26

Force Scaling as a Function of Object Mass when Lifting with Peripheral Fatigue

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1. General Introduction

Fatigue is a relevant and significant factor in many work related settings. Some of these settings include working on an assembly line at a factory, sitting in front of a computer all day or performing long surgeries in the operating room. These types of jobs demand that individuals perform repetitive tasks with either a high or low degree of force intensity for prolonged periods of time without adequate rest breaks (Clarkson et al., 1992; Franzblau et al., 1993). Even under highly repetitive, non-forceful tasks, repetitive strain injuries can result, causing the potential for task performance levels to decrease (Stock, 1991). In addition to the potential long term injury as a result of performing while fatigued, there are immediate performance adjustments that take place when generating motor skills in this state.

Historically, the effects of fatigue on motor performance and motor learning have been of interest. Alderman (1965) found that performance during practice suffered when an interpolated fatiguing protocol was administered when learning two similar motor tasks. However, performance during a retention test after full recovery from fatigue showed no differences between both the non-fatigued and fatigued groups for both motor tasks. Similarly, when participants were fatigued either early or late during practice and then retested in a retention test after full recovery from fatigue, performance during the practice stages of the study was affected and there were no differences between the control and experimental groups during a retention test. These two studies, along with others (Schmidt, 1969; Whitley, 1973), suggest that fatigue is *not* detrimental to the amount learned when practice is performed in a fatigued state. In opposition to these findings, Godwin and Schmidt (1971) found fatigue to be a powerful learning variable as they reported that transfer from a fatigued to non-fatigued condition was only moderate. Many others have supported Godwin and Schmidt's claim by reporting similar findings (Carron, 1972; Carron & Ferchuk, 1971; Pack et al., 1974; Thomas et al., 1975).

Bigland-Ritchie (1984) defined neuromuscular fatigue as any reduction in the force-generating capacity of the total neuromuscular system. Furthermore, Bigland-Ritchie explained that fatigue can occur within the central nervous system (CNS), the neural transmission from the CNS to the muscle, and within the individual muscle itself. The fatiguing protocol employed in this chapter was aimed to elicit task specific local neuromuscular fatigue (peripheral fatigue) of the muscles involved in a precision grasp between the index finger and thumb. The intent of the fatiguing protocol was to produce fatigue-like symptoms that resemble those endured in everyday life, but to produce them in a controlled laboratory environment where their motor effects could be effectively evaluated.

Two main types of peripheral fatigue are found in everyday tasks. Tasks that are of high intensity and short duration cause mainly high-frequency fatigue (HFF) and others that occur at low intensities over a substantial amount of time produce a greater amount of low-frequency fatigue (LFF). To support this definition, electrically stimulating a muscle at frequencies between 50-100 Hz has been shown to produce predominantly HFF whereas stimulating at frequencies of 2-20 Hz produces predominantly LFF (Lehman, 1997). An example of a HFF task may consist of having somebody bench press at 80 % of their maximum voluntary contraction (MVC) as many times as possible. This would send the participant to exhaustion very quickly, but recovery times for HFF tasks are also very rapid. The recovery time can be defined as the time it takes for a participant to recover to 80 % of their MVC (Schwendner et al., 1995). Schwendner et al. (1995) reported recovery times of up to eight minutes following a HFF protocol. The studies conducted in this chapter attempted to induce predominantly LFF as this type of fatigue has been shown to last up to 24 hours post-fatiguing protocol (Edwards et al., 1977) and when present, affects the forces emitted at lower frequencies (Edwards et al., 1977; Fuglevand et al., 1999) which was specific to the low level forces needed to complete the lifting tasks employed in the present studies. In addition, this type of fatiguing protocol satisfied the time constraints of the studies as many samples were collected over a considerable amount of time (approximately 0.5 hours post-fatigue protocol). Alongside fitting the abovementioned criteria, LFF is relevant to many settings such as assembly line work (Dennerlein et al., 2003), typing (Lin et al., 2004; Nakata et al., 1992) and surgery (Uhrich et al., 2002), and therefore, the information gathered about the effects of fatigue at low levels of exertion may help to improve these types of work environments.

Two studies are reported in this chapter. Due to the current lack of research in the area of fatigue related to simple motor control principles, it was the aim of the first study to determine the effects of fatigue on the ability to generate forces appropriate to the mass of lifted objects when using a precision grip. Unvarying visual cues were present in this first study, and therefore, the ability to anticipate object mass was eliminated. The study was designed solely to determine if fatigue altered one's ability to appropriately scale motor output to the varying mass of the lifted objects. The objective of the second study was to address the consequences of fatigue on one's ability to anticipate force and movement generation requirements. Therefore, visual size cues that are congruent with object mass were present in this study. This gave participants the opportunity to anticipate the force and movement characteristics required to lift the various sized boxes and in turn offered insight into whether anticipatory strategies are compromised by fatigue.

It was hypothesized that participants would show a reduction in overall force output after the fatiguing protocol and a reduction in the ability to control fingertip forces throughout the lift. The reduction in force control was expected to be demonstrated by the inability to correctly scale force output from the fingers to the mass of the object being lifted.

2. Study 1

The aim of this study was to examine the effects of neuromuscular fatigue during a precision grasp lifting task when object *mass* is manipulated.

2.1 Rationale

Literature has shown that some basic movement and force patterns are followed when lifting objects that differ in mass (Johansson & Westling, 1984; 1988; 1990). For example, the grip forces emitted by the fingertips increase with the increasing mass of the objects presented (Gordon et al., 1993; Johansson & Westling, 1988; 1990). This is known as force scaling as more force is used to lift and hold heavy objects than light objects. After the grasp has been established and the lift has begun, the grip and load forces have been shown to increase in parallel, with the grip force output being slightly greater than the minimum grip force required to prevent slips. These fundamental measures along with many others have been well documented only in studies with rested participants (e.g., Burgess & Jones, 1997).

The first goal of the present study was to form a template for comparison between a lift under normal and fatigued conditions. After a pre-fatigue test (test 1) was completed, half of the participants completed a fatiguing protocol and were then asked to complete the same lifting task immediately following (post-fatigue test or test 2). The remaining half of the participants, the Control Group, completed the pre- and post-fatigue tests without performing the fatiguing protocol. It was expected that these procedures would show the effects of fatigue on the ability to elicit the appropriate motor output at the object-digit interface based on the mass of the object being lifted.

It was hypothesized that after the fatiguing protocol participants would show a reduction in the overall force output and, in addition, would show alterations in the ability to control finger tip forces throughout the lift. This was to be demonstrated by the inability to correctly scale the force output from the fingers to the mass of the object lifted (e.g., higher forces are normally associated with heavier objects). Thus, it was thought that after the fatiguing protocol, participants may have adopted a cautious strategy when handling objects with a fatigued grip.

2.2 Methods

Participants

Twenty-four naïve, right-handed participants with normal uncorrected or corrected visual acuity and no reported previous history of upper limb neuromuscular injuries participated. The Fatigued Group in this study had 5 males and 7 females (ages 18-27 years) and the Control Group had 6 males and 6 females (ages 21-28 years). The study received ethics approval through the local Office of Research Ethics. Informed consent was obtained from all of the participants prior to their participation.

Apparatus

Five different masses were located centrally inside a uniform object. Therefore, the objects lifted were visually identical. The object mass was varied between 100 g, 200 g, 300 g, 400 g and 500 g. Density also varied, but was similar to 1.0 g^1 cm^{-3} – the density suggested to be common to most everyday handheld objects (Flanagan & Beltzner, 2000; Gordon et al., 1993). Refer to Table 1 for the properties of the objects.

Object	Mass (g)	Length of Side (cm)	Volume (cm^3)	Density (g/cm^3)
1	100	6.7	300.8	0.332
2	200	6.7	300.8	0.665
3	300	6.7	300.8	0.997
4	400	6.7	300.8	1.330
5	500	6.7	300.8	1.662

Table 1. Properties of objects used in Study 1

The object was outfitted with a clasp that attached to the handle. The handle consisted of an area that fastened onto the object and an area where an ATI Gamma Force/Torque transducer system could be mounted between two circular grasping surfaces (ATI Industrial Automation, Gerner N.C., U.S.A.). The force transducer was used to track force changes in the X, Y, and Z axes for the duration of every lift (see Fig. 1). In addition, an Optotrak motion analysis system was used to track the location of the object through space (RMS accuracy to 0.1 mm; resolution to 0.01 mm).

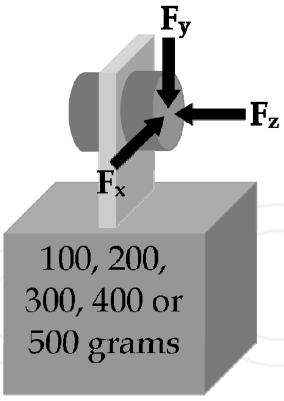

Fig. 1. Diagram of apparatus used in Study 1

Movement task description

Seated participants placed their dominant hand (right hand) in the arm brace located on the table. The arm brace secured the forearm in an attempt to make the lifting task and the fatiguing task as similar as possible. After a tone sounded, the participants lifted the object using a precision grasp (a grasp between the index finger and thumb) at the grasping surface. Participants held the object approximately 1 cm above the table surface for 5 s and then replaced it when told. See Fig. 2 for a schematic representation of the task.

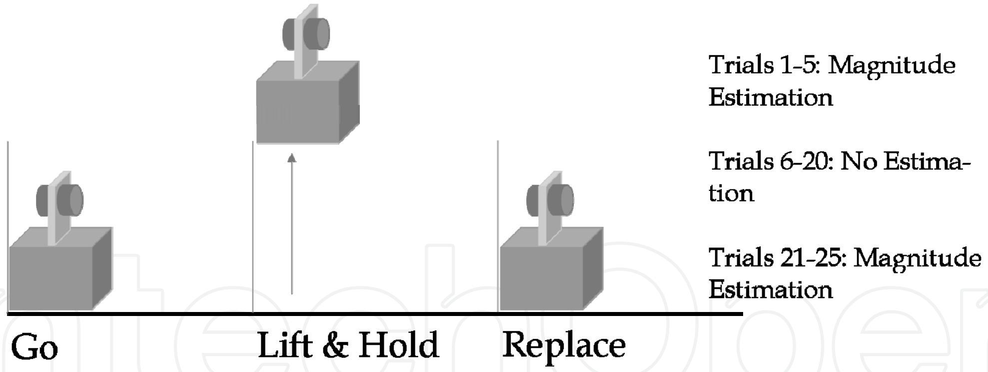

Fig. 2. The order of events during a single lifting trial

Fatiguing protocol

The fatiguing protocol was task specific as it was performed using the same grasping surface participants used to lift the objects during the lifting trials. As such, the width of the grasping area was controlled.

Participants first performed three MVCs. 50 % of the highest registered MVC was the force used in the fatiguing task. After 50 % MVC was calculated, participants completed a fatiguing protocol with a 0.5 duty cycle where they pinched the force transducer for five seconds (contraction time) to 50 % MVC then released it for five seconds (relaxation time) in a continuous cycle for 15 minutes (modified from Fowles et al., 2002). A visual display was available to assist participants with matching the required force output. MVC force output was collected immediately following the 15 minute fatiguing protocol and following the post-fatigue protocol lifting session.

2.3 Procedures

Fatigued group

Pre-fatigue test (test 1). Participants lifted five objects five times each for a total of 25 trials. The objects were presented in a pseudorandom order as each of the five masses was presented once every five trials. Therefore, each mass occurred once in each set of five trials with the first set (trials 1 to 5) and the last set (trials 21 to 25) having the same order of presentation for magnitude estimation purposes. Some example sequences are as follows: (3-1-5-4-2)-(4-5-1-2-3)-(2-4-3-5-1)-(4-5-1-3-2)-(3-1-5-4-2) (numbers 1 through 5 represent the 5 different masses with 1 being the lightest and 5 the heaviest). A 20 s rest period was provided between lifting trials to ensure that fatigue was avoided during the pre-fatigue test (cf. Valero-Cuevas et al., 1998).

Fatigue protocol. Participants were fatigued according to the above mentioned fatiguing protocol.

Post-fatigue test (test 2). An identical procedure to the pre-fatigue test was administered.

Control group

Participants in this group completed the same protocol as the fatigued group; however, these participants spent the 20 minutes between the pre-fatigue and post-fatigue tests of the study resting instead of completing the fatiguing protocol.

2.4 Data analysis

All raw data files were filtered with a second order Butterworth low-pass 15 Hz filter. Forces in the z-axis (F_z), load forces (F_{xy}) and grip rates at different intervals throughout the lift were analyzed. These measures included: peak grip force, peak rate of grip force generation, final grip force (just before participants put the object down), and peak load force. All motor data were analyzed using separate mixed 2 group (control / fatigued) x 2 test (before fatigue break (test1) / after fatigue break (test 2)) x 5 mass (100 g, 200 g, 300 g, 400 g, 500 g) x 5 trial (1 to 5) analyses of variance (ANOVAs), $\alpha = 0.05$. All significant interactions were explored using Tukey's honestly significant difference (HSD) method for post hoc analysis, $\alpha = 0.05$.

Maximum voluntary contraction data was recorded at the end of the test 1 trial set, immediately following the fatiguing protocol and immediately following test 2 for the Fatigued Group. The Control Group provided maximum voluntary contractions at the start of their 20 minute rest break following test 1 and again immediately following the test 2 trial set. A one-way analysis of variance was run on this data with time as a factor for each group. Thus, there were three levels of time for the Fatigued Group and two levels of time for the Control Group.

2.5 Results and Discussion

Grip force

In the analysis of **peak grip force** there was a three way interaction of test by mass by trial, F (16, 352) = 2.10, $p < .01$. As seen in Fig. 3, for the first trial of the first test, participants produced the same peak force for the 100 g and 200 g objects, and for the 300 g, 400 g, and 500 g objects. On all subsequent trials, for both tests, participants were generally able to scale forces according to object mass. Also, there was an overall decrease in peak grip force for test 2 in comparison to test 1. There were no statistically significant main effects or interactions with group ($p > .05$), which suggests that the fatiguing protocol had no effect on peak grip force output.

The analysis of **peak rate of grip force production** showed a main effect for mass, F (4, 88) = 12.12, $p < .01$, in addition to a test by trial interaction, F (4, 88) = 6.97, $p < .01$ (see Fig. 4). The main effect for mass showed that there was a larger rate of grip force production for the 300 g (36.3 N/s, SE = 1.3) and 400 g (38.4 N/s, SE = 1.3) objects in comparison to the 100 g object (31.5 N/s, SE = 1.3). The rate of force production for the 200 g (32.9 N/s, SE = 1.2) and 500 g objects (34.3 N/s, SE = 1.3) did not differ statistically from the others. This was unexpected because no visual cues were available such that participants could anticipate object mass. However, it is possible that at the time of peak grip rate (approximately 30 ms into the lift) enough time was available for haptic inputs to provide some information about object mass (Abbs et al., 1984).

The interaction of test and trial showed that for the first test, peak grip rates were higher for the first and second trials and stabilized on subsequent trials. For the second test, peak grip rate remained stable throughout all trials. This is consistent with the notion that forces produced on initial lifting trials tend to be larger and produced more quickly than on subsequent trials (Johansson & Westling, 1988).

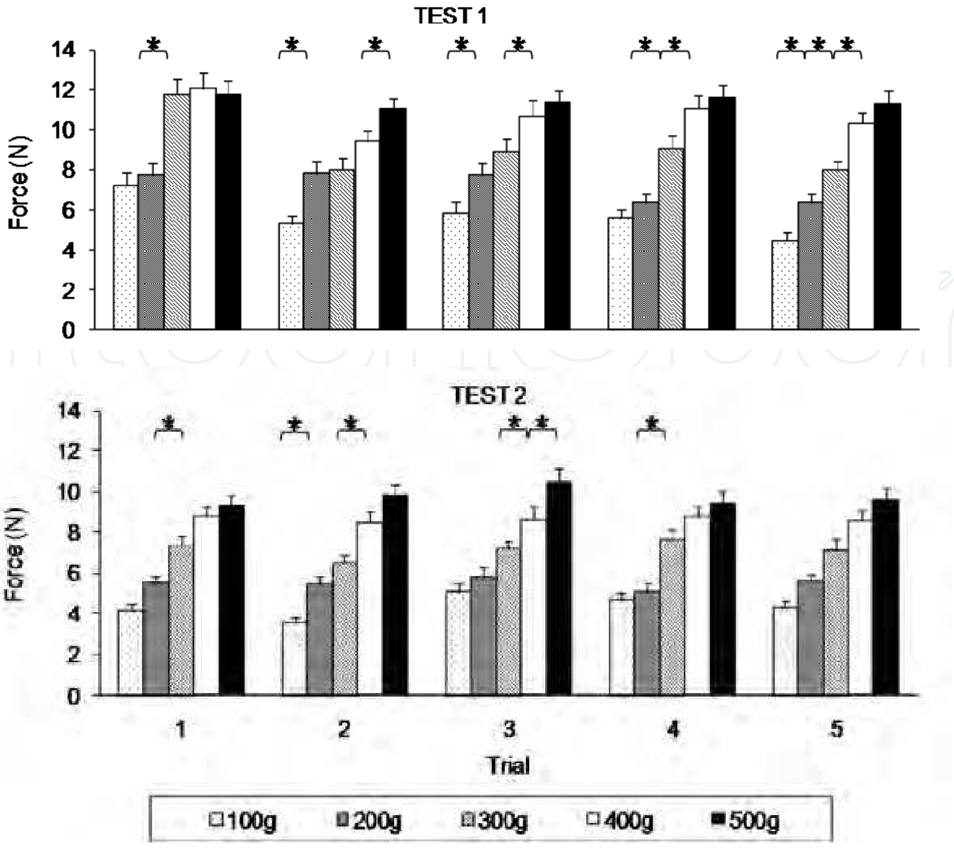

Fig. 3. Test by trial by mass interaction for peak grip force in Study 1 (all asterisks represent significant differences between adjacent masses within each trial set)

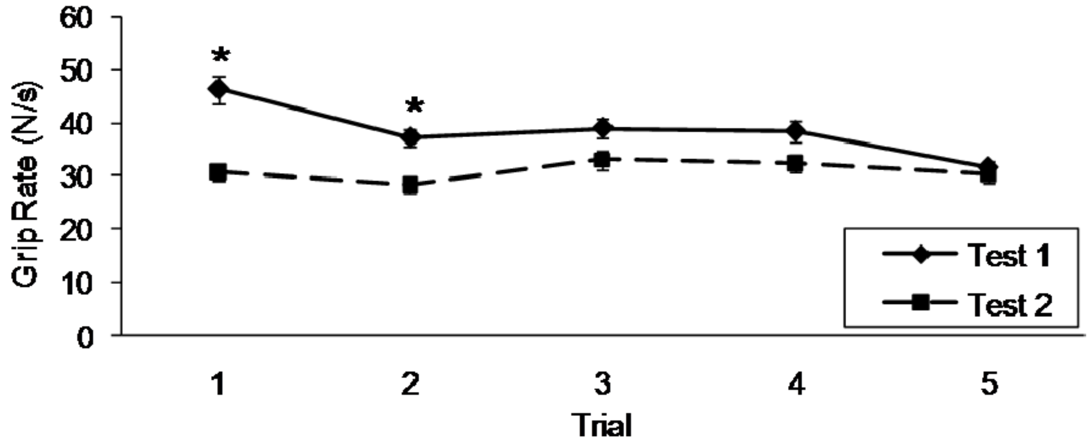

Fig. 4. Test by trial interaction for peak rate of grip force production in Study 1 (all asterisks represent significant differences between trials when compared across tests)

Load force

There was the expected main effect for object mass in the analysis of **peak load force**, F (4, 88) = 1084.5, p < .01 where load force increased as a function of object mass. The group by test interaction, F (1, 22) = 5.9, p < .05, for the analysis of peak load force showed that for the Fatigued Group, peak load force did not differ between test 1 (1.95 N, SE = .05 N) and test 2 (1.95, SE = .04 N). However, for the Control Group, peak load force decreased from test 1 (2.05, SE = .05 N) to test 2 (1.90, SE = .05 N). This is some evidence that the Fatigued Group may have been engaged in some sort of compensatory strategy in response to the muscle fatigue they were experiencing. The group by trial interaction, F (4, 88) = 3.4, p < .01, depicted in Fig. 5 showed that for the Control Group, peak load force in trial 1 was significantly higher than trials 1 and 2 for the Fatigued Group. However, by trial 2, both groups elicited the same peak load forces.

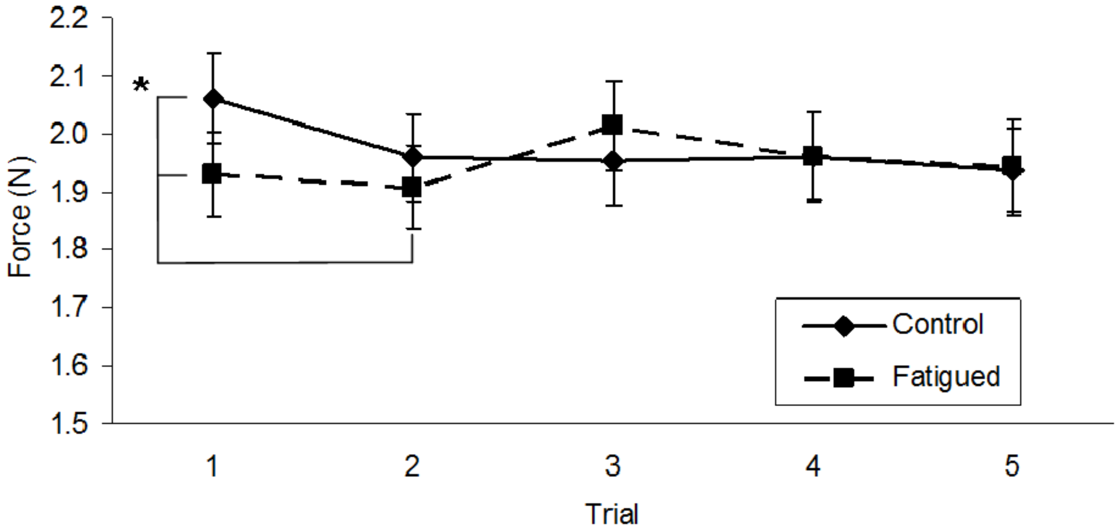

Fig. 5. Group by trial interaction for peak load force in Study 1 (asterisks represent significant differences between groups for each trial)

MVC data

The analysis of the maximum voluntary contraction data revealed that the Fatigued Group had a reduction in maximum force output immediately following fatiguing exercise but recovered to resting levels at the end of the second lifting session (*p* < .05). See Table 2 for means and standard errors.

Fatigued Group			
Time of MVC Test	**Mean (N)**	**SE**	
Prior to Fatiguing Protocol	45.00	2.00	*
Following the Fatiguing Protocol	37.17	1.98	
At the End of Test 2	43.83	2.49	
Control Group			
In Between Test 1 and Test 2	47.17	2.43	
At the End of Test 2	46.92	2.80	

Table 2. Means and standard errors for MVC data in Study 1 (significant differences have been marked by asterisks)

3. Study 2

The aim of this study was to examine the effects of neuromuscular fatigue during a precision grip lifting task when object *mass* and *size* were manipulated.

3.1 Rationale

Specifically, the purpose of Study 2 was to determine whether fatigue alters the ability of participants to appropriately scale their force characteristics in anticipation when size cues about object mass are provided (Gordon et al., 1993; Wolpert & Kawato, 1998). The intent of this experiment was to answer the following question: Will participants be able to utilize the appropriate sensorimotor representations and therefore, correctly anticipate the mass of the lifted objects after their motor control systems have been compromised by fatigue? It was thought that the same motor representations would be available while in a fatigued state, but it was unclear whether the retrieval of these motor representations would be affected by fatigue.

Similar motor effects to those hypothesized in Study 1 were expected to be present in this study. However, it was thought that, in this study, grip forces would likely remain scaled to object mass after the fatiguing protocol. Force scaling was expected because participants could now use the association of visual size information to object mass along with the pre-fatiguing protocol lifts to formulate the appropriate motor commands. Although scaling was expected to be present, it was still probable that participants would show a reduced force output for all levels of object mass in comparison to the pre-fatigued lifting session. However, the possibility remained that participants would be able to use fatigue as a parameter to update the internal models associated with each of the lifted objects. If this was true, no differences should be found in the motor responses between both control and fatigued groups both in the pre-fatigue test and post-fatigue test lifting conditions. Another measure of particular interest was the rate of grip force generation. It was expected that participants would scale their grip rates as they do their grip forces in this study. Thus, the heavier the object the higher the peak grip rate. This measure happens very early in the lift and can be classified as an anticipatory force control measure as it gives insight into the motor program that was selected for a particular lift based on pre-contact visual information and/or post-contact sensorimotor information from a previous lift (Flanagan et al., 2001; Gordon et al., 1993; Johansson & Westling, 1988). It was expected that, with visual cues, the fatigued group would produce lower overall peak grip rates but would scale them appropriately following fatiguing exercise.

3.2 Methods

Other than the changes listed below, the methods for Study 2 were identical to Study 1.

Participants

Twenty-four naïve, right-handed individuals with normal uncorrected or corrected visual acuity and no reported previous history of upper limb neuromuscular injuries participated (none of whom participated in Study 1). There were 6 males and 6 females (ages 19-28 years) in the Fatigued Group and 6 males and 6 females (ages 22-47 years) in the Control Group.

Apparatus

Five wooden blocks with a common density of 1.0 g^1 cm^{-3} served as the objects to be lifted as this is a good approximation of the densities encountered when dealing with everyday handheld objects (Flanagan & Beltzner, 2000; Gordon et al., 1993). Refer to Table 3 for the masses and sizes of the objects used to achieve the common density.

Object	Mass (g)	Length of Side (cm)	Volume (cm³)	Density (g/cm³)
1	100	4.64	100	1
2	200	5.85	200	1
3	300	6.69	300	1
4	400	7.37	400	1
5	500	7.94	500	1

Table 3. Properties of objects used in Study 2

3.3 Results and Discussion

Grip force

As seen in Fig. 6, the interaction of test by mass by trial, F (16, 352) = 4.71, $p < .01$, revealed that for the first trial of the first test, participants had difficulty scaling their forces as they produced the same peak forces for the 100 g and 200 g objects, and elicited too much force for the 300 g object while scaling forces appropriate to the 400 g and 500 g objects. On all subsequent trials, for both tests, participants were generally able to scale their forces according to object mass. This pattern was very similar to that seen in Study 1. Also, as in Study 1, there was an overall decrease in peak grip force for test 2 in comparison to test 1.

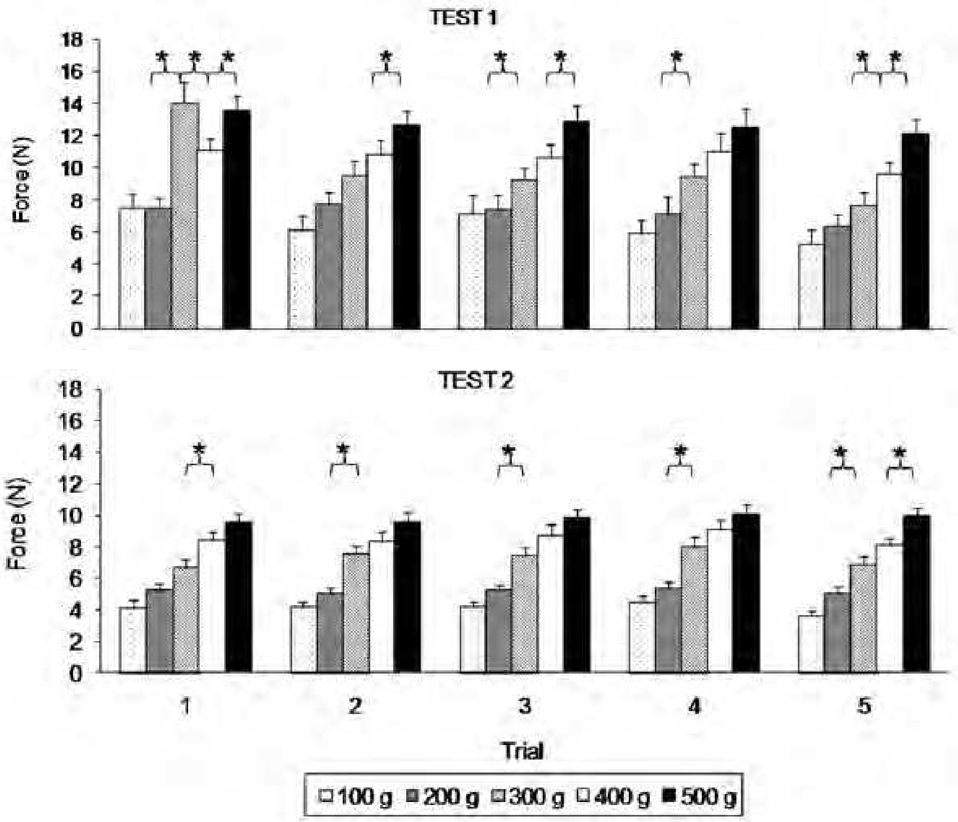

Fig. 6. Test by trial by mass interaction for peak grip force in Study 2 (asterisks represent differences between each mass level within each trial set)

The significant three way interaction of test, trial and group for the analysis of the **peak rate of grip force production,** F (4,88) = 2.98, $p < .05$, showed that peak grip rates increased as object size increased. This was expected as congruent visual information was available in this study such that participants could anticipate object mass. As seen in Fig. 7, the Fatigued Group produced lower peak grip rates on trials 1, 3 and 4 of test 2 in comparison to those same trials in test 1. For the Control Group, only trials 2 and 3 were different in test 2 when compared to those same trials of test 1.

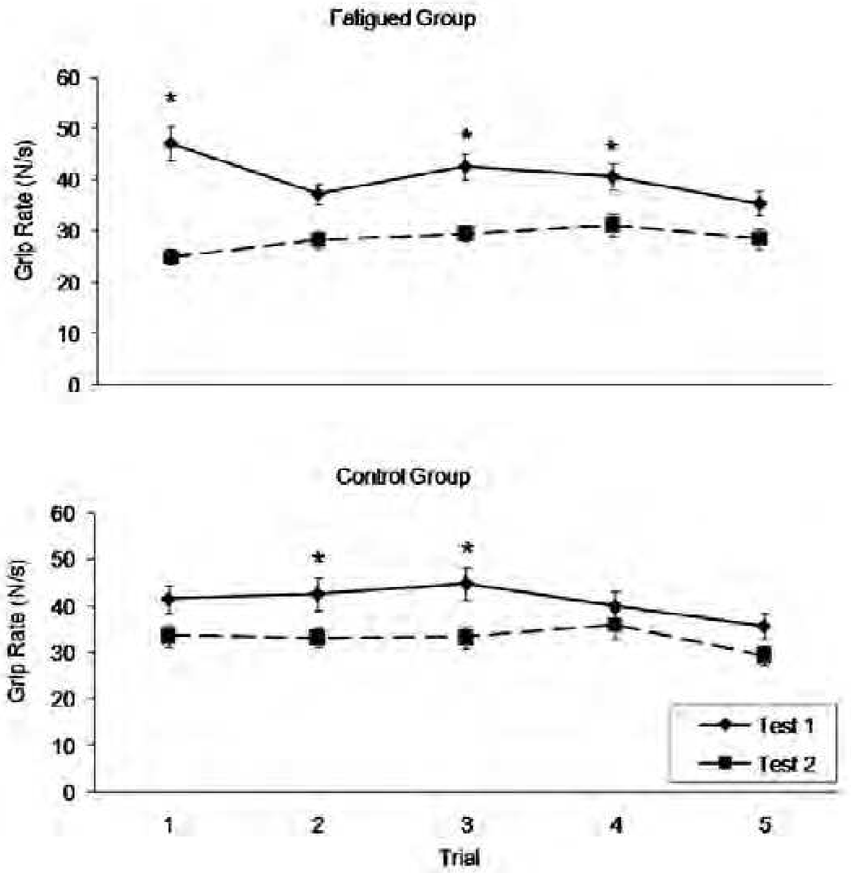

Fig. 7. Group by test by trial interactions for peak rate of grip force production in Study 2 (asterisks represent differences between corresponding trials of test 1 and test 2)

The three-way test by mass by trial interaction, F (16, 352) = 2.29, $p < .01$, revealed that for the first trial set of the first test, participants had difficulty scaling their peak grip rates as they produced the same peak grip rates for the 100 g, 200 g, 400 g, and 500 g objects and produced higher peak grip rates for the 300 g object (Fig. 8). However, on all subsequent trials, for both tests, participants were generally able to scale their peak grip rates according to object mass. In addition, overall lower peak grip rates were recorded over all trials and all levels of mass in test 2 (see Fig. 8).

The patterns discussed above and illustrated in the figures provide evidence that participants were successfully able to anticipate the masses of the objects they were lifting after the first trial. This was made possible by providing congruent visual size cues; i.e. the larger objects were heavier. Also, it is important to note the differences between the Fatigued and Control Groups in the group by test by trial interaction. In contrast to Study 1 where no group effects were shown, this study showed the fatiguing protocol to affect the way participants generated peak grip rates.

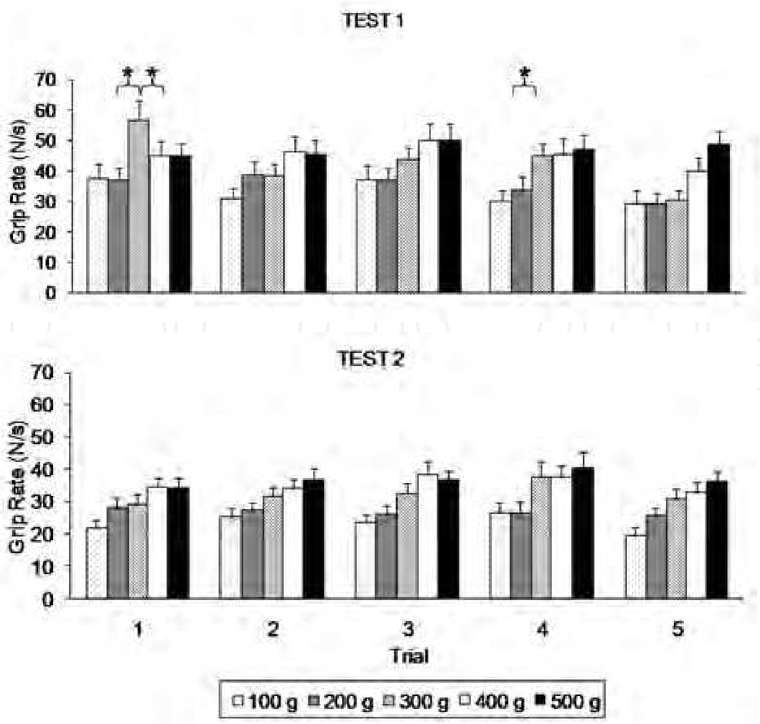

Fig. 8. Test by trial by mass interactions for peak rate of grip force production in Study 2 (asterisks signify differences between masses within each trial set)

Load force

The analysis of **peak load force** showed a two-way interaction of group by mass, F (4,88) = 3.39, $p < .05$, and a three-way interaction of test by mass by trial, F (16, 352) = 1.84, $p < .05$. The group by mass interaction showed that participants in the Fatigued Group produced less peak load force for the 400 g object (see Fig. 9). Although significance was only found between groups for the 400 g object, this finding provides some evidence that the Fatigued Group participants may have had more difficulty lifting the heavier objects. The three-way test by mass by trial interaction mimicked the previous findings with this interaction in that peak load forces stabilized after one exposure to all levels of mass. No differences in peak load forces were experienced in test 2 when compared to test 1 (see Fig. 10).

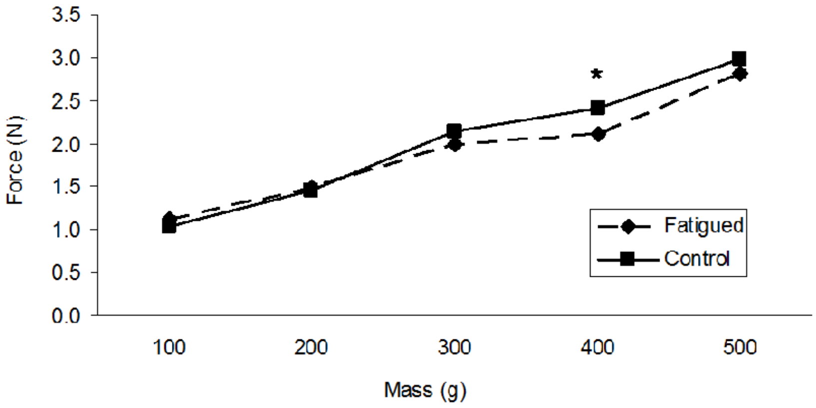

Fig. 9. Group by mass interactions for peak load force in Study 2 (significant differences in load force between groups at each level of mass are shown by an asterisk)

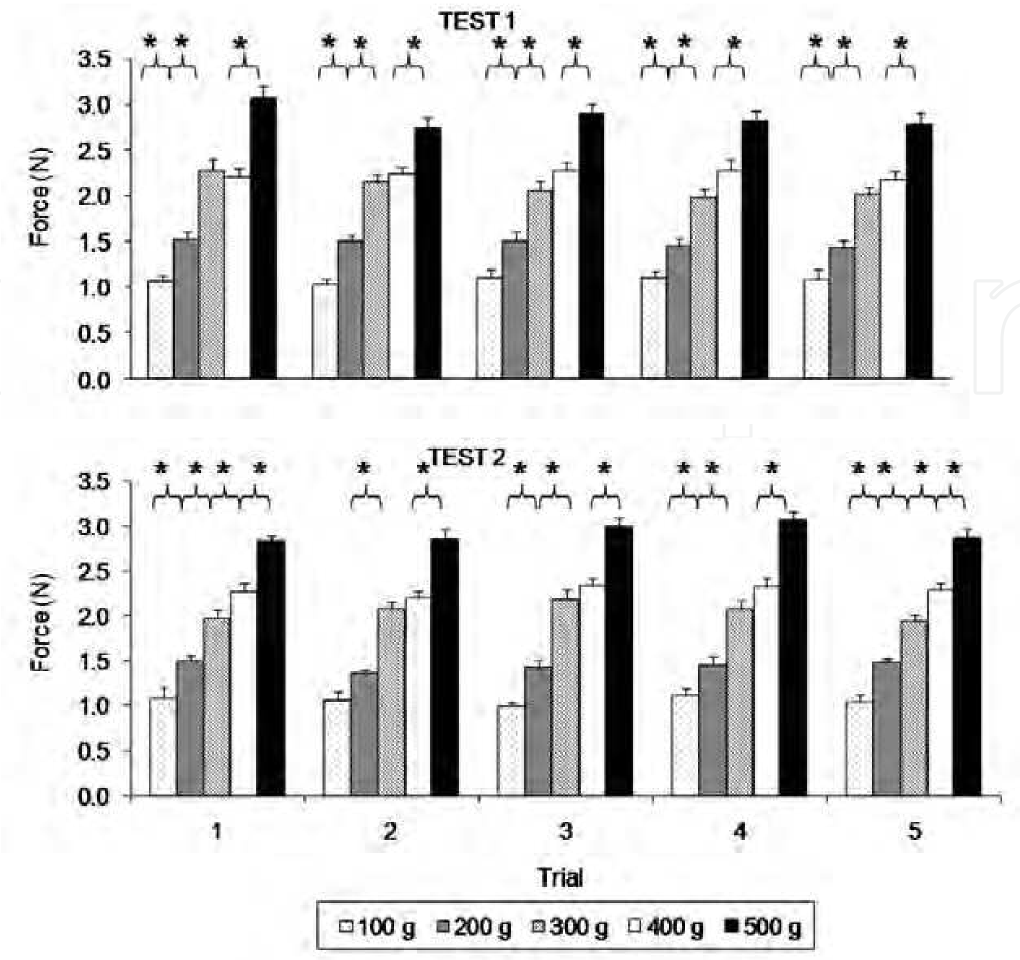

Fig. 10. Test by mass by trial interaction for peak load force in Study 2 (asterisks represent significant differences between masss within each trial set)

MVC data

The analysis of the maximum voluntary contraction data revealed that the Fatigued Group had a reduction in maximum force output immediately following fatiguing exercise but recovered to resting levels at the end of the second lifting session ($p < .05$). See Table 4 for means and standard errors.

Fatigued Group			
Time of MVC Test	**Mean (N)**	**SE**	
Prior to Fatiguing Protocol	46.08	2.28	*
Following the Fatiguing Protocol	38.17	1.80	
At the End of Test 2	41.83	2.58	
Control Group			
In Between Test 1 and Test 2	47.25	3.23	
At the End of Test 2	47.33	1.84	

Table 4. Means and standard errors for MVC data in Study 2 (significant differences have been marked by asterisks)

4. General Discussion

4.1 Summary of Results

Study 1 - Same Sized Objects
Regardless of the group, all participants in Study 1 appropriately scaled their grip forces to the mass of the lifted objects after a quick one trial adaptation. Therefore, after each object had been presented once, participants were able to scale their grip force outputs on subsequent trials. These findings are consistent with previous results by Johansson and Westling (1988) and Gordon et al. (1993). In the pre-fatigue test trials, peak grip rates were higher for the first and second trials and stabilized on subsequent trials whereas for the post-fatigue test, peak grip rate remained stable throughout all trials. Therefore, after a short familiarization period, participants were able to generate grip forces at a suitable rate for the mass of the lifted objects. All of these findings have been reported in previous literature (Gordon et al., 1993; Johansson & Westling, 1984; 1988). In addition, peak grip force outputs were generally lower over all levels of mass in each trial after the 20 minute break.

Peak load force showed that participants in the Fatigued Group produced lower peak load forces on trial one when compared to the Control Group for that same trial. In addition, it was found that the magnitudes of the peak load forces were linked to the masses of the objects in that the 500 g object produced the highest load force. This result is consistent with previous findings (Johansson & Westling, 1984; 1988).

Study 2 – Different Sized Objects
As in Study 1, participants appropriately scaled their peak grip forces to the mass of the lifted objects after the first exposure to all five masses. In addition, peak grip force was reduced immediately following the 20 minute break. Interestingly, after analyzing peak rate of grip force production it was found that participants in the Fatigued Group produced lower peak grip rates following the fatiguing protocol, but recovered by the fifth trial. The Control Group produced slightly lower peak grip rates following their 20 minute rest period; however, the differences were not as profound as those differences shown by the Fatigued Group. These findings suggest that the fatiguing protocol affected the participants' ability to achieve peak grip rate now that they could anticipate object mass. Also, participants in this study were able to scale their grip rates according to the size and mass of the presented objects. Therefore, participants appeared to be anticipating object mass as peak grip rate happens extremely early in the lift (Gordon et al., 1991a; b; c; Gordon et al., 1993; Johansson & Westling, 1984; 1988).

4.2 Revisiting the hypotheses

Study 1 - Same Sized Objects
Was there a reduction in overall force output following the fatiguing protocol? No. Participants in the Fatigued Group were not affected by the fatiguing protocol as no differences were found between test 1 and test 2 for peak grip force, peak rate of grip force generation or peak load force. The Fatigued Group and the Control Group behaved the same way for each of the abovementioned measures in this study.

Was there a reduction in the ability to control force output following fatiguing exercise? No. Following fatiguing exercise, participants appropriately scaled their peak grip and load forces to object mass. Therefore, it appears that participants in this study were able to detect mass differences and adjust their forces accordingly, regardless of their group assignment.

Study 2 - Different Sized Objects

Was there a reduction in overall force output but intact force scaling now that participants could anticipate object mass from visual cues? Or, could participants update their internal representations with their newly fatigued state and thus, compensate for their fatigued state? A reduction in overall force output was shown in this study as participants in the Fatigued Group produced less force during the static hold phase of the lift immediately following the fatiguing protocol.

Why did the fatiguing protocol affect each study differently?

The fatiguing protocol affected participants differently in each of the two studies. In Study 1 where the masses were visually identical, fatigue had no effect on motor control processes; however, in Study 2 where size cues were provided about object mass, significant fatiguing effects were produced. Why? To account for these differences, it is suggested that in the first study, movements were made using on-line feedback rather than anticipatory movement strategies like those used in Study 2. Thus, it appears that when movements are made on-line, any strength decreases that exist due to fatigue are detected and more force is generated. However, when movements are anticipated, the internal model does not take into account muscle fatigue and lower force output results. It is suggested that, in a fatigued state, participants who can anticipate movements use a feed-forward anticipatory strategy and are reluctant to switch to an on-line strategy once the feed-forward model has been selected and initiated.

As mentioned, there were no effects of fatigue for Study 1 and participants recovered from fatigue by the last trial of test 2 in Study 2. It is possible that, in Study 1, larger motor units were recruited to compensate for the effects of neuromuscular fatigue developed in the smaller motor units. Although this allowed for the same forces to be achieved, reduced fine motor control is associated with use of large motor units. Thus, fatiguing effects may have been found if the task involved an increased level of manual manipulation or finger dexterity.

In Study 2 there was no sign of force compensation directly following the fatiguing exercise. It could be argued that the gradual recovery observed over trials in this study was related to the adjustments made by the motor control system to switch from the smaller fatigued motor units to larger ones. Therefore, instead of recovery from fatigue, the adjustments made to achieve baseline levels of force by the end of Study 2 could be a result of compensatory strategies performed by the neuromuscular system to overcome the effects of fatigue. A better understanding of these physiological adjustments could be revealed using physiological stimulation techniques.

It can be disputed that the movements made in Study 1 were not purely on-line as participants were able to use vision to discern characteristics of the boxes they were lifting. Due to the strong influence of vision on human movement, it would be interesting to repeat the same experimental paradigm in the absence of vision. This could be achieved by eliminating vision entirely from Study 1, and by using haptic cues instead of visual cues about object size in Study 2. The influence of vision was quite evident in the present findings; however, would the same results be found if participants could only use their haptic system to anticipate object mass?

To our present understanding, no prior studies have incorporated a Control Group into this type of study design. For example, a study by Cote et al., (2002) suggested that when dealing with local neuromuscular fatigue, the dominant strategy is to maintain the output of the task, but to change the recruitment patterns of the muscles involved in producing the motor task. These researchers had participants saw through logs before and after fatiguing exercise. When differences were detected between the pre-test and post-test data, conclusions were drawn that the changes were due to fatigue. Could it be that participants had time to figure out how to better utilize their body configuration to more efficiently saw the log in the time they had between pre-test and post-test data collections? Adding a Control Group to this study would confirm that the findings were indeed due to fatigue.

Nature of fatiguing protocol

The task specific fatiguing exercise used in this experiment was meant to elicit local neuromuscular fatigue of the index finger and thumb. The fatiguing protocol was to be aggressive enough to elicit an increased level of low frequency fatigue as the effects of this type of fatigue last longer than those of high frequency fatigue (Edwards et al., 1977; Fuglevand et al., 1999; Lehman, 1997; Schwendner et al., 1995). The fatiguing protocol used in this experiment has been validated and used in studies evaluating the vastus lateralis musculature of the leg (Fowles et al., 2002). It would be beneficial to validate the protocol for use with a precision grasp, but because of the complicated anatomy of the human hand, it was difficult to isolate the muscles involved by means of superficial stimulation techniques. Thus, in the future it would be favorable to validate the fatiguing protocol for use specifically on the human hand using fine wire electrode stimulation techniques such as those used by Fuglevand et al. (1999). Adding this component to the present investigations would strengthen the argument that any differences found could indeed be attributed to the neuromuscular changes induced by the fatiguing exercise and not by some other intermediary factor.

Additionally, future studies that use a precision grasp lifting task should attempt to fatigue the wrist as well as the digits involved with the grasp. Incorporating fatigue at the wrist would make the fatiguing task and motor task more closely related as all of the musculature involved with a grasp to lift movement would now be fatigued.

5. Conclusion

Fatigue affected anticipatory and on-line motor control tasks differently. Only the anticipatory task was shown to be affected by fatigue as the motor control observations yielded differences after fatiguing exercise. Participants were unable to update their internal representations to take into account their newly fatigued state and were reluctant to switch to on-line strategies after initiating the lift.

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Advances in Haptics

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Haptic interfaces are divided into two main categories: force feedback and tactile. Force feedback interfaces are used to explore and modify remote/virtual objects in three physical dimensions in applications including computer-aided design, computer-assisted surgery, and computer-aided assembly. Tactile interfaces deal with surface properties such as roughness, smoothness, and temperature. Haptic research is intrinsically multi-disciplinary, incorporating computer science/engineering, control, robotics, psychophysics, and human motor control. By extending the scope of research in haptics, advances can be achieved in existing applications such as computer-aided design (CAD), tele-surgery, rehabilitation, scientific visualization, robot-assisted surgery, authentication, and graphical user interfaces (GUI), to name a few. Advances in Haptics presents a number of recent contributions to the field of haptics. Authors from around the world present the results of their research on various issues in the field of haptics.

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