BIMANUAL LIFTING: RESPONSE OF GRIP FORCE TO PERTURBATIONS IN WEIGHT AND FRICTION

by

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ABSTRACT

Context Being able to live an independent and active life is highly dependent on the ability to manipulate objects and use external supports around us. A body of literature suggests that an elaborate coordination of grip force (GF) and load force (LF) is typically used during successful object manipulation. In the kinetic level, this coordination is measured through several variables including GF scaling, GF-LF coupling, and GF modulation. The tasks are controlled both by a feed-forward and feedback neural mechanism and can be affected by many factors including weight of the object and the friction of the contact surface. The applied GF needs to be high enough to prevent slippage of the object, but low enough to prevent fatigue or crushing of a fragile object. Due to the partly predictive nature of this coordination, unforeseen changes in mechanical conditions can lead to applying inappropriate magnitudes of GF. It has been found that the GF can be affected by different weights and frictions experienced in previous trials in uni-manual tasks. However, it is unknown if the changes in GF are greater when weight or friction is changed. **Purpose** The purpose of this study is to explore the changes in GF to unforeseen mechanical changes in a bimanual simple task of lifting objects of different weight or friction that induce similar changes in GFmin. The aims of this study were 1) to discern between the effects of friction and weight on applied GF, 2) to observe the differences in changes in GF in the dominant and non-dominant hand, and 3) to explore the changes in GF in the ipsilateral and contralateral hand. **Subjects** 12 healthy, right handed participants between 18-35 years old who were free of any neurological issues were recruited. **Protocol** A bimanual simple lifting task using a precision grip was performed. The participants were acclimatized to a standard condition of an object requiring a low GF (LSC) or high GF (HSC) before a change in weight or friction was applied between trials unbeknownst to the participant. The changes imposed were designed to produce similar changes in the required minimum GF regardless of which property was altered. Changes in applied GF were measured during the lifting and holding phase of the movement as well as the rate of GF production. **Results** The results showed a larger change in applied GF when weight was altered compared to friction of the object in both the LSC ($p<.001$) and HSC ($p<.001$) in both the lifting phase and holding phase. Furthermore, during the holding phase a larger change was seen in the dominant hand compared to the non-dominant hand in the HSC ($p=.001$). **Conclusion** The increased changes in applied GF when weight was altered could be due to differences in the spindle and tactile activity associated with the applied interventions. The changes in GF observed in the dominant hand may be in line with the dynamic dominance hypothesis. This information can be applied to future study designs and in the design of objects intended to be manipulated by the hands.

Chapter 1

LITERATURE REVIEW

1.1 Forces and Variables

Being able to live an independent and active life is highly dependent on the ability to manipulate objects around us. Activities such as eating, cooking, using tools and lifting objects all require successful manipulations of objects within the environment. Analyzing the forces needed to manipulate objects around us has been typically based upon a simple mechanical model of holding a vertically oriented object (J. Randall Flanagan, 1990; Johansson, 1984). The two forces that are analyzed are grip force (GF) and load force (LF). GF is the normal force acting perpendicular to the contact surfaces of the object while LF is the force acting in parallel with the contact surfaces that is applied to overcome the weight and inertia of a hand held object. The coordination of these two forces along with coordination of different limbs is what allows for successful manipulations of objects on a daily basis.

According to the model mentioned above, there is a minimum GF that is equal to the ratio of the LF and the coefficient of friction (COF) of the object. Generally, an individual will apply a GF that is above this required minimum in order to prevent slippage. This excess GF is referred to as the safety margin. It is important to keep the safety margin low, as to provide enough GF to prevent slippage of the object, but limit excessive GF to prevent muscle fatigue and the possibility of breaking the object with the

GF (Westling and Johansson 1984). The sensory information provided by cutaneous mechanoreceptors provides feedback which allows for adjustments in grip force (Johansson and Westling 1984). If this feedback is decreased, as when local anesthesia is introduced, adjustments may not occur (Nowak et al 2001). It is thought that bending of skin due to changes in LF could be interpreted as slips which may cause the CNS to elevate the safety margin to prevent slippage of the object (de Freitas et al 2008).

The variables commonly used to assess the coordination of GF and LF are GF modulation, GF scaling, and GF-LF coupling (Flanagan 1990; Johansson1984; Johansson and Westling 1988; Jaric & Uygur, 2013). GF Modulation shows how much the GF adapts to changes in LF. It is assessed through regression lines determined by GF gain, which determines the slope of the regression line, and GF offset, which determines the intercept. GF scaling refers to the GF/LF ratio using either peak or average values for each force. Lower GF/LF ratios are related to better coordination of these forces despite a risk of dropping the hand-held object. GF-LF coupling is assessed through the relationship between them, typically through the cross-correlation coefficient and the corresponding time-lag found between GF and LF in a time series (J. R. Flanagan & Wing, 1995). These variables have been used to assess both uni-manual and bimanual tasks (Johansson 1984; Serrien and Weisendanger 2001; Jaric & Uygur 2013).

A continuous coupling, determined by a high GF-LF correlation and low time-lag, of GF with respect to changes in LF has been observed (J. R. Flanagan & Wing, 1995). This finding determines that a predictive feed-forward mechanism is applied prior to object manipulation. Therefore the CNS establishes a predicted GF to apply to an object based on various factors such as object size, movement to be produced and predicted weight of the object. The CNS also employs a feedback mechanism via tactile afferents of the digits and proprioceptive feedback from the muscles involved in the movement (Johannson and Westling 1988a; Johansson and Weling 1988b; Flanagan and Wing 1993; Flanagan et al 1993; Nowak et al 2001). This allows the CNS to modify the movement to account for unexpected properties of the object or movement.

Feldman proposed a hypothesis, deemed the Equilibrium Point Hypothesis, that may help to explain this mechanism of control (Feldman 1966). This hypothesis has three main points that it is based upon. First, it states the idea that a controller, aka the CNS, has to manipulate the parameters of a system in order to control it. Secondly, it states that the system tries to reach a state of minimal potential energy. This can be seen in the idea of a safety margin, in which we do not want to apply too much GF for risk of fatigue, but also need to employ enough to ensure a secure grip on an object. Lastly, the third principle talks about the idea of the controller setting the threshold of activation for neural cells. This idea would mean that the controller can set the level of activation for certain neural cells to be more or less sensitive during the movement (Latash 2010). For instance, muscle spindle activity may be heightened in order to closely monitor the appropriate predicted movement. All of these factors may play a role in how the CNS utilizes both feedforward and feedback mechanisms in order to produce movement.

1.2 Hand Dominance

When performing a bimanual task both the dominant and non-dominant hands are being implemented. In line with the dynamic dominance hypothesis (Sainburg 2002), it has been generally accepted that the dominant hand has an advantage when performing dynamic pre-programmed movements. More recently evidence has surfaced supporting this theory but with more detail (Yadav and Sainburg 2014). The current thought is that handedness can be explained by a serial hybrid control scheme. In this idea, there is a bi-hemispheric control of both arms which gives an advantage to the dominant hand for predictive functions such as initiation of movement trajectory, while the non-dominant hand has an advantage when it comes to impeding movement, like in the termination of movement or stabilizing functions (Yadav and Sainburg 2014). The initiation of the movement in either hand would be controlled by the dominant hemisphere of the brain while the termination of the movement would be controlled by the non-dominant hemisphere (Yadav and Sainburg 2014). Due to the predictive nature of the dominant hand, it could be more sensitive to perturbations or unexpected changes to the conditions of a task. It has been found that the GF coordination in static tasks is better in the non-dominant hand, which falls in line with the bi-hemispheric control scheme (Ferrand and Jaric 2006). The communication between the two hemispheres for the movement of each arm could allow for control of both the beginning and end of a movement.

1.3 Contralateral Effects

The communication between the two hemispheres during movements can sometimes cause interference between limbs during motion. The ideal situation for neural control is when the same parameters are allocated to each limb and they move simultaneously (Swinnen and Wenderoth 2004). Neural cross talk is when neural pathways interact and yield mutual interference between limbs during movement (Swinnen 2002). When considering bimanual coordination, this cross-talk occurs due to information exchanged across the corpus callosum (Swinnen 2002). This cross talk can be seen in tasks of bimanual and uni-manual force production. In a continuous force production task, it was shown that the arm that was not instructed to produce any force demonstrated subtle but significant force production that correlated to the contralateral arm's force production (Kennedy et al 2016). The effect of neural cross talk has also been seen when one limb is producing continuous force and the other is producing dynamic force pulses, and also when both limbs are producing dynamic force pulses at different frequencies (Kennedy et al 2016). The effect of neural cross talk may also play a role in the application of GF in bimanual tasks. The differences in grip force regarding the perturbed weight or friction remain under explored in the literature.

1.4 Effects of Mechanical Properties: Weight and Friction

A continuous coupling, determined by a high GF-LF correlation and low time-lag, of GF with respect to changes in LF has been observed (J. R. Flanagan & Wing, 1995). This finding suggests that a feed-forward mechanism is implemented by the neural controller. These feed forward, or predictive, mechanisms that are applied allow for error to occur when conditions, such as weight or friction of surface, are unexpectedly changed. GF is able to change with respect to the LF as it changes throughout dynamic movements (Flanagan and Wing 1993; Flanagan et al 1993; Nowak et al 2001). When completing multiple trials of lifting a weighted object and then implementing an unforeseen change in weight, a force output that was similar to the previous trial was found which supports the idea that the force output is controlled by a feed-forward mechanisms (Johansson & Westling, 1988a). More specifically one study found that when the unforeseen change was a decrease in weight, the GF applied to the lighter weight was relatively high, but subsequent trials revealed an adequate adaptation of GF to the new weight (Serrien & Wiesendanger, 2001). When the spontaneous weight change was an increase in weight, the force profile revealed a double peak, which demonstrates that the predicted force output required was not enough so sensory information was used to adjust to the newly required force output (Serrien & Wiesendanger, 2001). In addition, when known weight changes were going to occur during a freeholding task, an increase in the applied GF was found prior to initiation of the weight increase (Johansson and Westling 1988b). It was also found that when an unexpected change occurred that did not result in complete slippage of the object, the GF increased approximately 70ms after initiation of the perturbation (Johannson and Westling 1988b). These findings support the idea of both feed-forward and feedback control in coordination of grip and load forces.

Altering the frictional component of the surfaces of an object plays a role on force coordination as well. Similar to changing the weight of the object to be manipulated;

unexpectedly altering the frictional component of the object to be lifted alters the applied GF as well as the ability to coordinate the grip and load forces (Westling and Johansson 1984; Bilaloglu et al 2016; de Freitas et al 2009). When moving from a high friction surface to a lower friction surface, the result is a decreased GF than is normally applied to the lower friction surface (Westling & Johansson, 1984). Conversely, when moving from a low friction surface to a high friction surface, the applied GF is much higher than is needed for the newly increased frictional component of the object.

Although both weight and friction play a role in force coordination during the manipulation of objects, it is unknown which factor plays a larger role in determining the appropriate GF to be employed. It is also beneficial to understand if either of these factors, if altered on one hand, can influence the coordination of the contralateral hand. These issues are what lead to the design of this study and the gaps of knowledge that it intended to fill.

Chapter 2

SPECIFIC AIMS

Specific Aim 1: To discern between the effects of altered weight and friction of the lifted object.

Hypothesis 3.1: The larger changes in GF will be observed when the weight of the object is changed compared to when the friction of the object is changed.

Specific Aim 2: To compare the differences in the observed effects between the dominant and non-dominant hand.

Specific Aim 3: To explore the changes in GF when elicited by unilateral perturbations of mechanical conditions in the hand ipsilateral and contralateral to the perturbation.

Hypothesis 3.1: A unilateral change to mechanical properties of the object will result in greater changes in GF to the ipsilateral hand than the contralateral hand.

Chapter 3

MANUSCRIPT

3.1 Introduction

Being able to live an independent and active life is highly dependent on the ability to manipulate objects around us. Activities such as eating, cooking, using tools, and lifting heavy objects all require successful manipulations of objects within the environment. Analyzing the forces needed to manipulate objects around us has been typically based upon a simple mechanical model of holding a vertically oriented object (J. Randall Flanagan, 1990; Johansson, 1984). The two forces that are analyzed are GF and load force (LF). GF is the normal force acting perpendicular to the contact surfaces of the object while LF is the force acting in parallel with the contact surfaces that is applied to overcome the objects weight and inertia. The coordination of these two forces is what allows for successful manipulations of objects on a daily basis.

According to the aforementioned model, there is a minimum GF that is equal to the ratio of the LF and the coefficient of friction (COF) of the object. An individual will apply a GF above this minimum value in order to prevent slippage. The difference between the applied GF and the minimum required GF is called the safety margin (Johansson and Westling 1984). Individuals typically keep the safety margin low in order to prevent fatigue of the GF producing muscles and also to prevent crushing of fragile objects between the grasping surfaces (Westling and Johansson 1984). We can see this in a variety of tasks such as unimanual (Johansson 1984; Nowak 2001; Westling and Johansson 1984) bimanual (Serrien and Weisendanger 2001) , and unidirectional and bidirectional tasks (de Frietas et al 2007).

In bimanual tasks an individual utilizes both their dominant and non-dominant hands to manipulate objects. Recently, Yadav and Sainburg elaborated on the dynamic dominance hypothesis describing handedness in terms of a serial hybrid control scheme (Yadav and Sainburg 2014). In this control scheme, initiation of movement is controlled by the dominant hemisphere of the brain and yields an advantage to the dominant hand for predictive dynamic movements while the non-dominant hand has an advantage in termination of movement and stabilizing functions. The communication between the two hemispheres and the advantages that go along with each may play a role in the applied GF upon object perturbation. It is possible the dominant hand may be more susceptible to perturbations due to its dynamic nature, while the non-dominant hand may show less of an effect due to its stabilizing functions.

The communication between hemispheres during movement may have other effects on movement when manipulating two separate objects with both hands. Neural cross talk is when neural pathways interact and yield mutual interference between limbs during movement (Swinnen 2002). This cross talk usually results in contralateral effects, or effects seen in the limb that was either not instructed to produce force or movement, or instructed to produce a different movement. In both bimanual and uni-manual force production tasks, the limb not instructed to produce force demonstrated small amounts of force production and when the limbs produced different frequencies of force pulses, the frequencies tended to assimilate (Kennedy et 2016). These contralateral effects may be observed when mechanical perturbations are introduced on one hand in a bimanual lifting task and may play a role in the applied GF.

A feed-forward mechanism is implemented by the neural controller which is supported by a continuous coupling of GF with respect to changes in LF (J.R. Flanagan and Wing, 1995). This mechanism allows for error to occur when conditions of a movement or object, such as weight or friction, are unexpectedly changed. . GF is able to change with respect to the LF as it changes throughout dynamic movements (Flanagan and Wing 1993; Flanagan et al 1993; Nowak et al 2001). Unforeseen changes of weight yield a GF that is similar to the previous trial that was experienced (Johansson and Westling 1988b). More specifically when the unexpected change was a decrease in weight an excessive GF was applied. When the unexpected change was an increase in weight, the force profile demonstrated a double peak, illustrating that the initial force applied was not enough to lift the object (Serrien and Weisendanger 2001).

Similar to changes in weight, altering the COF of an object surface also alters the applied GF. Unexpectedly altering the frictional component of the object to be lifted alters the applied GF as well as the ability to coordinate the grip and load forces (Westling and Johansson 1984; Bilaloglu et al 2016; de Freitas et al 2009). When switching from a high friction surface to a low friction surface, the typical result is a decreased GF than is normally applied to the lower friction surface (Westling & Johansson, 1984).

Although we know both weight and friction play a role in the applied GF during object manipulation, it is unknown which factor plays a larger role. The purpose of this study was to 1) discern between the effect of altered weight and friction of the object by implementing changes to weight or friction that yield the same changes in the required GF min 2) compare differences in applied GF between the non-dominant and dominant hands and 3) to explore the changes in GF between the hands ipsilateral and contralateral to perturbations of weight and friction. The expected findings of this study could contribute to improving future study designs and further advance the knowledge of GF related to object manipulation.

3.2 Subjects

The study involved the recruitment of 12 healthy, right-handed participants between the ages of 18-35 years old. The sample size was determined by performing a power analysis of our previous findings (Krishnan & Jaric 2010; de Freitas et al 2009) using the G*Power program (Faul et al 2007) with an alpha of 0.05, power of 0.80, and an effect size of 0.5 set for clinical significance. All participants were without neurologic problems and current injuries to the wrist and hand. Exclusion criteria were neurological diseases, a recent or current wrist or hand injuries, and being either left hand dominant or ambidextrous.

3.3 Experimental Device

A custom designed device (Krishnan & Jaric, 2010) was used to record GF and LF during the simple lift task (Figure1). Two identical handles with parallel grasping surfaces, each weighing approximately 300 g, were covered with either a rubber surface, coefficient of friction (1.6), or an acetate surface, coefficient of friction (0.7), depending on the condition being performed. The CoF values were calculated during a pilot study using a previously established 'slip point' method (Westling and Johansson 1984). A single axis force transducer (WMC-50, Interface Inc., USA) is fixed between the two grasping surfaces in order to record the compression force. A multi axis force transducer (Mini40, ATI, USA) is attached beneath the grasping surfaces and recorded all three components of net force applied against the handle. GF was calculated as the average of two opposing forces acting perpendicularly against the grasping surfaces, while LF corresponded to the tangential force recorded by the multi-axis transducer (J. R. Flanagan & Wing, 1995; Uygur, Prebeg, & Jaric, 2014). In this study, a weight of 100 g or 600 g was attached to the device for a total mass of 400 g and 900 g respectively.

3.4 Experimental Task

The experimental task consists of a simple lifting task of a instrumented device (see above) that was performed bimanually while mechanical conditions were manipulated throughout the experiment (Serrien and Weisendanger 2001). The participants stood in front of a box containing both devices such that only the handles could be seen (Figure 2) and grasped them with the tips of their fingers and thumbs (precision grip). Then the participants lifted the weighted handles to a height of 12 cm on a cue sound. The participant then held the object at the 12 cm height for 5 seconds, at which point the participant heard a second cue sound and placed the object down. At no point in the experiment was GF be mentioned to the participant in order to obtain measures from the participant's natural coordination of forces during the lifting task.

The participant was be blind to any weight changes prior to lifting the object due to the box the devices were in and also due to a block placed inside the box to account for any height difference caused by adding weight. When the participant lifted the object, the weights were covered by a cloth in order to blind them from seeing the weight difference when the device was removed from the box. The lighting of the experimental area was sufficient enough to see the handles of the devices, however low enough where identification of change in surface was not attainable.

3.5 Experimental Protocol

There were a total of 4 perturbation conditions performed within 2 standard conditions. The mechanical properties of the device that were altered were weight and friction. The properties of weight were a higher weight (900g) which required a higher GF, or a lower weight (400g) which required a lower GF. The two frictional properties had either a high coefficient of friction of approximately 1.6 which required a lower GF, or a low coefficient of friction of about 0.7 which required a higher GF. The two standard conditions were a Low GF standard condition (LSC and High GF standard condition (HSC). The LSC consisted of a low weight and a high coefficient of friction to produce a low minimum required GF. The high GF standard condition (HSC) consisted of a high weight and a low coefficient of friction to produce a high minimum required GF.

The coefficient of friction can be measured through a routinely used “slip point” method which calculates the COF from the GF and LF at the moment of slip (Uygur et al 2010). A pilot study was performed to determine the average COF for both the rubber and the acetate frictional properties. The ratio of these two COF’s (2.26) was used to determine which weights should be assigned to each frictional component. We chose to use 400g as our lower weight for the Low GF standard condition and 900g for our higher weight for the High GF standard condition. These weights were chosen because they have a ratio of 2.25 which matches the ratio of our two frictional conditions. Therefore any change in friction or weight should illicit the same change in the minimally needed GF.

The perturbation conditions included either increasing the weight unilaterally or decreasing the friction unilaterally for the Low GF standard conditions, and decreasing the weight or increasing the friction unilaterally for the High GF standard condition. As a result, the mechanical perturbations applied through unexpectedly changed weight and friction always required an increase in GF under Low GF standard condition and always allowed for a decrease in GF under the High GF standard condition. The perturbations were applied to each hand. The first 3-5 trials consisted of a standard condition, either Low GF or High GF, followed by a perturbation trial, the order of which was randomized by blocks. The standard conditions were randomly assigned to 3, 4, or 5 trials in order to eliminate the ability of the participant to predict when the mechanical change will occur. In between each trial the participant was seated with a blindfold on while the experimenter either introduced a perturbation or re-create similar sounds and timing of introducing a perturbation. This was done in order to prevent the participant from discerning if a perturbation is coming or not.

This approach allowed us to explore the effects of an unknown perturbation of weight or friction on GF when the subject was expecting an already established standard condition. Since the study was designed to create the same change in the minimum required GF whether the weight or friction is altered, we were able to see if one factor played a stronger role in determining the applied GF than the other. We were also able to determine if the dominant or non-dominant hand adjusts differently to perturbations in mechanical properties of an object. Finally, we explored the differences between the hands that were ipsilateral and contralateral to the perturbation.

3.6 Data Processing

The GF and LF were collected using a custom written NI LabView software program. The data obtained from force transducers was sampled at 200 Hz and filtered by fourth-order recursive low-pass Butterworth with the cut-off frequency of 10 Hz. The data was collected and processed by custom-designed NI LabView software (version 2013, National Instrument Co., Austin, TX).

3.7 Statistical Analyses

We ran a total of 6 3x2 (Perturbation hand x Dominance x Condition) repeated measures ANOVA to test our aims. Specifically, ANOVA was run for each of our three variables, (percent change in GF during the lifting phase, the rate of GF development, and the percent change in GF during the holding phase) for both the low and the high grip standard condition. Percent change in GF during lifting phase was measured as the If an interaction effect was found, post-hoc analysis was performed with a Bonferroni correction with alpha set at p=.05. If the differences between the ipsilateral and contralateral hands were markedly different (e.g. Serrien and Wiesendanger 2001) we switched to 12 2x2 (Dominance x Condition) ANOVA's for straightforward data interpretation. Regarding Aim 1 we compared the percent change in GF during the lifting phase, the holding phase, and the rate of GF development between the perturbations of weight and friction. Regarding Aim 2 we compared the percent change in GF during the lifting phase, the holding phase, and the rate of GF development between the non-dominant and dominant hands. Regarding Aim 3 we were looking at the differences in percent changes in GF of the hands ipsilateral and contralateral to the perturbation.

3. 8 Results

Table 1 displays the average values for the variables observed for the non-dominant and dominant hand for both the Low Standard Condition (LSC) and the High Standard Condition (HSC). A student-T test was run to compare differences between the hands with an alpha of p=0.05. The only significant difference found was in grip force during the lifting phase in the LSC (p=0.016) with a moderate effect size of 0.579. All other comparisons failed to reach significance and on average revealed small effect sizes (0.12<ES<0.58).

Figure 3 panels show the force profiles of six trials in the ipsilateral hand of a single subject that represents the average data values. Each profile displays the standard force profile and the force profile created when a change to a mechanical property was present. Panel A shows the force profiles in the dominant hand when friction and weight were changed. Panel B shows the force profiles when Friction and Weight were changed in the non-dominant hand. Larger changes in force profiles can be observed when the weight is altered compared to friction in both the LSC and the HSC.

Figure 4 displays the percent of change relative to the standard condition for each variable in both the ipsilateral hand (Panels A, B, C) and the contralateral hand (Panels D, E, F). All of the variables are displayed as the percent change from the standard values. The change in grip force during the lifting phase, the change in rate of grip force development, and the change in grip force during the hold phase in the ipsilateral hand are represented in panels A, B and C respectively. The same variables in the contralateral hand are represented by panels D, E, and F respectively.

We initially intended to use a 3-way ANOVA of Perturbation (contralateral vs ipsilateral) X Hand (Dominant vs non-dominant) X Condition (weight vs friction).The results revealed an expected strong effect of perturbation hand (contralateral vs ipsilateral). For a more straightforward data interpretation, a 2-way repeated measure

ANOVA of Hand (Dominant vs non-dominant) X Condition (weight vs friction) was run for each variable assessed in both the LowGF standard condition and the High GF standard condition.

In the ipsilateral hand, a 2-way repeated measures ANOVA (Hand x Condition) analyzing percent change in GF during the lifting phase, revealed a non-significant effect of hand in both the LSC (f= 4.06,p=.144, eta^2=.289) and the HSC (f=4.479 , p=.06, eta^2=.309), but did show a significant main effect of condition in both the LSC(f=172.36 , p<.001, eta^2=0.945) and the HSC (f=29.9 , p<.001, eta^2=.749). When the rate of GF development was analyzed, it did not demonstrate a significant effect in the LSC for hand (f=.648,p=.439, eta^2= .061) or condition (f=0.284 , p=.605, eta^2=0.028) or in the HSC for hand (f=.219 , p=650, eta^2=.021) or condition (f=1.002 , p=.340, eta^2=.091). The analysis of the percent change in GF during the holding phase revealed a non-significant effect of hand in the LSC (f=3.17, p=.105, eta^2=.241) but a significant effect in the HSC (f=24.848, p=.001, eta^2=.713). It also demonstrated a significant main effect of condition in both the LSC (f=88.86, p<.001, eta^2=.899) and the HSC (f=156.27, p<.001, eta^2=.940). In summary, there was a larger increase in GF during the lifting phase in the LSC when weight was changed compared to friction and a larger decrease in the HSC when weight was changed. When the GF during the holding phase was analyzed there was a larger increase in GF in the LSC and a larger decrease in GF in the HSC when weight was changed and not friction, while the dominant hand had a larger decrease in GF than the non-dominant hand. There were no significant effects when change in the rate of force development was analyzed and no interactions were observed in any variable.

In the contralateral hand analysis, the 2-way repeated measures ANOVA revealed no significant main effect of hand (f=.559, p=.472, eta^2=.053) or condition (f=.029 , p=.868, eta^2=.003) for the LSC and a significant main effect of hand (f=13.08, p=.005, eta^2=.567) and condition (f=17.69, p=.002, eta^2=.639) in the HSC for the percent change of GF during the lifting phase. The analysis showed no significant differences in hand (f=.902, p=.365, eta^2=.083) or condition (f=.161, p=.697, eta^2=.016) in the LSC and no significant differences in hand (f=2.19, p=.170, eta^2=.180) or condition (f=3.48, p=.092, eta^2=.258) in the HSC for the percent change in rate of force development. When the percent change in GF during the holding phase was analyzed there were no significant differences in hand (f=1.49, p=.250, eta^2=.130) or condition (f<.001, p=.989, eta^2<.001) in the LSC and a significant effect of hand (f=8.63, p=.015, eta^2=.463) and a non-significant effect of condition (f=.903, p=.364, eta^2=.083) in the HSC. There were no interaction effects observed over any variable for either the LSC or the HSC. Overall when the dominant hand was the contralateral hand, it had a larger change in grip force in both the lifting and holding phase than when the non-dominant hand was the contralateral hand in the HSC only. There was a larger change in grip force during the lifting phase when the weight was changed compared to the friction in the HSC in the contralateral hand.

3.9 Discussion

In this study we set out to observe changes in applied GF during a simple lifting task while introducing perturbations of weight and friction designed to create the same magnitude of changes in GF. Our aims were to 1) to compare the effects between altering weight and friction of the lifted object 2) compare the differences in the changes in GF between the dominant and non-dominant hand, and 3) .explore the changes in GF elicited by unilateral perturbations of mechanical conditions in the hands ipsilateral and contralateral to the perturbation. We observed a larger change in applied GF on the hand ipsilateral to the perturbation opposed to the contralateral hand, which was expected. We also found larger differences in the applied GF after perturbations in the dominant hand compared to the non-dominant hand. Finally, we saw a larger change in the applied GF when weight was altered compared to friction, which may show a bias to unexpected weight changes during object manipulation.

The most novel finding of our study could be the greater change in the applied GF when perturbation was applied through the weight of an object as compared to its frictional property. The importance of this finding is emphasized by the fact that the study was designed to create the same magnitude of change in the minimum required GF regardless of which of the two perturbations was applied. Note, that the difference between the weights used to induce perturbation (500g) was a small percent of the muscle's maximum force capacity, while the perturbation induced for friction (0.7 vs 1.6) represented a major difference in coefficient of friction values (Uygur 2010).

There are numerous studies that confirm that both weight and friction play a role in the determination of the applied GF during object manipulation (Bilaloglu et al 2016; de Freitas et al 2009; Flanagan and Wing 1993; Flanagan et al 1993; Nowak et al 2001;

Serrien & Wiesendanger, 200; Westling and Johansson 1984). The present study adds the fact that there may be a bias to unforeseen weight changes compared to frictional changes of an object. The study was designed to produce the same change in minimum GF regardless of which property was altered. Knowing that the safety margin in individuals remains relatively invariant in individuals (de Freitas et al 2009) it would be likely that the relative changes in minimum GF would be seen in the applied GF as well. In this experiment that was not the case, as the change to the weight of the object elicited a significantly greater change in applied GF as seen in Fig. 4.

We expected that the applied GF would be controlled predominantly through a feedforward pre-programmed neural mechanism that only later on uses feedback to update the GF control (Augurelle et al, 2003; Nowak et al 2001; Westling and Johansson 1984). The sensory information provided by cutaneous receptors is needed to determine and apply the most appropriate GF to maintain a secure grasp on an object (Augurelle et al, 2003). In expected increases in load, GF was found to increase before the load increased, while in unexpected increases in load where a complete object slip did not occur, GF still increased, but not until 70-80ms after initiation of load increase (Johansson and Westling 1988). Altering both friction and weight results in localized slips in the contact area which are recognized by the large number of tactile afferents which are sensitive to local slips in the contact area (Johansson and Westling 1987). Recognition of these slips may alert the CNS of a decreasing safety-margin, or risk of object slippage, and result in an increase in applied GF.

It is possible that the unexpected increase in weight of the object activates the muscle spindle response. In regard to the equilibrium point hypothesis proposed by Feldman, the CNS has a prescribed set of parameters based on the previous lifts that create an optimal strategy for lifting an object. The CNS sets these parameters as the 'equilibrium' point for the movement. It also lowers the activation threshold of neurons in the system to detect deviations from the planned movement (Latash 2010). It has been shown that unexpected weight changes to an object resulted in stronger muscle activity in not only GF producing muscles, but also the surrounding musculature (Johansson and Westling 1988). Essentially the CNS has to play 'catch up' to the delayed lift-off event of the movement. With these mechanisms in mind, increasing the weight of object to be lifted could be expected to initiate a response from the muscle spindle, generating a stronger lift, which in turn will increase the applied GF as well. This response combined with the signals from tactile afferents due to 'micro-slips' may be the reason for a stronger response in the applied GF to changes in weight compared to friction.

Regarding our second aim to compare the differences between the non-dominant and dominant hands, we found that the dominant hand had larger increases in the applied GF, specifically during the holding phase, compared to the non-dominant hand. This finding was observed in the ipsilateral hand, or the hand that experienced the changes in weight or friction, and the contralateral hand as well. This finding may support the findings of Yadav and Sainburg (2014) which proposed that the dominant hand is more prone to perturbations during dynamic movements. The idea states that the dominant hand has an advantage in dynamic movements, but is more susceptible to perturbations, while the non-dominant hand has an advantage in stabilizing functions and is less prone to changes due to perturbations (Yadav and Sainburg 2014). While the change in weight or friction of the object is not a perturbation that occurs during the movement, but rather before the movement, this theory may still apply. The adjustments made during the movement may still demonstrate larger changes in the dominant hand due to the dominant hands' susceptibility to changes during movement.

Finally, regarding our last aim to explore the changes in GF when elicited by unilateral perturbations of mechanical conditions in the hand ipsilateral and contralateral to the perturbation, we observed that the ipsilateral hand demonstrated a marked change in the applied grip force, while minimal changes were observed in the contralateral hand. This point may seem obvious at first; however the slight variations we see in the contralateral hand may speak in favor of contralateral effects. The conditions on the contralateral hand did not change between trials while the condition on the ipsilateral hand did. Some changes were observed in the contralateral hand, which demonstrates the possibility of an effect of the ipsilateral hand on the contralateral hand. These differences were small and relatively inconsistent, so further studies on the contralateral effect of weight and frictional changes on applied GF may be needed. Future studies may want to explore the same adaptation in individuals with impaired hand function, such as elderly or neurological patients.

Regarding the limitations of the present study, we did not account for the effect of inertia due to different accelerations during tested lifting. Namely, it may have been an important factor to observe the change in the rate of the lift and how this may have affected the applied GF. In addition, the findings were observed only in bimanual symmetrical movements. These results may appear differently in uni-manual tasks, as well as in various asymmetrical movements.

In conclusion we found a potential bias of the neural control of GF to changes in weight compared to those as a response to changes in friction. This may be due to differences in the spindle and tactile activity associated with the two applied interventions. We also found a larger increase in changes in the applied GF in the dominant hand compared to the dominant hand that may be in line with the dynamic-dominance hypothesis. This information may be utilized in the occupational rehabilitation setting, because understanding the influence of object properties on object manipulation can enhance rehabilitation strategies. It can also play a role in ergonomy, for the design of tools, and in the design future research studies. Future studies are needed to find the cause of this bias, such as EMG recordings comparing of GF and LF producing muscles during unexpected lifts of weight vs friction. Future studies may also look to explore these changes when larger perturbations are introduced to the movements.

Chapter 4

GENERAL CONCLUSIONS

The proper application of GF is important for successful object manipulation. This application is dependant on two main factors of weight and friction, however it is unknown which of these factors is more important.We set out to observe the neural control mechanisms of adaptation to unexpected changes in load and friction of a lifted object. We also aimed to compare differences in the changes in applied GF in the dominant and non-dominant hands and to explore any effects in the hand contralateral to perturbations of weight and friction. We determined that there is a stronger effect ellicited when the weight of an object is unexpectedly changed compared to the change in friction of the object despite the fact that both changes should have required the same change in the minimum GF that prevents slipping of the object. It is plausible to assume that these changes are based on different contributions of different types of sensory information which stregnthens the error signal through feedback of infortmation. This altered signal would then result in a changed corrective action which is shown by the increased change in GF when weight was perturbed.

We also found a larger reaction to perturbation in the dominant hand compared to the non dominant hand. Unexpected changes in weight and friction lead to altered proprioceptive information. This altered information lead to differen adaptation of neural control of GFin the dominant compared to the non-dominant hand.

Finally we also observed the hypothesized greater effect on GF in the hand ipsilateral to the perturbation. The contralateral hand did demonstrate some change in force production, however the changes were relativey small compared ot the ipsilateral hand. It is possible that the perturbations introduced in our study were not large enough to create significant contralateral effects, and this should be explored in future studies.

The findings observed in the present study advance the current knowledge of the control of GF and its function in object manipulation. The results of this study may be applied in future research design regarding manipulation of various objects. Another application of these findings may be in the design of objects to be manipulated such as tools and utenils. Objects of different frictional properties are more likely to be either over gripped or dropped than the objects of different weights. The manipulation of objects is an important function for activities of daily living and the understanding of this function may be able to improve the quality of life various individuals.

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Appendix A

TABLES AND FIGURES

Table1. Average standard values

		LowGF Standard					HighGF Standard		
	Dom	NonDom	p	ES		Dom	NonDom	p	ES
GF_Lift	4.0 +/- 1.3	4.8+/- 1.9	0.016	0.579		14.9+/- 6.7	14.2+/- 4.9	0.265	-0.120
dGF/dt	39.1+/- 15.7	34.4+/- 13.7	0.414	-0.297		75.1+/- 30.4	64.4+/- 26	0.182	-0.356
GF_Hold	3.5+/- 1.8	3.9+/- 1.9	0.199	0.237		12.6+/- 5.7	11.8+/- 3.8	0.388	-0.144

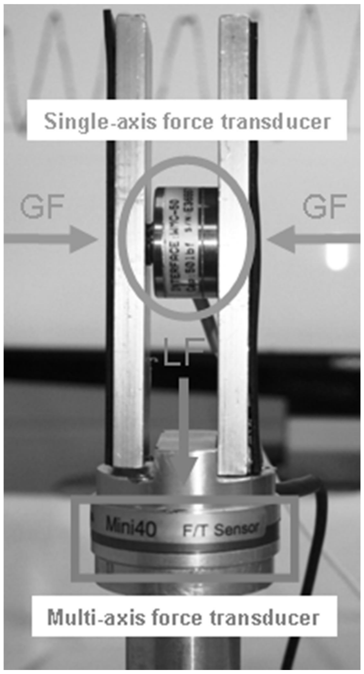


Figure 1: Experimental Device

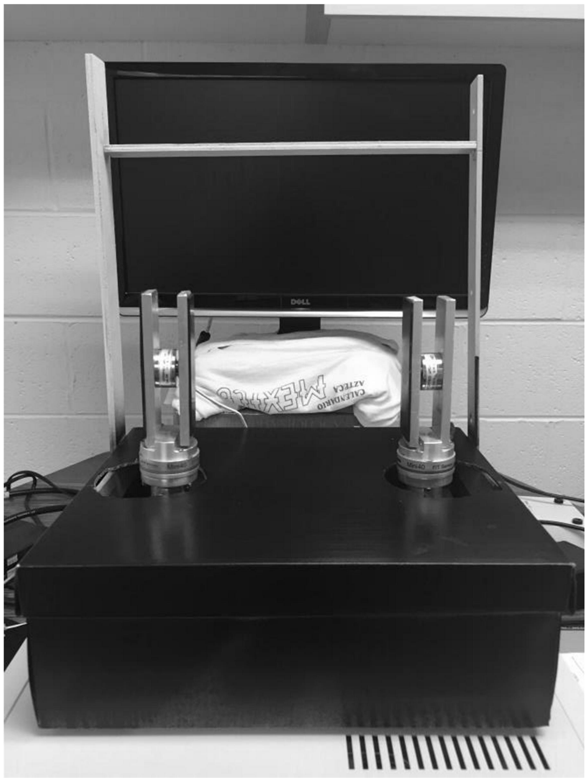


Fig 2: Experimental Set-up

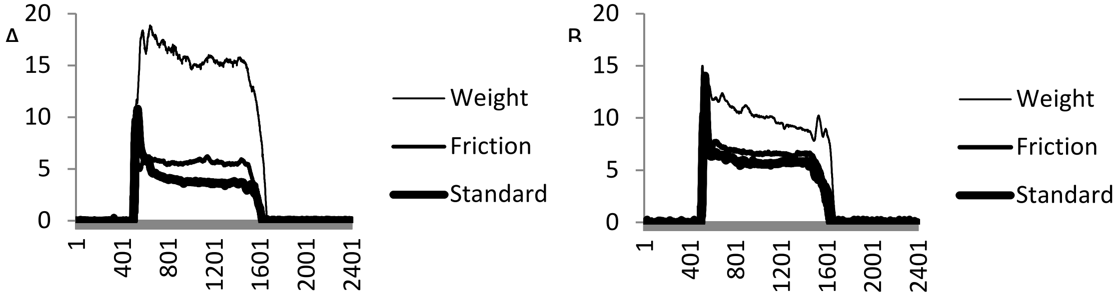


Fig 3: Force profiles of a representative subject during the LSC for the Dominant (A) and non-dominant (B) hands in the ipsilateral hand.

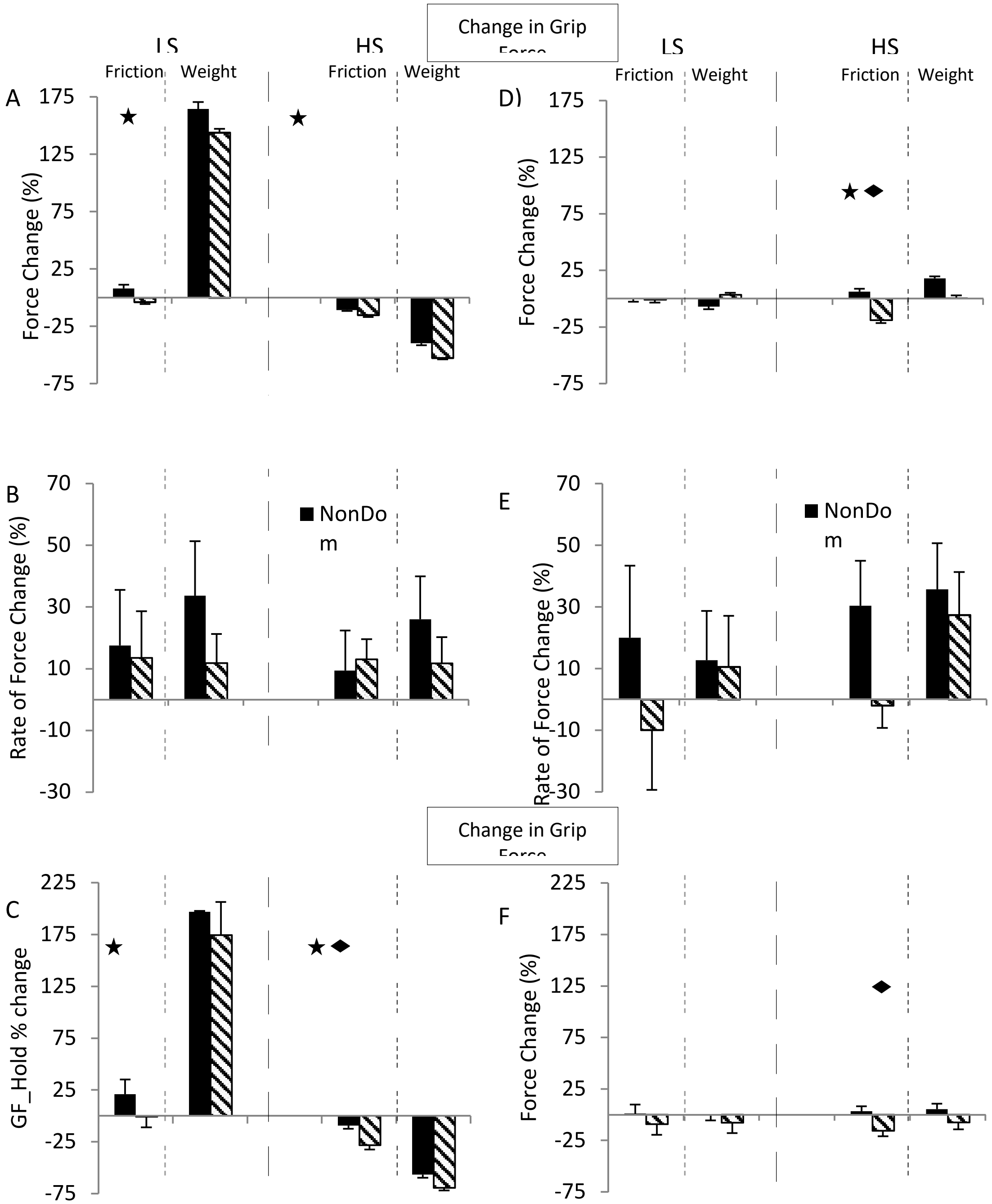
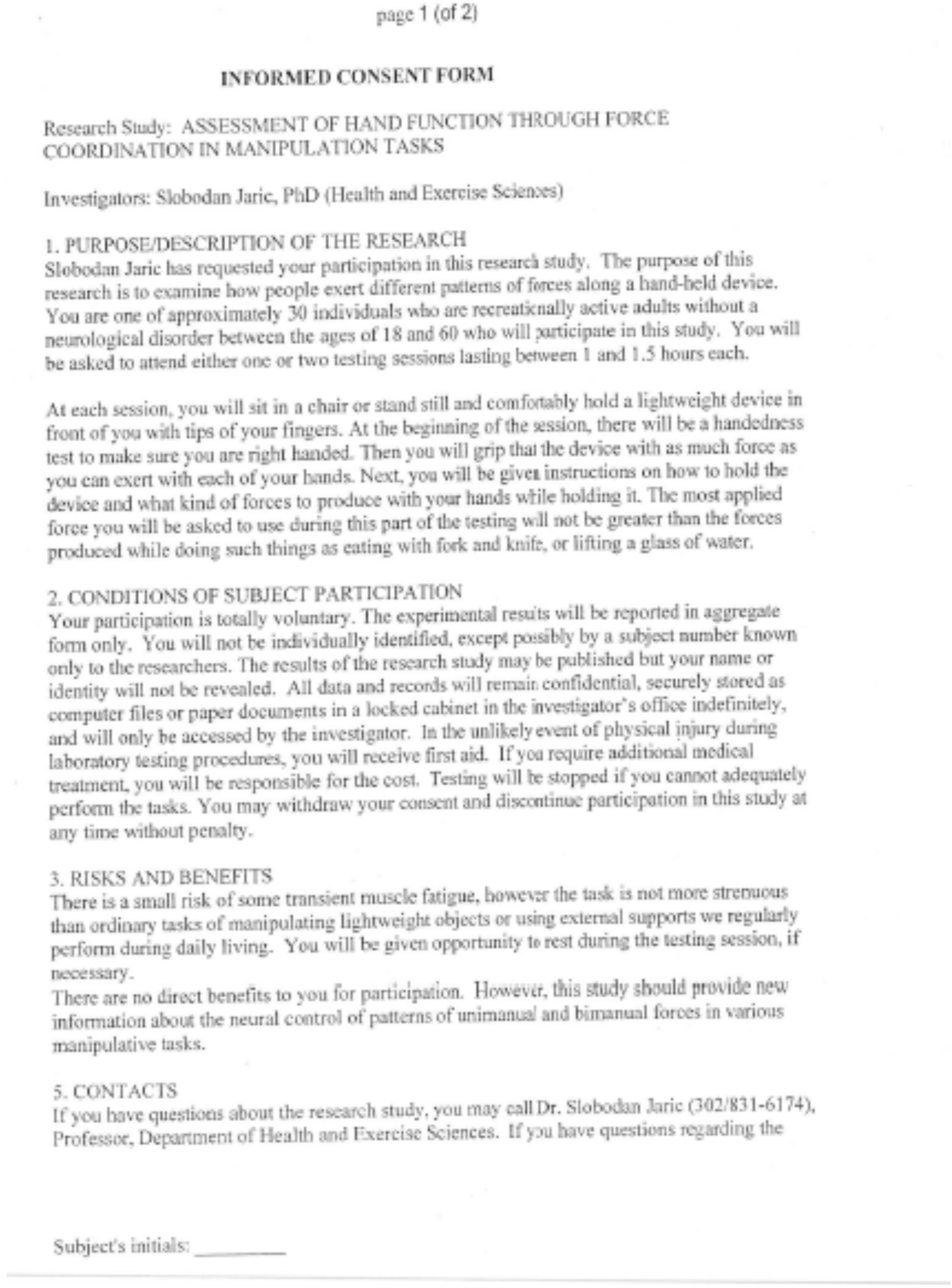

Change in Grip Force
LS
HS
Friction
Weight
A
D)
Force Change (%)
175
125
75
25
-25
-75
★
★ ◆
B
E
Rate of Force Change (%)
70
50
30
10
-10
-30
■ NonDom
C
F
GF_Hold % change
225
175
125
75
25
-25
-75
★
★ ◆
◆

Figure 4. Change in variables expressed as percent change from standard condition. Values for the ipsilateral hand are displayed in the left column and the values for the contralateral hand are displayed in the right column. The LSC is displayed on the left column of the ipsilateral hand and contralateral hand while the HSC is displayed on the right column of the ipsilateral hand and contralateral hand. Frictional perturbations are displayed in the left hand column of the LSC and HSC while the weight perturbations are displayed in the right column of the LSC and HSC. Row A displays the percent change in GF during the lifting phase, Row B displays the percent change in the Rate of Force change, and Row C displays the percent change in GF during the Holding phase. ★ Denotes a significant difference in conditions, while ◆ denotes a significant difference in hands.

Appendix B

IRB CONSENT FORM



page 1 (of 2)

INFORMED CONSENT FORM

Research Study: ASSESSMENT OF HAND FUNCTION THROUGH FORCE COORDINATION IN MANIPULATION TASKS

Investigators: Slobodan Jaric, PhD (Health and Exercise Sciences)

1. PURPOSE/DESCRIPTION OF THE RESEARCH
Slobodan Jaric has requested your participation in this research study. The purpose of this research is to examine how people exert different patterns of forces along a hand-held device. You are one of approximately 30 individuals who are recreationally active adults without a neurological disorder between the ages of 18 and 60 who will participate in this study. You will be asked to attend either one or two testing sessions lasting between 1 and 1.5 hours each.

At each session, you will sit in a chair or stand still and comfortably hold a lightweight device in front of you with tips of your fingers. At the beginning of the session, there will be a handedness test to make sure you are right handed. Then you will grip that the device with as much force as you can exert with each of your hands. Next, you will be given instructions on how to hold the device and what kind of forces to produce with your hands while holding it. The most applied force you will be asked to use during this part of the testing will not be greater than the forces produced while doing such things as eating with fork and knife, or lifting a glass of water.

2. CONDITIONS OF SUBJECT PARTICIPATION
Your participation is totally voluntary. The experimental results will be reported in aggregate form only. You will not be individually identified, except possibly by a subject number known only to the researchers. The results of the research study may be published but your name or identity will not be revealed. All data and records will remain confidential, securely stored as computer files or paper documents in a locked cabinet in the investigator's office indefinitely, and will only be accessed by the investigator. In the unlikely event of physical injury during laboratory testing procedures, you will receive first aid. If you require additional medical treatment, you will be responsible for the cost. Testing will be stopped if you cannot adequately perform the tasks. You may withdraw your consent and discontinue participation in this study at any time without penalty.

3. RISKS AND BENEFITS
There is a small risk of some transient muscle fatigue, however the task is not more strenuous than ordinary tasks of manipulating lightweight objects or using external supports we regularly perform during daily living. You will be given opportunity to rest during the testing session, if necessary.
There are no direct benefits to you for participation. However, this study should provide new information about the neural control of patterns of unimanual and bimanual forces in various manipulative tasks.

5. CONTACTS
If you have questions about the research study, you may call Dr. Slobodan Jaric (302/831-6174), Professor, Department of Health and Exercise Sciences. If you have questions regarding the

Subject's initials: _________

rights of individuals who agree to participate in this research you may call the Chair of the University of Delaware IRB (302/831-2137).

6. SUBJECT'S ASSURANCES

I have read the above informed consent. The nature, demands, risks and benefits of the project have been explained to me. I understand that I may withdraw my consent and discontinue my participation in this study at any time without penalty or loss of benefit to myself. My participation in this research study is not related to any course grade associated with the University of Delaware. A copy of this consent form has been given to me.

7. CONSENT SIGNATURES

Subject's Signature: ______________________________ Date:__________

Subject's Name (printed): ______________________________ Date:__________

I certify that I have explained to the above individual the nature and purpose, the potential benefits, and possible risks associated with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature. I have provided the subject with a copy of this informed consent document.

Signature of the Investigator: ______________________________ Date:__________

Subject's initials: ________