2 minutes was provided between trials. These force values were used to normalize the forces obtained in the remaining trials. The normalized forces are expressed as %MVC.

Hand position [POSN]

Participants fixed their hand around a foam cylindrical object with the same dimensions as the grip dynamometer without exerting any force. Participants were instructed to simulate the power grip posture as accurately as possible without causing the foam to compress.

Maintain a fixed force [FIXF]

Participants were asked to maintain a 75 N grip force for five seconds. Visual feedback was provided to the participant in order to keep the effort consistent.

Lift dynamometer [LIFT]

Participants were asked to reach and grip the dynamometer and elevate it without any horizontal movement to an approximate height of 20 mm (Westling & Johansson, 1984), hold it in the air for five seconds, then lower it gently back to the platform after the end of each trial. The dynamometer was fitted with an additional 2 kg mass, giving a total mass of 3.6 kg.

Protocol 2

Protocol 2 involved maximal voluntary contractions (described above as MAX) with no electromyographic recordings. Three trials were performed for each of the gloved conditions as well as with the bare hand. These MAX trials differed from Protocol 1 in that the grip span was adjusted for each condition to compensate for the loss of effective grip span caused by the increasing thicknesses of the gloves. The span of the dynamometer was adjusted such that while wearing each of the gloves, the tip of the thumb and index finger remained touching (as felt through the gloves). The order of the trials was block randomized according to glove condition. The Von Frey Hair Test and the anthropometric measurements were recorded during the rest breaks in Protocol 2.

Additional Task Conditions

Interdigital spacing

Each of the tasks described in Protocol 1 and 2 were performed with interdigital spacing, corresponding to the same distance the fingers would be separated would the participant have been wearing gloves. For example, the Class 2 glove has an average thickness of 1.78 mm (maximum range 1.27-2.29 mm), and as such, the fingers were separated by 3.56 mm (2 x 1.78 mm). Interdigital spacing was accomplished using specially constructed foam "spacers", as seen in Figure 9.

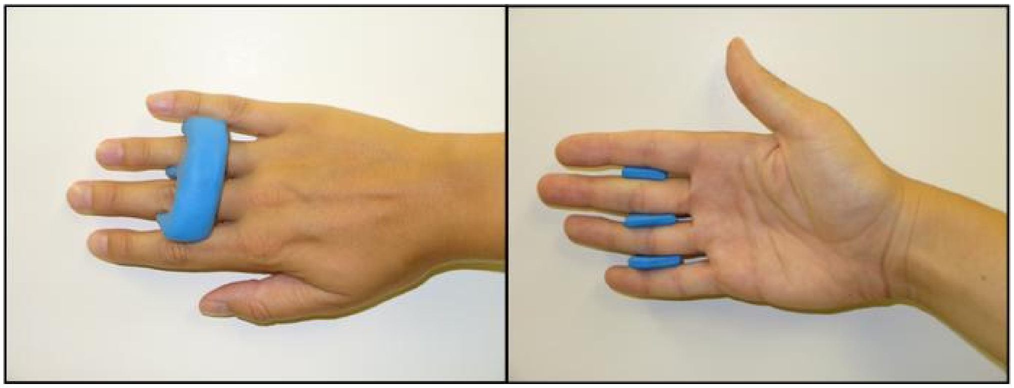


Figure 9. Example of Class 4 interdigital spacers.

Fatigue test

In order to determine if Protocol 1 caused muscle fatigue in the participants, a reference contraction of 60 N held for 5 seconds was performed at the beginning and end of the protocol.

Data Analysis

EMG processing

EMG data was full-wave rectified and low-pass filtered at 2.5 Hz (single-pass, 2^{nd} order Butterworth) to create a linear envelope signal for each of the seven muscles. The EMG signals were then normalized to the maximum activation determined during the MVE and MAX trials, and expressed as %MVE.

Grip force analysis

Maximal grip forces

Grip forces were normalized to the maximum barehanded force obtained during the maximal voluntary contraction and expressed as %MVC. The effect of glove class on the MAX force was determined by a 1-way ANOVA (glove condition) for each protocol. Further, t-tests between each protocol (adjusted vs. non-adjusted grip span, for each glove class) were run to determine if adjusting the grip span to compensate for the loss of effective grip span affected maximal force output.

Tactility and force

The gloves' detrimental effect on tactility and its postulated effect on grip force can be examined by looking at the forces required among glove classes for the lifting task. As illustrated in Figure 9, a difference between the grip forces for each glove type as compared to the barehanded task during the lift task can provide some insight into the overshoot of grip force expected with thicker gloves. Theoretically, the force output should be the same as all other task conditions remain constant other than the thickness of glove worn. If a difference is detected among glove classes, this change in force output could be attributable to decreasing tactility levels as glove thickness increases. A one-way ANOVA (glove condition) was performed on peak lifting and stable holding phase forces from the lifting task.

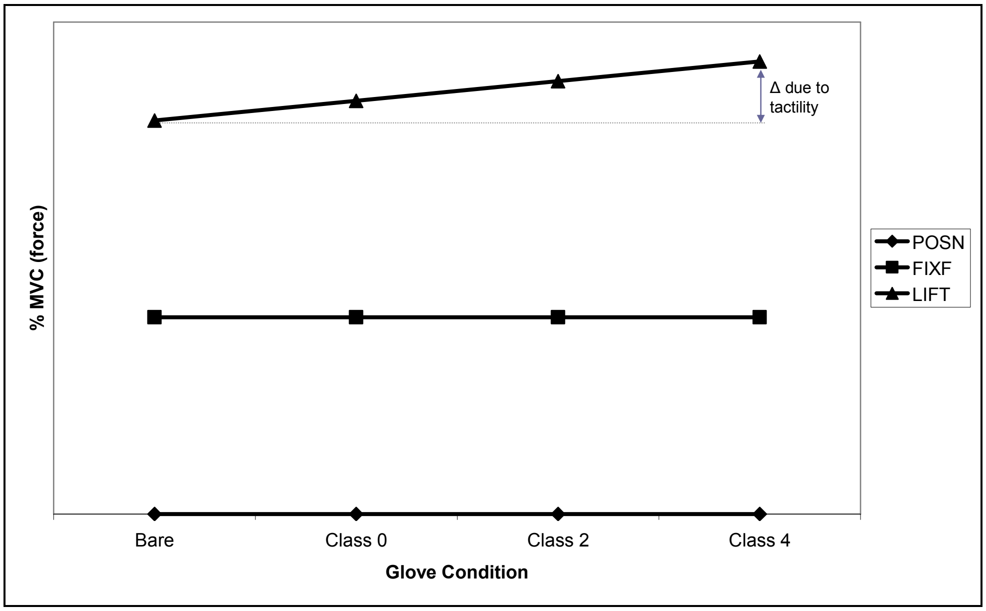


Figure 10. Predicted pattern of submaximal force levels for three tasks.

Von Frey hair test

Results from the Von Frey Hair Test were recorded as the first fibre number felt by the participants and converted to the hair's corresponding force value. These force values were analyzed using a 1-way ANOVA (glove condition) to assess between-subject variability and the differences between glove conditions. These results could provide additional information about loss of tactility across glove types.

Muscular electrical activity levels analysis

Submaximal exertions

The effect of glove on the muscular activity required to maintain a fixed force were examined by a 1-way ANOVA (glove condition) on %MVE arising from the FIXF condition for each muscle.

Mechanical factors

Increased muscular activity across glove types due to purely mechanical factors (suppleness) of the gloves can be derived from the positioning task. The positioning task can quantify the amount of muscular effort required to simply hold the glove in the gripping position without any exertion of force on the foam cylinder. Furthermore, if the difference in %MVE between FIXF and POSN is constant (see Figure 11, EMG_{fixf}-EMG_{posn}), then it can be determined that the extra effort at the submaximal force level (FIXF) is due to the effort to bend the fingers. The %MVE and %MVE difference for each muscle will be compared across glove condition in a 1-way ANOVA for each muscle.

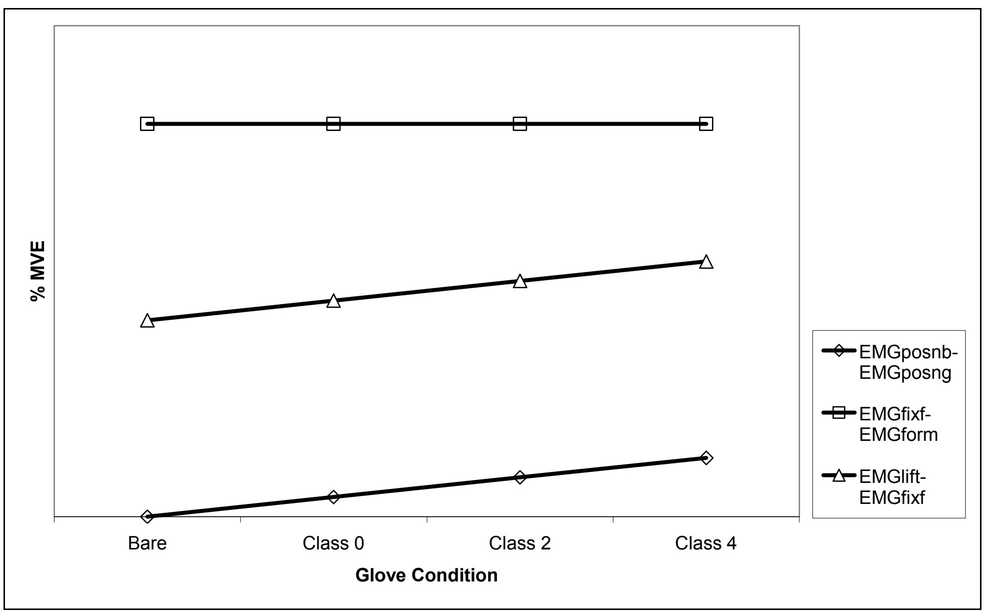


Figure 11. Predicted patterns of submaximal electromyographic activity for a given muscle for three tasks.

[posnb = POSN condition with bare hand, posng = POSN condition with gloves, EMGform = muscular effort to form grip, EMGposnb-EMGposng].

Tactility and muscular activity

The effect of tactility can be ascertained by examining the %MVE difference between the FIXF and LIFT conditions. As visual feedback was provided during the FIXF condition to replace the need for tactile feedback, the difference in muscular activity levels in the two conditions could be attributable to loss of haptic sensitivity while wearing gloves. This difference is illustrated in Figure 10 (EMGlift-EMGfixf). If this value is constant, then tactility does not affect muscle activity. A 1-way ANOVA (glove condition) was performed to test this.

Fatigue

A mean power frequency (MPF) analysis was performed on the muscular activity recorded during the pre- and post-protocol reference contraction. A paired 2-tailed t-test was conducted to determine if there was a statistically significant shift in MPF for each muscle.

Interdigital spacing

The amount of force exerted and muscular activity across all tasks under the interdigital spacing condition will help to resolve how this change in geometry affects %MVE and %MVC. Differences between each interdigital spacer and the barehanded condition were calculated, expressed as a percent change, and compared by task and muscle.

Ratings of Perceived Exertion

All RPE scores for each participant were averaged, and the mean value used for normalization of each individual's response (Pare, Carnahan, & Smith, 2002). RPE scores were then analyzed using a 2-way ANOVA (glove condition x task).

Chapter 4: Results & Discussion

Participants

Ten males and ten females participated in this study. Collective information about the participants is displayed in the table below. Each participant's hand was measured and fitted with a correctly-sized glove. Preliminary analyses of normalized grip forces indicated no significant differences between males and females, therefore, all participants were pooled for the results presented here.

Table 2. Participant information.

	Mean (± SD)
Age	25.3 ± 5.4 years
Glove Size	8.7 ± 0.4 (median size = 8.5)
Hand Length	18.8 ± 1.1 cm
Middle Finger Length	7.9 ± 0.5 cm
First Knuckle Depth	2.4 ± 0.3 cm
Palm Circumference	21.7 ± 1.5 cm
Breadth of Hand at Knuckles	9.1 ± 0.7 cm
Maximum Hand Circumference	28.0 ± 2.3 cm

Grip Force

<u>*Maximum Voluntary Contraction (MVC)*</u>

Maximum power grip forces across participants averaged 384.0 ± 79.2 N for the bare hand condition. These forces declined significantly with increasing glove thickness. With an unadjusted grip span, Class 0, Class 2, and Class 4 gloves caused decreases in maximum voluntary force of 10.4 ± 5.6 %MVC, 20.3 ± 8.0 %MVC, and 31.0 ± 6.8 %MVC respectively, as illustrated in Figure 12. A main effect of glove condition was found ($p<0.05$), with post hoc analyses revealing significant differences for all gloved-bare and glove-glove comparisons. The interdigital spacers caused significant force output decreases as compared to the bare hand ($p<0.05$), however, they did not differ significantly from each other. Spacer 0, Spacer 2, and Spacer 4 caused decreases of 5.6 ± 6.6 %MVC, 7.9 ± 4.9 %MVC, and 9.7 ± 5.9 %MVC, respectively. These values approach those found in previous research, where interdigital spacing ranging from 3-10 mm produced losses of maximum grip strength of 12 to 26% (Hallbeck et al., 1994; Hansen & Hallbeck, 1996). As the thickest glove used in this investigation corresponded with an approximate 6 mm spacing thickness (Spacer 4), these values are nearly equivalent to the smallest decreases reported.

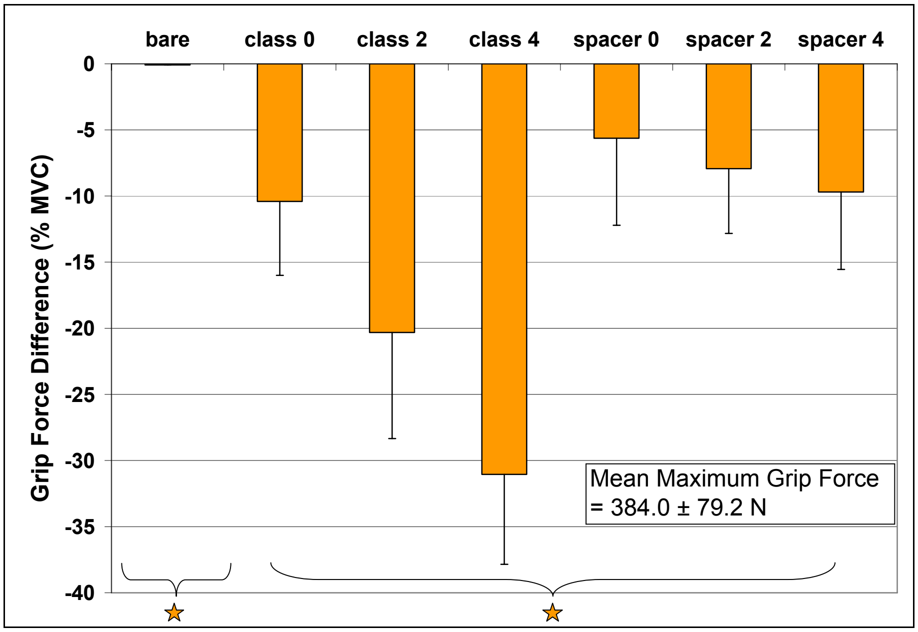


Figure 12. Force decrement in maximum power grip. Stars indicate the main post-hoc differences at p<0.05, with barehanded power grip significantly differing from all other conditions.

Though the friction at the glove(hand)-object interface is not the same across all conditions, it should be noted that this difference may not appreciably affect these results. Looking at the bare hand and interdigital spacing conditions (all the same coefficient of friction), regular decrements are seen as finger spacing increases. Similarly, the force loss between Class 0 and Class 2, and Class 2 and Class 4, also show regular decreases in force output. This suggests that it is in fact the increase in glove thickness and interdigital spacing, not the frictional differences between the bare hand and the gloves, that is causing maximum grip force loss.

Measured differences in the adjusted grip span are shown in Figure 13. There was a significant decrease in grip circumference to achieve the same hand posture with each step in increasing glove thickness ($p<0.05$). The average decrease in circumference between the bare hand and Class 4 glove condition was

27 mm. Maximum force output decreased significantly with each increase in glove thickness ($p<0.05$), with decreases of 13.7 ± 5.9 %MVC, 28.1 ± 5.5 %MVC, and 37.8 ± 6.5 %MVC, for class 0, class 2, and class 4, respectively.

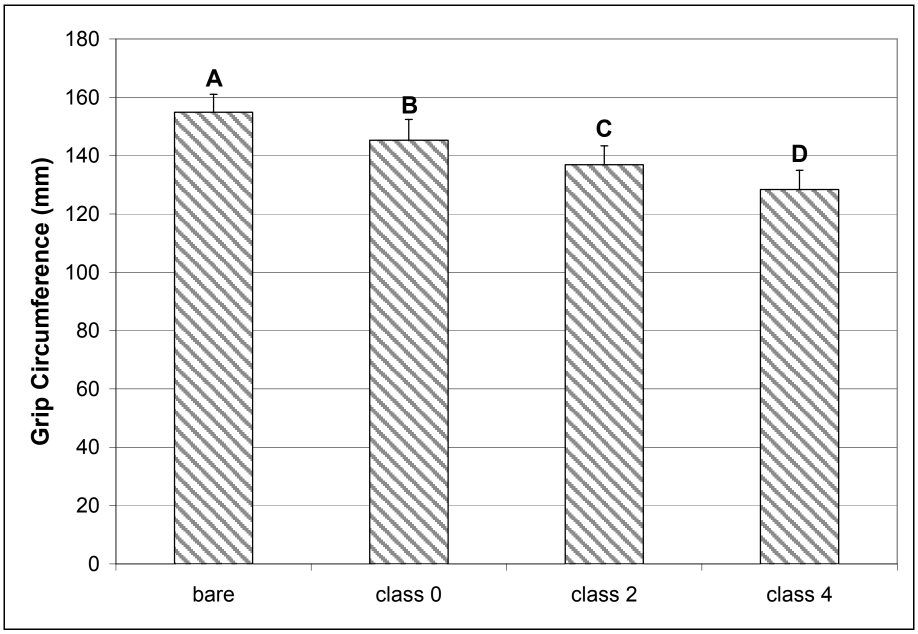


Figure 13. Average grip circumference used when adjusting grip dynamometer for the grip span changes in Protocol 2. Significant differences are as indicated, p<0.05.

Comparing MVC's of each glove class between protocols by means of t-tests showed significant differences for all three thicknesses ($p<0.05$). Surprisingly, this difference manifested itself as *decreases* in maximal force output after making grip span adjustments as compared to the non-adjusted grip. These differences are shown in Figure 14.

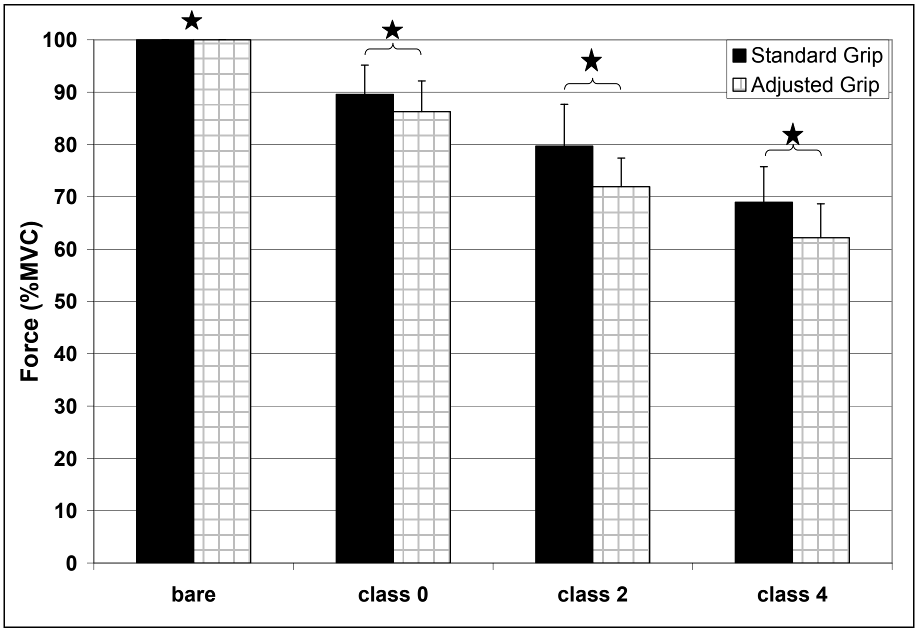


Figure 14. Maximum grip forces, adjusted vs. unadjusted grip span, expressed as %MVC normalized to the barehanded condition. Stars indicate significant force output changes between the grip spans of the 2 protocols, p<0.05.

Adjusting the grip span to try to compensate for the effective increase of grip size of the dynamometer incurred by wearing gloves did not help grip force output, as demonstrated by the significant differences in maximum force output between the adjusted and unadjusted grip spans. In fact, this adjustment caused a decrease in force compared with the unadjusted grip span. It was thought that by making such an adjustment, the more proximal phalanges should have been able to contribute more to the power grip, as opposed to without, where the proximal phalanges may not have been able to reach around the dynamometer as much due to the interference of the glove, thus forcing the distal phalanges to exert the force, decreasing the total force output (Hazelton, Smidt, Flatt, & Stephens, 1975). Despite this, it is possible that while the hand may have been in a more favourable position with the adjusted grip span to elicit maximum force output, there may be other factors at play. For example, with the adjusted grip span, the fingers bend as they do in a barehanded grip, but with the addition of increasing glove thickness to bend. Therefore, this additional force loss may be attributable to the force required to bend the glove further, which it seems from this data to limit maximum grip force more than the glove's interference with effective grip span.

Lift Grip Force

A representative look at a grip force profiles for the lifting task is shown in Figure 15. These grip force profiles are similar to those previously published (Monzee et al., 2003; Westling & Johansson, 1984), clearly showing a peak grip force followed by a slightly lower grip force once the grip became stable.

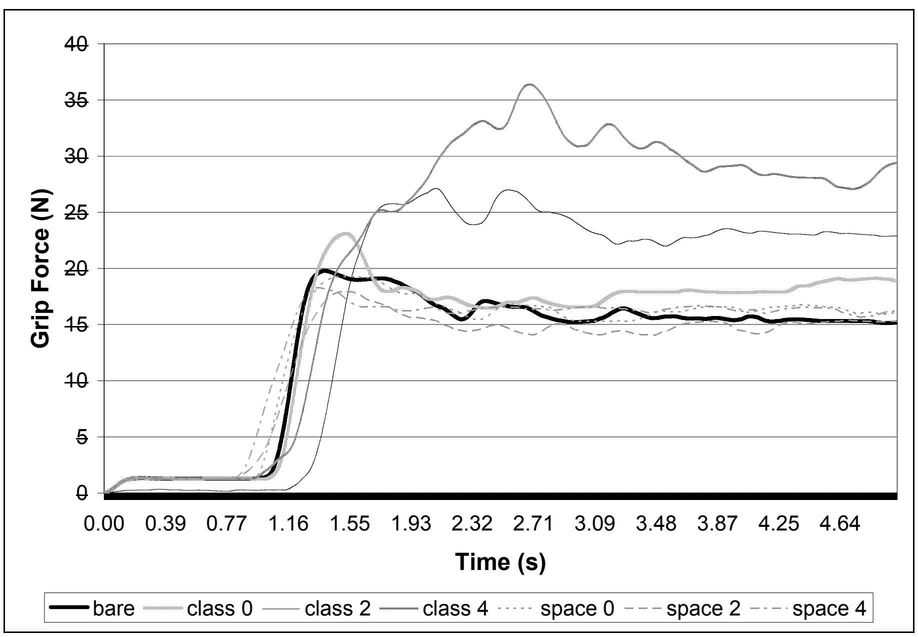


Figure 15. Grip force profiles for one subject when lifting the 3.6 kg dynamometer.

A main effect of glove condition was seen for peak grip force (p=0.01), but no significant difference was seen in peak lifting force with interdigital spacers as compared to the bare hand. Similar results were shown when considering the stable holding phase grip (p=0.002). The absolute force values seen for the lifting task were calculated and presented in Figure 16 for reference. The %RVC differences between each glove condition and the bare hand is presented in Figure 17.

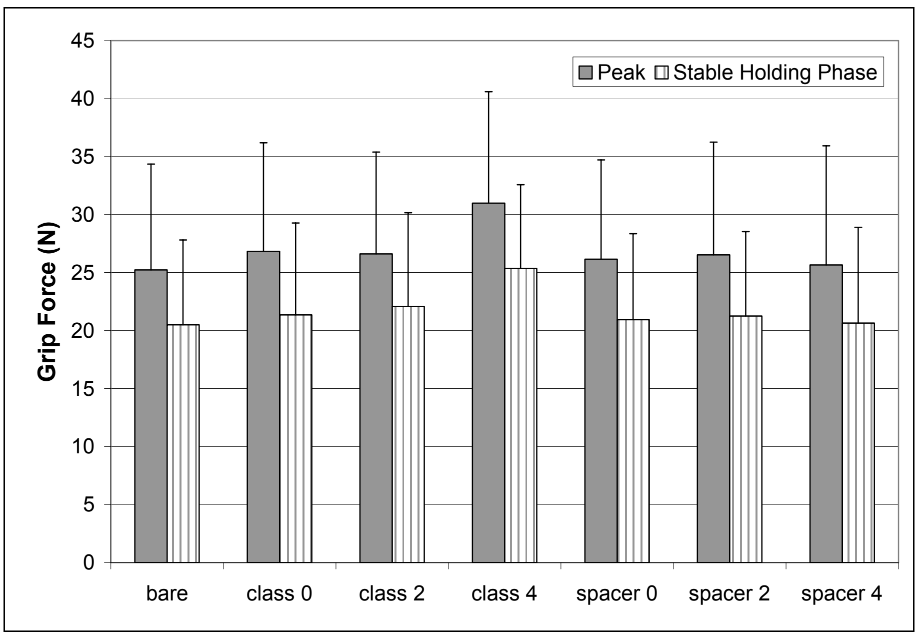


Figure 16. Absolute grip force values (N) for lifting task.

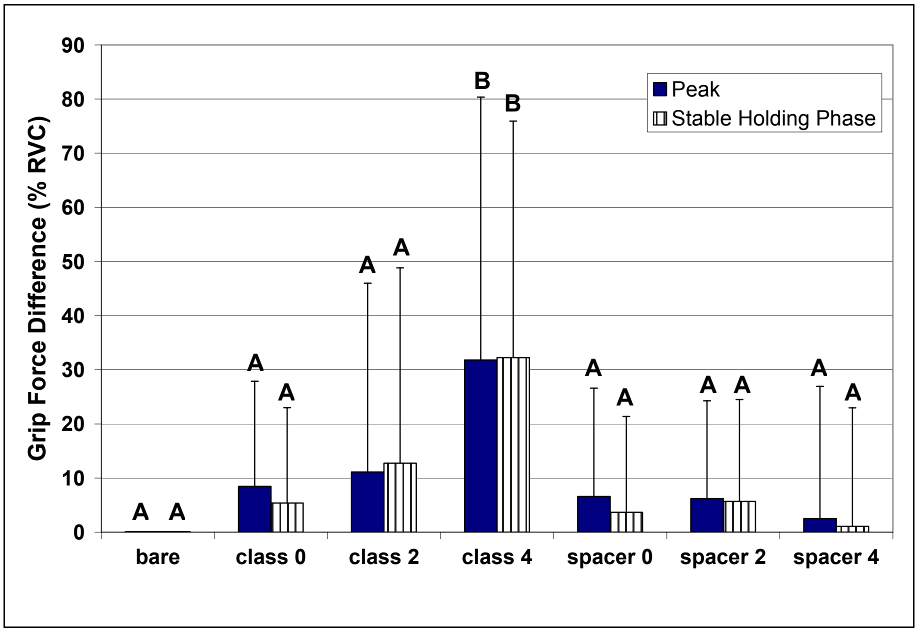


Figure 17. Peak and stable holding phase grip forces for the lifting task. Forces are expressed in %RVC difference from the bare hand, with RVC derived from the barehanded lift condition. Significant differences are indicated, p<0.05.

Fixed Force

Subjects were able to accurately maintain a fixed force of 75N with visual feedback across all glove conditions. The average absolute grip forces are pictured in Figure 18. A one-way ANOVA showed no significant differences in force output during the fixed force task ($p>0.05$), with an overall average force of 77.2 ± 1.3 N.

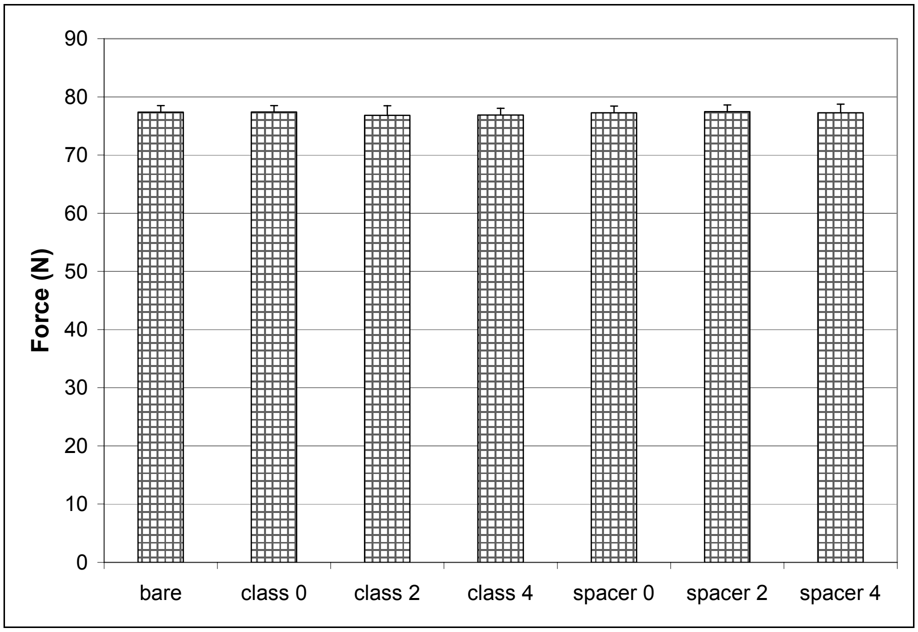


Figure 18. Absolute force readings (N) from the fixed force task. No significant differences were found between any glove condition.

Tactile Sensitivity

A main effect of glove type was found using the Von Frey hair test of tactile sensitivity ($p<0.05$). The perceived forces for the bare and gloved conditions are shown in Figure 19. Compared to the bare hand, post-hoc analyses showed statistically significant losses of tactility while wearing the Class 2 ($p=0.002$) and Class 4 ($p<0.05$) gloves. The only non-significant difference found was between the bare hand and the Class 0 glove ($p>0.05$).

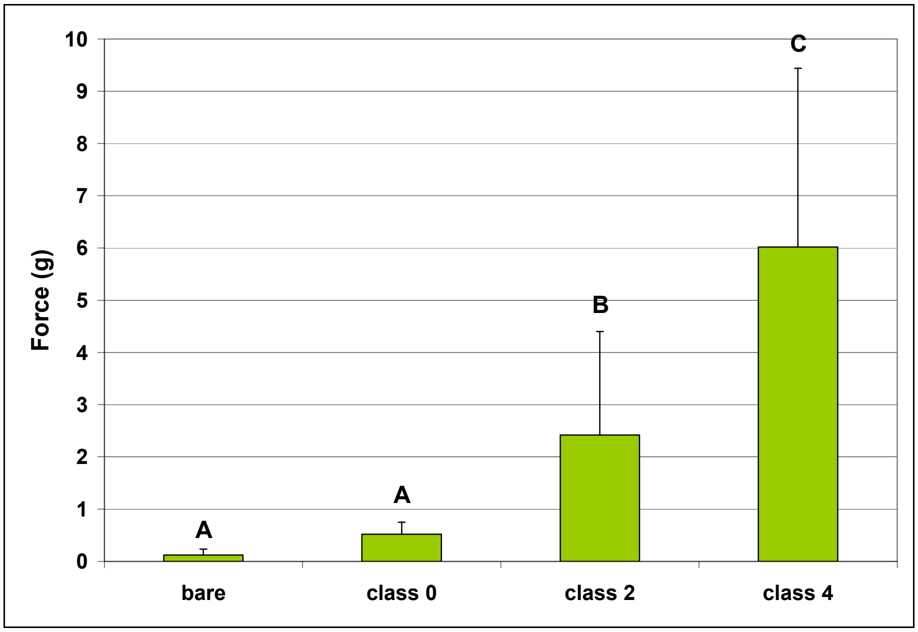


Figure 19. Von Frey Hair Test perceived forces, expressed in grams. Significant differences are as indicated, p<0.05.

Investigations of grip force using digital anaesthesia are interesting for comparison to investigations of grip force while wearing gloves. The increase of grip force during the lifting task seen here is similar to that shown with a total loss of tactile sensitivity, with forces approximately 30% MVC higher than the barehanded condition (see Figure 17). This comparison is enhanced by the observation that visual feedback provided to participants with anaesthetized digits allowed them to adjust and adapt their grip forces to normal levels (Jenmalm, Dahlstedt, & Johansson, 2000). This finding agrees with the results from this experiment, where participants were able to accurately maintain a fixed submaximal force with visual feedback across all glove conditions.

As load force is constant, and the glove material (and thus the frictional characteristics of the glove-object interface), remains the same across trials, it could be assumed that any changes in the grip force may be attributable to changes in glove thickness. If these values increase with thickness in lifting, as they do with loss of sensory feedback via anaesthesia (Monzee et al., 2003; Westling & Johansson, 1984) and seen in Figures 3 and 4, the culprit might then be interference with the mechanoreceptors of the fingers and decrement of sensory input arising from the fingertips. However, more current research has shown that this lack of tactile sensitivity in turn influences the placement of the fingers (in fact it misaligns the digits on the object) and it is this effect that influences the increase in grip force and increase in muscular effort by increasing the torques produced (Monzee et al., 2003). It should be noted, however, that power grip has not been examined as thoroughly as precision grip, and has not been investigated under the effects of anaesthesia. The data from this experiment show that grip force did increase with increases in glove thickness as expected while lifting, however, our equipment was not equipped to measure each finger's contribution to the grip force so moments could not be calculated. Other glove research has shown similar results, with grip forces during a lifting task increasing while wearing one, two, or three surgical gloves (R. H. Shih et al., 2001). Therefore, under the appropriate task comparison, tactile sensitivity could be isolated as a factor contributing to force decrement while wearing gloves.

EMG

Individual muscle results are presented in full in Appendix D. Results presented in this section will describe the pattern of muscle activity for all muscles, unless otherwise noted. Though not tested for, the EMG suffers from crosstalk from neighbouring muscles and as such the muscles' interdependency is described in a general discussion.

Maximum Grip Trials

Generally, muscular activity during maximum contractions is close to that seen during the barehanded condition, but there are some decreases in EMG in some muscles with thicker gloves.

Reduced activation is demonstrated most clearly with the EMG results from the FDS, illustrated in Figure 20, where a distinct drop in %MVE is seen with thicker gloves. Though other muscles do not show such a difference, for this particular muscle, it is surmised that the fingers were simply not able to reach around the dynamometer as per normal. This placed the fingers so that force is exerted more on the distal phalanx. This requires activity of the flexor digitorum profundus (unmeasured), rather than the monitored FDS which inserts into the middle phalanx (Long, 1970). This perhaps illustrates most directly how seemingly small alterations in hand position on the dynamometer, caused by increases in glove thickness, change the contribution of prime movers and disrupt grip performance.

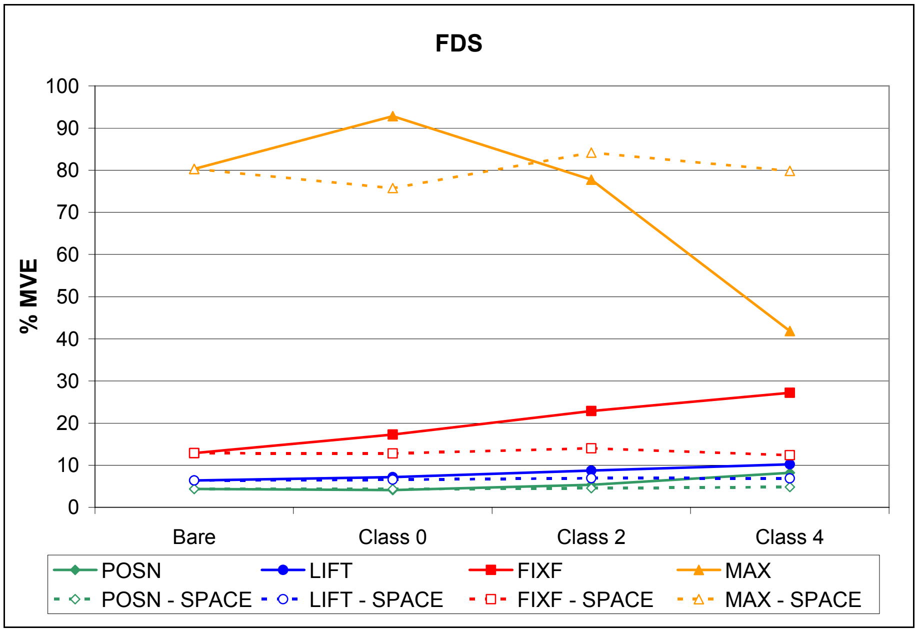


Figure 20. Muscle activity for the FDS during the experimental trials, expressed as %MVE.

The FDS however, was the most extreme example of such a decrease in muscular activity during the MAX trials. There was a 38.4 %MVE drop from the bare hand to the Class 4 gloved condition. The ED and FCR also showed significant differences in muscle activity during the maximum contractions ($p<0.05$), however, both increased by 24.1 %MVE and 38.1 %MVE respectively, unlike the FDS. Most muscles did not register much change in muscle activity, as can be seen in Figures 21 and 22, showing more typical examples of the flexor (FCU) and extensor (ECU) response to increases in glove thickness. It is unclear why these results are conflicting.

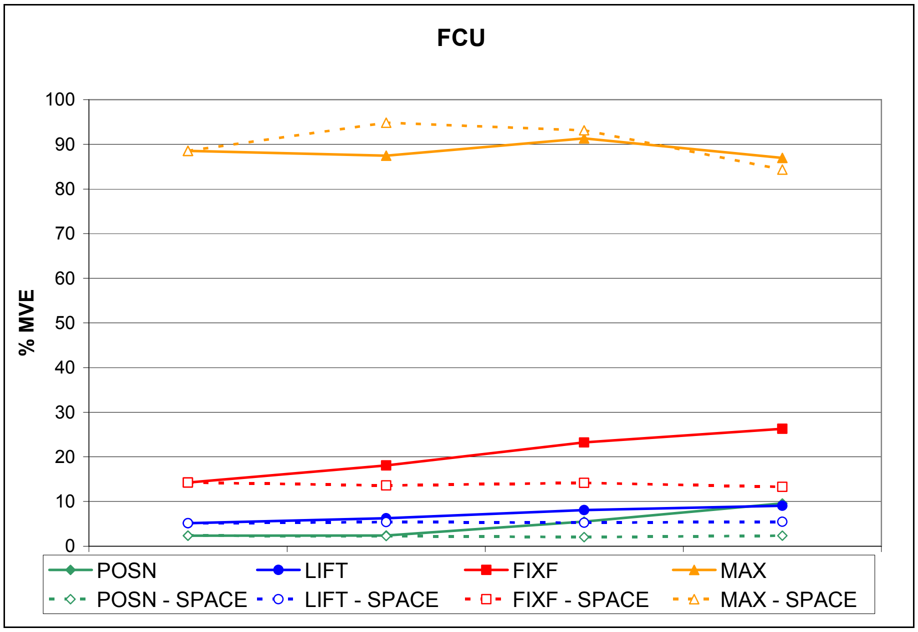


Figure 21. Muscle activity for the FCU during the experimental tasks, expressed as %MVE.

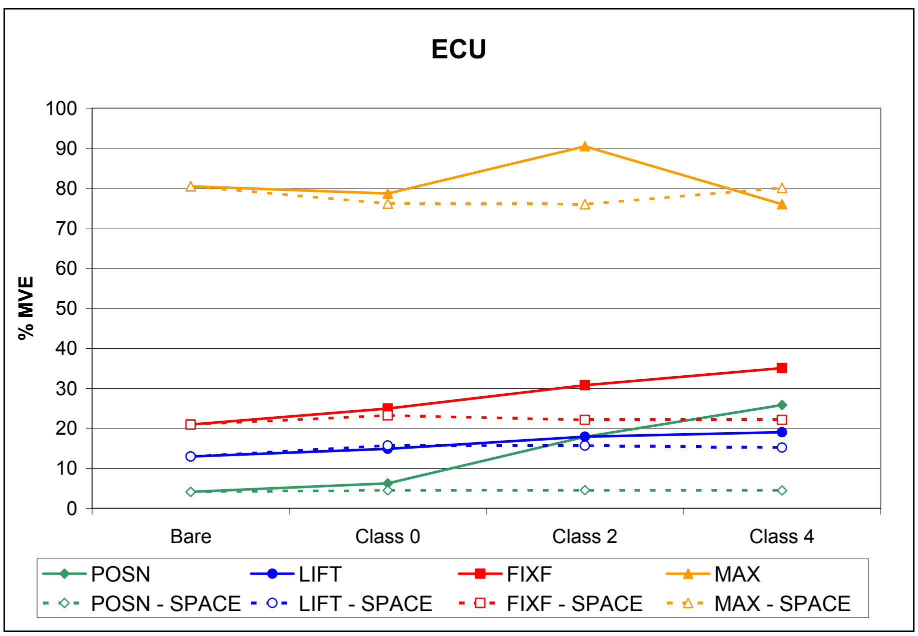


Figure 22. Muscle activity for the ECU during the experimental tasks, expressed as %MVE.

Interdigital Spacing

Increased interdigital spacing caused no significant change in muscular activity in all tasks across glove conditions during submaximal effort tasks ($p>0.05$). Interdigital spacing results are illustrated for these tasks with hatched lines in Figures 20, 21 and 22.

Fatigue

In six of the seven muscles, no significant differences appeared between mean power frequencies measured pre- and post-protocol ($p>0.05$). The ECU was the only muscle to show a significant difference ($p=0.031$); however, this was seen as an increase in MPF, countering the well-documented phenomenon of a spectral frequency shift to lower frequencies after muscle fatigue (for example, (Bigland-Ritchie, Donovan, & Roussos, 1981; Petrofsky & Lind, 1980). In addition, the randomization of trials was designed to reduce the effect of fatigue.

Submaximal muscular activity

Mechanical factors and muscular effort

The extra muscular effort required when forming a grip while wearing gloves is shown in Figure 23. The muscular effort to solely move the bare hand during the positioning task was subtracted from the muscular activity recorded when performing the same task with the three classes of gloves. A significant main effect of glove condition ($p<0.05$) was observed for all muscles. As can be seen from the graph, muscular activity increased a minimum of 3.8% (FDS) to a maximum of 32.3% (ED). These increases reflect the amount of muscle activity needed just to *move* the glove into a functional gripping posture alone. Interestingly, the extensors all had greater increases in EMG activity than the flexors, corroborating previous research which found that forearm extensors are more sensitive to exertions made during gripping activities than flexors (Hagg & Milerad, 1997; Lariviere et al., 2004; Roy et al., 1990).

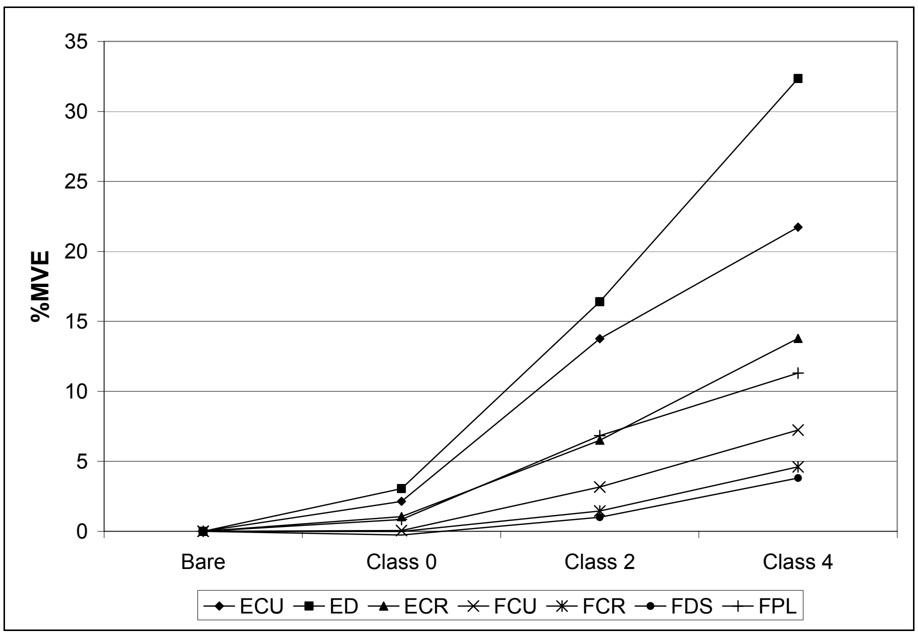


Figure 23. Differences between glove classes and the bare hand in the power grip positioning task, expressed as % MVE difference from the barehanded condition.

Figure 24 shows the difference in muscle activity between the fixed force task and the positioning task. The muscular activity differences illustrated in Figure 24 should theoretically be equal across glove conditions, given that the difference between them should only reflect the extra muscular effort required to reach a fixed grip force, without the effect of tactile sensitivity loss and muscle activity needed to bend the gloves around the dynamometer. The trends show that the extensors decrease, and the flexors increase, however, only the ED and FDS show significant differences. This may be due to grip differences between the fixed force and the positioning task. In the positioning task, subjects were instructed to create a true power grip posture, whereas in the fixed force task, participants concentrated more on attaining the set force and may not have been wrapping the fingertips as tightly around the dynamometer perhaps changing the recruitment of FDS relative to FDP.

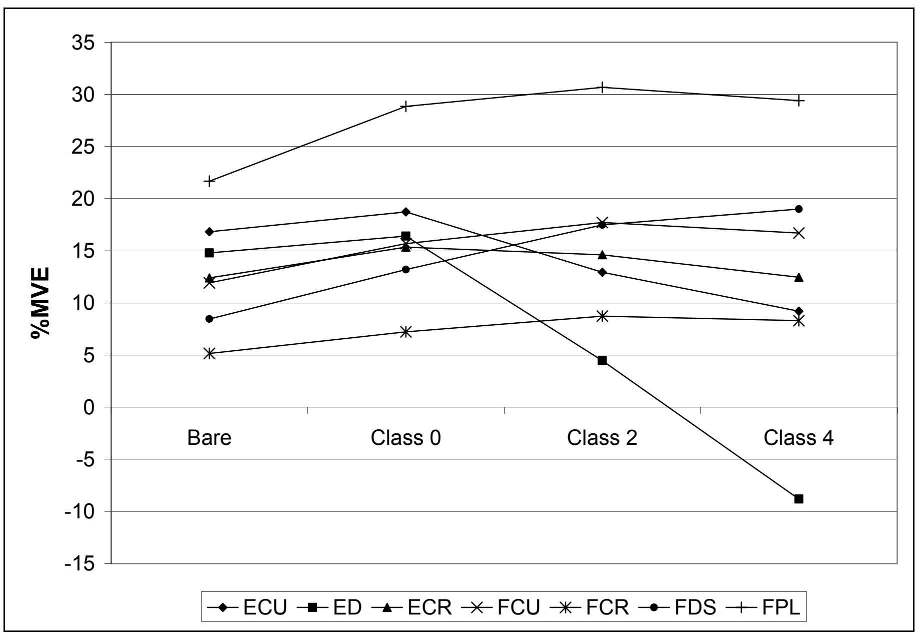


Figure 24. Difference in muscle activity of the fixed force task minus the power grip hand position, expressed in %MVE.

Effect of decreased tactile sensitivity on muscular activity

Figure 25 illustrates the differences between the EMG activity between the fixed force task and the stable holding phase grip force of the lifting task. As visual feedback was provided during the fixed force task (and subjects were able to maintain a fixed force) subtracting the lift grip force eliminates the contribution of effort required to bend the glove. An increase in the remainder in this comparison across glove types could be attributable to a loss of tactile sensitivity. Though the activity of the seven muscles generally seems to increase over and above that seen during the fixed force trial with increasing glove thickness, only the flexors showed statistically significant main effects of glove condition: FCR (p=0.037), FDS (p=0.005), and FPL ($p<0.05$). Therefore, it could be concluded from this data that a loss of tactile sensitivity may cause increases in muscular activity in the forearm flexors.

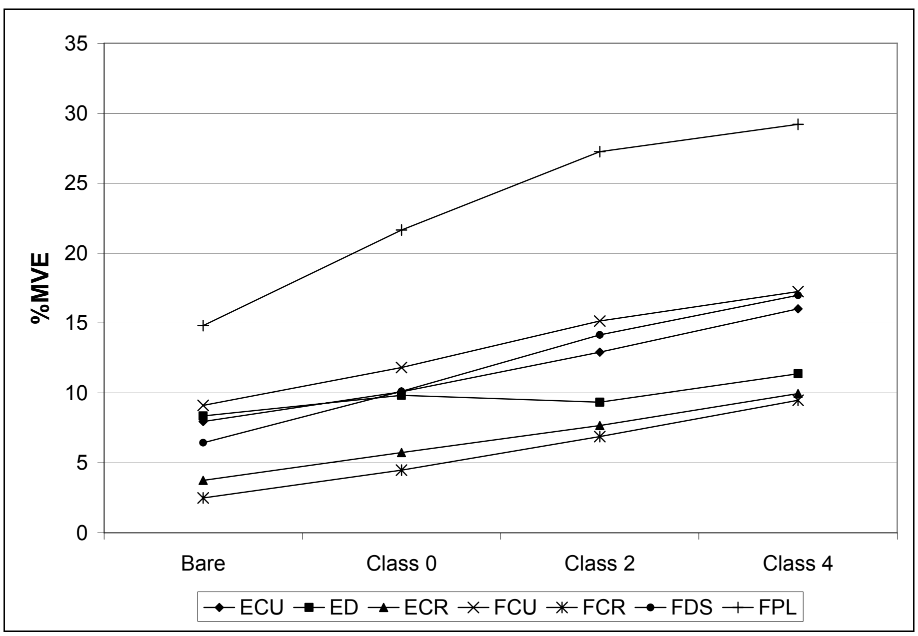


Figure 25. Difference in muscle activity of the fixed force task minus the stable holding force of the lift task, expressed in %MVE.

Hand Geometry

Interdigital spacing had different effects on maximal and submaximal tasks. For maximum effort power grip, interdigital spacing decreased the force output by as much as 10%, and showed a range of muscle activity responses. No change in muscle activation was recorded during the trials with interdigital spacing.

For submaximal tasks, no significant differences in either muscle activity or force output was seen across glove conditions and tasks. Therefore, the overall force capability of the gloved user is hindered at near maximal effort, but may not be for tasks requiring lower grip force, such as the lifting task condition which required roughly 20%MVC in this experiment. It is possible that the differences were simply too small to detect, particularly with the variability encountered in the data. If, for example, a 10% decrement is seen at 100%MVC, then scaling down to lower grip forces, this decrease could be seen as 3% at 30%MVC. This is theoretically the same decrement, but may not appear as a statistically significant difference.

Ratings of Perceived Exertion

For all submaximal force tasks (Positioning, Fixed Force, and Lift), RPE scores significantly increased as a function of glove thickness ($p<0.05$), as shown in Figure 26. As indicated by increased in RPE scores, subjects felt that wearing gloves while performing the experimental tasks took significantly more effort than performing them with bare hands. The interdigital spacers did not significantly affect the RPE scores reported for any of the tasks.

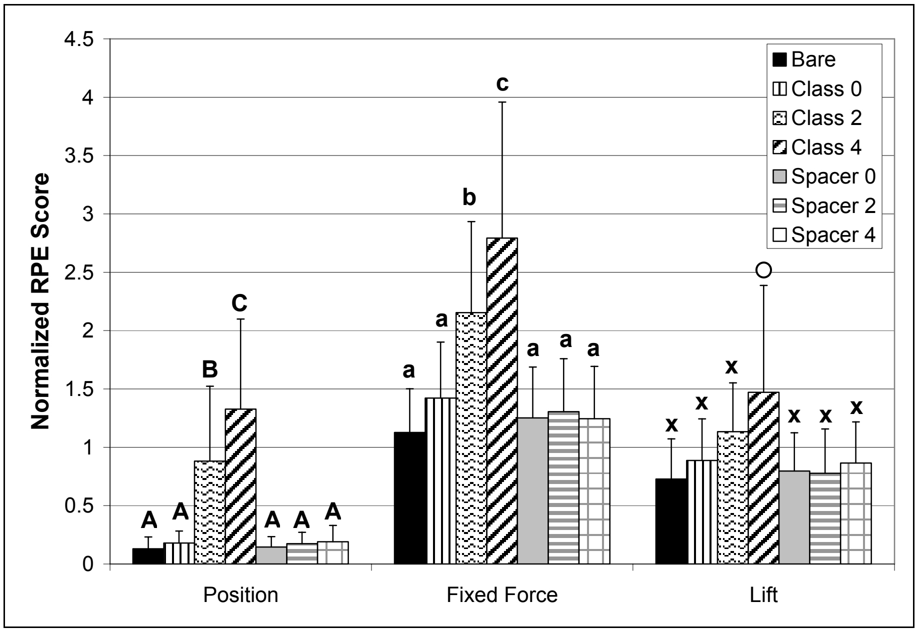


Figure 26. Normalized RPE scores for manual tasks. Significant differences are as indicated, $p<0.05$.

Chapter 5: General Discussion & Conclusions

Glove research has rarely quantified glove attributes, and often compared gloves of varying material and physical properties. In this research, we had the unique opportunity to control previously unregimented factors in current glove research by using rubber powerline maintainer's gloves. Since these gloves are highly regulated protective equipment, they cannot vary widely. Properties such as thickness, material, and dimensions are constant. These gloves also come in a variety of sizes, and participants were measured and fitted with a correctly-sized glove.

Despite the relatively large variability encountered, statistically significant differences were still seen between glove classes and interdigital spacing conditions for all tasks. This suggests that the trends seen can be interpreted as strong indicators that even small increases in glove thickness affect user performance and effort.

The results from this research were able to answer the questions posed in our initial objectives. To reiterate:

- Increasing glove thickness corresponds to
    - decreasing maximal power grip force capabilities, with up to 31%MVC loss wearing the Class 4 glove;
    - increases in peak and stable holding phase grip forces during a lifting task of roughly 30% from the bare hand for both grip forces wearing the Class 4 glove ;

- increases in muscular activity levels (though sometimes not statistically significant) for submaximal effort tasks.

- Standardizing the hand posture, by changing the grip span to compensate for glove thickness, did not improve maximum force output; however, other factors may have been counteracting the postulated benefits of optimizing grip span.
- Changes in hand geometry in the form of interdigital spacing contribute to force decrement of approximately 10%MVC in maximal efforts, but did not significantly affect tasks of submaximal effort. Interdigital spacing also does not appear to significantly alter muscular activity in either maximal or submaximal effort tasks, though some statistically insignificant increasing trends were observed.
- As indicated by the results of the Von Frey Hair Test, increases in glove thickness reduces tactile sensitivity. Comparing the differences in muscular activity between the fixed force and the lifting tasks further helped to suggest that the loss of tactile sensitivity may be associated with higher than normal grip forces during submaximal tasks.

Separate from the obvious implications for the current users, these results have the capacity to assist in future glove research and guide potential design changes. For example, reducing interdigital spacing, such as in a mitten-style glove already designed where the last three digits work as one, may lessen the effect of interdigital spacing seen in this experimentation and increase the ability of the 4th

and 5th fingers to contribute to power grip and reduce the load placed on the thumb and first two fingers. Further investigation into this different style of glove may indicate lower overall flexor and extensor activity if the contribution of the smaller fingers to grip force is not occluded by individually bending each glove finger with disadvantageous hand geometry (or that the thickness itself impedes performance).

As with all research, this investigation is not without its limitations. Though we were able to isolate thickness as an independent glove attribute, the functional consequences due to this thickness may be interdependent. For example, even though interdigital spacing was simulated, it may not necessarily reflect the actual detrimental effects due to this change in geometry as there may be innate (dis)congruous mechanical factors with a whole glove attenuating force. Further, though an attempt was made to sequester the contributors to grip force loss, there remain difficulties in doing so. This investigation also only looked at a single posture, one type of grip, and one type of glove. Different glove materials may not produce similar results. Friction at the glove-object (dynamometer) interface was constant across the gloved conditions; however, it was not possible to maintain the same friction for the gloved and barehanded conditions (bare and interdigital spacing). Some of the differences seen between bare and gloved conditions may be attributed to frictional differences. The participant population was also quite young and different from the user population of powerline maintainers. Therefore, these results may not directly extend in application to an older or more experienced glove user.

Comparing the trends of the RPE scores with muscular responses for the submaximal tasks leads well into a discussion concerning the appropriate selection of muscles for this investigation. For example, significant increases in both RPE scores and relative muscle activation between the barehanded and Class 4 conditions appear in the lifting, positioning, and fixed force tasks. As well, no differences in RPE and muscular activity between the bare and all interdigital spacing conditions were seen. These similarities suggest that the selections of the 7 muscles measured are representative of the entire forearm. Furthermore, electromyographic studies by Long et al. indicated that the ED and FDS (along with other intrinsic muscles), are among the extrinsic muscles moving the fingers and hand in a simple squeeze power grip (Long, 1968; Long & Brown, 1964; Long, Conrad, Hall, & Furler, 1970). It is interesting to note for future work that as the participant's perception of effort closely matched the amount of muscular activity recorded, using ratings of perceived exertion to quantify effort could act as a viable alternative to EMG in the workplace.

The EMG results must also be interpreted with some caution, as crosstalk between forearm muscles is likely high. Previous research has reported that the magnitude of common signal between adjacent electrodes over forearm extensors has reached nearly 50%, while flexors approached 60% (Mogk & Keir, 2003a). As such, the similarity of response between muscles may be due to crosstalk, but the overall patterns seen should not change the general discussion of the results. Additionally, individual muscles demonstrated differences from their functional groups (such as the reduction of muscle activity of the FDS in maximal efforts), so independent responses did occur despite the probability of high amounts of crosstalk.

Contributors to maximum grip force loss

An attempt was made to distinguish individual contributions to force loss during maximal efforts while wearing a Class 4 glove, assuming linear force-EMG relationships. Reduced activation was calculated as the reduction in EMG during the MAX trials, bending of glove was determined from the positioning task and interdigital spacing by the difference between maximum barehanded and Class 4 grip force. The contribution of loss of tactility was calculated using EMG from the lifting task, by looking at the change of EMG activity between bare and Class 4, divided by the %MVC required for the lift while wearing the Class 4 glove.

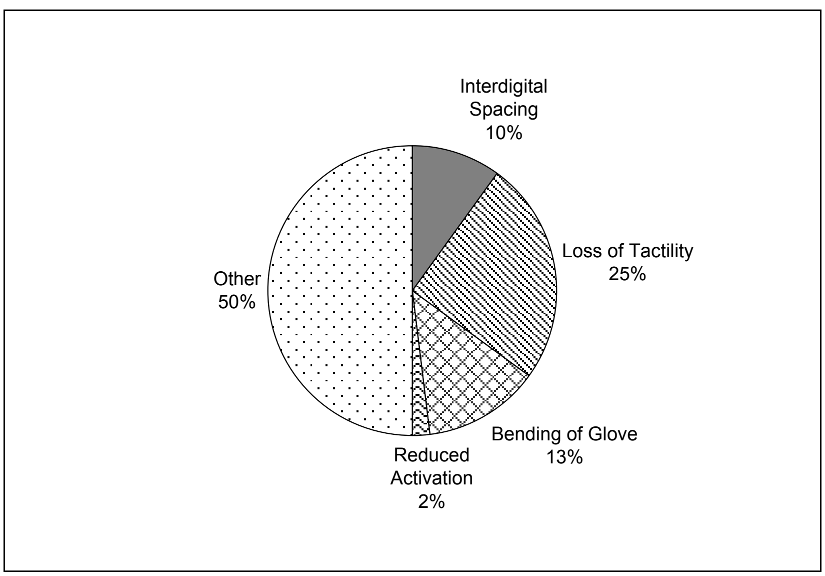


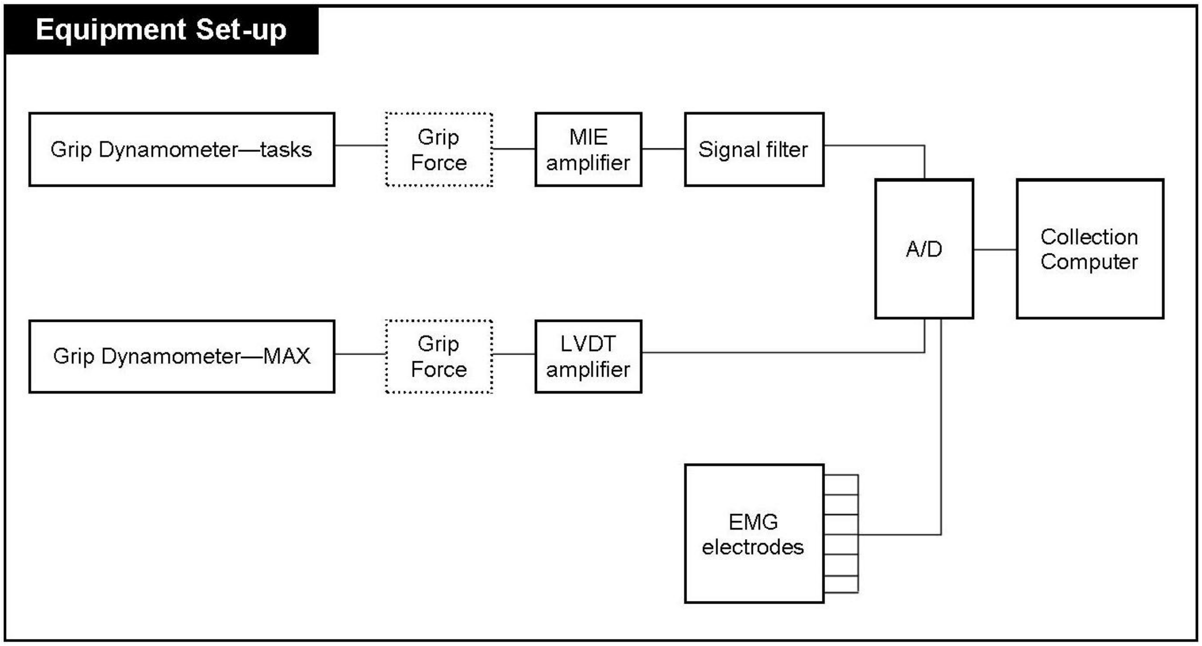
Figure 27. Schematic of the contribution to a drop in maximum grip force while wearing a Class 4 glove, estimated from changes in force and EMG activity in 7 forearm muscles.

It was estimated that the factors identified in this study would lead to a loss of approximately one half of maximum grip force while wearing Class 4 gloves. This was larger that the directly measured force reduction of 31% and is likely due to the lack of independence between the identified factors. It is nevertheless a useful starting point for understanding the reduction in maximal force capability while wearing gloves. Further investigation considering other glove properties, such as friction at the glove-object interface, has the potential to distinguish all possible contributors to maximum grip force loss while wearing gloves.

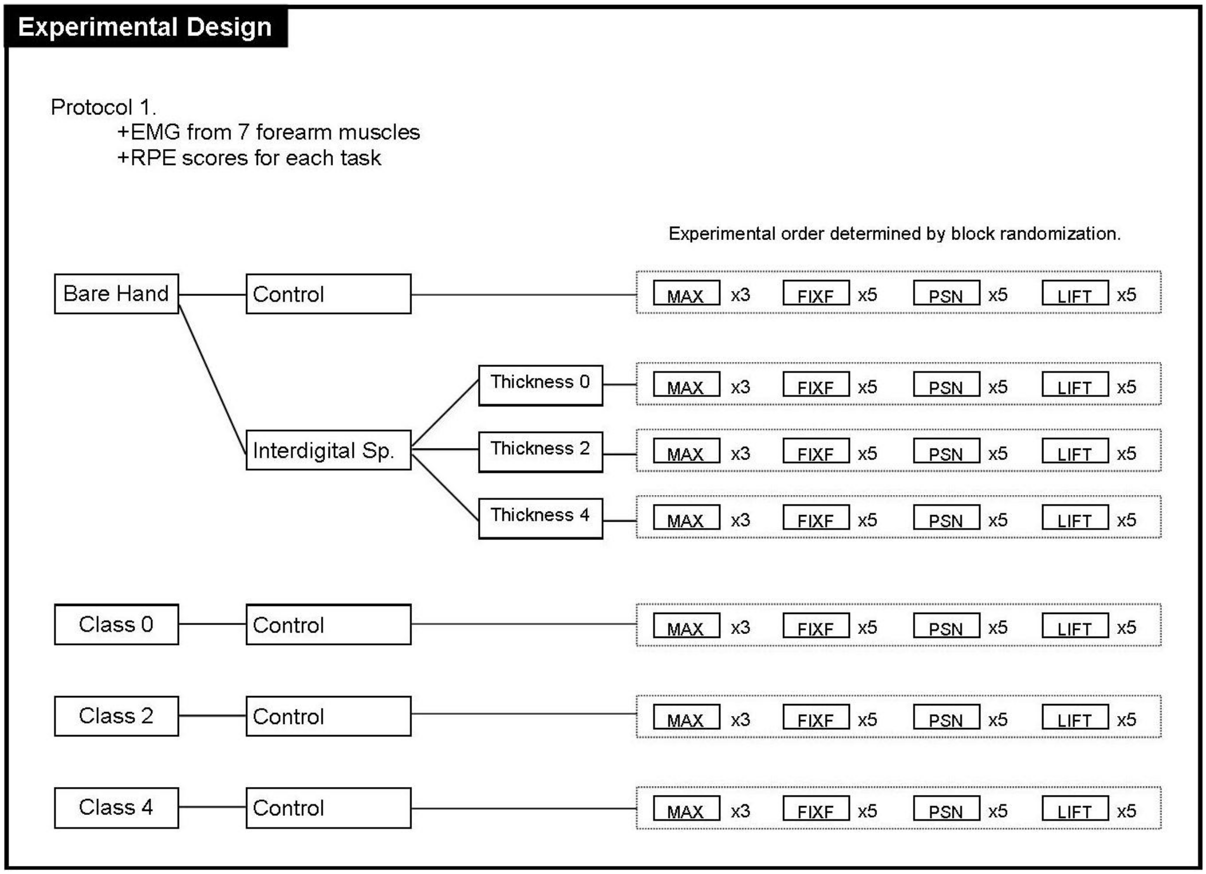
The sizes of the effects of wearing gloves seen in this research, particularly at maximal effort, were decidedly substantial. The impact of wearing these gloves on the users, the powerline maintainers, is a considerably increased effort to work. This research should contribute to a greater understanding of why and how gloves inhibit performance.

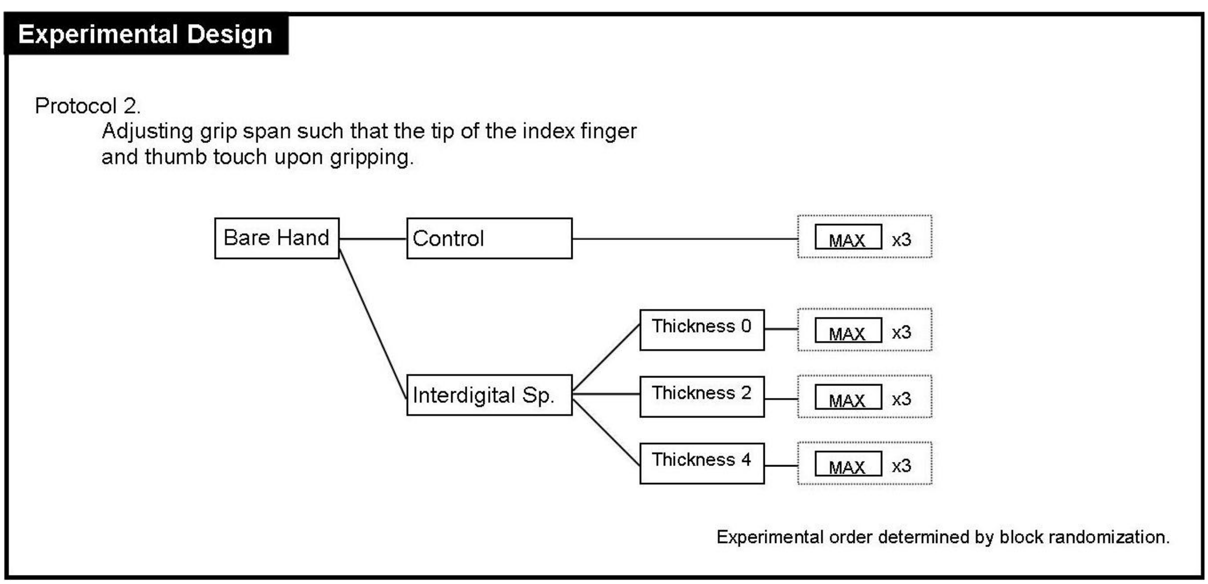
Appendices

A. Equipment Set-Up

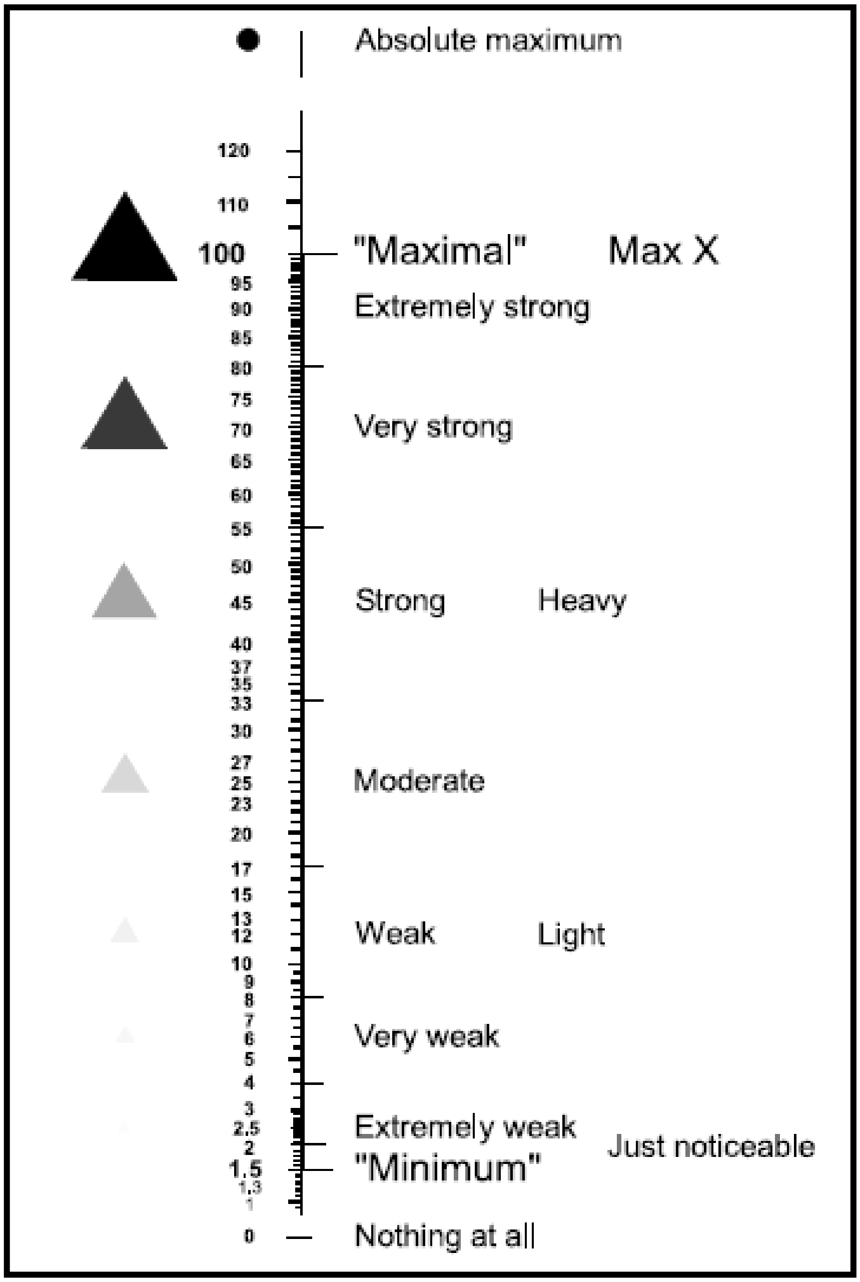


B. Experimental Design

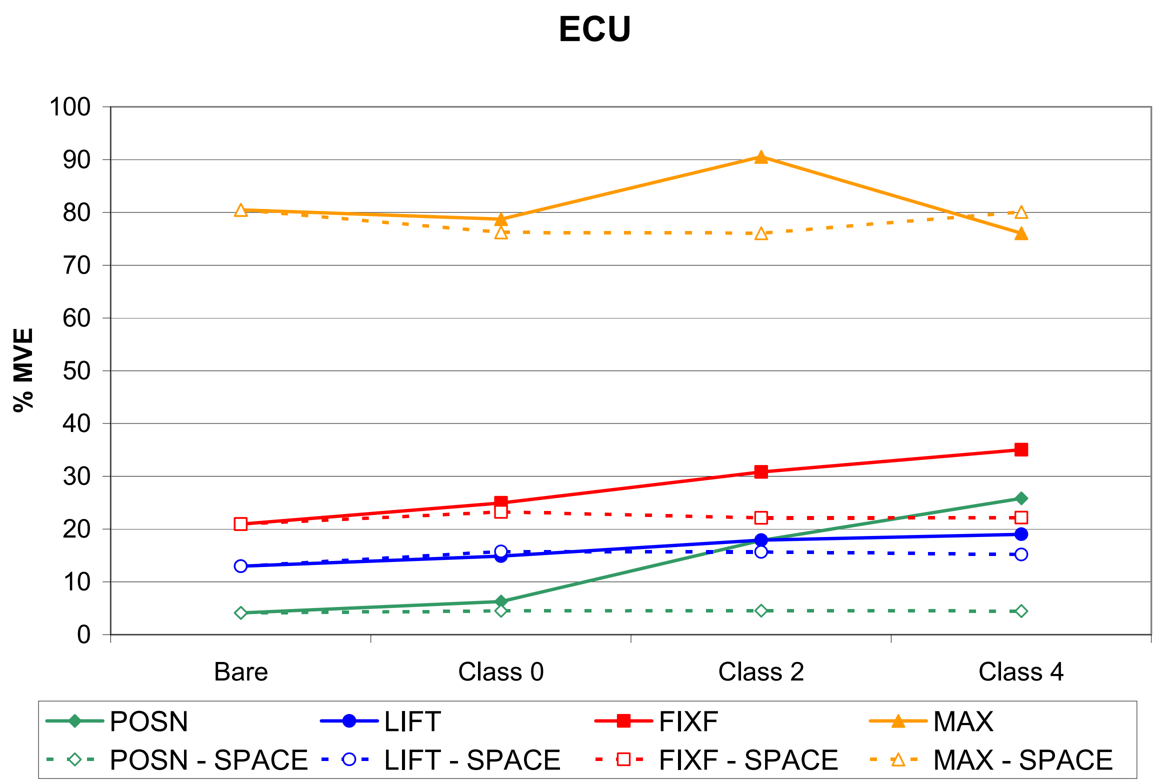


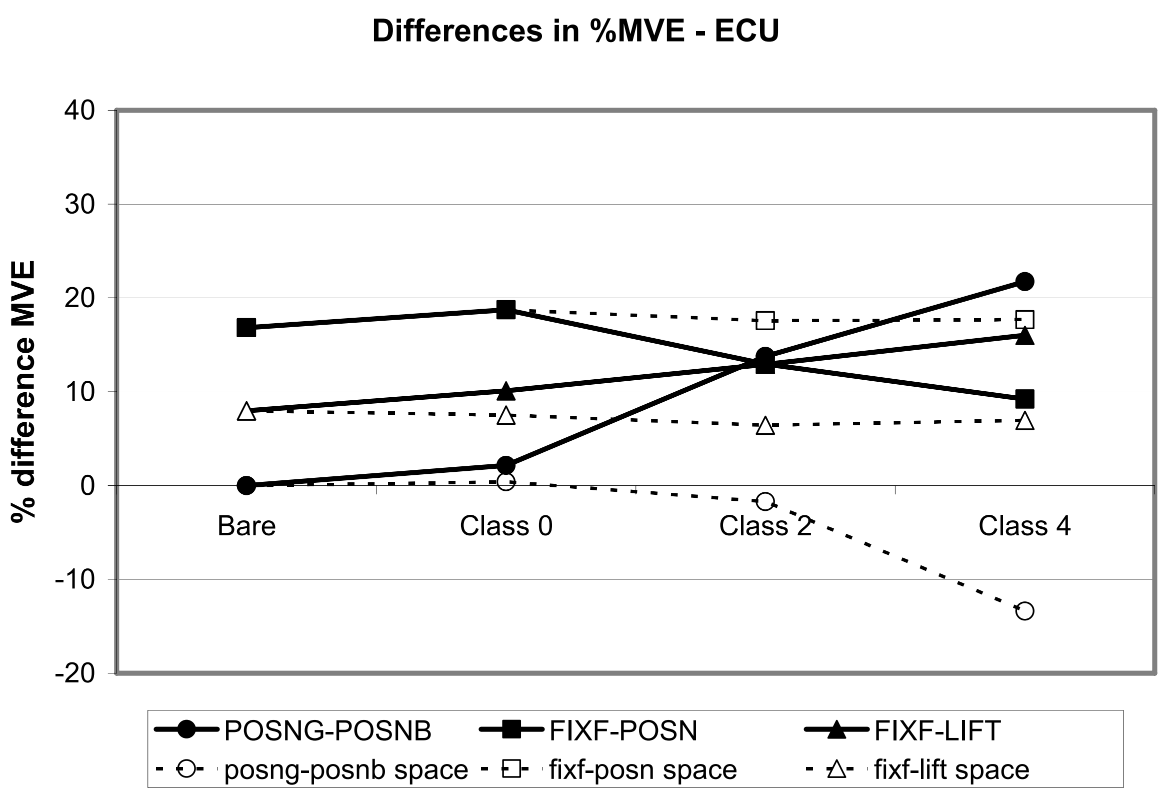


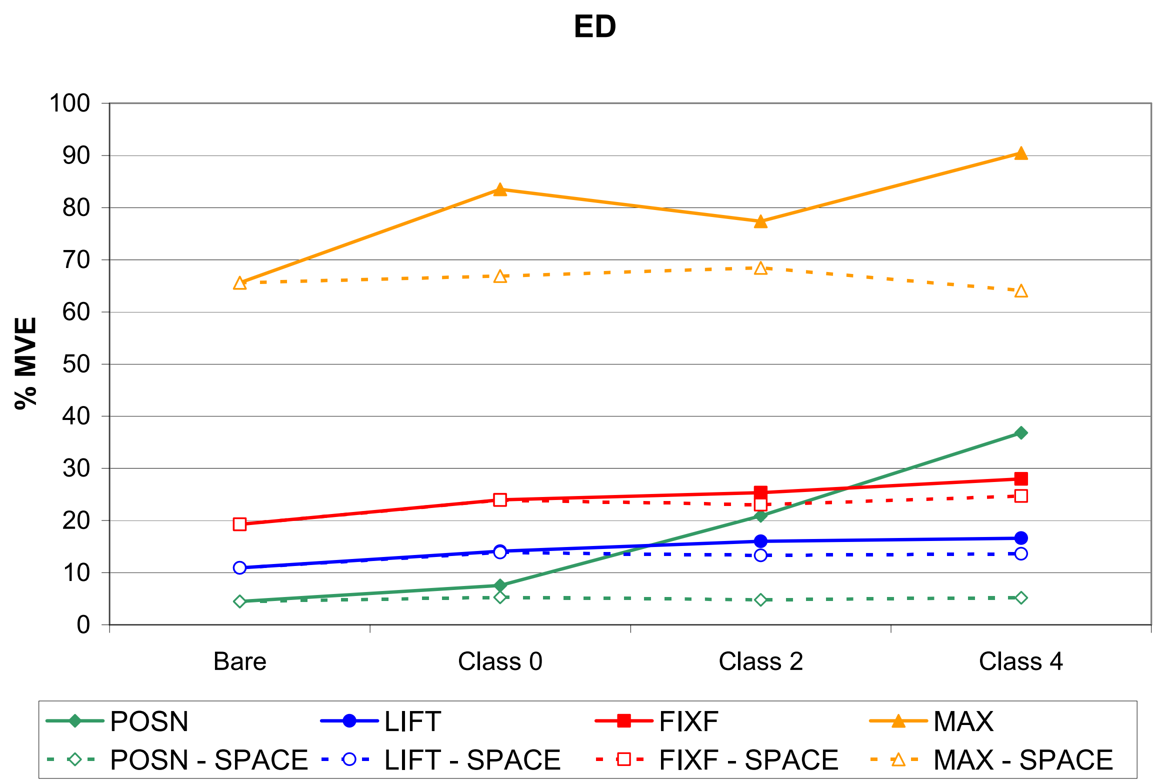
C. Ratings of Perceived Exertion, CR100 scale (© Borg & Borg, 1998)

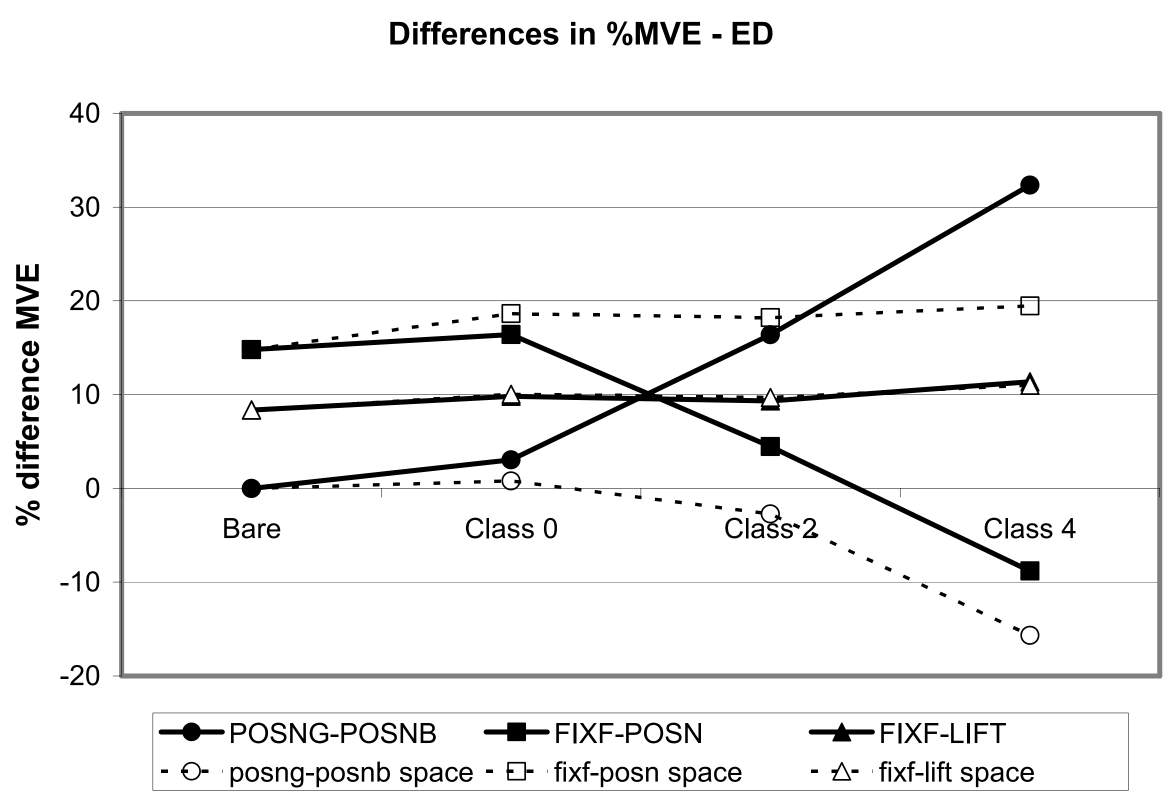


D. Muscle Activity Charts

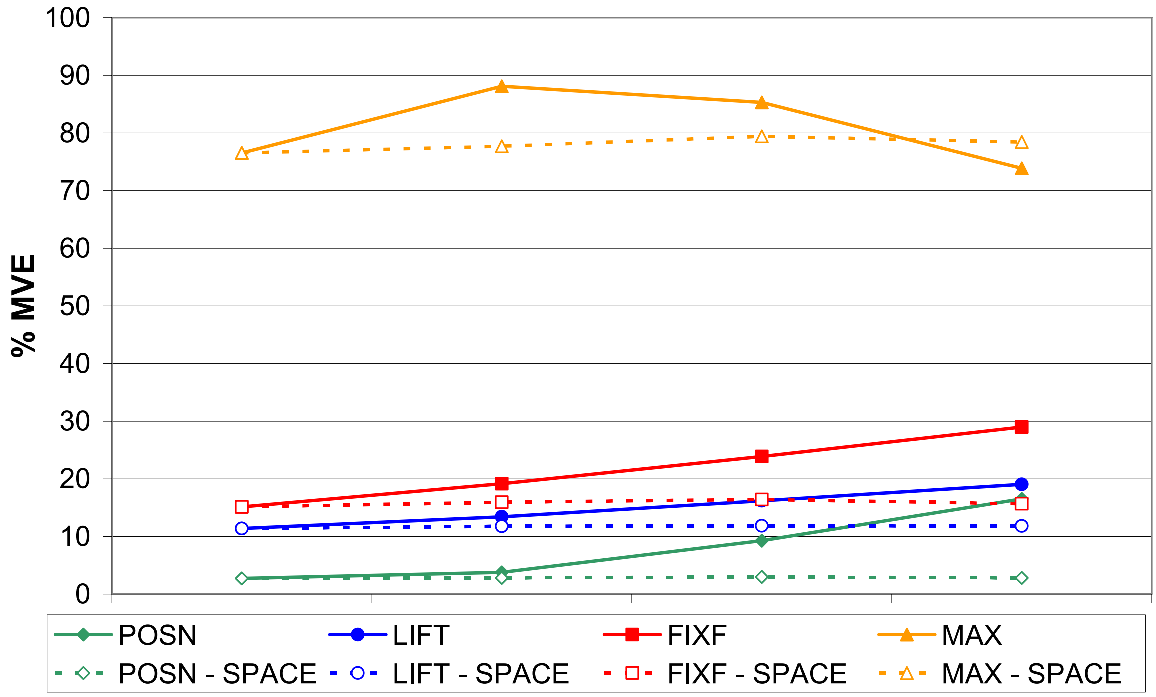




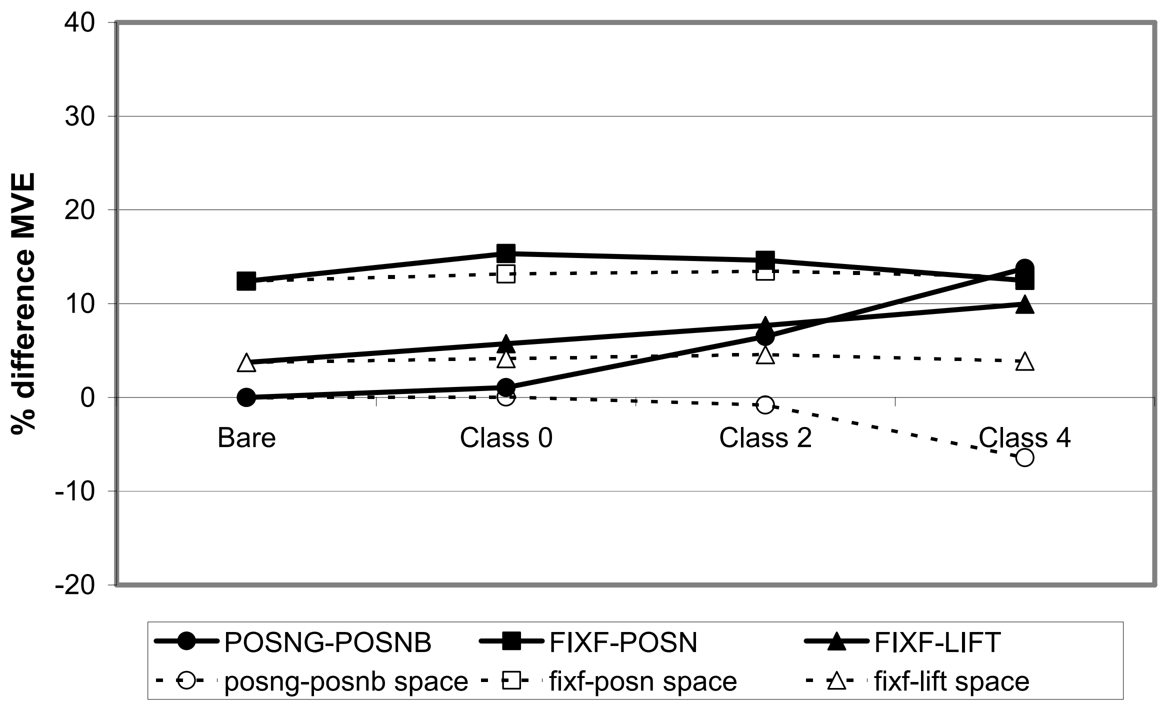

ED
% MVE
100
90
80
70
60
50
40
30
20
10
0
Bare
Class 0
Class 2
Class 4
POSN
LIFT
FIXF
MAX
POSN - SPACE
LIFT - SPACE
FIXF - SPACE
MAX - SPACE


Differences in %MVE - ED
% difference MVE
40
30
20
10
0
-10
-20
Bare
Class 0
Class 2
Class 4
POSNG-POSNB
FIXF-POSN
FIXF-LIFT
posng-posnb space
fixf-posn space
fixf-lift space

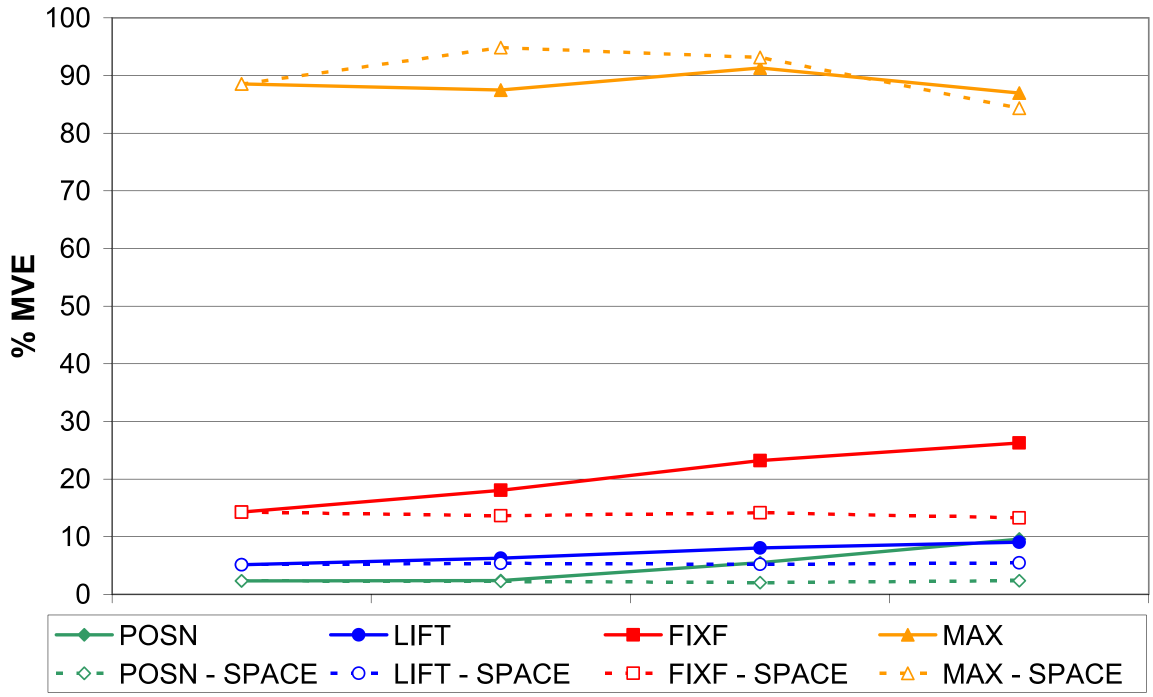
ECR



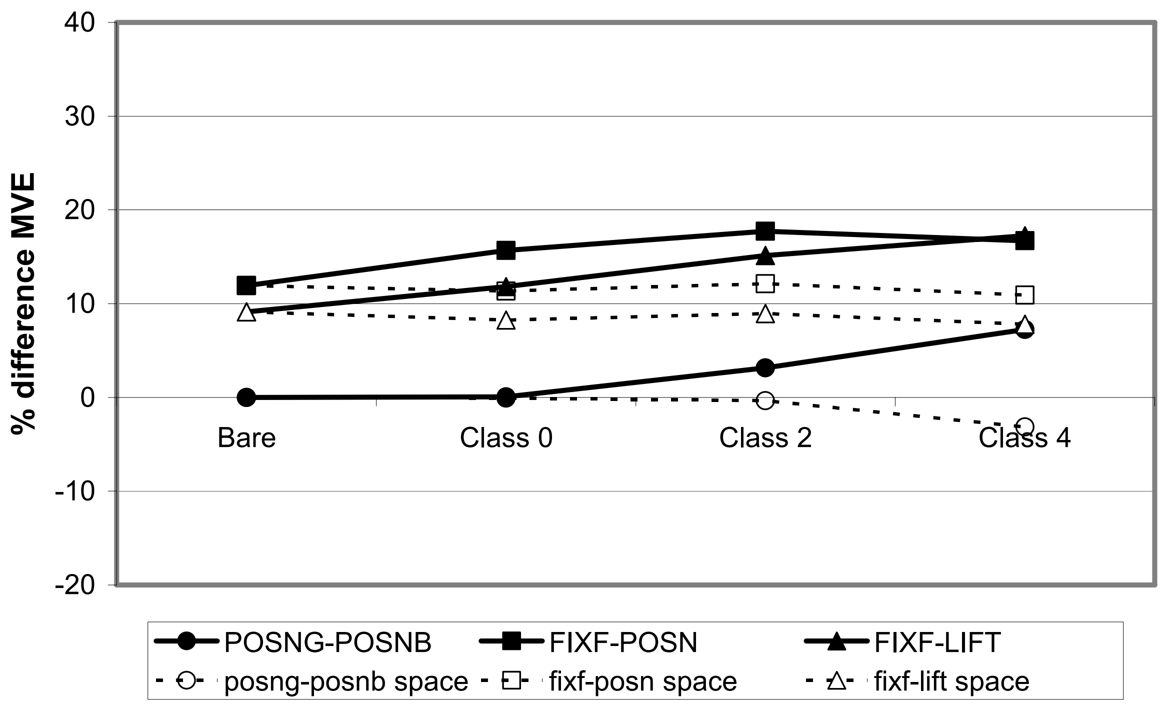
Differences in %MVE - ECR

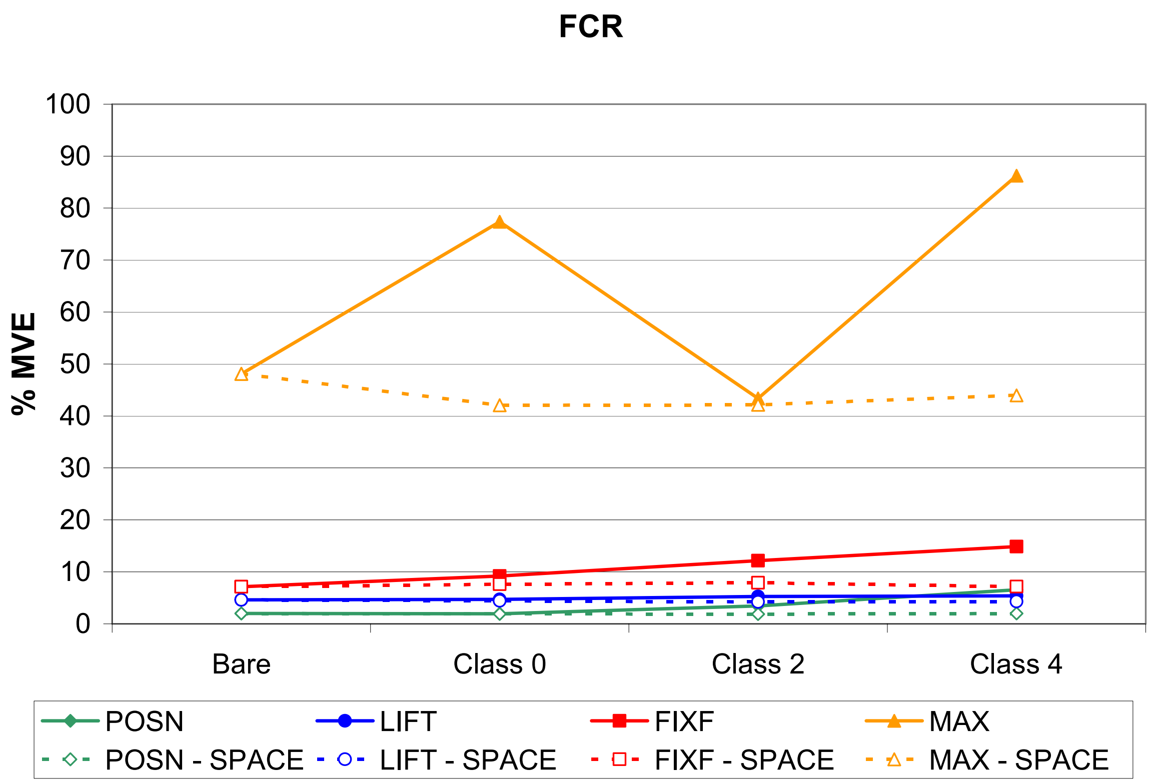


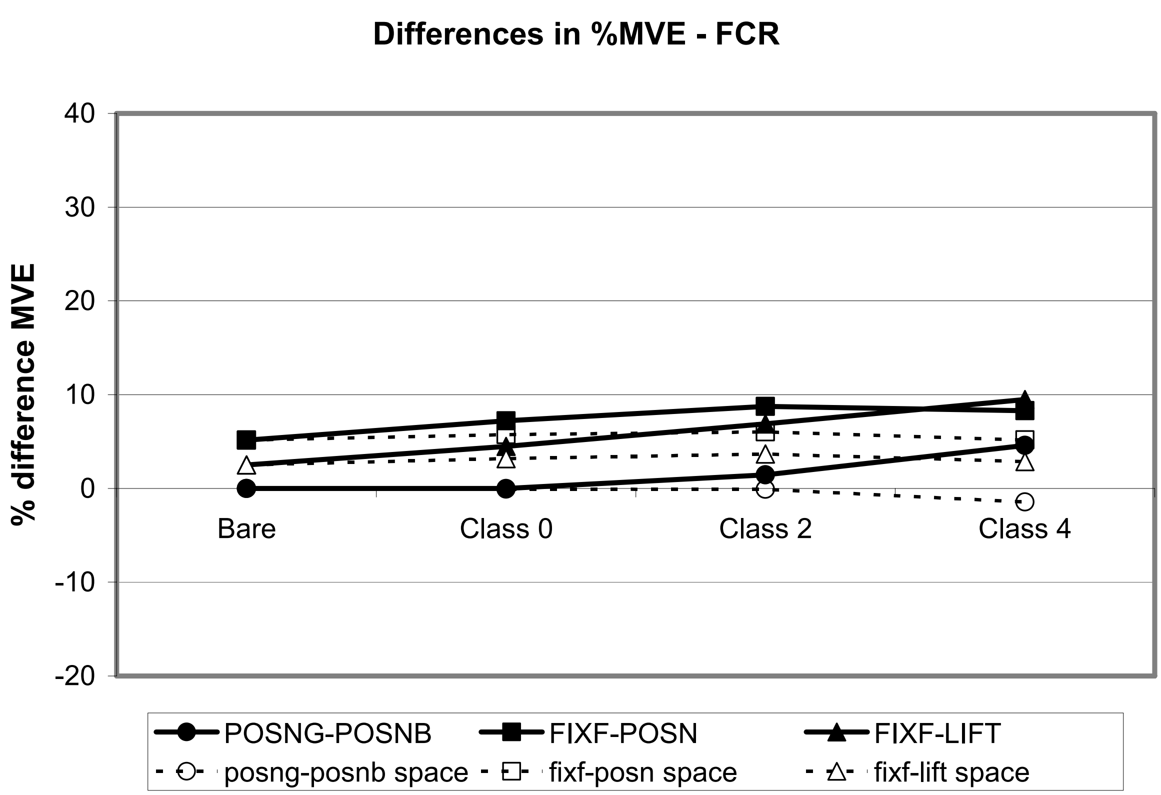
FCU



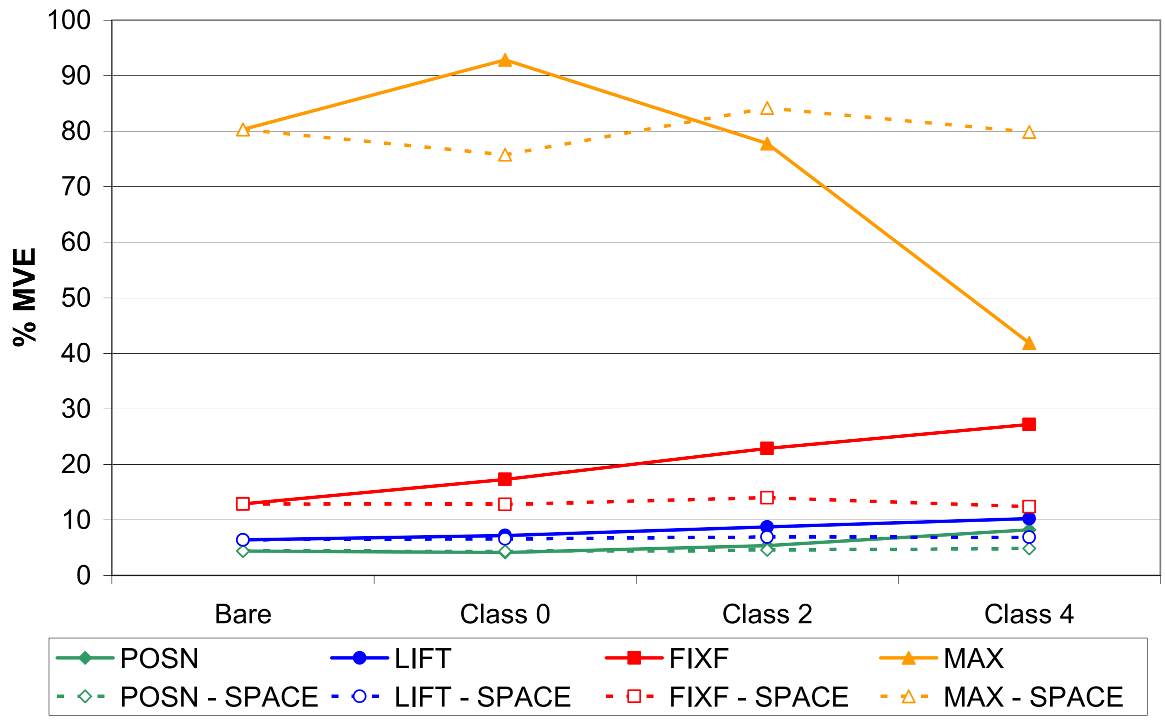
Differences in %MVE - FCU



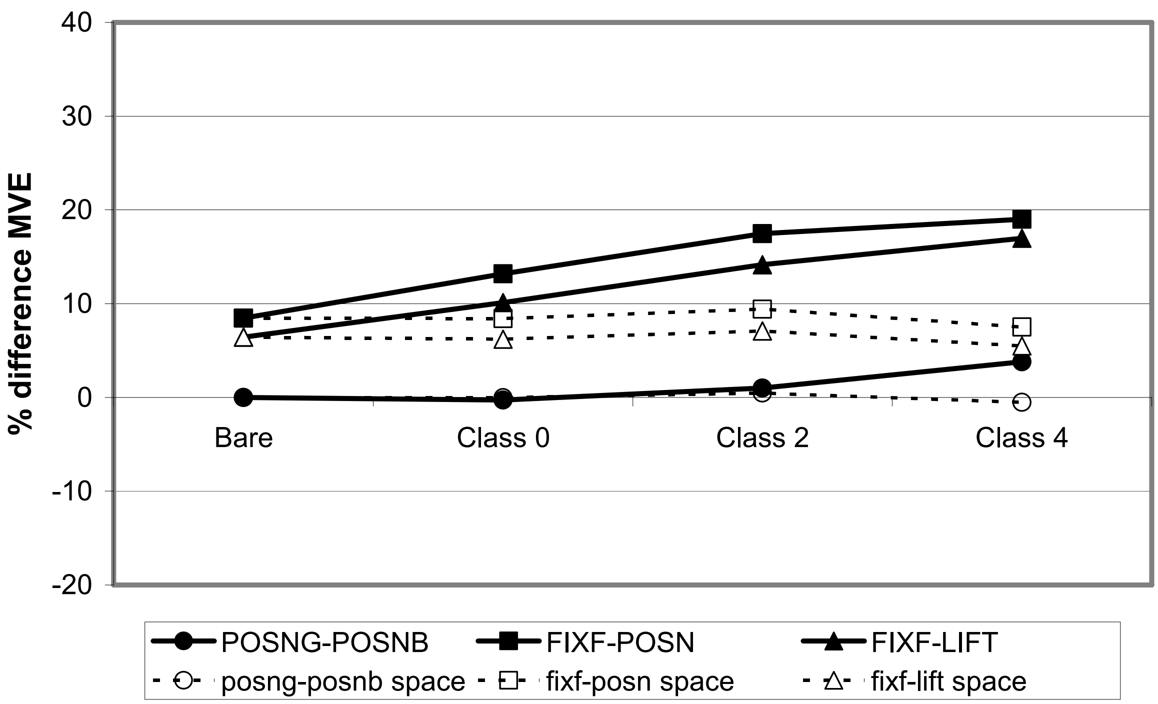

FCR
% MVE
100
90
80
70
60
50
40
30
20
10
0
Bare
Class 0
Class 2
Class 4
POSN
LIFT
FIXF
MAX
POSN - SPACE
LIFT - SPACE
FIXF - SPACE
MAX - SPACE

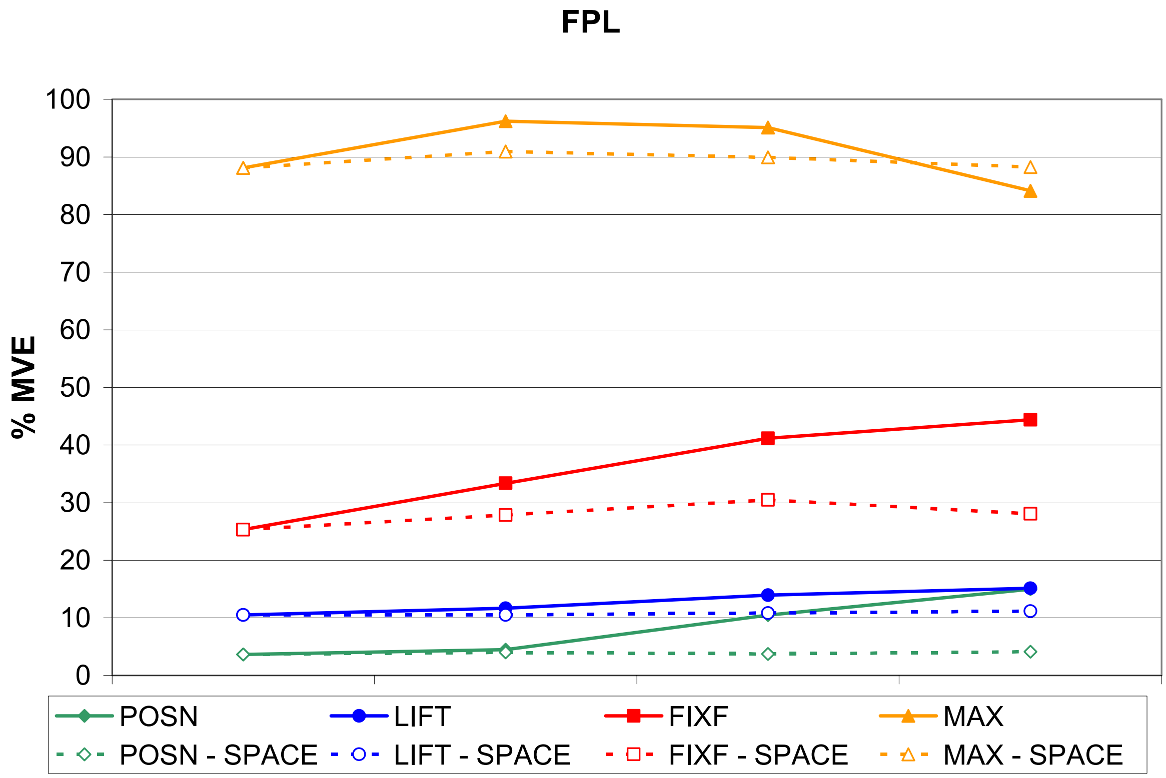

Differences in %MVE - FCR
% difference MVE
40
30
20
10
0
-10
-20
Bare
Class 0
Class 2
Class 4
POSNG-POSNB
FIXF-POSN
FIXF-LIFT
posng-posnb space
fixf-posn space
fixf-lift space

FDS



Differences in %MVE - FDS




FPL
% MVE
100
90
80
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40
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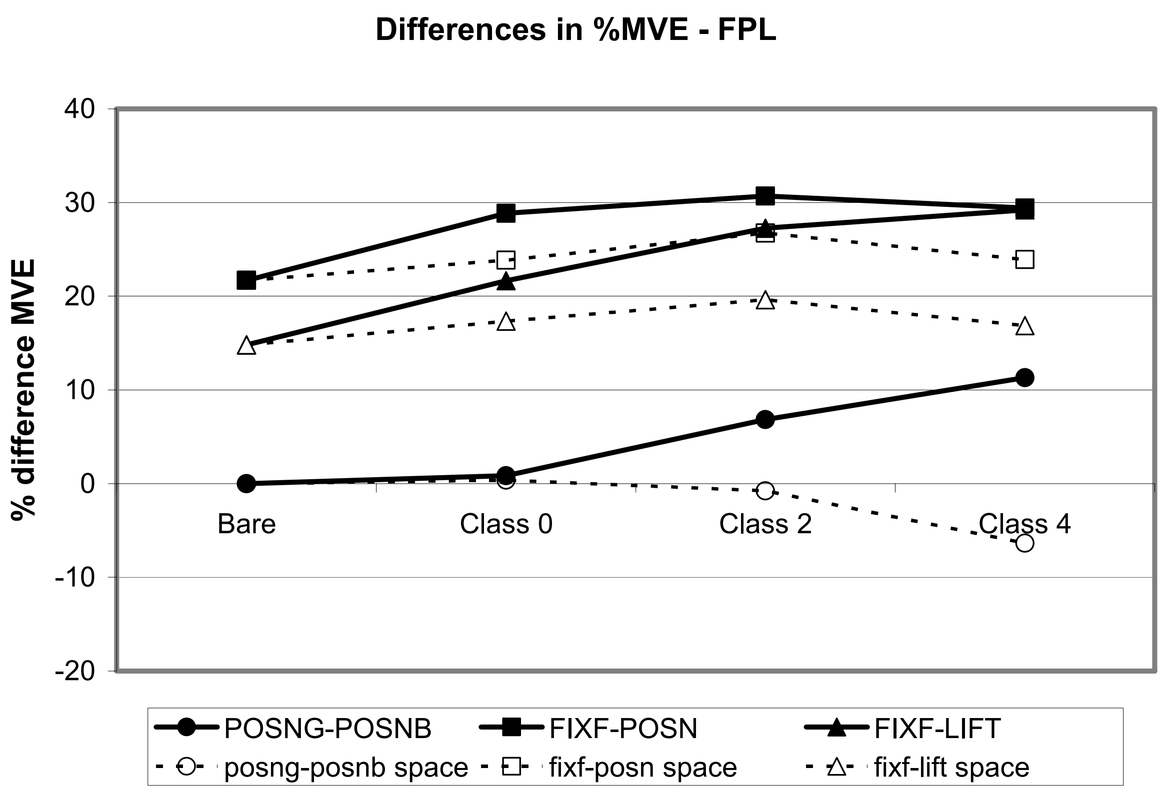
MAX
POSN - SPACE
LIFT - SPACE
FIXF - SPACE
MAX - SPACE


Differences in %MVE - FPL
% difference MVE
40
30
20
10
0
-10
-20
Bare
Class 0
Class 2
Class 4
POSNG-POSNB
FIXF-POSN
FIXF-LIFT
posng-posnb space
fixf-posn space
fixf-lift space

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