Feasibility of Isokinetic Dynamometry During Functional Magnetic Resonance Imaging of Maximal Dorsiflexor Contractions.

By

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Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

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"Feasibility of Isokinetic Dynamometry During Functional Magnetic Resonance Imaging of Maximal Dorsiflexor Contractions."

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

Contents:

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Glossary of Terms

B_0 – The main magnetic field of a Magnetic Resonance Imaging (MRI) magnet.

Concentric contraction – Tension is produced by the muscle while the overall length of the muscle decreases.

Dorsiflexor muscles – The muscles located in the anterior lower leg. Contraction of the dorsiflexors moves the top of the foot towards the shin.

Eccentric contraction – Tension is produced by the muscle while the overall length of the muscle increases.

Ferromagnetic – Compounds containing unpaired electrons. These compounds are subject to the forces created by magnetic fields.

fMRI – Functional magnetic resonance imaging. Using MRI techniques to acquire images during brain function, based on the changes in oxygenation associated with alterations in local metabolic demand.

Gauss – A unit for the strength of a magnetic field. One Tesla is equal to 10 000 Gauss.

In vivo – Within the body.

In vitro – Within experimental conditions.

Isokinetic dynamometry – A method of measuring in vivo muscle torque while controlling the velocity and type of contraction.

Isometric contraction – Tension is produced by the muscle but the overall muscle length does not change.

Motor unit – The efferent nerve fiber and all of the muscle fibers it innervates.

MRI – Magnetic resonance imaging. A method of imaging human structure and function based on the magnetic properties of the proton.

NMR – Nuclear magnetic resonance. See MRI

Precession – The "wobble" of protons about the axis on which they rotate.

Radio frequency (RF) emissions – Emissions from electronic devices that can be picked up by the MRI scanner, causing artifacts in the images.

Z axis – The long axis oriented from the head to the toes of the subject when supine on the MRI bed.

T_1 relaxation – The release of energy from aligned protons to the environment. Also known as spin – lattice relaxation.

T_2 relaxation – The disappearance of transverse magnetization due to spin – spin energy transference. Also known as spin – spin relaxation.

Wave guide – A hole in the wall of an MRI room, connecting the console room to the magnet room. Radio frequency shielding is maintained by a copper tube inserted in the hole.

Abstract

Functional magnetic resonance imaging (fMRI) can be used to evaluate brain activation during cognitive, sensory, and simple motor tasks. To date, the available research regarding fMRI and motor tasks is based upon small muscle groups with little attention paid to muscle output variables such as relative load, speed of contraction or type of contraction. To improve the information gained from these types of studies, these important variables must be considered. Isokinetic dynamometry has long been the conventional method for the measurement of muscle force during neuromuscular studies, but due to the unique environment of magnetic resonance imaging (MRI), dynamometry has been limited in functional imaging studies. Strong magnetic interactions between the dynamometer and the magnet, and artifact in the images resulting from contraction induced head motion and radio frequency (RF) interference from the dynamometer provide technical challenges in the incorporation of these two technologies. In order to evaluate the validity of the modified set up of a Biodex for the MRI environment, we tested 15 subjects during maximal dorsiflexor muscle contractions at 30^0/sec and 60^0/sec on a modified dynamometer and an unmodified dynamometer. Average peak torque values from the modified and the unmodified apparatus were compared via paired t-tests to establish the validity of the modified apparatus. The results yielded no significant difference in average peak torque with the exception of the concentric trial at 60^0/sec, and the coefficient of variation ranged from 12.2% to 18.2%. Furthermore, we performed fMRI using a block design on 4 subjects during maximal concentric and

eccentric contractions. Although the challenges of magnetic interactions and RF interference were overcome, we were unable to reduce the motion artifact to an acceptable level in the MRI images during maximal contractions. Our head restraint system could not restrict head motion in the in/out direction to the extent necessary. Future efforts towards reducing the displacement of the head in this direction may allow for studies such as this to be done. Although this methodology may not be suitable for maximal muscle activation as it is, it may provide an excellent system for MRI research on issues such as muscle fatigue, spectroscopy and other research using MRI technology.

Background

The human neuromuscular system has been extensively studied. Studies have examined both the intrinsic properties of muscle, and the nervous system involvement in muscle contraction based on electromyography (EMG). However, little is known about the role of the central nervous system in gross motor tasks. The central mechanisms involved in motor tasks have been largely unexplored. To date, fMRI (functional magnetic resonance imaging), positron emission tomography, electroenchephalography (EEG) and other modalities have provided a cursory look at central mechanisms in motor tasks, often employing simplistic movements such as finger tapping. Although informative, many parameters were left unspecified in these studies.

Liu *et al.* (2002) developed a method of measuring muscle output function on a superficial level using a force transducer and a hand grip device. This device allowed the simultaneous recording of muscle force output, EMG, and fMRI. Although useful, this system did not consider contractions other than isometric, or issues pertaining to velocity of movement. Using a variant of this system, Dai *et al.* (2001), examined brain activation during isometric contractions of varying loads. This study showed that brain activation varied with increases in muscle force. Again, only isometric contractions were performed and no consideration was given to other variables such as speed of contraction. Furthermore, muscle groups aside from finger muscles could not be examined by this method. Using EEG Fang *et al.* (2001), examined movement related cortical potential differences in concentric and eccentric

contractions. This study addressed differences resulting from contraction type, but employed a rudimentary loading mechanism. Subjects were required to perform eccentric and concentric contractions using a pulley and resistance of 10% of the subject's body weight. As with the previous study, this system failed to consider several important factors including velocity of contraction, and the changes in resistance throughout the range of motion resulting from the pulley mechanism. Due to instrument limitations, research to date using fMRI and other imaging modalities has been forced to compromise on their control of muscle output variables. To gain more insight into neuromuscular function, methods of controlling these variables must be combined with functional imaging techniques.

In recent years fMRI has often been the modality of choice for investigating brain function. The ability to obtain high spatial resolution with fMRI has provided many useful insights into brain function, and marks it as one of the leading tools in these types of studies. One of the major limitations of using fMRI to study motor function is the incompatibility of most electronic devices with the MR environment.

Isokinetic dynamometers are heavy, ferromagnetic instruments that produce radio frequency (RF) emissions making them less than ideal for studies using magnetic resonance (MR). The purpose of this project was twofold. Technical modifications were made to a Biodex dynamometer allowing it to be operated in close proximity to an MRI machine. These modifications were tested to ensure that the validity of the torque measurements of the dynamometer was maintained, and that it remained an effective tool for studying in vivo neuromuscular function. The dynamometer was then used in conjunction with fMRI to determine if functional

imaging can be performed using an isokinetic dynamometer to measure maximal dynamic contractions, adding a level of sophistication to motor fMRI studies. To do this, functional brain activation of maximal eccentric versus concentric dorsiflexor muscle contractions were compared.

Hypotheses

1. We predicted that the torque values obtained using the modified dynamometer would not be significantly different than those obtained using the unmodified dynamometer.
2. We also predicted that the technical issues surrounding the use of an isokinetic dynamometer in the MR environment could be over come and functional activation maps could be generated while specifying loading parameters using a Biodex System 3 dynamometer.

Introduction

Relevance of lengthening versus shortening contractions

Muscle can generate force during shortening, lengthening or static contractions. In vitro, maximal concentric force development is less than tension developed during lengthening or static contractions and eccentric moments are greater than isometric (Edman, 1988, Flitney and Hirst, 1978, Lombardi and Piazzesi, 1990).

Consistent with in vitro findings, maximal voluntary static contractions generate greater force than concentric, and eccentric contractions yield a significantly higher force output than isometric (Bigland and Lippold, 1954, Doss and Karpovich, 1965, Dudley *et al*, 1990).

During maximal isometric and concentric contractions a superimposed electrical stimulation typically fails to generate a greater force output (Allen *et al*, 1995, Westing *et al*, 1990). This indicates an activation of most or all of the available motor units during voluntary concentric movements, implicating cross sectional area as the primary contributor to increased force output. An increase in available fibers corresponds to an increase in force production, and conversely force production is limited strictly by the amount of muscle available. However, despite using all of the available muscle during maximal concentric muscle contractions, the body is still able to generate higher torque values during voluntary lengthening contractions (Enoka, 1996). This is the result of an intrinsic property of lengthening contractions to generate greater amounts of force per fiber than shortening contractions (Gulch *et al,* 1991, Lombardi and Piazzesi, 1990). However, when exogenous stimulation is applied during maximal voluntary eccentric contractions force production increases (Westing *et al*, 1990). This indicates a reserve of muscle fibers present during these types of movements. Not all muscle fibers are being recruited despite maximal effort.

Using an imposed stretch during isometric contractions, supra – maximal in vivo eccentric moments have been demonstrated (Webber and Kriellaars, 1997). This demonstrated that although a maximal voluntary contraction is performed, increases in force output could be elicited by administering an unplanned stretch in the muscle.

This unexpected imposed stretch provided a means of assessing the potential force generating capacity in the muscle by creating an artificial eccentric contraction. Because the imposed stretch was performed during a maximal voluntary isometric contraction the involved muscle mass was near equivalent to the available muscle. As a result the moment generated by the contractile properties of the muscle was summed with the moment generated by the elastic properties of the muscle. The torque produced following the quick stretch was closer in magnitude to in vitro eccentric force development, indicating that although the in vivo muscle has the ability to generate higher torque values it is somehow down regulated. The mechanism behind the discrepancy between concentric and eccentric fiber recruitment during maximal voluntary contractions is unknown. Inhibition in the central nervous system may act as a physiological safety mechanism preventing the activation of excessive muscle fibers, avoiding soft tissue damage (Hortobagyi and Katch, 1990, Westing and Seger, 1989, Westing *et al,* 1988).

Functional Imaging

MRI Basics

Magnetic resonance imaging is based upon the interaction between magnetically susceptible nuclei and a strong external magnetic field (B_o). Hydrogen nuclei are of particular interest due to their abundance in human tissues. When placed in a magnetic field, protons align in one of two fashions: parallel or anti –

parallel (Woodward and Freimarck, 1995). Due to the higher energy state of the anti – parallel orientation, slightly less protons are aligned anti – parallel to B_o. This imbalance in alignment creates a longitudinal magnetization, and it is this net magnetization that is detected during NMR (Oldendorf and Oldendorf, 1991).

During a relaxed state the net magnetization is aligned with B_o. When a radio frequency pulse is applied at the Larmor frequency the protons flip, producing a net magnetization at an angle to B_o. The Larmor frequency is determined by the strength of B_o and a constant known as the gyromagnetic ratio, that is a property of the nucleus involved (Woodward and Freimarck, 1995). This net magnetization can be described by its longitudinal and transverse components. The degree to which the protons flip, and hence the amount of transverse magnetization created, is the result of the strength of the RF pulse that is applied (Woodward and Freimarck, 1995). For example, a 90^0 pulse eliminates the longitudinal magnetization and the net magnetization is composed only of the transverse component. When the RF pulse is removed, the protons begin to realign with B_o. This relaxation can be described based on the components of the net magnetization. The disappearance of transverse magnetization is called T2 relaxation and is the result of spin – spin transference of energy. T2 relaxation is the result of the dephasing of the protons following the removal of the RF pulse (Woodward and Freimarck, 1995). Spin lattice or T1 relaxation also occurs and is the result of energy released to the environment and the return to B_o. Tissue contrast is obtained based on differences in relaxation time. For example, T1 weighted images yield images where fat appears bright and water

appears dark (Woodward and Freimarck, 1995). The opposite is true for T2 weighted images.

BOLD Imaging

The signal changes during BOLD imaging are the result of the paramagnetic characteristics of deoxyhemoblobin (Kim and Ugurbil, 1997). Because most other body compounds are diamagnetic, the concentration of deoxyhemoglobin can affect the T2* signal. As a result, the oxygenation state of blood found in the brain vasculature strongly influences the MR signal in T2 and T2* weighted images (Kwong *et al*, 1992, Ogawa and Lee, 1990). Proton spin phase coherence is lost as a result of T2 and local field inhomogeneities and is a measure of the presence of deoxyhemoglobin (Ogawa and Lee, 1990). In BOLD imaging T2* is the source of image contrast. Changes in local metabolic demand create changes in the oxyhemoglobin to deoxyhemoglobin ratio which in turn alter the local magnetic field susceptibility (T2*) (Ogawa and Lee, 1990). It is important to note that these changes reflect oxygenation changes and not perfusion or blood flow alterations. Although local blood flow increases with neural activity, the relative oxygen extraction decreases (Fox *et al*, 1988). This over – compensation in oxygen delivery decreases the deoxyhemoglobin concentration in the venous vasculature with increasing metabolic activity (Fox and Raichle, 1986, Fox *et al,* 1988). As a result, cognitive perturbations lead to a decrease in deoxyhemoglobin and an increased T2* signal intensity during BOLD imaging.

Typical fMRI studies employ an epoch or block design. During these studies, the time course is divided into segments representing active and rest periods. During the active periods some form of stimulus is presented, or a cognitive or motor task is performed by the subject. The BOLD technique is then used to quantify the resting signal intensity which is then subtracted from the active intensity. Activation maps are then generated based on the T2* signal increases in specific brain regions during the active periods, modulated by the oxyhemoglobin to deoxyhemoglobin ratio (Ogawa, 1990).

Motion artifact in MRI

In the conventional multi slice spin echo imaging sequence, each line of k-space is acquired individually separated by a period of time, time to repeat (TR). Motion during these types of sequences generally occurs during the TR, as it represents a greater percentage of the total imaging time than the actual acquisition (Larkman, D. *et al*, 2004). The frequency encoding takes on the order of milliseconds and therefore motion during this time is much less problematic. It is for this reason that ghosting and blurring are common motion problems with multi-shot imaging techniques. Position is determined by phase, and as a result motion during the TR has profound effects on position. The acquisition of several lines of data is repeated one after the other, separated by a user defined repetition time. The sequential acquisition of these lines proceeds in what is known as the phase, or y, direction. If motion is random, irregular intensity mismatches occur in the phase direction of the image due

to the movement of the subject during the time that separates the acquisition of each subsequent line of data. These random errors cause blurring in the image. If the motion is cyclic, the intensity errors in the phase direction create ghostlike occurrences in the images (Contsable, 2003) due to the regular repeating occurrence of the motion. For fast imaging sequences such as single shot spin echo and echo planar imaging, resolution is sacrificed for short imaging times (Provost *et al*, 1986). In this form of imaging one excitation is followed by the acquisition of several lines of k-space (k-space is the frequency representation of the data prior to the mathematical conversion to its spatial image). There is less opportunity for motion to occur between lines of k-space. As a result, phase mismapping is reduced, and ghosting and blurring become less of a problem. However, with these fast sequences motion between the time points for a given slice can be problematic. Following the excitation pulse, multiple lines of k-space (sometimes all) are filled before the TR. The acquisition is performed so quickly that there is little time for motion to occur between lines of k-space. After the acquisition of each slice (all lines of k-space) there is a period of time before the next acquisition and it is during this time that motion can occur. Incorrect reading of the slice from one time to the next can result. Instead of phase mismapping, this type of motion can create misregistration errors in the images, and for functional studies artifactual brain activation (Larkman *et al*, 2004). As a result, the primary focus during this study was on the manual reduction of motion artifact, and the employment of commercially available registration algorithms to maintain image quality during the motor task.

Isokinetic Dynamometry

When investigating human neuromuscular function several factors must be considered. Perhaps the most significant factor is the type of muscle contraction performed. Lengthening, shortening, and static contractions are possible and each contraction type is not equal in regards to the motor units recruited, activation strategy employed, elastic contribution to torque generation, and maximal force production (Nardone *et al*, 1989, Flitney and Hirst, 1978, Gulch *et al*, 1991, Doss and Karpovich, 1965, Enoka, 1995, 1996). Clearly, this means that during studies of in vivo human neuromuscular performance the type of contraction must be considered. Among other parameters to be considered are range of motion and velocity of contraction. Isokinetic dynamometers have emerged as the traditional method for controlling these types of issues. Using a dynamometer, the type of contraction can be dictated, allowing investigations to focus on one type of movement. Furthermore, for maximal contractions, torque values obtained using an isokinetic dynamometer are maximal throughout the entire range of motion. For isotonic movements (such as those produced using a dumbbell) the relative torque produced will be variable, based on the resistance present at that point in the range of motion. The dynamometer provides an accommodating resistance, allowing maximal torque production throughout the range of motion. In addition, this range of motion can be accurately maintained, and set based on anatomical landmarks. This ensures similar movement across subjects and more accurate comparisons can be made. Velocity of contraction can also be controlled with the use of a dynamometer. The potential force output

during a muscle contraction is based in part on the velocity at which the contraction is performed (Westing *et al*, 1990, Hortobagyi and Katch, 1990). Therefore, physiological comparisons can only be made if velocity is carefully controlled. Simpler methods of imposing resistance (dumbbells, sandbags, etc.) during neuromuscular studies cannot control the velocity of the movements, therefore making comparisons across trials difficult. Isokinetic dynamometers have emerged as the gold standard for *in vivo* neuromuscular studies, and have been well established as reliable and valid (Taylor *et al*, 1991). Furthermore, studies focusing on the ankle musculature have also demonstrated the reliability of these instruments (Holmbäck *et al*, 1999, Holmbäck *et al*, 2001).

Methodology

Three major constraints have precluded the use of isokinetic dynamometers during fMRI. First, strong magnetic interactions between the magnet and the dynamometer can create potentially hazardous conditions. As a result, robust mechanical modifications to the standard dynamometer must be made for use in the magnetic environment. Second, the dynamometer is a major source of RF interference during image acquisition, and third, substantial motion artifacts may result from head movement as a result of the muscle contractions. The majority of the methodology of this study was directed towards overcoming these three

constraints. The various steps towards the final modifcations can be seen in Appendix K.

Equipment Development

Mechanical considerations

The Biodex dynamometer underwent several mechanical modifications before the final setup was established. The factory setup was unsuitable for use in the MR environment for several reasons. With the subject positioned in the bore of the magnet, the MR patient bed prevented the use of the conventional ankle attachment. With the subject's lower limb hanging off the edge of the Biodex chair during normal operation, the manufacturer's ankle attachment was designed so that the free hanging foot would rest upon it. When in the magnet, the foot is positioned approximately in the middle of the bed, making it impossible to mate the ankle attachment with the foot. Furthermore, the position of the foot is variable due to the height of the subject. The head must always be positioned in the centre of the magnet bore during image acquisition, and as a result the foot of a taller subject rests in a different position on the MRI bed than that of a shorter subject. To accommodate this, the ankle unit needed to be capable of adjustment along the z axis (movement into and out of the magnet bore) to allow for correct placement of the subject in the bore.

The second complication was that the dynamometer is ferromagnetic and must be kept beyond the 5 Gauss line for safety reasons. At 5 Gauss, the magnetic field is

sufficiently weak that the risk associated with introducing a large magnetic instrument into the MRI room is minimal. Maintaining the dynamometer beyond the 5 Gauss line creates a distance between the subject's foot and the dynamometer spindle of approximately 10 feet depending on the height of the individual being tested. Bridging this gap represented another technical challenge, and further modifications were necessary.

To overcome these issues, a rigid connection between the dynamometer spindle and the ankle unit was used. It was critical that the tubing be both light and rigid. Any bowing of the tube during contractions would result in an inefficient transfer of torque from the modified ankle unit to the dynamometer. The force produced by the subject during the muscle contractions would be, in part, absorbed in the flex of the connecting tube, leading to an under prediction of the force generated. Although this error would be systematic (although not linear), it was preferable to minimize it as much as possible. Square aluminum tubing was used, and to accommodate the variable length required, several holes were drilled at the end closest to the dynamometer. The holes allowed the tubing to be connected to the dynamometer at varying positions, allowing a shorter or longer connection distance to be used. The modified set up allowed for a range of heights ranging from approximately 1.55m to 1.90m.

To replace the factory ankle unit, a non-ferromagnetic unit was crafted. The modified ankle unit was constructed of wood with brass screws (brass is not ferromagnetic) to allow it to be used in close proximity to the magnet bore. A generic shoe was bolted into the ankle unit with Velcro straps to secure the foot. This

accommodated feet of varying sizes. The ankle unit was then fastened to the magnet bed with custom made wooden clamps (see Figure 1).

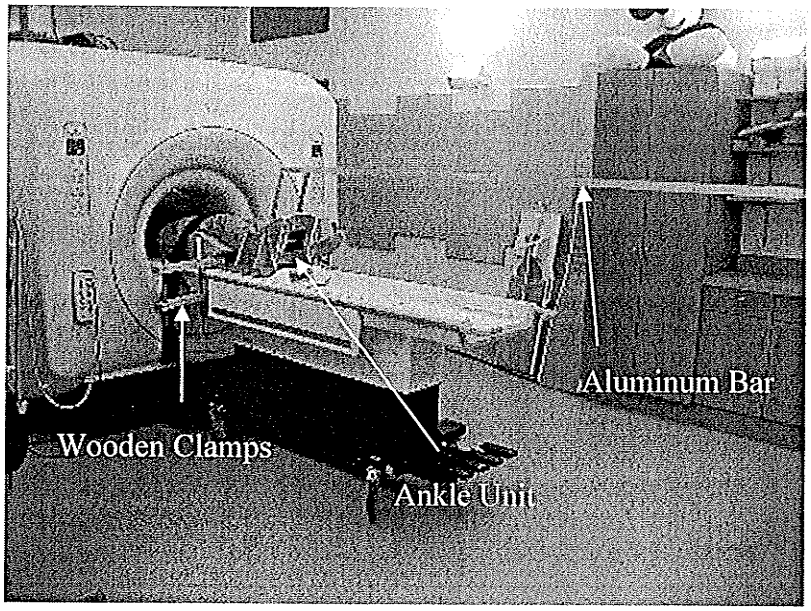


Figure 1. Mechanical linkage between ankle unit and dynamometer

Radio Frequency Interference

Magnetic resonance is based on the radio frequency signal emitted by protons as they relax following an excitation pulse. Operating an electronic device in the MR environment has the potential to induce radio frequency (RF) artifact during image acquisition. The MRI scanner can pick up any source of radio frequency emissions in the magnet room expressing it as artifact in the images. There are several possible sources of interference from the dynamometer: the signal and power cables, the

personal computer (PC), and the motor component. Each of these has an electronic component requiring RF shielding to function in the magnet room (see Appendix J for details on the testing process for RF leakage).

The simplest component to shield was the computer. The cables were long enough to position the computer and controls outside the magnet room, using the room's shielding to eliminate RF interference from this source. The power and signal cables were fed through the wave guide in the wall, connecting the motor and the computer. The wave guide is a small breach in the MRI room shielding that allows power cables to run from the console room to the magnet room. The hole is made of copper tube inserted through the wall. Radio frequency emissions are normally prevented from traveling through the tube based on the wavelength of the RF and the length of the wave guide. However, this system did not provide enough attenuation, and further measures were required to shield the cables. A hollow copper conduit was constructed to connect the wave guide to the motor component of the dynamometer. This completely covered the length of the cables that were in the magnet room, beginning at the wave guide.

The most complicated component to shield was the motor complex. It required flexible shielding to allow easy set up and disassembly and a hole in the shielding for the spindle to protrude. Spindle exposure was required to connect to the Biodex arm that was in turn attached to the connecting rod projecting towards the bore. Furthermore, it must rotate within the hole in the shielding, while electrical contact between the spindle and the shielding was maintained. Also, electrical contact between the Biodex arm and the connecting rod must be avoided to prevent

the projection of RF emissions into the bore. At the bottom of the motor complex a copper sheet was bolted under the motor post. This provided a conductive anchor for the remaining shielding components. A double layer bag was tailored from conductive fabric and covered the motor complex. The bag covered approximately one third of the motor and post. At the top, a hole in the fabric allowed the spindle to protrude. An extension of the bag covered the Biodex arm and allowed the spindle to rotate without compromising the shielding. The bottom two thirds of the motor and post were shielded by a custom built wooden box, covered in copper sheeting. The net effect was a complete conductive covering of the motor complex, with electrical isolation from the connecting rod. This covering was electrically connected to the cable shielding which was attached to the wave guide. This produced a copper extension of the RF shielding of the magnet room, beginning at the wave guide and extending around the entire Biodex assembly (see Figure 2).

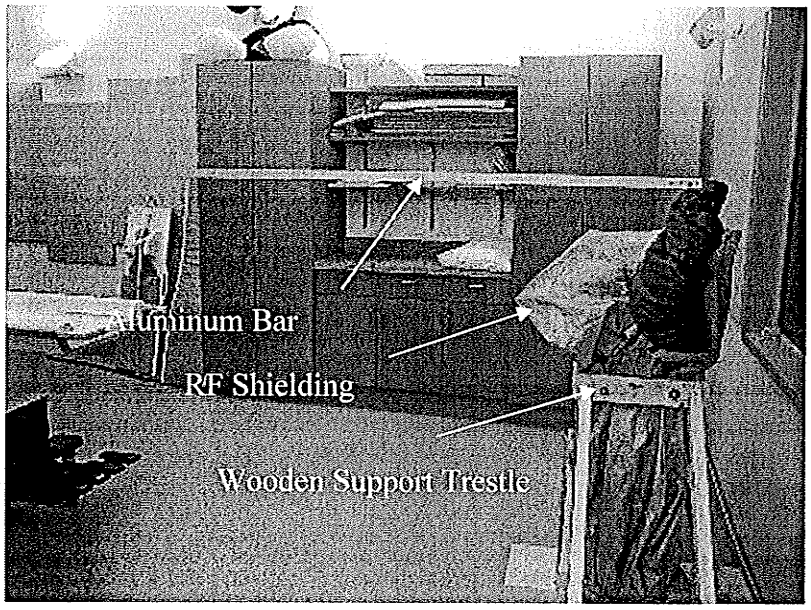


Figure 2. Dynamometer with radio frequency shielding and support trestle.

Motion Artifact

Perhaps the most daunting of all the technical challenges was reducing motion artifact. Head motion is a major consideration in fMRI. Movement on the order of millimeters has the potential to induce artifact, and spatial mislocalization in the images. A novel head restraint system was constructed to address this issue. During maximal dorsiflexor contractions the primary movement of concern was thought to be z axis displacement (movement in and out of the magnet bore). Displacement in the x (shifting left or right) and in the y (moving the head up off the bed and back again) were much less severe during preliminary scans. Rotation was a minor concern in all planes. Conventional head restraint systems such as the bite bar were ethically limited and their efficacy was questionable for such extreme motion conditions. The restraint system must reduce x, y, z axis motion, be easily evacuated, be comfortable physically and emotionally, fit inside the head coil, and be magnet compatible.

To accomplish this, a cylinder constructed of plastic and fiberglass was designed. The basic design involved a padded head plate at one end and an anatomically designed chin bar at the other. The head plate could be tightened via a threaded post, applying pressure to the top of the subject's head in a graduated fashion. The chin bar was fixed, providing a stable section against which the head was secured. The subject's head was stabilized in the z plane by the padded plate and the chin bar, whereas rotation was prevented by two telescoping pads secured against the head at right angles to the z axis. During the muscle contractions, the head remained immobile due to the pressure of the chin bar. As the subject pulled against the dynamometer the chin is secured against the bar, reducing the head movement out

of the magnet bore. During recovery or movement resulting from plantar flexion the force is transmitted to the head plate, reducing head movement into the magnet bore. For concentric contractions movement in the plantar flexion direction is passive, and therefore the forces into the magnet bore are considerably less than out of the magnet bore. Even during eccentric contractions the force was moving the subject out of the magnet bore, and therefore the stabilization was focused on resisting this movement.

To increase comfort the chin bar is equipped with adjustable pads. The pressure from the chin bar is applied through two pads running along the border of the mandible. The adjustable pads allow for a comfortable fit regardless of mandible size and shape. Furthermore, a longer chin pad was chosen to increase comfort by dispersing the pressure from the chin bar evenly across the mandible. Through two simple latches the subject could be evacuated quickly by disengaging the chin bar from the cylinder. This enabled the subject to slide out of the cylinder unimpeded. The portion of the cylinder above the subject's face was open, allowing adequate ventilation and therefore giving it a more open feeling in the small space of the magnet bore (see Figure 3).

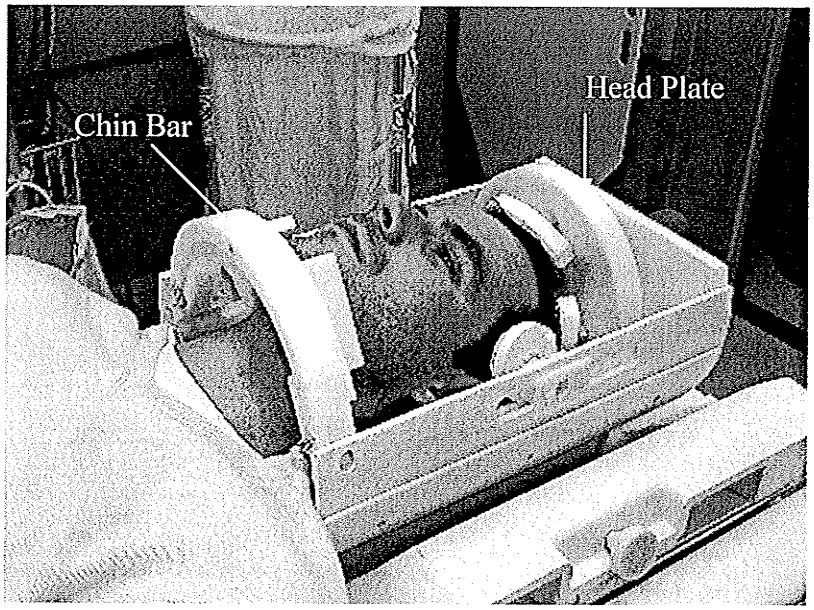


Figure 3. Head Immobilization Device.

Protocol A – Validity of the Modified Dynamometer

Purpose

The modifications made to the Biodex dynamometer were designed to allow it to be operated in the MR environment. These modifications involved making significant changes to the method of transference of torque from the subject to the dynamometer. As a result, the validity of the modified dynamometer apparatus needed to be established prior to using it as a testing tool. The modified version was compared to an unmodified dynamometer, using the protocol that was employed

during functional imaging, to demonstrate the continued validity of the instrument despite the modifications.

Subjects

Fifteen subjects, both male and female, ranging in age from 20 – 40 years were recruited (n = 15). All subjects were active but not highly trained, and were excluded if taking any medication that may affect neuromuscular function, or if they had or have had, within one year, an injury affecting the tested limb. Each subject was required to answer a Physical Activity Readiness Questionnaire (Appendix D). In addition, the inclusion criteria for the functional imaging protocol were met, with the exception of the medical examination (see protocol B). Informed consent was provided prior to testing as per approval from the University of Manitoba Education/Nursing Ethics Review Board (Appendix A).

Protocol

The protocol consisted of several tests. Both concentric and eccentric torque production were measured using the modified dynamometer setup and the factory dynamometer setup. Velocity order (30^0/sec and 60^0/sec) was evenly distributed among the subjects, as was the order of the type of contraction performed (concentric and eccentric). Subjects were instructed to perform all contractions maximally.

Modified Testing

The subject were supine, with the right foot strapped into the modified ankle attachment. Two Velcro straps secured the foot, one proximal on the dorsal surface of the foot and the other more distal. The knee was bent at approximately 40 degrees (measured by a goniometer), and supported from beneath by a wooden pyramid to prevent extension. A four inch wide Velcro strap fastened around the leg and table assisted with stabilization.

The geometry of the modified setup was carefully considered to ensure efficient transference of torque from the subject to the dynamometer. The height of the dynamometer spindle and length of the movement arm were carefully adjusted to ensure an equal angle between the connecting rod and the ankle unit at one end and the connecting rod and the Biodex arm at the other end (see Diagram 1). If the angle between the rod and ankle unit arm was not equal to the angle between the rod and Biodex arm then there would have been an inefficient transfer of torque from the subject to the dynamometer. More specifically, if these angles were not equal an under prediction of torque would have occurred because some of the force would be transmitted through the long axis of the Biodex arm, and not measured as torque by the dynamometer. To ensure these angles were equivalent a level was used. The connecting rod was adjusted to horizontal, and the Biodex arm and the ankle unit arm were adjusted to vertical.

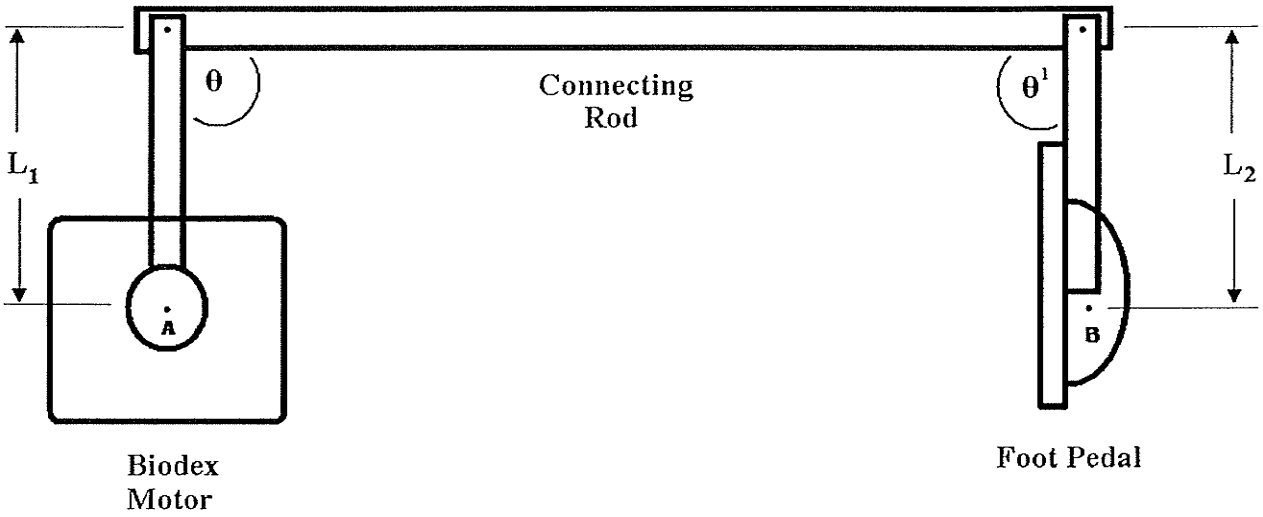


Diagram 1. Schematic of the modified dynamometer setup. To ensure proper transference of torque from the subject to the dynamometer the mechanical setup was carefully controlled. A summary of the angles and positions is as follows.

$$L_1 = L_2$$

$$\theta = \theta^1$$

The points A and B represent the axis of rotation for the dynamometer spindle and the ankle unit respectively.

Due to the limitations of using equipment in the MR suite, the subjects did not perform a general warm up apart from the familiarization trials. The familiarization trials consisted of 2 submaximal bouts per type of contraction. Each bout lasted 12 seconds and included 3 muscle contractions. Between each 12 second bout, a 12 second rest interval was given. During the familiarization trials, only one velocity was used. However, two trials were performed, once for each contraction type. This design matched the MR imaging paradigm (see Diagram 2).

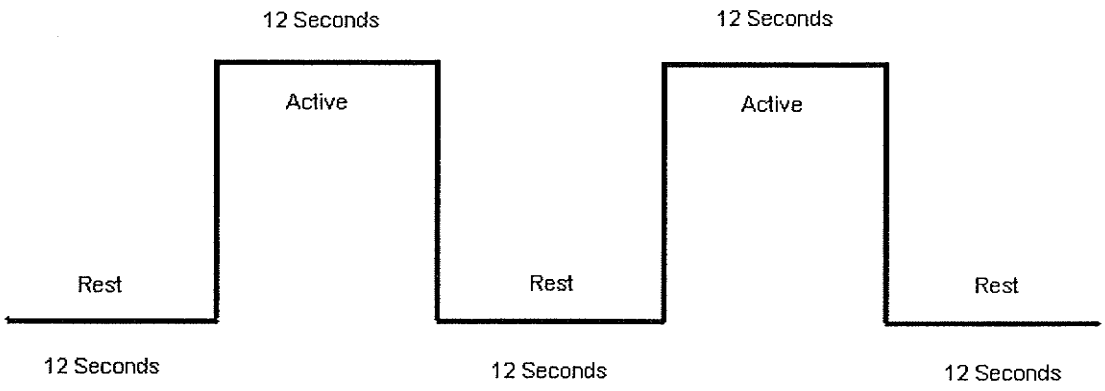


Diagram 2. The Imaging paradigm. The overall scan time is 63 seconds with 2, 12 second active periods and 3, 12 second rest periods. In the isokinetic testing the first and the last rest period are inconsequential.

The ankle range of motion was set at 40 degrees. The zero degree mark was denoted when the tibia and fibula were at right angles to the long axis of the foot. Ten degrees of dorsiflexion and 30 degrees of plantar flexion were performed from this reference point.

Each bout was performed in the passive mode of the Biodex. For the concentric portion the subject pulled the foot towards the tibia, and relaxed during the movement in the plantar flexion direction. For the eccentric contractions the subject was instructed to resist during the plantar flexion movement and relax during dorsiflexion. During both movements, the dorsiflexor muscle group was utilized. Following the familiarization trials a 2 minute rest time was given before the testing began. Both contraction types were tested at 30 degrees per second and 60 degrees per second. Half of the subjects began with 30 degrees per second and half at 60 degrees per second, and the contraction order was equally distributed among subjects. Each subject performed two maximal bouts lasting 12 seconds (3 contractions), separated by a 12 second rest period, for the concentric movements at 30^0/sec. This was also done at 60^0/sec, and again for the eccentric contractions at the two velocities. Each trial was separated by a 2 minute rest interval.

The angular velocity of 30 degrees per second represented the optimal balance between limiting muscle fatigue and reducing the noise in the torque data as a result of the mechanical modifications. In preliminary testing the torque values became increasingly noisy as the velocity of contraction increased. Therefore this represented

a velocity that minimized the artifact but did not require the subjects to maintain a contracted state for an extended period of time, inducing large amounts of muscle fatigue. In addition, 30 degrees per second is a typical velocity cited in the relevant research (Holmbäck *et al,* 1999, Holmbäck *et al,* 2001, Connelly and Vandervoort, 2000), making comparisons with normative data easier. Sixty degrees per second was chosen for comparative purposes, and it was expected that 60^0/sec would lead to increased noise in the data sets.

Factory Testing

The testing performed on the factory setup proceeded in a similar fashion to the modified protocol. The subjects were given the same familiarization bouts, lasting 63 seconds. Following this the testing trial commenced. Again, concentric and eccentric torque was measured at 30^0/sec and 60^0/sec. The knee angle was maintained at 40 degrees. The primary difference in protocols was alignment of the lateral malleolus to the axis of rotation of the dynamometer. In the modified protocol this was impractical because the shoe in the ankle unit was non-adjustable, whereas with the factory setup this was possible.

Data Analysis

Average peak torque for the modified versus unmodified tests at 30 degrees per second was compared by dependent t – tests, as were the results for the 60 degrees per second trials.

In addition, Bland and Altman plots were constructed to visually assess the agreement between the two measures and coefficient of variation for the difference in means was calculated for each contraction type at the two velocities.

Protocol B – Feasibility of Isokinetic Dynamometry in fMRI

Purpose

The feasibility of integrating isokinetic dynamometry with fMRI was examined. Subjects were required to perform a series of concentric and eccentric muscle contractions during which functional images were acquired. The purpose of this study was to demonstrate that the modifications made to the isokinetic dynamometer and the use of the head restraint system enabled the use of the dynamometer during fMRI. The primary objective was to generate reasonable activation maps of the region of interest for each contraction type. Should the equipment modifications prove successful, comparisons between the extent and intensity of the activation would have been made between the contraction types.

Subjects

The subjects recruited for this protocol met several exclusion criteria (Appendix C). All subjects were free from metal implants, pacemakers, tattoos, or extensive metallic dental work. Pregnant women were ineligible, as were persons with anxiety disorders. In order to ensure the participants met these requirements they passed a medical screening by a physician. In addition the exclusion criteria for

protocol A were also met. The subjects were free from injury to the tested leg, neuromuscular pathology, and were active but not highly trained. The subjects were also familiar with performing muscle contractions using an isokinetic dynamometer. Four male and female subjects participated in the protocol (n = 4). Ethics approval was obtained from the Institute for Biodiagnostics (IBD) Human Studies Ethics Review Board and all subjects again provided written informed consent (Appendix B). Subjects were paid $25.00 for participation in this portion of the study, according to standard practice at IBD.

Protocol

All images were acquired using a General Electric (Waukesha, WI) 1.5T Signa LX MR scanner equipped with Echospeed actively – shielded gradient coils (22mT/M, 120 T/m/s). A single shot gradient recalled EPI sequence with a TE of 60ms and TR of 1500ms was used. Twelve slices, 8mm thick, with a 24cm field of view and resolution of 64x64 were acquired, totaling 42 volumes. To help reduce image artifact resulting from z axis displacement the slice orientation was sagittal. As a result, z axis motion was in plane and could be corrected for more easily using commercially available statistical packages.

A block design was used with 12 second periods and a total scan time of 63 seconds. The block design was constructed as off, on, off, on, off and therefore consisted of three rest segments and 2 active segments. The subject was instructed to perform the muscle contractions during the on phase, and to relax during the off phase.

The subject was placed in the head restraint system and positioned in the magnet bore. Following this, the right foot was secured in the modified ankle unit and the knee angle was adjusted to 40 degrees. The upper leg was strapped to the magnet bed with a Velcro strap to help reduce body movement and to maintain the knee angle of 40 degrees.

Two bouts of maximal concentric and eccentric contractions were performed, lasting 12 seconds each (each consisting of 3 contractions). These contractions were done at 30 degrees per second to minimize torque artifact, and muscle fatigue. Subjects were instructed to perform the contractions maximally but to minimize body movement as much as possible. Each subject performed both concentric and eccentric movements at 30 degrees per second, and the contraction order was divided equally to reduce order effects.

Data Analysis

Parametric analysis is based on matching time course data to a predetermined imaging paradigm. Frequencies within the data are assessed based on their correlation with the paradigm and designated as activation using a minimum threshold value. This technique is successful for time series with minimal task correlated confounds. However, it is possible that physiologically relevant activation is indistinguishable from task correlated motion artifact using model – based analysis. In task correlated motion artifact, the undesired signal begins and ends with the imaging paradigm in a similar fashion to the BOLD effect. In this study, when the subject began dorsiflexor muscle contractions local metabolic changes in the primary

motor cortex resulted in an increased BOLD effect, however, head translation also occurred with the contractions. Due to the small magnitude of the BOLD effect and the large effect created by motion, we thought discrimination may not be possible using parametric models.

The primary concern of this analysis was the motion artifact confound. For example, eccentric muscle contractions may have generated more motion artifact as a result of increased torque values. This may have created greater motion artifact in these data sets and systematically caused them to be excluded from the analysis. As a result, the effectiveness of the head restraint system was paramount in the success of the project. The data was analyzed using the common fMRI analysis program Statistical Parametric Mapping (SPM). SPM is the most common analysis program used today in fMRI, and as a result, controlling the head motion to the extent that analysis would be possible using this software was the best case scenario. Comparisons with other studies would become more meaningful and straightforward if this was possible.

The primary motor cortex (foot region) was identified a priori as the region of interest (ROI) and activation maps were generated for the concentric and eccentric movements. Comparisons between the movement types were to be made based on the extent and intensity of activation. For comparison of extent, the number of active voxels was to be compared using a dependent t-test. Intensity, expressed as peak activation, was also to be compared using a dependent t-test.

Data for subjects in which the activation maps depicted only artifact or without activation in the ROI were excluded from the analysis. This approach

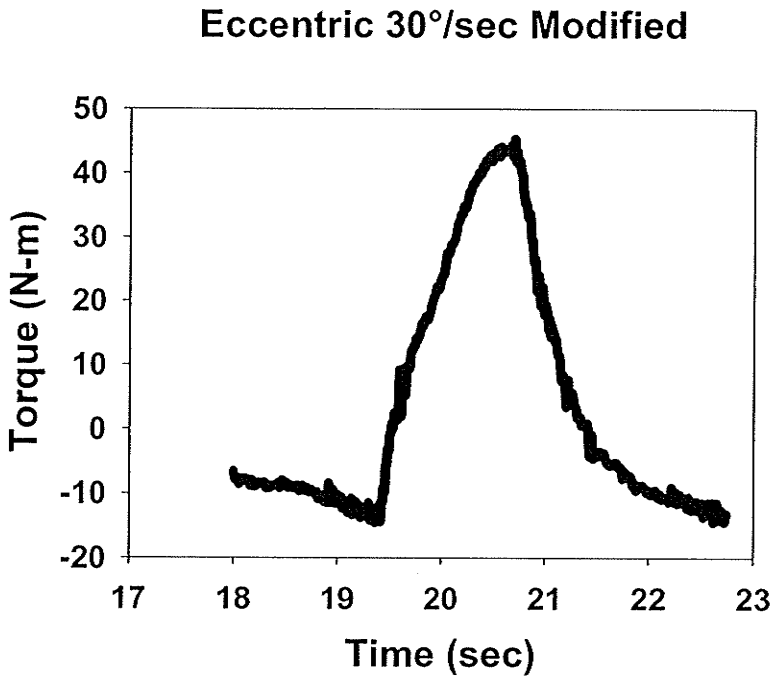
allowed for the selection of the subset of data to be used in the eccentric versus concentric comparison.

Furthermore, translation data was also compared across contraction type to investigate the possibility of a non random fluctuation in head displacement. The head displacement was tested via repeated measures ANOVA to examine the difference between contraction types, across head restraint conditions. For these comparisons, z, x and y mean displacement values were used. All of the statistical comparisons were performed using SPSS Sigmastat 3.0 at a significance level of $p<0.05$.

Results – Protocol A

At 30°/sec there were no significant differences in average peak torque between the modified apparatus and the unmodified apparatus (see Table 1). Type of contraction did not influence these results. Concentric and eccentric contractions produced similar average peak torque values and similar torque profiles (see Figure 4) whether measured using the modified apparatus, or the unmodified apparatus.

A.



B.

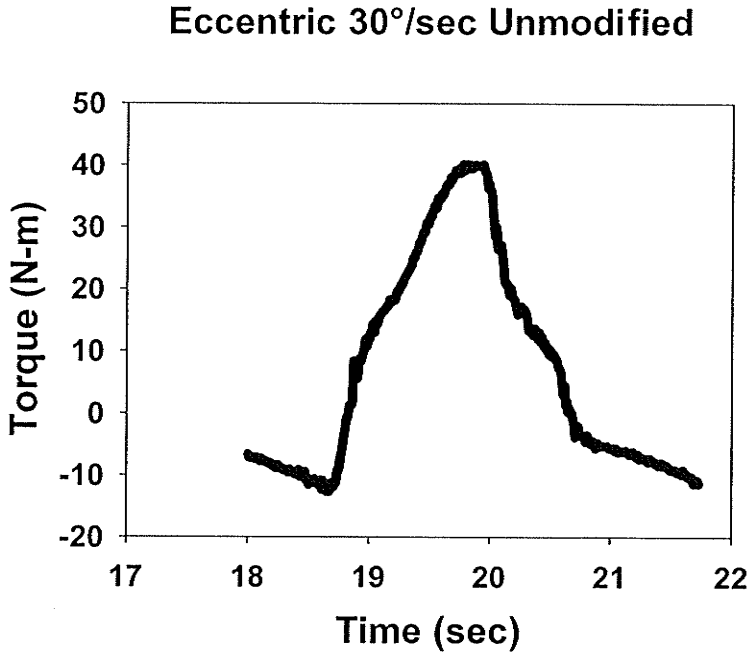
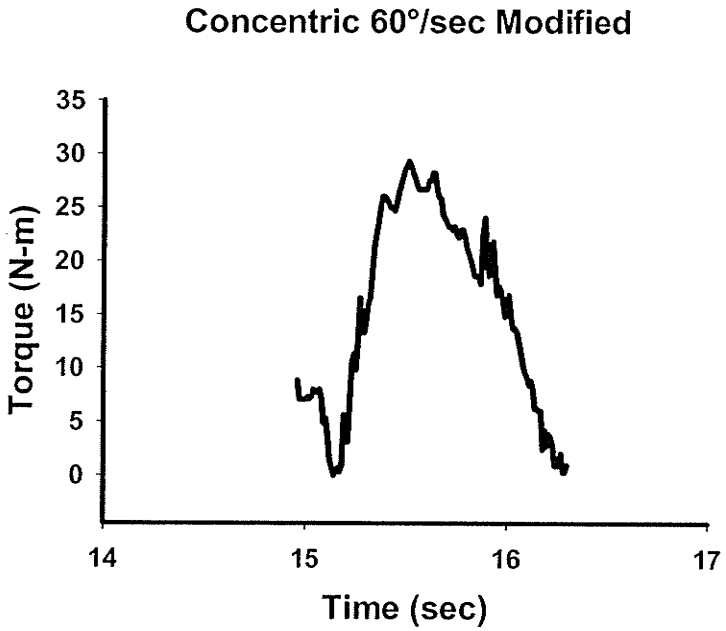


Figure 4. Sample torque profile for the A) Modified and B) Unmodified apparatus at 30°/sec during eccentric contractions for a single subject.

The results were similar at 60°/sec. With one notable exception, no differences were found between the average peak torque values for the modified and unmodified conditions at each of the contraction types. For the concentric trial at 60°/sec a significant difference ($p < 0.05$) was found between the two apparatus during one set. However, it is important to note that the variability at the higher velocity was much greater, rendering the significance of this discrepancy less meaningful. Individual torque profiles at 60°/sec showed higher irregularities in the curve, reflecting the higher variability (figure 5). Furthermore, the first set of concentric contractions at that velocity was not significantly different than those of the other apparatus.

The coefficient of variation for the differences in means ranged from 12.4% to 18.2%. The slower velocity had much less variation than the higher velocity. In addition, the variation for the concentric trials was slightly less than that of the eccentric trials at 30°/sec. At the faster velocity, the variation was higher, and again it was higher in the eccentric contractions than in the concentric. See Table 1 for a summary of this information.

A.



B.

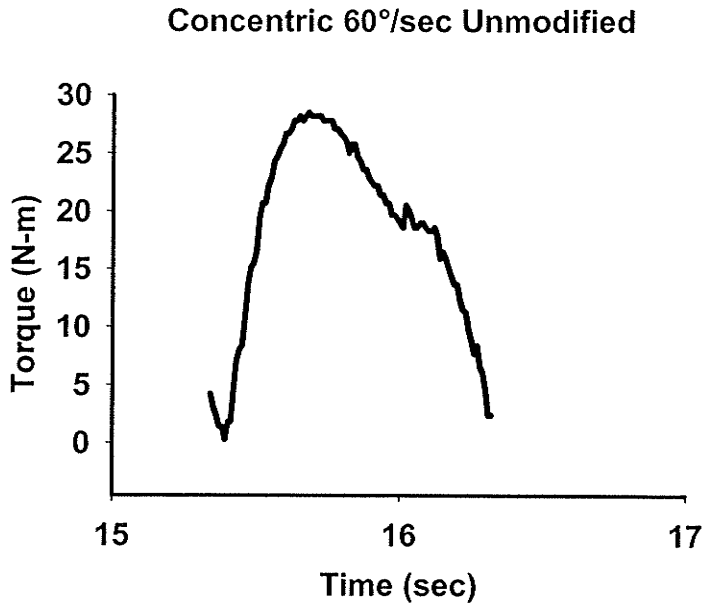


Figure 5. Sample torque profile for the A) modified and B) Unmodified apparatus at 60°/sec during concentric contractions for a single subject.

Table 1. Paired T-test results and Coefficient of Variation (%) values for comparisons between the average peak torque of the modified and unmodified apparatus.

Trial	Modified Mean ±SD	Unmodified Mean ±SD	Coefficient of Variation
Concentric 30°/sec Set 1	24.5±6.2	26.2±7.1	12.4
Concentric 30°/sec Set 2	24.0±6.7	25.6±6.7	12.2
Eccentric 30°/sec Set 1	36.7±9.3	36.8±10.9	13.6
Eccentric 30°/sec Set 2	37.7±9.7	34.9±10.6	13.4
Concentric 60°/sec Set 1	21.6±5.3	23.1±7.7	14.9
Concentric 60°/sec Set 2*	20.8±5.1	23.4±5.9	14.9
Eccentric 60°/sec Set 1	36.8±8.9	34.7±10.1	15.7
Eccentric 60°/sec Set 2	37.3±9.0	33.6±10.7	18.2

* Denotes significant difference ($p<0.05$)

Bland Altman plots were also constructed for the data (see Figures 6-9). When the difference in the mean was plotted against the mean, several things became evident. First, no obvious trend was found that would indicate a consistent misrepresentation of torque values by the modified apparatus. The data points fell equally above and below the zero line, indicating that the apparatus did not consistently over or underestimate the torque produced by the subjects. In addition,

consistently over or underestimate the torque produced by the subjects. In addition, the data points did not trend above or below the zero line at particular ranges. For example, if the data points consistently fell above the line of agreement at higher torque values this would represent a systematic misrepresentation of the torque produced at higher torque values.

It is important to note that there was greater variability for the eccentric contractions. Presumably this is due, at least in part, by the higher force output associated with these types of muscle actions.

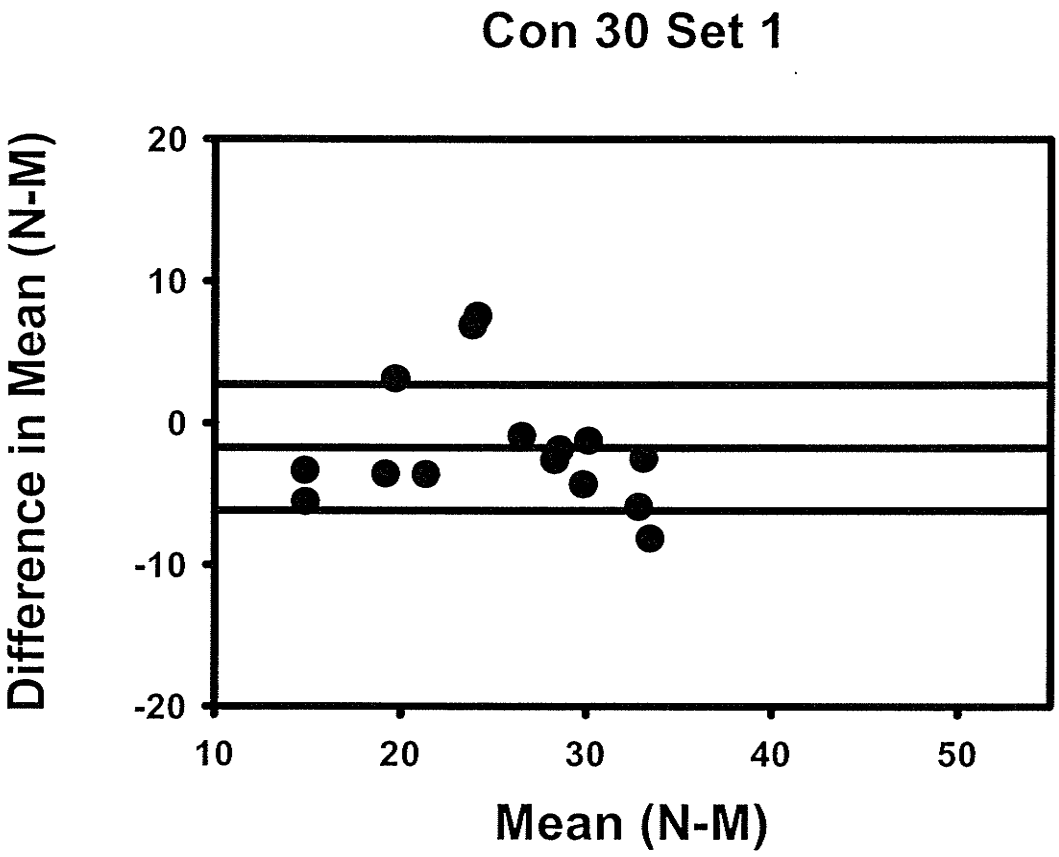


Figure 6. Bland Altman plot for comparison between the modified and unmodified apparatus at 30°/sec for concentric contractions.

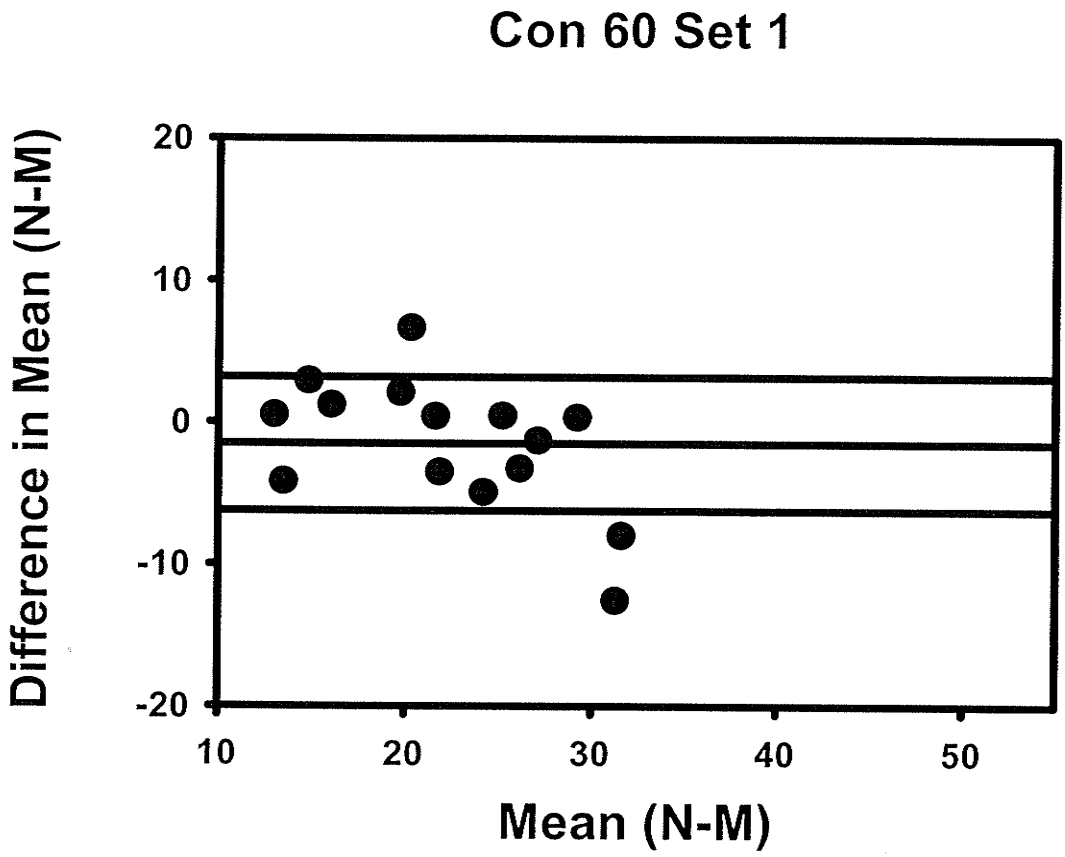


Figure 7. Bland Altman plot for comparison between the modified and unmodified apparatus at 60°/sec for concentric contractions.

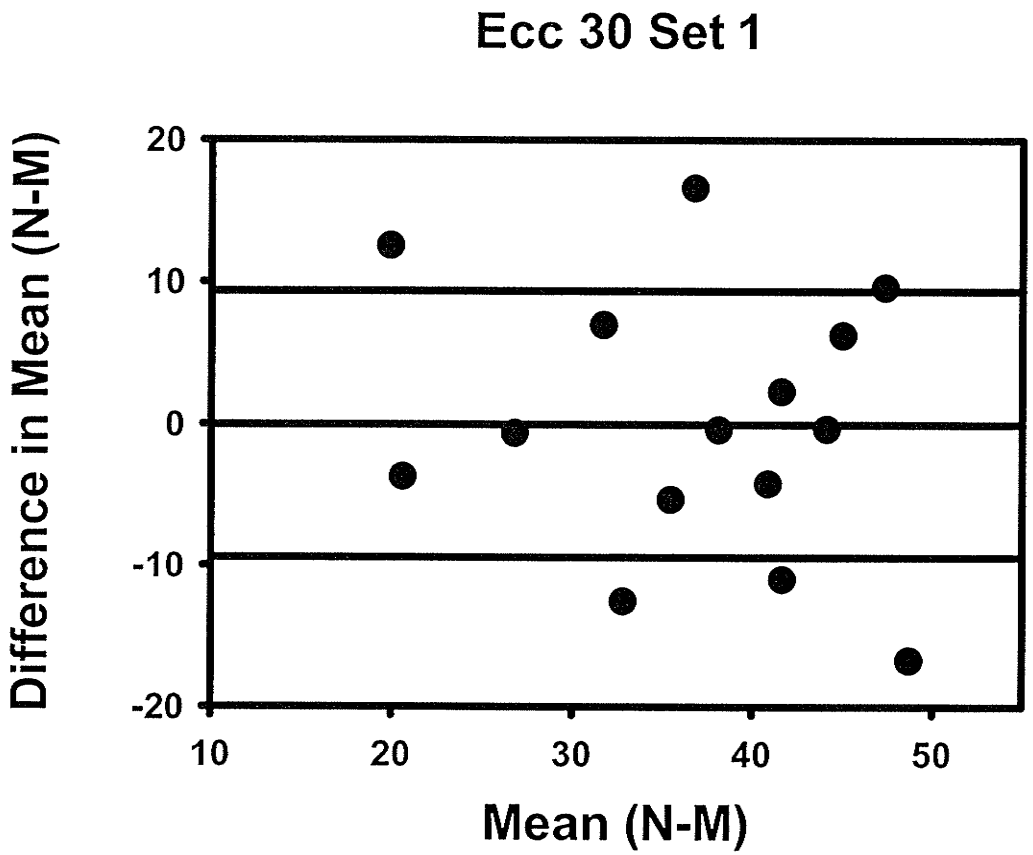


Figure 8. Bland Altman plot for comparison between the modified and unmodified apparatus at 30°/sec for eccentric contractions.

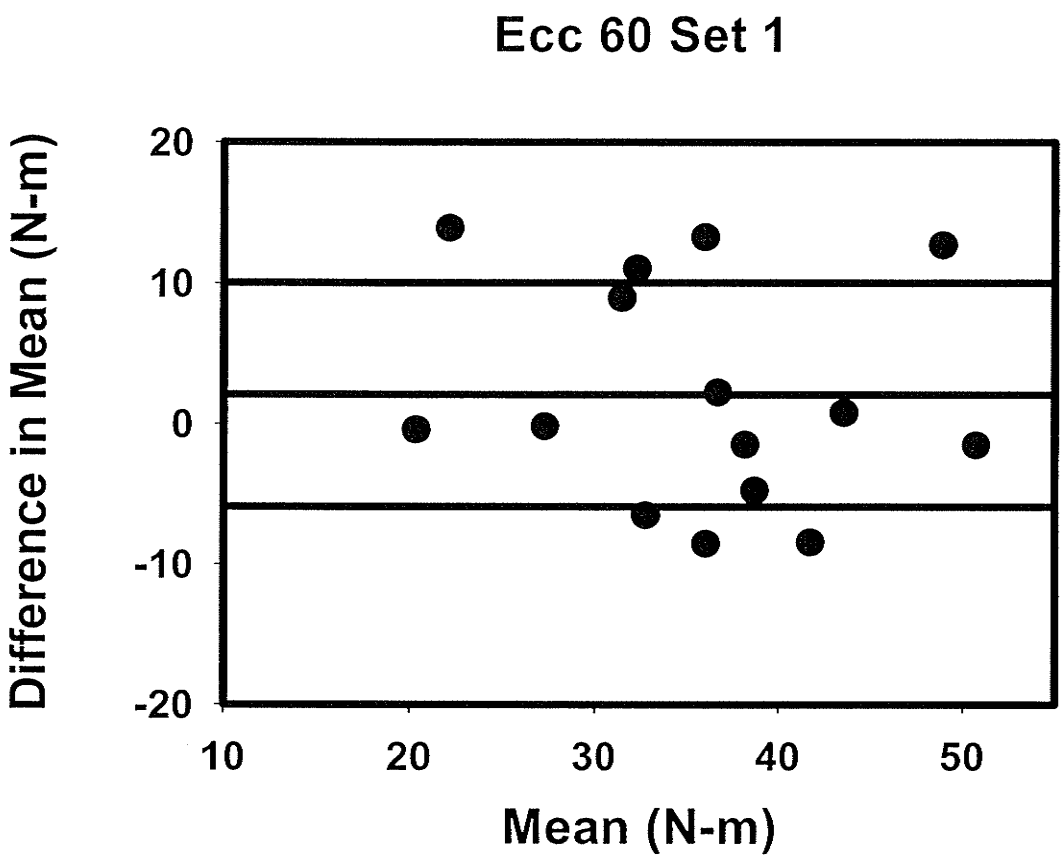


Figure 9. Bland Altman plot for comparison between the modified and unmodified apparatus at 60°/sec for eccentric contractions.

Results – Protocol B

When the translation data was examined using a repeated measures analysis of variance, there were no significant differences ($p>0.05$) found between the head restraint and non head restraint displacement, or between type of contraction (see Table 2). The displacement data was expressed in positive and negative values to denote the direction of the head movement during imaging. Both the absolute values and the actual values were examined using a repeated measures analysis of variance, and it was found that sign had no effect on the significance of the difference between the means.

Table 2. Mean values for repeated measures ANOVA for x, y, z axis head displacement (mm)

	Head Restraint	**No Head Restraint**
Concentric	X = -1.4±2.3 Y = 0.2±.5 Z = 5.5±6.6	X = -0.1±1.4 Y = -0.1±.4 Z = 6.5±6.0
Eccentric	X = -0.7±0.8 Y = 0.1±0.3 Z = 2.5±2.3	X = -0.5±.1 Y = -0.1±0.4 Z = 2.3±5.3

Due to the small sample size it is impossible to make conclusive observations. However, it is of note that although the Z axis displacement was not significantly different with or without the head restraint system, the actual amount of displacement was relatively large.

Plots were constructed for each plane of motion and type of contraction. For the x and y plane the head restraint system seemed to have little effect on the amount of head motion present (see Figures 11, 13, 14, 16). However, in both of these planes the actual magnitude of the motion was low regardless of whether the head restraint was used or not. This brings into question the sensitivity of the measurement device (the MR scanner) at detecting motion during the image acquisition. It may be possible that there is not enough sensitivity to reliably detect small changes in the motion during imaging and as a result the data become equivocal. For the z dimension during concentric contractions, the motion was reduced in all four of the subjects, although not significantly (see Figure 12). Also, the magnitude of the motion in this plane was much greater than that of the other two planes, regardless of contraction type. From these results it seems as though the head movement did not occur to any great extent in the x and y planes, and that the head restraint system need not be directed towards preventing these types of movements. Rather, the head restraint system must be focused towards preventing z displacement.

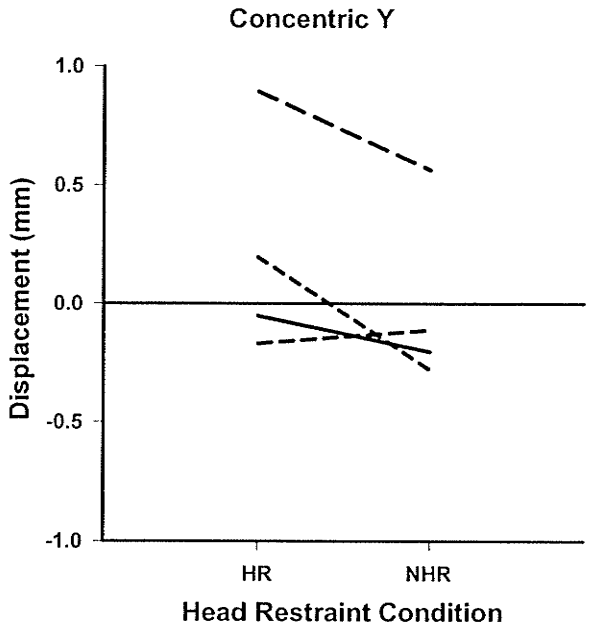


Figure 11. With (HR) and without (NHR) head restraint y axis head displacement during maximal concentric dorsiflexor contractions.

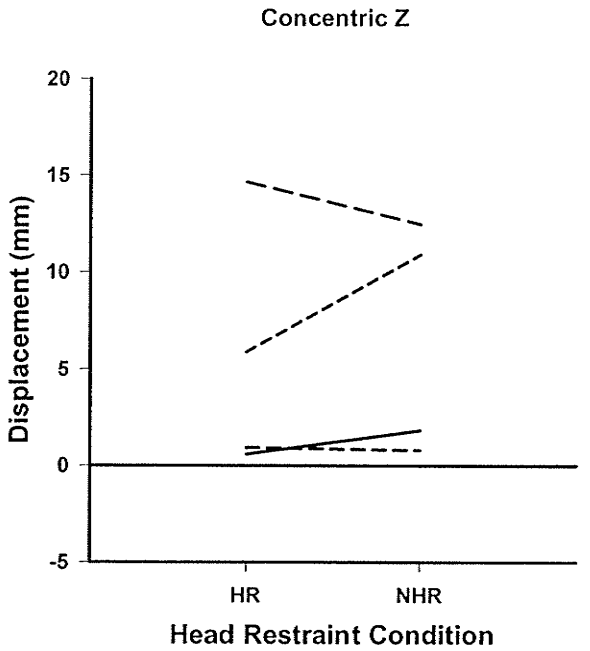


Figure 12. With (HR) and without (NHR) head restraint z axis head displacement during maximal concentric dorsiflexor contractions.

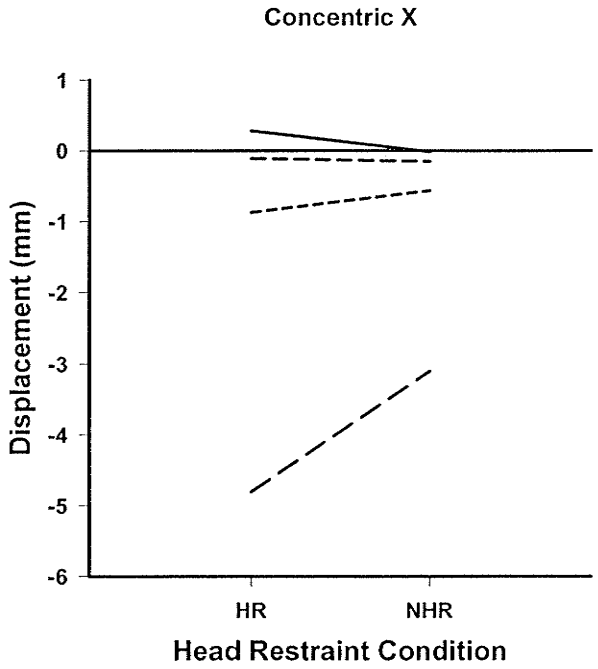


Figure 13. With (HR) and without (NHR) head restraint x axis head displacement during maximal concentric dorsiflexor contractions.

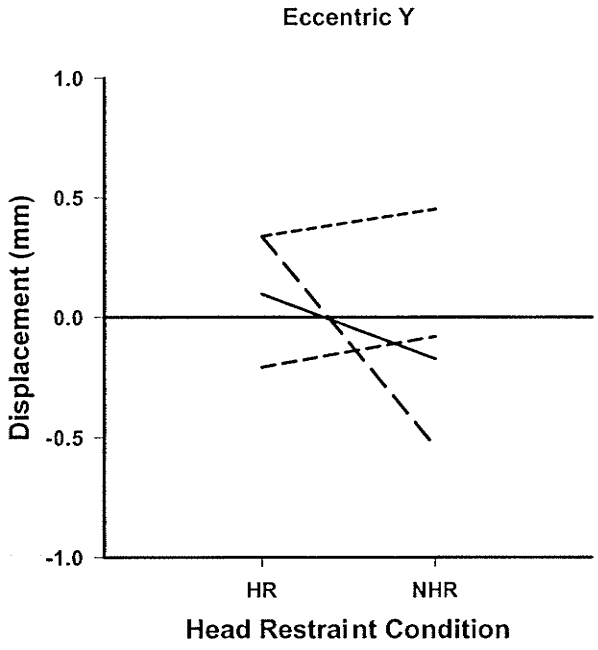


Figure 14. With (HR) and without (NHR) head restraint y axis head displacement during maximal eccentric dorsiflexor contractions.

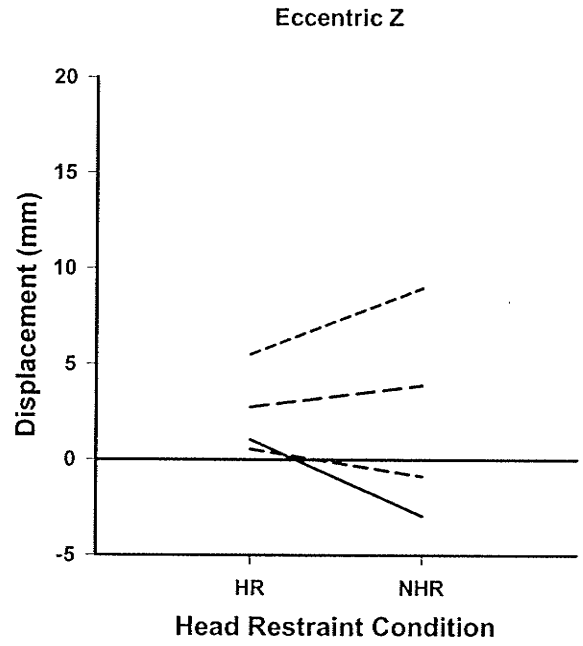


Figure 15. With (HR) and without (NHR) head restraint z axis head displacement during maximal eccentric dorsiflexor contractions.

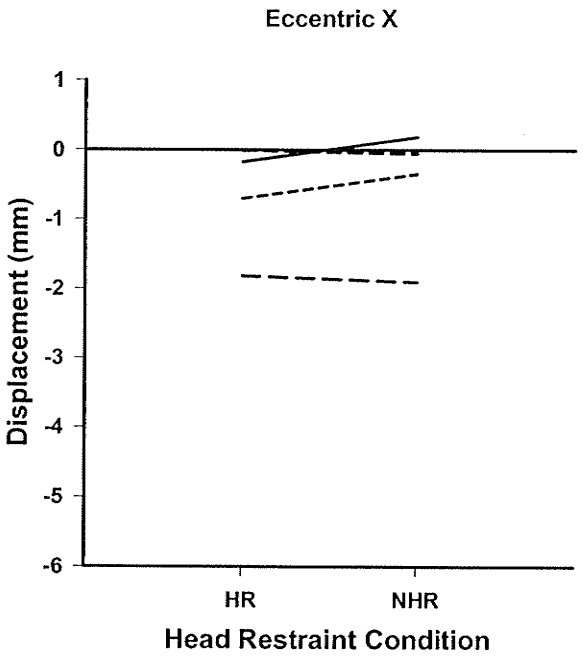


Figure 16. With (HR) and without (NHR) head restraint x axis head displacement during maximal eccentric dorsiflexor contractions.

Although the number of subjects was small, it was hoped that images in the head restraint condition would show some level of activation in the region of interest (Brodmann area 4 and 6), and the unrestrained group would show high levels of artifact covering many areas of the brain, as is typically seen from motion during fMRI studies. As was anticipated, the trials without the head restraint system produced artifact induced activation patterns that covered the entire brain, without region specific trends (see Appendices F and I)). The motor cortex, and most other structures of the brain were equally covered in motion induced activation. Upon examining the trials with the restraint device, it was found that the activation levels seemed to be less prominent and although the activation was still widespread, it appeared to be less "flooded" (see Appendix G and H)). Even with the head restraint system in use, the activation maps generated were unusable for comparative purposes due to the widespread false activation. In addition, the activation clusters often fell outside of the brain template; this halo effect is also typical of motion problems during imaging. Although this trend applied to most of the data, one of the trials had more motion artifact with the restraint device than without. This finding was of note because the translation data showed that although the motion artifact increased when using the restraint system, the actual displacement of the head was slightly reduced.

Discussion – Protocol A

The torque values obtained using the modified apparatus at 30°/sec were similar to those obtained using the conventional set up. These findings suggest that the modified apparatus is a valid tool for measuring peak torque during dorsiflexion at 30°/sec. This held true for both concentric and eccentric movements. However, at 60°/sec significant differences were evident between the torque values, and the modified apparatus became less valid for isokinetic testing.

Although the Bland Altman plots showed no substantial deviation from the zero line in a systematic manner, there was a noticeable increase in the scatter of the data for the eccentric movements. For the slower movements, the coefficient of variation was moderate, ranging from 12.4% for concentric movements to 13.4% for eccentric. This indicates that the increased scatter in the plots was mostly attributable to the higher mean values, rather than increased variability. However, it should be noted that there was a slight increase in the variability, and that not all of the scatter could be accounted for by increased mean values. For the higher velocity bouts, the variability was substantially higher, ranging from 14.9% to 18.2%. This rendered the apparatus less effective for testing during the functional MRI portion at this velocity. High variability would make comparisons between brain activity for the different types of contraction more difficult because it would be less possible to determine the exact nature of the motor task performed. With more error in the torque values it would not be possible to determine if the bout was maximal. Typically, coefficient of variation values are lower than those reported in this study (Holmbäck, *et al*, 1999).

For example, values of 6% for concentric contractions have been reported for velocities up to 60°/sec. Our findings of 12-13% push the bounds of acceptability, and mimic values seen at velocities in excess of 120°/sec (Holmbäck, *et al*, 1999). With variation beyond this level, the usefulness of the apparatus becomes limited. The higher variability was predominantly due to the increased number of joints and the greater amount of play in them when compared to the factory apparatus. To reduce the coefficient of variation, tighter joints could be manufactured to reduce the amount of slippage during a muscle contraction. This laxity caused slight spikes in the torque profiles and as a result, a higher coefficient of variation.

It may be possible to improve the variability at higher testing velocities by small changes to the mechanical set up. During the higher velocity contractions there seemed to be an increase in the flex of the connecting rod, and an increase in the play at the joints between the rod and the dynamometer/ankle unit. The more ballistic movements may have caused the connecting rod to flex more, which in turn would alter the torque values as seen by the dynamometer spindle. If a more rigid tube could be found, these oscillations may be reduced to acceptable levels. Furthermore, the joints at either end of the connecting rod could be manufactured to ensure a tighter fit, reducing the amount of play during the contractions. It is likely that the small extraneous movements at each joint contributed to the variability. During the 60°/sec movements artifactual spikes could be seen in the torque profiles as a result of the play in these connections. Modifications such as these may allow higher velocities to be used with confidence, and improve the validity of the more common testing speed of 30°/sec.

The torque values obtained using the modified apparatus are similar to those found in current research (see Table 3). With the exception of the findings of Porter et al, the peak torque values obtained in this study seemed slightly lower than previous research (Porter *et al*, 1997). The subjects in other studies ranged from athletes to recreationally active individuals, and this may have had an impact on the comparison between studies. Furthermore, the age range for Porter et al (1996) was much higher than in the present study, and this could have contributed to the discrepancy between peak torque values. One final contributing factor may be differences in body weight. Should there have been significant differences in body weight (in particular, lean mass), the peak torque values could vary significantly from study to study.

The modified apparatus produced comparable torque values to those produced with the unmodified apparatus at slower velocities, and to those reported in other research. As a result, we were able to use the modified apparatus within the MRI room with confidence that the torque values would be valid, despite the slightly higher variability. The magnetic interactions and RF interference was resolved using the modified apparatus, leaving the production of functional maps dependent on the success of the head restraint system.

Table 3. Comparisons of dorsiflexion peak torque (at 30°/sec) among recent studies.

Study	Sex	Age	PT Concentric (N · m)	PT Eccentric (N · m)
Porter et al, 1996	M & F	20 - 75	20	38
Alexander, 1990	M & F	21	31	40
Wennerberg, 1991	M	18 - 22	40	-
Oberg et al, 1987	M	35 ± 9	40	-
Holmbäck et al, 1999	M & F	23 ± 3	35M 28F	-
Holmbäck et al, 2001	M & F	23.8 ± 3M 22.1 ± 2F	-	52M 36F
Current Study	M & F	18 - 38	24.3	37.2

Discussion – Protocol B

This project was aimed at solving two major problems that are common to fMRI studies. First, the equipment needed to be modified to prevent radio frequency emissions from contaminating the MRI images. Second, the subject's head needed to be secured in such a fashion as to reduce the motion artifact in the images. Through trial and error we were able to produce RF shielding with enough attenuation to allow clean images. However, the problem of head motion was much more difficult to overcome. Commercial units are available to help reduce head motion, although there are none that we know of that are capable of preventing motion during maximal leg muscle dynamic contractions. Some of the difficulty arose when trying to find a balance between the comfort of the subject and performance of the device. The head restraint system had to be firm enough that it held the head in place sufficiently, but at the same time it had to be soft enough to be tolerable. In addition, a quick release needed to be possible in the event of an emergency. As a result, the degree to which the restraint system held the head in place was compromised slightly to make it tolerable for the subject. However, the total amount of head motion created during the muscle contractions was not atypical for fMRI motor tasks. Our initial assumption that z axis displacement was the paramount concern may have been misplaced. Although most of the force is transmitted in the z axis direction during these types of movements, it may be that the head restraint system was sufficient to reduce this movement, but not that of another plane. Although the displacement values that we examined had no significant difference between them, despite the

presence of heavy motion artifact in the images, it may have been due to unrestricted displacement in other planes.

A vast portion of current and past research has been directed at reducing motion artifact in MRI (Alsop, *et al*, 1995, Lauzon and Rutt, 1993, Stark *et al*, 1987). Post processing, breathholding, and single shot echo planar imaging have all been cited as methods of reducing motion artifact in MRI (Van de Walle *et al*, 1997, Norris, 2001). However, in functional MRI large motor tasks can produce motion severe enough to cause artifacts even during fast acquisition techniques such as single shot echo planar imaging. As a result, fMRI studies have been limited to small motor tasks, avoiding activities such as maximal effort, or large muscle activation. No effective method has been established to prevent artifact during more robust motor tasks, and as a result restricting the motor task performed during these types of studies has been the only successful method of controlling motion artifact in the images. It may be that simply adjusting the head restraint system to more aggressively restrict rotation or y displacement may render the methodology useful for maximal contractions.

Maximal contractions represent the most extreme conditions for functional MRI. The successful shielding of the Biodex assembly, and its use within the MR room is a significant accomplishment, opening the door to exciting future research. The presence of RF interference and the magnetic interactions were overcome using conductive fabric and a custom mechanical linkage. Fatigue studies, or MR spectroscopy can employ this technology and add a level of sophistication to the research currently being done. The ability to carefully control variables such as the

speed of contraction, or to maintain a given percentage of maximal during a muscle contraction is paramount in studies of neuromuscular function. The ability to do this during functional imaging studies is groundbreaking, and allows many more questions to be answered. Brain activation could possibly be compared during submaximal concentric and eccentric contractions, or between a fatigued and non fatigued state at a given percentage of maximum. Nuclear magnetic spectroscopy can compare metabolites during muscle fatigue, and now fatigue can be measured and standardized across subjects. To date, brain activation has been assessed during simple motor tasks, without regard to velocity or relative load. With this method comparisons could possibly be made between brain activation of varying muscle groups during submaximal contractions. Studies examining neuromuscular pathology can employ this method to look at brain activation, or muscle metabolites during muscle contractions in health and disease. For example, looking at the central or peripheral mechanisms of multiple sclerosis, Parkinson's, and muscular dystrophy with carefully set loading parameters may yield new information regarding these serious afflictions.

Future Directions

Future directions for research involving fMRI and muscle contraction include further development of a successful head restraint system. Head motion is a common problem in fMRI. Using the fundamental concepts behind our head restraint system, a more effective system could be produced and tested in a variety of conditions

including gross motor tasks. For motor tasks using this methodology the limiting factor seems to be motion into and out of the magnet bore. Increasing the effectiveness of the head restraint in this direction might make future studies involving maximal dorsiflexor contractions possible. However, with the existing apparatus studies looking at muscle metabolites or brain activation during submaximal contractions may be possible. In the future it may be prudent to pursue neuromuscular issues beginning from movements that produce the least amount of movement possible, and to expand to higher force contractions after successful studies at the lower force levels. Furthermore, research must be done to determine the exact nature of the motion artifact. If comparisons of brain activation are to be made between types of muscle contractions it is critical to know if the degree to which the head moves is dependent on the type of contraction performed. If this is the case, brain activation may be confounded with motion artifact for some types of contractions.

Conclusion

Functional Magnetic Resonance Imaging is an excellent tool for evaluating brain activity during motor tasks. However, the MR environment limits the types of studies conducted. Strong magnetic interactions, RF interference, and head motion all present potential limitations during motor studies using fMRI. Most motor studies have used small muscle groups and simplistic loading methods to avoid these complications. In order to overcome these issues a Biodex dynamometer was modified, and tested to ensure it remained a valid testing tool. There was no

significant difference in the peak torque values of the modified apparatus from the unmodified at 30 or 60^0/sec for either contraction type, with the exception of one set at 60^0/sec during concentric contractions. The coefficient of variation ranged from 12.2% to 18.2%, and was noticeably higher for the faster velocity trials. From the fMRI portion it was not possible to generate activation maps for the motor task due to excessive motion confounds, despite the use of a head restraint system. The movement into and out of the magnet bore mimicked the imaging paradigm closely and as a result confounded the activation maps with motion induced artifact. Although the x and y translation was minimal the z axis movement was unrestricted by the head restraint system. Although activation maps could not be generated using this method, the modifications to the dynamometer can still be applied to other imaging studies. Performing submaximal contractions may be enough to reduce motion artifact to the extent necessary to generate activation maps. If possible, studies of muscle fatigue, neuromuscular pathology and other issues may be explored using this method.

References

Aine, C., (1995). A conceptual overview and critique of functional neuroimaging techniques in humans: I. MRI/FMRI and PET. *Critical-Review-Neurobiology.* **9:** 229-309.

Alexander, M. J. L. (1990) Peak torque values for antagonist muscle groups and concentric and eccentric types for elite sprinters. *Archives of physical medicine and rehabilitation.* **71:** 334-339.

Allen G. M., S. C. Gandevia, D. K. McKenzie. (1995). Reliability of measurements of muscle strength and voluntary activation using twitch interpolation. *Muscle & Nerve.* **18:** 593-600.

Bigland, B., and O. Lippold, (1954). The relation between force, velocity, and integrated electrical activity in human muscles. *Journal of Physiology.* **123:** 214-224.

Connelly, M., A. A. Vandervoort, (2000). Effects of isokinetic strength training on concentric and eccentric torque development in the ankle dorsiflexors of older adults. *Journal of Gerontology: Medical Sciences.* **55:** B465-B472.

Constable, R. (2003). MR physics of body MR imaging. *Radiologic Clinics of North America*. **41:** 1-15.

Dai, T. H., J. Z. Liu, V. Sihgal, R. W. Brown, G. H. Yue. (2001). Relationship between muscle output and functional MRI – measured brain activation. *Experimental Brain Research.* **140:** 290-300.

Doss, W., and P. Karpovich. (1965). A comparison of concentric, eccentric, and isometric strength of elbow flexors. *Journal of Applied Physiology.* **20:** 351-353.

Dudley, G. A., R. T. Harris, M. R. Duvoisin, B. M. Hather, P. Buchanan. (1990). Effect of voluntary vs. artificial activation on the relationship of muscle torque to speed. *Journal Applied Physiology.* **69:** 2215-2221.

Edman, K. (1988). Double-hyperbolic force-velocity relation in frog muscle fibres. *Journal of Physiology.* **404:** 301-321.

Enoka, R. (1996). Eccentric contractions require unique activation strategies by the nervous system. *Journal of Applied Physiology.* **12:** 2339-2346.

Enoka, R. (1995). Morphological features and activation patterns of motor units. *Journal of Clinical Neurophysiology.* **12:** 538-559.

Fang, Y., V. Siemionow, V. Sahgal, F. Xiong, G. H. Yue. (2001). Greater movement – related cortical potential during human eccentric versus concentric muscle contractions. *Journal of Neurophysiology.* **86:** 1764-1772.

Flitney, F., and D. Hirst. (1978). Cross – bridge detachment and sarcomere "give" during stretch of active frog's muscle. *Journal of Physiology.* **276:** 449-465.

Fox, P., M. Raichle. (1986). Focal physiological uncoupling of cerebral blood flow and oxidative metabolism during somatosensory stimulation in human subjects. *Proceedings of the National Academy of Sciences of the United States of America.* **83:** 1140-1144.

Fox, P. T., M. E. Raichle, M. A. Mintun, C. Dence. (1988) Non – oxidative glucose consumption during focal physiologic neural activity. *Science.* **241:** 462-464.

Gulch, R., P. Fuchs, A. Geist, M. Eisold, H. C. Heitkamp. (1991). Eccentric and post-eccentric contractile behavior of skeletal muscle: a comparative study in frog single fibres and in humans. *European Journal of Applied Physiology and Occupational Physiology.* **63:** 323-329.

Holmbäck, A., M. M. Porter, D. Downham, J. Lexell. (2001). Ankle dorsiflexor muscle performance in healthy young men and women: reliability of eccentric peak torque and work measurements. *Journal of Rehabilitation Medicine.* **33:** 90-96.

Holmbäck, A., M. M. Porter, D. Downham, J. Lexell. (1999). Reliability of isokinetic ankle dorsiflexor strength measurements in healthy young men and women. *Scandinavian Journal of Rehabilitation Medicine.* **31:** 229-239.

Hortobagyi, T., and F. I. Katch. (1990). Eccentric and concentric torque-velocity relationships during arm flexion and extension. Influence of strength level. *European Journal of Applied and Occupational Physiology.* **60:** 395-401.

Kim, S. G., K. Ugurbil, (1997). Functional magnetic resonance imaging of the human brain. *Journal of Neuroscience Methods.* **74:** 229-243.

Kwong, K. K, J. W. Belliveau, D. A. Chesler. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. *Proceedings of the National Academy of Sciences of the United States of America.* **89:** 5675-5679.

Larkman, D. J, D. Atkinson, J. Hajnal. (2004). Artifact reduction using parallel imaging methods. *Topics in Magnetic Resonance Imaging.* **15:**267-275.

Liu, J., L. Zhang, B. Yao, G. H. Yue (2002). Accessory hardware for neuromuscular measurements during functional MRI experiments. *Magnetic Resonance Materials in Physics, Biology, and Medicine*. **13:** 164-171.

Lombardi, V., and G. Piazzesi. (1990). The contractile response during steady lengthening of stimulated frog muscle fibres. *Journal of Physiology* **431:** 141-171.

Nardone, A., C. Romano, M. Schieppati.. (1989) Selective recruitment of high – threshold human motor units during voluntary isotonic lengthening of active muscles. *Journal of Physiology.* **409:** 451-471.

Oberg, B., T. Bergman, H. Tropp. (1987) Testing of isokinetic muscle strength in the ankle. *Medicine & Science in Sports & Exercise.* **19:**318-322.

Ogawa, S., T. M. Lee. (1990) Magnetic resonance imaging of blood vessels at high fields: in vivo and in vitro measurements and image simulation. *Magnetic Resonance in Medicine.* **16:** 9-18.

Ogawa S., D. W. Tank, R. Menon, J. R. Ellermann, S. G. Kim, H. Merkle, K. Ugurbil. (1992). Intrinsic signal changes accompanying sensory stimulation: functional brain mapping with magnetic resonance imaging. *Proceedings of the National Academy of Science of the United States of America.* **89:** 5951-5955.

Ogawa S., T. M. Lee, A. S. Nayak, P. Glynn. (1990) Oxygenation-sensitive contrast in magnetic resonance image of rodent brain at high magnetic fields. *Magnetic Resonance in Medicine.* **14:** 68-78.

Oldendorf, W, and W. Oldendorf. (1991) MRI Primer. *Raven Press.* New York.

Pauling, L., Coryell, C., (1936). The magnetic properties and structure of hemoglobin, oxyhemoglobin, and carbonmonoxyhemoglobin. *Proceedings of the National Academy of Science of the United States of America.* **22:** 210-216.

Porter, M.M, Anthony A. Vandervoort, John F. Kramer. (1996). A method of measuring standing isokinetic plantar and dorsiflexion peak torques. *Medicine & Science in Sports & Exercise.* **28:**516-522.

Porter, M.M, Anthony A. Vandervoort, John F. Kramer. (1997). Eccentric peak torque of the plantar and dorsiflexors is maintained in older women. *Journal of Gerontology: Biological Sciences.* **52A:** B125-B131.

Provost, T. J, R. E. Hendrick. (1986). Maximizing signal-to-noise and contrast-to-noise ratios in spin echo imaging using non-standard flip angles. *Magnetic Resonance Imaging.* **4(c):** 105-110.

Taylor, N. A., R. H. Sanders, E. I. Howick, S. N. Stanley. (1991). Static and dynamic assessment of the Biodex dynamometer. *European Journal of Applied Physiology and Occupational Physiology.* **62:**180-188.

Turner, R., D. Le Bihan, C. T. Moonen, D. Despres, J. Frank. (1991). Echo-planar time course MRI of cat brain oxygenation changes. *Magnetic Resonance in Medicine.* **22:** 159-166

Webber, S., and D. Kriellaars. (1997). Neuromuscular factors contributing to in vivo eccentric moment generation. *Journal of Applied Physiology.* **83:** 40-45.

Wennerberg D, A. L. Hicks, N. McCarthy. (1991). Reliability of an isokinetic dorsiflexion and plantar flexion apparatus. *American Journal of Sports Medicine.* **19:** 519-522.

Westing, S., and J. Y. Seger. (1989). Eccentric and concentric torque-velocity characteristics, torque output comparisons, and gravity effect torque corrections for the quadriceps and hamstring muscles in females. *International Journal of Sport Medicine.* **10:** 175-180.

Westing, S., J. Y. Seger, A. Thorstensson. (1990). Effects of electrical stimulation on eccentric and concentric torque – velocity relationships during knee extension in man. *Acta Physiologica Scandinavica.* **140:** 17-22.

Westing, S. H., J. Y. Seger, E Karlsson, B. Ekblom. (1988). Eccentric and concentric torque – velocity characteristics of the quadriceps femoris in man. *European Journal of Applied Physiology and Occupational Physiology.* **58:** 100-104.

Woodward, P., R. Freimarck. (1995) MRI for Technologists. *Mcgraw – Hill Inc.* United States of America.

Wyper, D., (1993). Functional neuroimaging with single photon emission computed tomography (SPECT). *Cerebrovascular and Brain Metabolism Reviews.* **5(3):** 199-217.

Appendix A

Research Project Title: An adapted system to measure torque
Researchers: Dr. Michelle M. Porter, Mr. Brennan Ryan

Subject Information and Consent

This information, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand the summary of the project.

Summary of Project

Modifications to strength testing equipment must be made in order to use the equipment during magnetic resonance imaging (MRI) experiments. The purpose of this study is to test the validity of the ankle strength testing device after these modifications have been made. Comparisons will be made between the modified and unmodified equipment in testing the muscles in the front of the shin, the dorsiflexors. These muscles act to pull the foot towards the shin. The testing will be done in the **Neuromuscular laboratory** (207 Max Bell Centre) at the Health Leisure and Human Performance Research Institute at the University of Manitoba. For this study there will be no MRI machine involved. The tests include different types of contractions (shortening and lengthening) and speeds (slow and moderate). The total time for the testing will be approximately 90 - 120 minutes.

Prior to the testing you will be asked to complete a questionnaire regarding your health and ability to participate (called the PAR-Q). Following this your resting blood pressure and heart rate will be assessed to ensure that they are both at safe levels. Your height and weight will both be measured in sock feet prior to the testing taking place.

All of the tests will be performed using a measurement device called a Biodex isokinetic dynamometer. You will be lying on your back with your right foot attached to a foot plate. Your upper body will be stabilized to prevent any unnecessary movement of the trunk. For some of the

contractions you will be pulling the toes towards the shin – in this case the muscle is shortening. For the other type of contraction you will be resisting the machine as it pulls your foot away from the shin – in this case the muscle is lengthening. Before the testing begins you will be given practice trials, for the different types of contractions and velocities. In these trials you will not be required to try as hard as you can. A 2 minute rest time will be given after the rest trials.

Once testing has begun you will be asked to contract your muscles as quickly and as hard as you can, for the two types of contractions (shortening and lengthening) as well as the two velocities (slow and moderate speed). Testing will consist of 8 sets of 5 maximal contractions for the modified and unmodified set up. Between sets you will be given rest to prevent fatigue.

Confidentiality

All experimental data associated with you will be identified with a subject number only. All subject files will be kept in a locked filing cabinet in the Neuromuscular Laboratory. In any written reports you will not be identified. The only persons to have access to your data will be Dr. Porter and her graduate students at the University of Manitoba.

At the end of the study we will ask you if you would like to participate in a separate study of the Institute for Biodiagnostics (IBD) and the University of Manitoba (also involving Dr. Porter and Brennan Ryan). This study would involve the same types of muscle contractions with measurements made by a magnetic resonance imaging (MRI) machine. You are not obligated to participate as it is a totally separate study. If you are interested we will give you the contact information for the subject recruitment department at IBD. Some of your strength data from this study may be used by Dr. Porter and Brennan Ryan.

Benefits

There will be no direct benefit to you from these procedures beyond learning about your strength. If requested, a performance report will be provided to you. To obtain a performance report for your testing session, indicate this to the tester immediately following the testing session. If you

would like more details on the results of the study please contact Dr. Porter using the phone number on the consent form.

Risks

There are risks associated with any type of physical activity. We have tried to minimize risks to you by asking you questions about your health status. You will also be highly supervised by trained individuals.

The likelihood of severe injury from this type of testing is very low. Typically exercise – related events that occur during testing of this nature include exacerbations of a pre – existing hernia and underlying arthritis or other joint abnormalities. Subjects will be screened for any kind of joint abnormality or other condition that could be exacerbated by the testing. Even though the risk of severe injury other than temporary muscle soreness is very low, there is a theoretical possibility that a tear in a muscle or tendon could occur as a result of this type of testing. If there is any pain at any time during the testing, the test will be discontinued.

There is also the remote possibility of a cardiovascular incident (e.g., heart attack) during testing. In order to minimize cardiovascular events, all subjects will be screened for cardiovascular conditions such as recent or previous heart attacks or strokes, and other cardiovascular risk factors. To minimize the increase in blood pressure which can occur with straining, subjects will be instructed to breathe out while being tested.

Research Project Title: An adapted system to measure torque
Researchers: Dr. Michelle M. Porter, Mr. Brennan Ryan

Consent Form (Participant Copy)

Your signature on this form indicates that you have read and understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

Dr. Michelle Porter	474-8795
Mr. Brennan Ryan	474-7085

This research has been approved by the Education / Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Secretariat at 474-7122. A copy of this consent form has been given to you to keep for your records and reference. I agree to participate in this study, but understand that I may withdraw at any time without prejudice or consequence.

Name (print): _____

Signature: _____ Date: _____

Investigator (print): _____

Investigator: _____ Date: _____

Appendix B

Protocol Number 1999-12 Central mechanism of preservation of eccentric muscle strength with age **11 March 1999**
(Revised 19 May 1999 and 09 October 2002)

National Research Council Canada | Conseil national de recherches Canada
Institute for Biodiagnostics | L'Institut du biodiagnostic

NRC · CNRC

RESEARCH STUDY SUMMARY AND CONSENT FORM

Protocol number 1999-12

Central mechanisms of preservation of eccentric muscle strength with age

Institute for Biodiagnostics, National Research Council and
Faculty of Physical Education and Recreation Studies, University of Manitoba

Principal Investigators:
Michelle Porter, PhD
Faculty of Physical Education and Recreation Studies, University of Manitoba
Lawrence Ryner, PhD
MR Technology, Institute for Biodiagnostics, National Research Council

Collaborator and Project team members:
Ryan D'Arcy, PhD, Brennan Ryan, BSc and Adina Mincic, PhD, MR Technology, Institute for Biodiagnostics, National Research Council

WHAT IS THE RESEARCH ABOUT?

Studies of animal muscle have found a unique relationship between the force that a muscle exerts and the velocity with which the muscle is lengthening (eccentric movement) or shortening (concentric movement). However, many studies in humans have found that the maximal voluntary force exerted in eccentric contractions is much lower than would be expected from the animal experiments. The reason for this is not understood, but it is obvious that the muscle is not used to its full capacity. Aging, on the other hand, has many detrimental effects on the neuromuscular system, such as reduced strength, slowing of contraction, slowing of relaxation, increased passive stiffness, and decreased muscle mass. However, eccentric muscle strength is relatively preserved in older humans, unlike concentric muscle strength. This suggests that, with aging, the nervous system adapts in order to utilize more of the actually lessened muscle mass to preserve function. In functional magnetic resonance (fMRI) experiments, we will measure differential patterns of brain activation between younger and older subjects, and between eccentric and concentric movements. Each experiment will show if the mechanism of preserved eccentric strength is peripheral or central. This is of general interest, as it may show how the central nervous system can cope with the deterioration in function of a body organ.

Subject number: _____ Subject initials ___

AM I ELIGIBLE TO PARTICIPATE?

Two groups of healthy people are being recruited for this study:
Group1: those aged 65 or older
Group 2: those aged 20 to 40

In order to participate in this study, you must be healthy, physically active (but not highly trained), over 65 or aged 20 to 40.
You will not be able to participate in the study if:

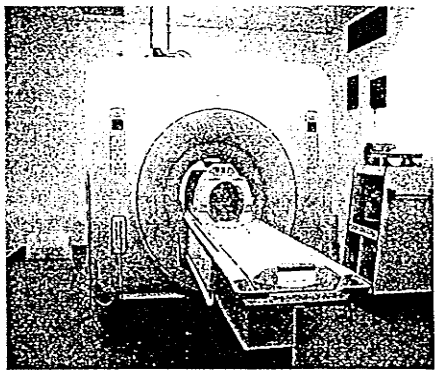
1. you are involved in running and jumping sports or do resistance training of the lower legs
2. have any neuromuscular condition, have any recent (within one year) orthopaedic problems with the ankle joint, have any recent orthopaedic problem of other joints (feet, hips, knees) which has affected your gait (within one year), have any condition which would preclude strength testing or are taking any kind of medication which might influence neuromuscular performance.
3. You have metal objects inside your body. MRI may be dangerous for anyone with metal implants or metal objects inside their body.
4. You, in the opinion of the screening physician or investigators, have a medical condition that could be made worse by any stress associated with participation in a research protocol. These conditions include heart and circulatory problems, seizure disorders, anxiety disorders, and mental disorders.
5. You have claustrophobia
6. You are or may be pregnant.
7. You weigh more than 350 pounds

Screening by a physician is a requirement to participate. If you have been screened previously for one of our other MR studies, you may not need to have another form completed (Please check with the Human Studies Co-ordinator at 984-2433).
Please note that, if you are aged 20 to 40, you may be eligible to participate in a companion study "Validation of an adapted system to measure torque". This study will be conducted by Dr. Michelle Porter and will be described to you in a separate package. Please note that you are under no obligation to participate in both studies. Also, you are free to withdraw from either study at any time.

WHAT WILL I HAVE TO DO?

You will make one visit to the Health Sciences Centre MRI unit when you will have a Magnetic Resonance (MR) scan of the brain while you are carrying out some foot and leg exercises that you will be doing during the scan. The scan itself will take about 90 minutes, but **allow a total of 2 1/2 hours for the visit.** You will be asked various questions before your appointment to make sure that there are no metal objects in your body, so that it is safe for you to have an MRI scan done. Please call the Human Studies Co-ordinator at 984-2433 if you would like more information about the study or if you would like to make an appointment to participate in the study. At your appointment for the MR scan, an investigator will go through the Screening Form with you, give you information about the study and show you the MRI system (see the picture) and the equipment that will be used for the study.
The investigator will explain to you the exercises that you will do, such as pulling up or pushing down your foot against an attached weight. The researcher will also give you detailed instructions during the

study. You should make sure that all your



questions are answered and you agree to participate in the study before signing the consent form. Before entering the magnet room, you will be asked to change into clothing which does not contain metal. You have a choice of wearing your own clothing, if it is metal-free (e.g., jogging suit) and has ample room for leg movements, such as pulling up your foot against the attachment or the hospital gowns that we can provide. For the MRI scan, you will be positioned comfortably on your back and provided with soft earplugs to reduce the noise from the MRI scanner (the sound it produces is a loud knocking noise). A special receiver will be placed around your head, that is shaped like a helmet.. You will then be slid into the large, tunnel-shaped scanner until your head is at the centre of the magnet. The scanner at the Health Sciences Centre has a field-strength of 1.5T (similar to most hospital MRI scanners). The tunnel is 60 cm (about 2 feet) across and is open at both ends.

During the scan, the MR operator will talk with you regularly through a two-way intercom to let you know what to do and will tell you when you should do the exercises. At times you will be asked to remain very still so that the images will be sharp.

After the scan has been completed and you have left the magnet room, we will ask you to fill out a questionnaire about how the study went for you.

IS THE STUDY CONFIDENTIAL?

Normally, only people directly involved with the research procedure are allowed in the study area. However, as this is a clinical facility, people not involved in the study may occasionally require access. All staff at the Health Sciences Centre are required to keep health information confidential, in accordance with the Health Information Act of Manitoba.

If you participate both in this study and the companion study "Validation of an adapted system to measure torque", data acquired in either study may be used in the analysis of the other study.

Information gathered in this research may be published or presented in public forums; however your name will not be used or revealed. Medical records that contain your identity will be treated as confidential in accordance with the Personal Health Information Act of Manitoba. All data obtained during your scan will be stored with an alpha-numerical code instead of your name. Only your file, which is kept securely in the Human Studies Coordinator's office, will have information which relates your name to the code.) Despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Organizations that may inspect and/or copy your research results for quality assurance and data analysis include groups such as the National Research Council Research Ethics Board and the University of

Manitoba Health/Biomedical Research Ethics Board.

WHAT ARE THE POSSIBLE HARMS OR BENEFITS?

MRI may be dangerous for anyone with metal inside their body. Some metal objects may move or heat up due to the magnetic force and radiofrequency waves used for MRI. We will screen you to make sure that it is safe for you to participate. You must tell us if you have had surgery, as metal may be left in your body after certain types of surgery. Please consider if you have any of the following:

- Previous Surgery, such as:
  - Surgery involving metal, such as: clips, rods, screws, pins, wires.
  - Heart pacemaker
  - Implanted electrodes, pumps or electrical devices
  - Cochlear (inner ear) implants
  - Intraocular lens (eye) implants (Cataract lens allowed except for Brain Imaging studies)
- Any metallic foreign body, shrapnel or bullet (Have you have ever been a grinder, metal worker, welder, wounded during military service, etc.?)
- Intrauterine contraceptive device (IUD) or contraceptive diaphragm
- Dental work held in place by magnets
- Metal dental work, unless it is composed predominantly of precious or semi-precious alloy or amalgam (Please discuss with the Human Studies Co-ordinator)
- Tattooed eyeliner
- Some tattoos (if you have tattoos, please discuss with the Human Studies Co-ordinator)
- Non-removable metal jewellery (body piercing)

MRI is completely painless, but some people have felt minor, transient discomforts during MRI scans (e.g. dizziness, lightheadedness or a feeling of continued motion after being moved into the magnetic field) which usually subside within a few minutes. In rare cases, the dizziness progressed to the point of nausea, but subsided quickly outside the magnetic field. Some people may have a feeling of claustrophobia while they are in the scanner, and in extremely rare cases this feeling seems to have triggered a more persistent claustrophobia. Please let us know immediately if you experience claustrophobia (or any other discomforts), and we will discontinue the study.

No long-term adverse effects of MRI have been reported. We would contact you if any new risks are discovered. Please contact us or ask your physician to contact us if you experience any effects that you feel may be a result of your participation in the study.

Before you enter the magnet room, we will ask you to remove all metal objects, such as keys, coins, since they could be attracted to the MRI scanner with great force. If a metal object hit anyone in the way, it could cause serious injury.

After the exercises, you may experience some discomfort in the muscles in the front of the shin for up to 3 days after testing. This is a normal consequence of maximal strength testing and it should go away on its own. However, if there is any pain at any time during the testing, the test will be discontinued. There are risks associated with any type of physical activity. We have tried to minimize risks to you by asking you questions about your health status. You will

also be highly supervised by trained individuals. The likelihood of severe injury from this type of testing is very low. Typically exercise – related events that occur during testing of this nature include exacerbations of a pre – existing hernia and underlying arthritis or other joint abnormalities. Subjects will be screened for any kind of joint abnormality or other condition that could be exacerbated by the testing. Even though the risk of severe injury other than temporary muscle soreness is very low, there is a theoretical possibility that a tear in a muscle or tendon could occur as a result of this type of testing. If there is any pain at any time during the testing, the test will be discontinued. There is also the remote possibility of a cardiovascular incident (e.g., heart attack) during testing. In order to minimize cardiovascular events, all subjects will be screened for cardiovascular conditions such as recent or previous heart attacks or strokes, and other cardiovascular risk factors. To minimize the increase in blood pressure which can occur with straining, subjects will be instructed to breathe out while being tested.

This is a research study so you will not personally benefit by participating in this study.

WHAT ELSE SHOULD I KNOW?

You have the right to withdraw from the research study at any time and for any reason. The investigators reserve the right to end your participation for any reason.

We will give you $25 to cover any expenses you incur to participate in this research study. You may also request a copy of some of the images. Although this is not a diagnostic scan and any images obtained are for research purposes only, it is possible that the MR scan may disclose an unknown abnormality. In this event, a medical imaging specialist will review the images and we would send a report to your physician.

Please contact us if you would like any more information about the study. Please let us know if you would like copies of any published scientific reports about the research project.

HOW CAN I GET MORE INFORMATION?

The following people may be contacted for additional information.
Dr. Michelle Porter, PhD, at 474-8795
Dr. Lawrence Ryner, PhD, at 984-7693
Dr. Valerie Strevens, PhD, (Human Studies Co-ordinator at 984-2433
For questions about your rights as a research subject, you may contact:
Ms. Bev Venn, National Research Council Winnipeg Research Ethics Board, phone 984-4533

CONSENT FORM

I have received a copy of and I have read the Research Study Summary. I understand the nature of the study, including the potential risks and benefits. I have had adequate time to consider the information. I have talked to Michelle Porter or Lawrence Ryner and/or their colleagues. All my questions about the study have been answered. If I have any more questions, I may call Michelle

Subject number: _____ Subject initials ___

Porter at 474-8795 or Lawrence Ryner at 984-7693. I understand that I will be sent a copy of this consent form, after signing it.

I understand that information regarding my personal identity will be kept confidential, but that confidentiality is not guaranteed. I agree to the inspection of my research records by the National Research Council Winnipeg Research Ethics Board, and the University of Manitoba Biomedical / Health Research Ethics Board. I give permission to disclose information to the Institute for Biodiagnostic's medical imaging specialist and the physician I have named for the purpose of follow-up.

I have named Dr. _____ at _____ as the physician to be contacted for follow-up purposes.

I realize that by signing this document I am not waiving any legal rights.

I hereby agree to participate in the research protocol, **"Central mechanism of preservation of eccentric muscle strength with age"** and I understand that I can end my participation at any time and for any reason.

My consent has been given freely.

_____
Name of research subject (Print)

_____ _____
Signature of research subject Date

_____ _____
Name of person obtaining consent (Print) Role in study *(e.g. Investigator, MR Technologist, Study Nurse)*

_____ _____
Signature of person obtaining consent Date

Subject number: _____ Subject initials ___

Appendix C

Protocol Number 1999-12 Central mechanism of preservation of eccentric muscle strength with age **11 March 1999**
(Revised 19 May 1999 and 09 October 2002)

Letter to Prospective Participants
Date

Dear Prospective Participant:

I enclose information about a Magnetic Resonance (MR) Imaging study being performed by researchers from the Institute for Biodiagnostics (IBD) of the National Research Council of Canada (NRC) and form the University of Manitoba.

This study is called **"Central mechanisms of preservation of eccentric muscle strength with age".**

Please note that you must be either 20 to 40 years of age or 65 years of age or over, to participate in this study. The MRI scans will be performed at the Health Sciences Centre MRI Facility.

If you are in the age range 20 to 40, Dr. Michelle Porter will be providing you with a separate information package about an associated study called "Validation of an adapted system to measure torque"

Please:

1. Read the enclosed material. It contains information that we hope will answer any questions you may have regarding your participation in this study. If this does not answer all your questions, please feel free to call us.
2. Carefully review the list of medical conditions that might exclude you from this study. This is mainly for your safety. If you have any of the exclusion criteria, you should not enter the study. If you have any questions or concerns, we will be glad to help you address them.
3. The enclosed **"Magnetic Resonance Screening Form"** must be completed by a physician before you can participate in the study. A list of screening physicians has been provided in the package or you may have your own physician complete this form. Your physician may direct the invoice to me. NRC will pay the physician a maximum of $22.00 for this consultation.
4. Please allow yourself at least 24 hours after reading the information in this package before scheduling an appointment for this study. When you wish to participate in this study, **please call me to arrange a date and time.**

If you have any questions or concerns, please telephone me at 984-2433 and I will either answer your questions directly or make a referral to an appropriate member of the research team.

Sincerely,

Valerie Strevens, PhD
Human Studies Co-ordinator

Protocol Number 1999-12 Central mechanism of preservation of eccentric muscle strength with age 11 March 1999
(Revised 19 May 1999 and 09 October 2002)

MAGNETIC RESONANCE SCREENING FORM

This questionnaire is intended to confirm eligibility of potential research subjects and to identify factors which could make participation in an MRI study hazardous. For your safety, please complete the following screening form with your physician:

Research Subject's Name: (please print) _____

Date of birth (D/M/Y): _____

Male ☐ Female ☐ Weight ____lb. *or* ____kg. Height ____ ft ____ cm

Please refer to the Exclusion Criteria for MR studies and the examples provided.

SECTION A
If you have any metal in your body as a result of surgery, you will NOT be eligible to participate in our MRI research studies

		YES	NO
A 1	Have you ever had any surgery? If yes, please list surgeries and approximate dates: _____ _____	☐	☐
	To the best of your knowledge and your physician's knowledge, did any surgery require any metal to remain in your body?	☐	☐

(If there is doubt, the Human Studies Co-ordinator will ask your permission to check your medical records)

SECTION B

If you answer YES to one or more of the questions in Section B, you will NOT be eligible to participate in our MRI research studies.

B1	Do you have any of the following?	YES	NO
	Heart Pacemaker or Defibrillator Implant	☐	☐
	Aneurysm clip	☐	☐
	Intravascular coils, filters and stents	☐	☐
	Artificial heart valve	☐	☐
	Neurostimulator Implant	☐	☐
	Cochlear (inner ear) implants	☐	☐
	Metallic implants or objects of any kind (including orthopedic implants)	☐	☐
	Prosthetic devices	☐	☐
	Artificial limb or joint	☐	☐

	YES	NO
B 2 Have you ever worked as a grinder, metal worker, machinist, welder or other occupations where you may have come in contact with small metal slivers?	☐	☐
B 3 Have you ever been injured in the head, eye or body by a metallic foreign body that was not removed? (e.g. bullets, shrapnel, metallic slivers)	☐	☐
B 4 Do you have dental work held in place by magnets?	☐	☐
B 5 Do you have body piercing (non-removable metal jewellery)?	☐	☐
B 6 Is there any chance you may be pregnant?	☐	☐
Are you breast-feeding?	☐	☐
B 7 Do you have an IUD or contraceptive diaphragm?	☐	☐
B 8 Are you being treated for, or do you have a history of:		
Claustrophobia (fear of closed spaces)	☐	☐
Seizures	☐	☐

SECTION C

Some medical conditions can be made worse by stress. If you suffer from any of the following AND you think you may experience stress during the course of the study, please consult with your doctor before participating.

C 1 Do you have:	YES	NO
Uncontrolled high blood pressure	☐	☐
Ischemic heart disease	☐	☐
Congestive heart disease	☐	☐
Angina	☐	☐
Heart palpitations	☐	☐
Other heart disorders:	☐	☐
Specify:_____		
Panic attacks	☐	☐
Any other anxiety disorders:	☐	☐
Specify:_____		
_____		
C 2 Do you have any other illnesses?	☐	☐
Specify:_____		
_____		

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(Revised 19 May 1999 and 09 October 2002)

SECTION D
The pigment used in some tattoos is iron based and may cause skin irritation during the MRI scan, especially if the tattoo is large and has been done recently. If you have a tattoo, please discuss with the Human Studies Co-ordinator.

	YES	NO
D 1 Do you have a tattoo?	☐	☐

SECTION E - EXCLUSIONS FOR BRAIN / HEAD IMAGING
If you answer yes to questions E 1 or E 2, you will NOT be eligible to participate in brain/head imaging studies.

Do you have:	YES	NO
E 1 Cataract Lenses	☐	☐
E 2 Tattooed eyeliner	☐	☐

If you have any metal dental work you will be able to participate in brain studies if it is composed predominantly of precious or semi-precious alloys or amalgam.
Most dental work e.g., in crowns, bridges, caps, fillings, is composed of gold, semi-precious alloys or amalgam and is allowed (Please discuss your dental work with the Human Studies Co-ordinator if it contains metal)

	YES	NO
E 3 Do you have braces on your teeth or non removable dental retainers?	☐	☐
E 4 Do you have crowns or non-removable dental bridgework	☐	☐

All information provided on this form is accurate to the best of my knowledge.

Physician's Name: (please print) _____

Physician's Address (please print) _____

_____

_____

Physician's Signature _____ Date _____

Research Subject's Signature _____ Date _____

Appendix D

Protocol Number 1999-12 Central mechanism of preservation of eccentric muscle strength with age 11 March 1999
(Revised 19 May 1999 and 09 October 2002)

PAR-Q

1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

Yes ____ No ____

Comments:

2. Do you feel pain in your chest when you do physical activity?

Yes ____ No ____

Comments:

3. In the past month, have you had chest pain when you were not doing physical activity?

Yes ____ No ____

Comments:

4. Do you lose your balance because of dizziness or do you ever lose consciousness?

Yes ____ No ____

Comments:

5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?

Yes ____ No ____

Comments:

6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

Yes ____ No ____

Comments:

7. Do you know of any other reason why you should not do physical activity?

Yes ____ No ____

Comments:

I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction.

Name _____

Signature _____ Date_____

Appendix E

Protocol Number 1999-12 Central mechanism of preservation of eccentric muscle strength with age **11 March 1999**
(Revised 19 May 1999 and 09 October 2002)

Certification of Protocol Information Form

1. PRINCIPAL INVESTIGATOR'S CERTIFICATION

I certify that to the best of my knowledge the information provided is a full, accurate and reasonable representation of the facts.

_____
Name of Principal Investigator *(Print)*

_____
Signature of Principal Investigator

_____
Date

2. PRINCIPAL INVESTIGATOR'S CERTIFICATION

I certify that to the best of my knowledge the information provided is a full, accurate and reasonable representation of the facts.

_____
Name of Principal Investigator *(Print*

_____
Signature of Principal Investigator

_____
Date

3. GROUP LEADER'S CERTIFICATION

I certify that to the best of my knowledge the information provided is a full, accurate and reasonable representation of the facts.

_____
Name of Group Leader *(Print)*

_____
Signature of Group Leader

_____
Date

4. DIRECTOR GENERAL'S CERTIFICATION

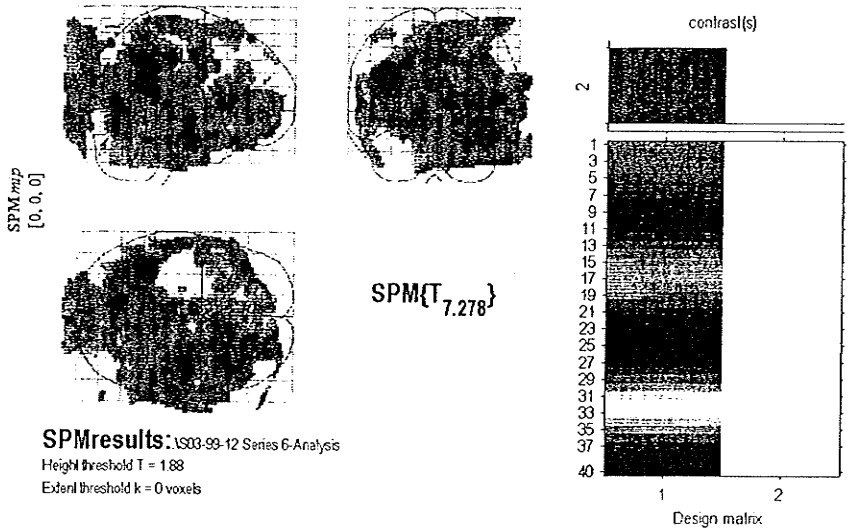
I certify that to the best of my knowledge the information provided is a full, accurate and reasonable representation of the facts.

_____ _____
Director General Date

Appendix F

Sample Activation Map – Eccentric No Head Restraint

Contraction



SPMresults: \S03-99-12 Series 6-Analysis
Height threshold T = 1.88
Extent threshold k = 0 voxels

Statistics: *volume summary (p-values corrected for entire volume)*

set-level		cluster-level			voxel-level				x,y,z [mm]
p	c	$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{corrected}$	T	(Z_e)	$p_{uncorrected}$	
1.000	16	0.000	58826	0.000	0.073	15.96	(4.98)	0.000	-38 -46 34
					0.163	14.23	(4.82)	0.000	46 22 10
					0.234	13.52	(4.75)	0.000	36 -10 -10
		1.000	33	0.765	1.000	4.50	(3.02)	0.001	66 50 12
					1.000	2.28	(1.92)	0.027	56 54 10
		1.000	251	0.355	1.000	4.40	(2.98)	0.001	-54 0 -30
					1.000	3.20	(2.45)	0.007	-44 0 -42
		1.000	38	0.745	1.000	4.01	(2.82)	0.002	-20 36 58
		1.000	21	0.820	1.000	3.44	(2.57)	0.005	32 -68 44
		1.000	19	0.831	1.000	3.35	(2.53)	0.006	62 -78 -26
		1.000	179	0.438	1.000	2.98	(2.33)	0.010	-48 12 60
					1.000	2.63	(2.14)	0.016	-46 20 58
		1.000	19	0.831	1.000	2.54	(2.08)	0.019	-8 -72 66
		1.000	30	0.778	1.000	2.39	(1.99)	0.023	-14 58 38
					1.000	2.38	(1.99)	0.023	-18 50 46
		1.000	11	0.879	1.000	2.15	(1.84)	0.033	-20 -16 36
		1.000	6	0.918	1.000	2.14	(1.83)	0.033	14 50 24
		1.000	1	0.974	1.000	1.95	(1.71)	0.044	32 -84 2
		1.000	1	0.974	1.000	1.94	(1.70)	0.045	60 52 26
		1.000	2	0.960	1.000	1.93	(1.69)	0.046	6 -82 -36
		1.000	1	0.974	1.000	1.91	(1.67)	0.047	-34 -70 60
		1.000	1	0.974	1.000	1.90	(1.67)	0.047	-14 -66 68

table shows at most 8 local maxima > 8.0mm apart per cluster

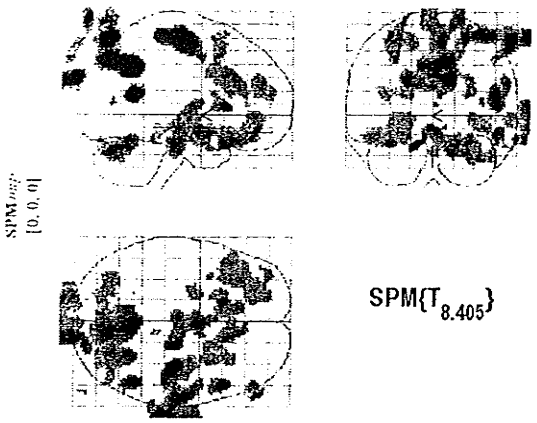
Height threshold: T = 1.88, p = 0.049 (1.000 corrected)
Extent threshold: k = 0 voxels, p = 1.000 (1.000 corrected)
Expected voxels per cluster, <k> = 316.640
Expected number of clusters, <c> = 60.35

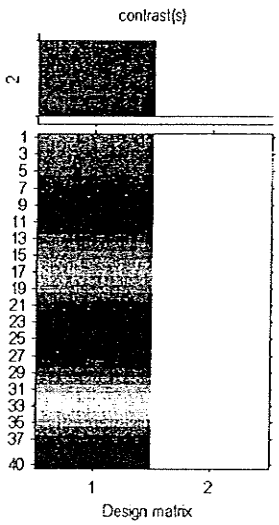
Degrees of freedom = [1.0, 7.3]
Smoothness FWHM = 14.6 14.5 16.6 [mm] = 7.3 7.3 8.3 [voxels]
Search volume: S = 1851816 mm^3 = 231477 voxels = 493.4 resels
Voxel size: [2.0, 2.0, 2.0] mm (1 resel = 468.75 voxels)

Appendix G

Sample Activation Map – Eccentric Head Restraint

Contraction





SPMresults: \S07-EccHR\S07-EccHR-MRFiles
Height threshold T = 1.85
Extent threshold k = 0 voxels

Statistics: *volume summary (p-values corrected for entire volume)*

set-level		cluster-level			voxel-level				x,y,z [mm]
p	c	$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{corrected}$	T	(Z_e)	$p_{uncorrected}$	
0.990	35	1.000	232	0.431	0.928	6.48	(3.78)	0.000	50 -54 14
		0.653	2260	0.021	0.995	5.47	(3.48)	0.000	4 -52 40
					0.995	5.44	(3.47)	0.000	10 -74 42
					1.000	4.91	(3.28)	0.001	6 -74 58
		0.965	1338	0.067	0.999	5.12	(3.36)	0.000	36 -22 64
					0.999	5.00	(3.32)	0.000	76 -32 62
					1.000	4.49	(3.12)	0.001	62 -16 58
		0.999	799	0.147	1.000	4.84	(3.26)	0.001	4 -2 -14
					1.000	4.02	(2.93)	0.002	20 -22 -22
					1.000	3.99	(2.91)	0.002	-14 18 -24
		1.000	735	0.163	1.000	4.54	(3.14)	0.001	12 -108 28
					1.000	3.73	(2.79)	0.003	-20 -106 28
					1.000	2.85	(2.32)	0.010	0 -110 24
		1.000	158	0.522	1.000	4.03	(2.93)	0.002	52 20 8
					1.000	2.34	(2.00)	0.023	56 12 16
		1.000	197	0.471	1.000	3.62	(2.73)	0.003	26 -68 64
		1.000	167	0.509	1.000	3.60	(2.73)	0.003	20 -90 76
		1.000	33	0.795	1.000	3.45	(2.65)	0.004	-30 -106 46
		1.000	87	0.646	1.000	3.29	(2.57)	0.005	60 46 26
		1.000	524	0.235	1.000	3.26	(2.55)	0.005	-34 -72 62
					1.000	2.69	(2.22)	0.013	-26 -76 70
					1.000	2.59	(2.16)	0.015	-22 -74 78
		1.000	52	0.733	1.000	3.22	(2.53)	0.006	50 44 -14
		0.999	832	0.139	1.000	3.21	(2.52)	0.006	-12 28 24
					1.000	3.13	(2.48)	0.007	12 22 32
					1.000	2.48	(2.09)	0.018	8 32 20

table shows at most 3 local maxima > 8.0mm apart per cluster

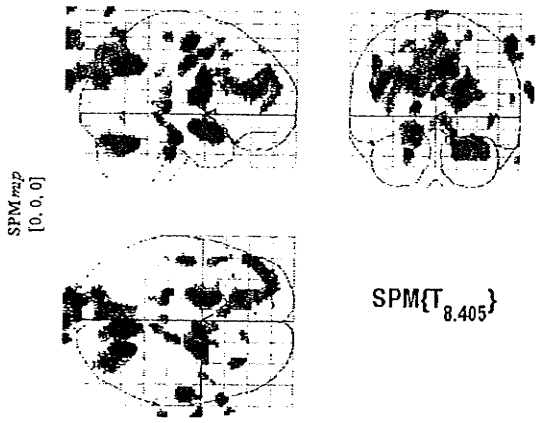
Height threshold T = 1.85, p = 0.049 (1.000 corrected)
Extent threshold k = 0 voxels, p = 1.000 (1.000 corrected)
Expected voxels per cluster, <k> = 400.023
Expected number of clusters, <c> = 50.12

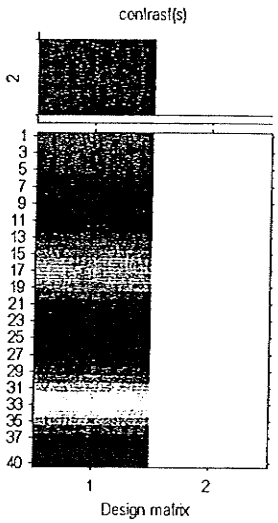
Degrees of freedom = [1.0, 8.4]
Smoothness FWHM = 15.1 17.1 16.5 [mm] = 7.5 8.6 8.2 [voxels]
Search volume: S = 1870240 mm^3 = 233780 voxels = 410.6 resels
Voxel size: [2.0, 2.0, 2.0] mm (1 resel = 531.79 voxels)
Page 1

Appendix H

Sample Activation Map – Concentric Head Restraint

Contraction





SPMresults: \S08-ConHR\S08-ConHR-MRFiles
Height threshold T = 1.85
Extent threshold k = 0 voxels

Statistics: *volume summary (p-values corrected for entire volume)*

set-level		cluster-level			voxel-level				x,y,z (mm)
p	c	$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{corrected}$	T	(Z_u)	$p_{uncorrected}$	
0.944	43	0.992	1037	0.089	0.986	5.89	(3.61)	0.000	24 -56 -26
					1.000	3.33	(2.59)	0.005	34 -76 -20
		1.000	683	0.160	0.999	5.07	(3.34)	0.000	-16 4 -10
					1.000	3.51	(2.68)	0.004	-16 6 -18
					1.000	3.15	(2.49)	0.006	-22 -10 -10
		0.999	842	0.122	1.000	5.04	(3.33)	0.000	22 -8 18
					1.000	4.52	(3.14)	0.001	24 0 26
					1.000	4.50	(3.13)	0.001	4 -4 24
		0.995	974	0.098	1.000	5.01	(3.32)	0.000	-50 36 20
					1.000	4.58	(3.16)	0.001	-42 48 30
					1.000	4.23	(3.01)	0.001	-46 46 22
		1.000	169	0.486	1.000	4.91	(3.28)	0.001	10 -4 48
					1.000	2.07	(1.81)	0.035	18 10 60
		0.380	2825	0.009	1.000	4.69	(3.20)	0.001	6 -66 40
					1.000	4.43	(3.10)	0.001	-20 -108 30
					1.000	3.43	(2.64)	0.004	-12 -100 34
		1.000	229	0.413	1.000	3.67	(2.76)	0.003	60 -14 56
		1.000	141	0.527	1.000	3.62	(2.74)	0.003	-48 -14 42
		1.000	171	0.483	1.000	3.59	(2.72)	0.003	2 -110 60
		1.000	86	0.631	1.000	3.50	(2.67)	0.004	-22 -28 -30
		1.000	51	0.722	1.000	3.43	(2.64)	0.004	16 -110 24
		1.000	97	0.607	1.000	3.33	(2.59)	0.005	-16 -30 8
					1.000	2.02	(1.78)	0.038	-18 -42 8
		1.000	192	0.455	1.000	3.28	(2.56)	0.005	14 -22 -22
					1.000	3.14	(2.49)	0.006	6 -36 -4
					1.000	2.70	(2.23)	0.013	12 -28 -12

table shows at most 0 local maxima > 8.0mm apart per cluster

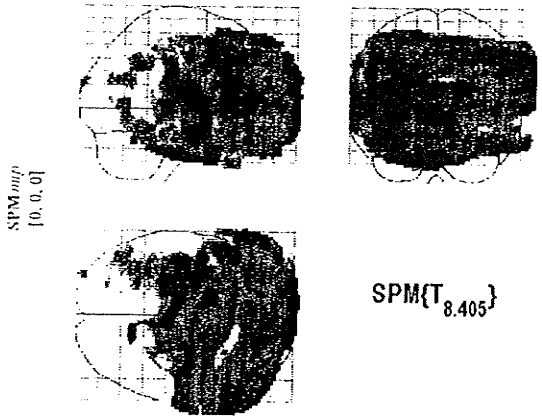
Height threshold: T = 1.85, p = 0.049 (1.000 corrected)
Extent threshold: k = 0 voxels, p = 1.000 (1.000 corrected)
Expected voxels per cluster, <k> = 365.808
Expected number of clusters, <c> = 53.89

Degrees of freedom = [1.0, 8.4]
Smoothness FWHM = 14.8 16.5 15.9 [mm] = 7.4 8.3 8.0 [voxels]
Search volume: S = 1864224 mm^3 = 233028 voxels = 447.5 resels
Voxel size: [2.0, 2.0, 2.0] mm (1 resel = 486.30 voxels)
Page 1

Appendix I

Sample Activation Map – Concentric No Head Restraint

Contraction



SPMresults: \S08-ConNHR-MRF.mat
Height threshold T = 1.85
Extent threshold k = 0 voxels

Statistics: *volume summary (p-values corrected for entire volume)*

set-level		cluster-level			voxel-level				x,y,z [mm]
p	c	$p_{corrected}$	k_E	$p_{uncorrected}$	$p_{corrected}$	T	(Z_{up})	$p_{uncorrected}$	
1.000	22	0.000	53371	0.000	0.515	8.30	(4.21)	0.000	-28 -28 2
					0.622	7.78	(4.10)	0.000	-52 20 8
					0.738	7.26	(3.98)	0.000	-26 -28 22
		1.000	519	0.190	1.000	4.62	(3.18)	0.001	-38 -50 36
					1.000	3.17	(2.50)	0.006	-46 -62 22
		1.000	28	0.789	1.000	3.84	(2.84)	0.002	-44 -30 56
					1.000	2.35	(2.01)	0.022	-38 -24 52
					1.000	2.01	(1.77)	0.038	-46 -20 50
		1.000	119	0.537	1.000	3.35	(2.60)	0.005	6 -42 48
					1.000	3.10	(2.46)	0.007	8 -36 40
					1.000	2.77	(2.27)	0.012	24 -30 48
		1.000	18	0.838	1.000	2.89	(2.34)	0.010	-32 -94 24
		1.000	25	0.803	1.000	2.86	(2.33)	0.010	-22 -76 22
		1.000	7	0.910	1.000	2.86	(2.32)	0.010	38 -36 -22
		1.000	13	0.867	1.000	2.81	(2.29)	0.011	-66 12 -12
		1.000	200	0.415	1.000	2.35	(2.01)	0.022	-54 44 -18
					1.000	2.30	(1.97)	0.024	-46 44 -36
		1.000	8	0.902	1.000	2.11	(1.85)	0.032	-24 20 -8
		1.000	4	0.937	1.000	2.04	(1.80)	0.036	-42 -42 12
		1.000	2	0.960	1.000	2.03	(1.79)	0.037	30 -36 56
		1.000	21	0.822	1.000	2.00	(1.77)	0.039	-6 16 12
		1.000	8	0.902	1.000	1.99	(1.76)	0.039	-4 -32 22
		1.000	9	0.895	1.000	1.96	(1.74)	0.041	28 18 -26
		1.000	1	0.975	1.000	1.94	(1.72)	0.042	-46 -22 42

table shows at most 8 local maxima > 8.0mm apart per cluster

Height threshold: T = 1.85, p = 0.049 (1.000 corrected)
Extent threshold: k = 0 voxels, p = 1.000 (1.000 corrected)
Expected voxels per cluster, <k> = 322.076
Expected number of clusters, <c> = 44.24

Degrees of freedom = [1.0, 8.4]
Smoothness FWHM = 16.5 12.9 16.1 {mm} = 8.2 6.5 8.0 {voxels}
Search volume: S = 1253936 mm^3 = 156742 voxels = 337.3 resels
Voxel size: [2.0, 2.0, 2.0] mm (1 resel = 428.16 voxels)
Page 1

Appendix J

Assessment of Signal to Noise Ratio During Isokinetic Dynomometry in the MR Environment

Brennan Ryan[1,2], Wolfgang Richter[1], Michelle Porter[2]
[1]National Research Council of Canada, Institute for Biodiagnostics, [2]University of Manitoba, Winnipeg, MB, Canada

Abstract

Functional MRI studies involving isokinetic dynamometry are limited in the MR environment by three major factors: 1) The ferromagnetic nature of the dynamometer dictates significant consideration to safety precautions and technical complications during equipment setup; 2) Broadband RF emissions from the dynamometer can create significant image artifacts; and 3) The magnitude of motion artifacts produced during muscle contractions can cause severe spatial mislocalization. Here, we show that the signal to noise ratio can be maintained while the dynamometer is operated, through the employment of custom shielding.

Introduction

Quantifying load and imaging brain function are critical factors in neuromuscular investigations. However, it is difficult to obtain data from both of these measures simultaneously. Specifying the parameters of a muscle contraction during fMRI have traditionally been restricted to rudimentary means at best. For example, velocity of shortening or lengthening and relative load are undefinable without the aid of a dynomometer. These characteristics have significant effects on the neural proscessing employed (1). Three major limitations have precluded the use of isokinetic dynamometers during fMRI. First, strong magnetic interactions between the magnet and the dynamometer can create potentially hazardous conditions. Second, the dynamometer is a major source of broadband RF interference during image acquisition, and third, substantial image motion artifact may result from the muscle contractions. In this study we will show that RF interference can be overcome with adequate shielding of the dynamometer. It was our prediction that the signal to noise ratio will not be significantly different between imaging during the operation of the shielded dynamometer, and in the images acquired with the dynamometer disconnected.

Methods

All experiments were performed on a General Electric (Waukesha, WI) 1.5 Signa LX MR scanner equipped with Echospeed actively-shielded gradient coils (22mT/m, 120 T/m/s). Two slices, 10 mm thick, with a resolution of 64x64, were acquired, totaling 10 volumes. Slice orientation was axial, and all data was analyzed using the statistical package Stimulate.

The test machine was a System 3 Biodex Isokinetic Dynamometer (see Figure 1). It consisted of three main areas capable of generating RF interference; the computer console, the power and signal cables and the motor. Placing the computer outside the magnet room and relying on the shielding inherent in the room eliminated computer generated RF interference. The signal cables were fed through the wave guides and connected to the Biodex motor which was situated outside the 5 Gauss line. The shielding of the signal and power cables was provided by a copper conduit electrically connected to the wave guide at one end, and the motor shielding at the other. A conductive fabric bag custom built to accommodate the dynamometer shielded the motor.

Two conditions will be imaged. The first will provide images with the Biodex disconnected (Condition D), rendering it incapable of generating RF interference. The second will be acquired with the Biodex running (Condition R) (see Figure 2). During both conditions the shielding will be applied. The mean signal intensity for 20 random points inside and outside the phantom will be calculated for each condition. Also, the standard deviation of these points will be determined. Based on the signal intensity and standard deviation of the randomly selected values the signal to noise ratio will be calculated as follows:

$$S:N = \text{Mean Signal Intensity}/SD$$

The result will be 20 signal to noise ratios for each series for both inside the sphere and outside. These values were compared between conditions via Student's T-tests to assess the efficacy of the shielding.

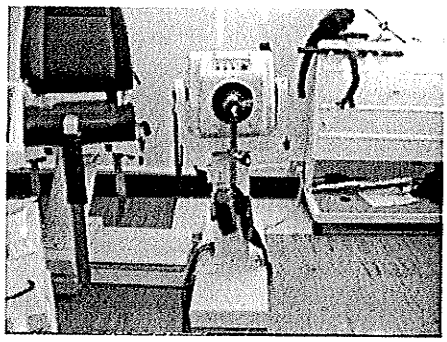


Fig. 1 Isokinetic Dynamometer without Console

Results

The T values were determined as follows:

Outside Sphere

$$Sp^2 = \frac{\Sigma x_1^2 - (\Sigma x_1)^2/n_1 + \Sigma x_2^2 - (\Sigma x_2)^2/n_2}{n_1 - 1 + n_2 - 1}$$

$$Sp^2 = \frac{175.02 - 156.46 + 155.87 - 145.48}{38}$$

$$Sp = .87$$

$$\text{Standard Error} = \sqrt{\frac{Sp^2}{n_1} + \frac{Sp^2}{n_2}}$$

$$\text{Standard Error} = 0.28$$

$$\text{Difference Between Means} = 2.8 - 2.7 = 0.1$$

$$\text{T Value} = 0.1/0.28 = .3571$$

Inside Sphere

$$Sp^2 = \frac{\Sigma x_1^2 - (\Sigma x_1)^2/n_1 + \Sigma x_2^2 - (\Sigma x_2)^2/n_2}{n_1 - 1 + n_2 - 1}$$

$$Sp^2 = \frac{372425 - 359141.44 + 390760.53 - 374158.95}{38}$$

$$Sp = 28.04$$

$$\text{Standard Error} = \sqrt{\frac{Sp^2}{n_1} + \frac{Sp^2}{n_2}}$$

$$\text{Standard Error} = 8.86$$

$$\text{Difference Between Means} = 134 - 136.78 = 2.78$$

$$\text{T Value} = 2.78 \div 8.86 = .3138$$

For 38 degrees of freedom the calculated t value for the values outside the sphere was 0.3571. This is far below the p .05 critical value of 2.021, indicating that there was no significant difference between group D and group R.

For the values inside the sphere, the calculated t value was 0.3138 for 38 df. Again, this is far below the critical value of 2.021. (p 0.05). There was no significant difference between the two groups.

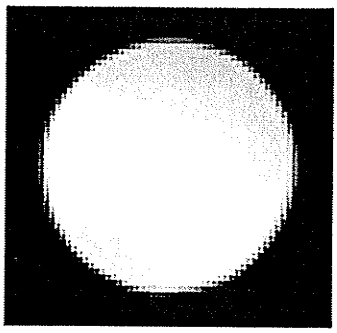


Fig. 2 Phantom image acquired with dynamometer disconnected

Discussion

Studies of neuromuscular physiology have been limited by a lack of control for variables such as relative load and speed of contraction. Inferences about brain activation while these variables are uncontrolled are speculative at best. The use of dynamometers such as the Biodex System 3 allows these variables to be accounted for and expands the list of potential applications of fMRI.

The results of this study demonstrate the possibility of using an isokinetic dynamometer in the MR environment. The absence of a significant difference in the signal to noise ratio of the Biodex during operation versus unpowered clearly shows the effectiveness of the shielding. However, other technical considerations cannot be overlooked when considering isokinetic dynamometry during fMRI. Motion artifact resulting from muscular contractions can be a serious complication. Furthermore, although this study demonstrates the possiblility of dynamometer use in the MR environment, it must be noted that the EMI was a sporadic problem. The shielding was effective when it was properly secured but any slight fault in it's application resulted in RF leakage. Extraordinary care must be employed during equipment setup to avoid the unexpected appearance of RF induced artifact in the images. With this in mind the isokinetic dynamometer can be employed for future studies directed at topics such as muscle fatigue, muscle pathology, and stroke recovery.

Acknowledgements

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References

1. Enoka, R.M., J. Appl. Physiol., 81:2339-2346, 1996.

Steps Taken before Final Modifications

The magnetic interactions, RF interference, and motion artifact were the three main obstacles to be overcome. For each of these issues, the final solutions were the product of several intermediate steps along the way. This section describes those preliminary steps.

The magnetic interactions were the simplest of the three problems to resolve, and required the least amount of trial and error. The initial idea had been to use a simplistic sand bag and pulley system to provide the load during the muscle contractions, and as a result, the magnetic interactions and RF interference would not have been an issue. However, the loading method was unsatisfactory. Controlling the speed of contraction, relative load, and the ability to perform only one type of contraction were not possible with this method. This meant that an isokinetic dynamometer was needed and the decision to use the Biodex was made. With this decision came the understanding that much more extensive modifications were needed in order to incorporate this technology.

The connecting rod that attached the ankle unit to the Biodex assembly was initially constructed of wood, and regardless of the loading mechanism, it was obvious that the wooden connector had too much flex and could not transfer the torque from the subject to the dynamometer effectively. A square aluminum pole was substituted, to much greater success. The ankle unit was generally unmodified from its initial construction, apart from the addition of a wooden support beneath the subject's knee to add a level of stability and a more standardized knee angle.

The RF shielding underwent several changes through the course of the project. The shielding was initially constructed of conductive fabric surrounding the entire Biodex module and a flexible metal conduit was used to shield the cables. After several unsatisfactory testing trials it was determined that this method was ineffective, and instead a wooden box was built and covered in copper sheeting to house the dynamometer. This box provided a solid copper encasement surrounding the entire Biodex apparatus with the exception of the cabling and the computer. The cables were encased in a soldered copper conduit extending from the Biodex to the wave guides. After acquiring clean images with the dynamometer inside of the copper box the problem of attaching the connecting rod was addressed. With the box completely sealed it was determined that it was possible to provide effective shielding. The question then became how to breach the shielding to allow the aluminum connecting rod to attach to the Biodex armature while maintaining the integrity of the shielding. To do this the conductive fabric was used. Due to the intermittent nature of the problem, several testing sessions were needed to proceed via trial and error. Trials were performed with the connecting rod separated by a plastic (non conductive) junction between the connecting rod and Biodex armature, with a single layer of conductive fabric used, with conductive tape used to cover any imperfection or hole in the fabric, and with a double layer of conductive fabric. The end result was electrical isolation of the connecting rod from the Biodex, and the employment of a double layer of conductive fabric. The RF shielding was a time consuming and difficult problem to over come due to its inconsistency. On several occasions clean images were obtained using one method, only to have artifact in the images on the scheduled testing day. Testing for those days was cancelled and the RF

troubleshooting continued. However, the difficulty developing the head restraint system proved to be the most troublesome of issues.

The head restraint system began as a fiberglass half pipe with Velcro straps to restrict head motion in each plane. Initially, two straps were used. One prevented motion in and out of the magnet by securing under the chin of the subject and to the top of the cylinder. The other prevented head motion up and down, and to a lesser extent side to side. It was quickly discovered that this system was insufficient and an adjustable top plate was added to increase the effectiveness. In this prototype the chin strap secured the head against the top plate, and the top plate could be tightened to further restrict the head. Again it was determined that the strapping system was inadequate, and the remaining two straps were eliminated. In their place a rigid chin bar was developed that provided a fixed point of contact for the head. This allowed the top plate to hold the head more securely against a fixed stop. After further testing it was deemed necessary to add restrictions targeted at reducing the side to side motion of the head. For this task telescoping pads were designed that could be secured against the side of the head to prevent rotation and side to side motion. The end product in the development of the head restraint system saw the use of the top plate, the chin bar and the telescoping side pads.

Appendix K

Steps Taken before Final Modifications

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