# Investigating Upper Limb Vibration as an Exercise Modality for Persons with Spinal Cord Injury

by

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Strong upper limb musculature is important for persons with spinal cord injury (SCI) to operate manual wheelchairs in order to live independent and meaningful lives. Furthermore, strong upper limb musculature can help to prevent injury and improve pain caused by overuse. Targeted upper limb vibration may be a viable option for persons with SCI to build muscle quickly and efficiently, can be performed in the home and eliminates some of the barriers associated with strength training for persons with SCI. Two research studies aimed to investigate the use of upper limb vibration for persons with SCI. The first research study assessed the feasibility of completing a single training session using upper limb vibration and compared vibration training to standard dumbbell training with respect to power output, blood lactate, heart rate and rating of perceived exertion. More than 80% of participants were able to hold the dumbbell for 45s for only three exercises on the right side and 2 exercises on the left side. Participants perceived exertion was significantly greater when training with vibration for 4 out of the 7 exercises ($p < .033$). The second study aimed to assess the feasibility, acceptability and implementation of a 12-week training program using upper limb vibration. The secondary aim was to assess the impact of the training program on upper limb strength, power and pain, as well as changes in wheelchair propulsion and transfer ability. The 12-week training program met some of the criteria for feasibility and implementation. One of the three participants who completed the training protocol found vibration training to be acceptable. Improvements in wheelchair propulsion and transfer ability were seen at 12-weeks compared to baseline for two participants. Other results from the 12-week training study

were mixed, with no clear success for many of the outcomes. Future studies with dumbbell exercise being completed isometrically are needed to show a difference in physiological measures between vibration training and dumbbell training, which can be truly attributed solely to the addition of vibration. Furthermore, an additional study should be conducted to determine appropriate starting weight for training and appropriate training progression.

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# 1.0 Introduction

Participation in physical activity is vital for a healthy lifestyle (ODPHD). However, more that 80% of adults do not participate in physical activity at the recommended levels (CDC). For persons with physical disabilities, it is particularly challenging to engage in physical activity (Greer et al., 2012). Of the 3.6 million non-institutionalized wheelchair users in the United States, 2.8 million are manual wheelchair users (Greer et al., 2012; LaPlante & Kaye, 2010). Strong upper limb musculature is essential for people who have paraplegia from spinal cord injury (SCI), dysfunction or disease to operate manual wheelchairs in order to live independently and perform activities of daily living such as wheelchair propulsion, wheelchair transfer activities, and weight relieving maneuvers (ML. et al., 2005). These activities, however, place high demands on the shoulders, elbows and wrists (Gagnon et al., 2009; Morrow, Hurd, Kaufman, & An, 2010; Sabick, Kotajarvi, & An, 2004), and practicing them over time negatively impacts upper limb health (Brose et al., 2008). The benefits of upper limb resistance training for wheelchair users with paraplegia have been well documented and include moderate to large gains in muscle strength, endurance, and performance of activities of daily living (Fisher, McNelis, Gorgey, Dolbow, & Goetz, 2015; Jacobs & Nash, 2004; Valent, Dallmeijer, Houdijk, Talsma, & van der Woude, 2007). Beyond increased strength and work capacity, resistance training can assist in combating muscle imbalances that have been shown to lead to overuse injuries and pain (Curtis et al., 1999; Mulroy et al., 2011a; Van Straaten, Cloud, Morrow, Ludewig, & Zhao, 2014). Resistance training may help to prevent pain and injury, while improving quality of life and performance of activities of daily living such as transfers and wheelchair propulsion.

## 1.1 Strength Requirements for Activities of Daily Living

Wheelchair transfers and propulsion have been shown to require high demands on the upper extremities. While level propulsion has been shown to require low to moderately high demands on shoulder and elbow muscles , greater demands are required for more intense propulsion tasks such as propelling up ramps, curbs, non-level surfaces, rough terrain and fast propulsion (Chow et al., 2009; Lalumiere et al., 2013; Morrow et al., 2010; Van Drongelen et al., 2005); ramp propulsion has been classified as the most intensive propulsion activity (Morrow et al., 2010). Sabick et al measured peak upper limb torques during a ramp task (2.9 degrees) and compared those to the isometric peak torque strength generating capacity of arm muscles. The demands for shoulder flexion and external rotation, elbow extension, and forearm muscles during ramped propulsion were close to their full muscle generating capacity suggesting that they may be highly prone to overuse and fatigue (Sabick et al., 2004). Additionally, daily wheelchair propulsion tasks such as startup and braking impart much higher demands on the shoulder joint and require higher muscle demands compared to level propulsion (A. M. Koontz et al., 2005; Morrow et al., 2010). Furthermore, pressure relief tasks and transfers impart shoulder forces that are three times greater than level wheelchair propulsion (Morrow et al., 2010).

In addition to propulsion tasks, manual wheelchair users with SCI perform between 15 and 20 wheelchair transfers per day (Gagnon et al., 2009). During transfers, the triceps, trapezius, latissimus dorsi, serratus anterior, supraspinatus, infraspinatus, pectoralis major, anterior deltoid, and biceps are recruited for lifting and moving the body (Gagnon et al., 2009). During the lift phase of a transfer, the pectoralis major works at approximately 81% of its muscle capacity, suggesting that it is the primary muscle in lifting, supporting, and shifting trunk weight (Gagnon et al., 2009). In addition, the triceps, deltoid, trapezius, and latissimus torsi also all exhibit high peak intensities during transfers, which are greater than 50% of their maximum capacity (Gagnon et al., 2009). Transfers that are non-level, either higher or lower than the wheelchair seat height (e.g.., wheelchair to floor transfers) increases the muscular demands compared to level transfers (Gagnon et al., 2009). Wheelchair users are encouraged to make level transfer whenever possible, however, many transfers that wheelchair users make daily are not level. Transfers such as car transfers as well as many surfaces found in the community (i.e., public toilets, amusement parks, restaurant seats/benches) are not easily modifiable and involve transfers to higher and lower seats (Toro et al., 2013). Furthermore, having to make higher and lower transfers compared to level, have been found to greatly limit participation in certain places, activities and events (Arva et al., 2009; Kulich et al., 2015).

While vital for independence and community participation, the high demands caused by wheelchair propulsion and transfers often lead to pain and overuse injuries . The shoulders, elbows and wrists are all highly susceptible to degeneration, overuse injuries, and pain (Sie et al., 1992). In particular, the shoulder is the most common site of upper extremity pain in manual wheelchair users, with reported pain ranging from 32% to 78% (Morrow et al., 2010). A range of pathological conditions at the shoulder have also been documented including impingement syndrome, adhesive capsulitis, recurrent dislocations, rotator cuff tears, and tendinitis (Boninger et al., 2001). One proposed method to mitigate pain and pathology is strength training and exercise. A recent study by Mulroy et al (Mulroy et al., 2015) prospectively followed a group of manual wheelchair users with paraplegia to see if lower shoulder strength at baseline, higher transfer frequencies and greater daily wheelchair activity would be predictive of those who developed shoulder pain. About 40% of the participants developed pain over the three year study, and lower shoulder strength across all shoulder muscle groups was observed in the group that developed pain . The study also found less strenuous wheelchair activities (e.g. slower daily velocities) and fewer transfers within the group that eventually developed pain, suggesting that the demands of the various activities required after SCI exceeds the muscle capacity for many people. Therefore, increasing the strength of the upper limb muscles has the potential to improve one's ability to meet the demands of high-intensity propulsion and transfer tasks and potentially reduce the propensity to develop shoulder pain.

### 1.2 Effects of Strength Training in Spinal Cord Injury

For persons with SCI, engaging in structured resistance training of the upper limbs 2-3 times/week leads to improvements in muscle strength, increased performance during activities of daily living and improved quality of life (Valent et al., 2007). While a combination of endurance and resistance training is recommended for overall increased fitness, resistance training targets and leads to greater gains in upper limb work capacity, muscle strength, and power compared to endurance training (Dost et al., 2014; Jacobs & Nash, 2004). Resistance training is also recommended for combating muscle imbalances associated with overuse (Burnham et al., 1993; ML. et al., 2005) and for treating shoulder pain (Curtis et al., 1999; Mulroy et al., 2011a; Van Straaten et al., 2014). In one study wheelchair users with SCI who concentrated on strengthening the muscles of the posterior shoulder and upper back while stretching the muscles of the anterior shoulder and chest reported greater pain relief and an easier time performing propulsion and weight relief activities when compared to an attention control group who received video instruction on pain relief (Mulroy et al., 2011a). Most of the studies evaluating effects of training report outcomes of muscle strength, anaerobic power, endurance, pain, and general improvement in the performance of daily tasks (e.g. Functional Independence Measure) (Fisher et al., 2015). Few studies have examined the effects of resistance training on propulsion performance and skills (Durán, Lugo, Ramírez, & Lic, 2001; Fisher et al., 2015; Rodgers, Keyser, Rasch, Gorman, & Russell, 2001). A study by Duran et al. found significantly the time to complete the wheelchair skills test, as well as specific items related to wheelchair propulsion to be significantly less following a 16-week exercise program (Durán, Lugo, Ramírez, & Lic, 2001). Another study by Rodgers et al. found that after a 6-week strength training program, participants had significantly better wheelchair propulsion economy compared to baseline. Furthermore, no studies have looked specifically at the impact of resistance training on transfer ability.

### 1.3 Barriers to Strength Training in Spinal Cord Injury

Many barriers associated with strength training and exercise in general in persons with SCI are present including, architectural/environmental barriers, physiological barriers as well as inadequate ways to measure and track weight or body composition (Scelza et al., 2005). Transportation and lack of accessible equipment in gyms were identified as major environmental barriers to exercising. The majority of gym equipment used for strength training and endurance training require difficult transfers that the majority of wheelchair users are unable to perform, with additional equipment not having a range of adjustability appropriate for wheelchair users (Rimmer et al., 2004). Additionally, fear of exercising and strength training, a lack of knowledge of appropriate exercise regimens, as well as a feeling of a lack of support from medical professionals have been identified as psychological barriers (Levins et al., 2004). Societal stigma and lack of motivation have also been cited as barriers to exercise (Kehn & Kroll, 2009). Physiologically, it is also more difficult for persons with SCI to change their body composition; both losing weight and gaining muscle. Due to a lower basal metabolic rate (BMR), they are less able to mobilize adipose stores in the body. Additionally, due to prolonged sitting, poor nutrition and over eating can cause more detrimental effects in a person with SCI compared to the able-bodied population (Myers et al., 2007). Lastly, an accurate and effective way to measure weight and body composition in SCI is lacking. Due to differences in fat distribution and muscle atrophy, traditional scales and body composition measures, in particular BMI, are not as accurate for SCI (Spungen et al., 2003).

### 1.4 Vibration as an Exercise Modality

Vibration exercise has recently gained popularity showing in numerous studies to increase muscle strength, power and performance when integrated into a resistance training program (Y Osawa et al., 2013; Jörn Rittweger, 2010) or when used as a supplement to alternative modes of training (Mueller et al., 2015). The majority of exercise programs with vibration have been performed using whole body vibration, where the exercise is performed on a vibrating platform (Jörn Rittweger, 2010). The effects of vibration on the body have been extensively studied and guidelines have been developed to regulate exposure (L. Griffin et al., 2001). The frequency, amplitudes and exposures used in previous vibration studies are considered acceptable and safe (Jörn Rittweger, 2010; Rubin et al., 2003). Results from these studies combined suggest that vibration may be an effective and safe tool for enhancing resistance training among wheelchair users with SCI.

### 1.4.1 Theory Behind Vibration

After the initiation of a consistent standard resistance training program, two adaptations occur: neural adaptations and muscular adaptations (Kenney, 2015). Early neural adaptations allow for increased efficiency of motor unit recruitment and improved responses to myofibril depolarization. Later muscular adaptations include improved cellular metabolism leading to increased actin and myosin synthesis causing greater cell density and volume. Combined, these adaptations lead to strength gains after initiation of resistance training.

During standard resistance training muscle contraction is initiated when the motor cortex sends an action potential from the brain though the peripheral nervous system to the motor neuron innervating the muscle that will contract. This action potential arrives at the neuromuscular junction signaling the release of acetylcholine which binds to the outer membrane of the muscle and the t-tubules depolarize. This depolarization elicits the release of calcium ions from their sacs. The calcium then binds to troponin causing a conformational change, inducing movement of tropomyosin to uncover active sites on actin allowing the myosin heads to bind to the active actin sites. Muscle contraction is induced when the actin slides relative to the myosin (Baechle & Earle, 2008). Together, groups of fascicles that make up the muscle, contract together to cause muscle movement and stability. The early neural adaptations to resistance training change this muscle contraction process, allowing for increased muscle contraction and fiber recruitment.

Vibration is believed to enhance the neural adaptations that occur with exercise by eliciting a tonic stretch reflex (Boucher et al., 2013). A reflex is a response to a stimulus that does not involve the brain (figure 1). There are two parts to a reflex: the afferent signal pathway and efferent signal pathway. When an external stimulus is applied, a quick stretch is delivered to the muscle and spindles embedded parallel to the muscle fibers (Lundy-Ekman, 2013). An afferent impulse signal is then sent to the spinal cord where an association neuron transfers the impulse to the efferent neuron. An efferent impulse signal is sent back to the neuromuscular junction and acetylcholine is released. The muscle contracts following the steps of a standard muscle contraction described above (Matthews, 1991; Stam & Van Crevel, 1990). Compared to a muscle contraction that is initiated within the brain as with standard resistance training, the initiation of the contraction is coming from an external stimulus that triggers the sensory fibers in the muscle.

There are two types of stretch reflexes: a phasic and a tonic reflex (Lundy-Ekman, 2013). A phasic reflex is a muscle contraction in response to a quick stretch. The reflexive muscle contraction of the quadriceps after tapping the quadriceps tendon is an example of a phasic stretch reflex. A tonic stretch reflex is a prolonged sustained contraction which is present as long as the stretch is maintained (e.g. stimulus from vibration). During a tonic stretch reflex, the primary endings of the muscle spindles are being continuously stimulated leading to a sustained muscle stretch. The reflex pathway is then being continuously initiated and the muscles are receiving signals for continuous muscle contraction(Lundy-Ekman, 2013).

Vibration acts as an external stimulus that triggers the tonic stretch reflex (Jordan, Norris, Smith, & Herzog, 2010; Jörn Rittweger, 2010). The tonic vibration reflex (Mahieu et al.) has been suggested by numerous studies to be a neural reflex associated with vibration training (Boucher, Abboud, Nougarou, Normand, & Descarreaux, 2015; Cardinale & Bosco, 2003). Furthermore, the tonic reflex has been suggested as a unique response to vibration, a physiological response that doesn't occur with standard resistance training (Jörn Rittweger, 2010). Once the vibration stimulus is applied, the muscle spindles inside the muscle detect the stimulus is stretching the muscle and send a signal through the afferent pathway to the central nervous system. The ends of the muscle spindle fibers are highly sensitive to vibration stimulus. When vibration is applied, the afferent pathway is hyperactive causing the primary endings of the muscle spindles to be constantly stimulated (Cardinale & Bosco, 2003). This causes the completion of the stretch reflex muscle contraction as described above to occur continuously. When the vibration frequency exceeds a certain frequency (10 Hz for plates, and 15 Hz for dumbbells) the stretch reflex is initiated. As the frequency of the stimuli increases, so does the frequency of the stretch reflex, until the reflex becomes tonic. When this happens, the muscles do not have time to complete the full contraction and relaxation cycle, leading to the tonic vibration reflex (Pollock, Woledge, Martin, & Newham, 2012).

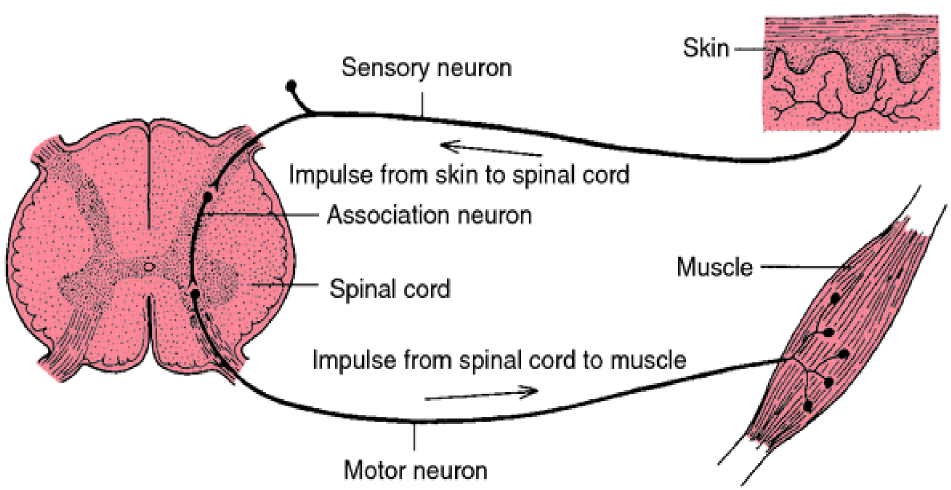



**Figure 1. Diagram of the stretch reflex pathway that leads to a muscle contraction after the muscle is stimulated by anexternal stimulus**

### 1.4.2 Vibration Mechanism and Electromyography

Several studies have used electromyography (EMG) in order to understand and explain the physiological response to whole body vibration. As explained above, vibration is thought to enhance motoneuron recruitment and activation as well as increase the neuromuscular recruitment patterns (Eckhardt et al., 2011). Eckhardt et al. showed that squatting with vibration compared to squatting without vibration had increased integrated EMG values and increased percent maximum voluntary contraction (MVC) values in the vastus lateralis (Eckhardt et al., 2011). Another study showed increased percent MVC values in the vastus lateralis and biceps femoris when vibration was added to dynamic squatting compared to not using vibration (Tom J. Hazell et al., 2007). Furthermore, as the frequency of the vibration increased, the EMG muscle activity increased. These and other studies collected EMG data continuously throughout the training sessions. While other studies have looked at differences in MVC before and after a single session of vibration training. Results from the literature where EMG was measured before and after training are mixed compared to the body of literature that measured EMG continuously during the vibration training. Previous studies have resulted in no change, increases and decreases in MVC values before and after vibration training (Di Giminiani et al., 2014a; Humphries et al., 2004; Mischi & Cardinale, 2009). Decreases in the MVC values post training have largely been attributed to fatigue from training. Although results are mixed in studies that have examined MVC values before and after vibration training, muscle activity collected during vibration training has shown increased muscle activity compared to standard isometric or dynamic training. This evidence assists in supporting the hypothesis that vibration increases the muscle activation and recruitment patterns.

### 1.4.3 Vibration Parameter Selection

Vibration as an exercise intervention has been studied in a variety of populations, with varying ages, levels of fitness, and persons with disabilities and without disabilities. However, the results are highly varied within the same study population, even within the same outcomes. Many parameters are adjustable and can be manipulated when developing a vibration protocol. Standard parameters have yet to be established, likely adding to the wide range of results presented in the literature. These parameters include frequency, amplitude, duration of vibration, rest period between exposures, body position, loading while using vibration and type of vibration.

#### 1.4.3.1 Frequency and Amplitude

Frequency and amplitude have been widely studied compared to other vibration parameters. Frequency refers to the number of times a complete wave takes place during one second. The vibration amplitude describes the intensity of the vibration stimulus, described by its displacement, or distance from the central point; also, can be described as the height of the signal. The displacement, also known as peak to peak displacement, is the maximum movement in one direction and the peak movement in the opposite direction (Cidem et al.). Generally, results of previous research studies indicate that when frequencies are above 30Hz, higher muscle activities and better performance results were obtained compared to lower frequencies. Muscle activity tends to increase linearly with higher frequencies leading to greater muscle activities and performance outcomes. Forty hertz has been shown to be the optimal frequency to see maximal EMG activity (Tom J Hazell, Kenno, & Jakobi, 2010; Lienhard, Cabasson, Meste, & Colson, 2014; Ramona Ritzmann, Gollhofer, & Kramer, 2013). Frequencies greater than 50Hz cause detrimental effects on muscle activity and performance suggesting that muscle fatigue may occur at these higher frequencies (Bedient et al., 2009).

Larger amplitudes also lead to higher muscle activations and greater improvements in performance outcomes (Pollock et al., 2010) (Marín et al., 2009). Greater improvements were seen in lower extremity muscle strength, flexibility, power and blood cell velocity with larger amplitudes (table 2) (Gerodimos et al., 2010; Lythgo, Eser, De Groot, & Galea, 2009; Petit et al., 2010). Amplitudes greater than 4 mm have a greater effect on strength and performance outcomes compared to amplitudes smaller than 4 mm. Frequency and amplitude are closely related; higher frequencies paired with larger amplitudes lead to the greatest improvements in strength and performance outcomes, as well as other outcomes such as blood velocity; with optimal parameters being the combination of 40Hz and 4mm. Thus, higher frequencies and amplitudes in combination leads to greater improvements in vibration outcomes with optimal parameters being 40Hz and 4mm.

#### 1.4.3.2 Duration

The duration of vibration can be studied in two ways; the time per bout of vibration as well as the total time of vibration, multiple vibration bouts, during one session (i.e. one training day or study session). Studies that have looked at the duration of vibration found that as little as 30 seconds per bout of vibration can lead to acute effects in power and counter movement jump height (Adams et al., 2009). However, 60 seconds per bout of vibration has been shown to be the optimal length of time, leading to the greatest improvements in performance outcomes (Da Silva-Grigoletto et al., 2011). Whereas, 90s per bout showed decreases in power output, as measured by squat jump performance and counter movement jump performance; likely due to muscle fatigue (Da Silva-Grigoletto et al., 2011). Also, a total of 3, 1-minute sessions were not enough to affect squat jump and counter jump performance. However, 9 total sessions of 1-minute bouts of vibration had negative effects on these outcomes, suggesting that nine total minutes of vibration on the same muscle is too long, leading to fatigue. Six bouts of 1 minute of vibration led to the greatest improvement in squat jump and counter movement jump (Da Silva-Grigoletto et al., 2011). Previous research comparing rest times, at different rest intervals in between bouts of vibration, showed that rest time interval did not affect outcomes of vertical jump and performance.

Although there were no group differences, there were some individual differences among participants, based on their tolerance to WBV, the duration of each bout of vibration and the total number of sessions. This suggests that the required rest period may be different for each individual (Dabbs et al., 2011). For optimum results in strength and performance outcomes, 60 second bouts of vibration for 6 sets will show the greatest improvements.

#### 1.4.3.3 Body Position

Body position and additional load also play a role in the effects of vibration on performance outcomes and muscle activity. Most studies have looked at lower body position during vibration exercise, primarily the feet and knees. Compared to standing in a fully upright position with the knees extended, knee angles of 45 and 60° have showed a greater increase in muscle activity. Also, when the heels were lifted off of the platform, EMG activity was significantly greater in the lower extremities compared to when the feet were flat on the platform (Ramona Ritzmann et al., 2013). In addition, completing vibration training in static postures compared to dynamic movements resulted in greater improvements in strength. EMG activity was recorded in the lower extremities also showed there was increased muscle activity during static squatting compared to dynamic squatting (Abercromby et al., 2007a; D. J. Cochrane, Stannard, Firth, & Rittweger, 2010; Delecluse, Roelants, Diels, Koninckx, & Verschueren, 2005).

#### 1.4.3.4 Loading with Vibration

Multiple studies have shown that adding a load to vibration exercise significantly increases EMG activity and performance measures compared to using only vibration or a control group that did not use additional loading (Tom J Hazell et al., 2010; Lienhard et al., 2014; Ramona Ritzmann et al., 2013; H.-H. Wang et al., 2014). Load was added in a variety of ways from having the subjects hold a barbell over their back, holding the barbell in the front rack position or with the subject holding dumbbells while on the vibration platform. In one instance the subjects wore a weighted vest while standing on the platform. The effects of WBV on performance outcomes are increased when additional weight in some form is added to the training compared to vibration training alone.

#### 1.4.3.5 Type of Vibration

The last vibration parameter is the type of vibration. Generally, two types of vibration platforms have been used: vertical vibration and side alternating vibration. The side alternation platforms pivot/tilt around a central point like a seesaw. The left and right sides alternate moving up and down while the center of the board remains fixed at the pivot point. The amplitude is adjusted by how far the feet are placed from the central pivot point. Also, compared to vertical vibration side to side platforms vibrate asynchronously, meaning force is applied alternately to the left and right foot. Contrastingly, vertical vibration platforms remain horizontally level the entire time with the entire platform moving up and down the same amount. Vertical vibration platforms generally have lower amplitudes compared to side alternating platforms. Also, unlike side alternating vibration platforms, the vibration is synchronous, where both feet move symmetrically together (Abercromby et al., 2007b). Generally, side alternating platforms produce greater muscle activations and improvements in performance compared to vertical vibration, although many studies have also found success when using vertical vibration plates. This is in part due to the ability to have larger amplitude values (Adams et al., 2009; Ramona Ritzmann et al., 2013). Compared to side alternating vibration, the stimulus from vertical vibration plates can travel further through the body. This leads to greater discomfort from using vertical vibration platforms compared to side alternating platforms.

### 1.4.4 Functional Outcomes from Vibration Training

In addition to improving strength and power, vibration has been shown to affect functional outcomes such as flexibility, bone mineral density and blood flow.

#### 1.4.4.1 Flexibility

Training with lower frequencies results in significant effects on flexibility compared to the higher training frequencies that are required for gains in strength and performance measures (Gerodimos, Zafeiridis, Chanou, Karatrantou, & Dipla, 2015; Gerodimos et al., 2010; Kurt & Pekünlü, 2015; Sands, McNeal, Stone, Russell, & Jemni, 2006). Improvements in flexibility have been shown after one session of vibration as well as after multiple sessions of vibration (Gerodimos et al., 2010; Karatrantou, Gerodimos, Dipla, & Zafeiridis, 2013; Kurt & Pekünlü, 2015); with longer lasting effects being seen after multiple sessions with programs lasting more than 4 weeks, using WBV more than 3 times per week seeing the greatest lasting effects (Gerodimos et al., 2015; Sands et al., 2006). However, not all populations benefit equally compared to other populations. Athletes and trained individuals do not benefit as much compared to individuals that are untrained, or older adults (Kurt & Pekünlü, 2015; Sands et al., 2006). This suggests that the characteristics of the population may play a role in addition to frequency and amplitude. The number of sessions/total vibration exposure also plays a role in the long-term effects on flexibility. Although shorter studies with less vibration exposure found improvements in flexibility, the effects were not long lasting. This indicates the need for longer total vibration exposure time to see longer lasting effects. Additionally, multiple sessions of vibration may benefit those populations who are already trained.

#### 1.4.4.2 Balance

Sitting balance and posture are important for manual wheelchair users; allowing for more efficient propulsion, better transfers and a greater ability to complete activities of daily living. Like flexibility, the higher frequencies that are required to see improvements in strength and muscle performance, are not required to see improvements in balance (Ebersbach, Edler, Kaufhold, & Wissel, 2008; Melnyk, Schloz, Schmitt, & Gollhofer, 2009; Moezy, Olyaei, Hadian, Razi, & Faghihzadeh, 2008; Tseng et al., 2016). Additionally, vibration was shown to improve balance in a variety of populations, from persons with disabilities using vibration to assist with balance for improved ability on activities of daily living, to athletes using vibration as a method of rehabilitation following surgery (Ebersbach et al., 2008; Moezy et al., 2008). However, there was less effect in populations that were young, healthy and athletes not using vibration for rehabilitation (Melnyk et al., 2009; Tseng et al., 2016).

#### 1.4.4.3 Pain

Vibration parameters also affect the success of decreasing pain. WBV has been shown to decrease pain in persons with chronic low back pain and osteoarthritis. However, among these populations, the results are mixed with some studies finding a reduction in pain, but others finding no improvements. Vibration has also been used to reduce pain in persons with diabetic neuropathy and fibromyalgia (Kessler & Hong, 2013). Due to the lower frequency needed and the ability to decrease pain in a variety of populations, WBV can be used alone or in combination with traditional methods of rehabilitation for these populations. The variation in results of pain reduction may in part be due to different populations and pathologies of the conditions. Also, different pain scales are used in different populations and for different conditions. A variety of pain scales have been used, some with good psychometric properties and others with poor psychometric properties. These scales are also subjective, possibly contributing to some of the differences in findings.

#### 1.4.4.4 Spasticity

Reduction of spasticity is of interest to manual wheelchair uses, especially those with SCI, cerebral palsy (CP), stroke and other disabilities. Lower training frequencies are needed to reduce spasticity compared to the higher training frequencies that are used for improving muscle strength and performance. However, when measured as a secondary outcome in studies with higher training frequencies, spasticity was still reduced. A lower frequency is recommended however, if the primary outcome of the study is not related to improvements in strength. Spasticity has been successfully reduced in adults and children with CP, with frequencies as low as 12Hz for children. Additionally, when paired with passive stretching vibration training resulted in significantly reduced spasticity compared to stretching alone (Ahlborg, Andersson, & Julin, 2006; Ibrahim, Eid, & Moawd, 2014; Tupimai, Peungsuwan, Prasertnoo, & Yamauchi, 2016). Vibration has also reduced spasticity in other populations including MS and stroke. The reduction in spasticity also led to improvements in walking and gait characteristics in these populations (Chan et al., 2012). At lower frequencies vibration may be more tolerable compared to the higher frequencies. For manual wheelchair users, especially those with SCI, MS or CP using a lower frequency may be more favorable.

#### 1.4.4.5 Bone Mineral Density

Bone mineral density (BMD) is an important potential benefit of vibration training. Results are mixed on whether vibration can increase bone mineral density. However, the primary determination on improvements in bone mineral density appears to be the subject population.

Multiple studies have shown no increase in bone mineral density in young healthy populations. A variety of frequencies and amplitudes were used as well as long and short sessions. Regardless of other parameters, participants' with healthy robust skeletons did not see an increase in bone mineral density after using vibration (Yusuke Osawa, Oguma, & Onishi, 2011; Torvinen et al., 2003). Contrastingly, in populations where bone mineral density is already decreased, such as in post-menopausal women and persons with osteoarthritis, vibration is more beneficial. In both populations, vibration increased BMD in the femur, hips and spine. Under a variety of different parameters, there were increases in BMD in participants' that already have decreased BMD.

### 1.4.5 Vibration for Spinal Cord Injury

Most of the research on vibration use among individuals with SCI has been focused on WBV and studies of a longitudinal nature. Several studies have shown that WBV significantly reduces muscle spasticity (Murillo et al., 2011; Sadeghi & Sawatzky, 2014), increases leg blood flow and activates leg muscle mass in individuals with a complete injury (ASIA A) (Herrero et al., 2011), and can after a period of consistent use significantly increase cadence, step length and walking speed among those with SCI who can ambulate (Ness & Field-Fote, 2009). Whole body vibration exercise has also been shown to reduce muscle oxygenation levels which can enhance training effects (Yamada et al., 2005).

The features of vibration and the parameters that can be adjusted for the desired training outcomes were largely accomplished with whole body vibration. Whole body vibration is typically administered with a platform or plate as shown below in figure 2. However, for persons with paraplegia, these options are not always feasible.


**Figure 2. Vibraiton platform and plate**

There have been a limited number of studies that use whole body vibration with persons with SCI. These studies involve an intricate set up involving tables and strapping as well as supervision by multiple people in order to implement whole body vibration. Figure 3 shows the set up for use of whole body vibration using a plate in a study conducted by Hererro et al (Herrero et al., 2011). While feasible in a laboratory setting, this type of set up is prohibitive for long term use and for use out of the laboratory setting. Furthermore, due to the intricacy of set up, the plates are better suited for therapy and rehabilitation and less suited to be used in an exercise program for persons with SCI.

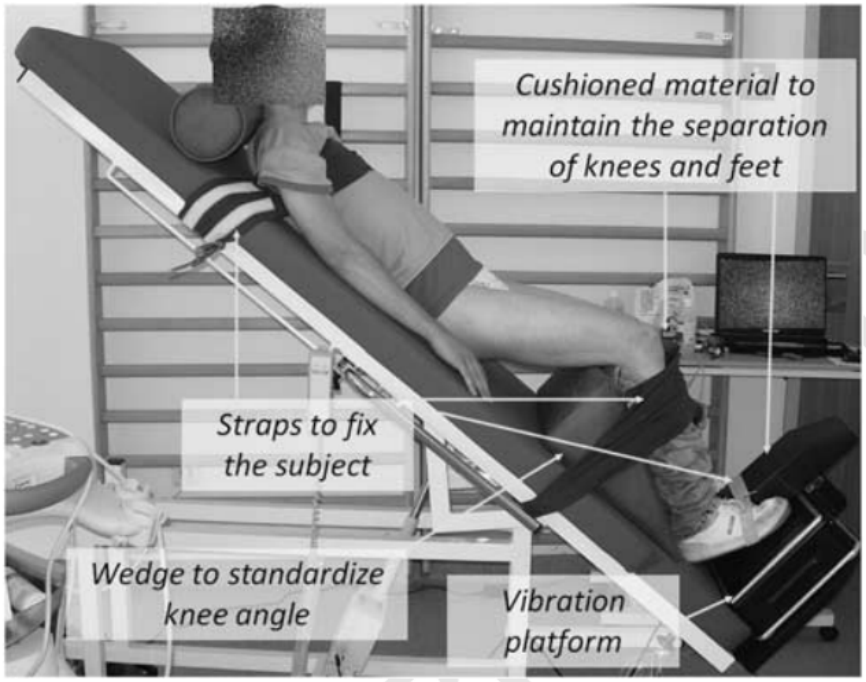



**Figure 3. Set up for use of whole body vibation with a person with SCI**

A vibrating dumbbell was recently developed in order to apply targeted vibration to the upper limbs (figure 4). When using the dumbbell, the vibration is applied directly at the hands and targets the muscles of the upper limbs, back and trunk. Upper limb vibration research in general and particularly in persons with SCI is scant. In one study involving 10 recreational swimmers with paraplegia a vibrating handle bar (30 Hz) was held in an isometric arm curl, daily, for 5 minutes of daily exposure in 5, 60 second intervals (Melchiorri et al., 2007). Average muscle velocity and average muscle power increased significantly in the dominant limb after 12 weeks however no significant differences were noted on the non-dominant side (Melchiorri et al., 2007). While these results are promising, the study had several limitations, including the training and examination of only one muscle group (elbow flexion) and a 30 Hz maximum training frequency. Exposure to higher levels of vibration further increases activation of muscle fibers and increases the potential to reach a maximum exhaustive state of the muscle (Jörn Rittweger, 2010). Although the studies are limited, the vibrating dumbbell has the potential to be an option for strength training for persons with SCI. Furthermore, it allows for persons with SCI to use vibration as more than just a tool for therapy or rehabilitation due to its ability to be used outside of the laboratory and with minimal to no supervision.

**Figure 4. Vibrating dumbbell**

In addition to a limited number of studies using targeted upper limb vibration with SCI, most of the studies with persons with SCI haven't looked at strength or power outcomes or other physiological parameters related to exercise, whereas these are very common measures in studies with able bodied persons. Vibration has been used more to decrease spasticity, increase bone mineral density, and increase blood flow in persons with SCI. The goals have generally not been to use vibration as an exercise modality in order to increase muscle strength and power. This may largely be due in part to the set up for the vibrating plate and platforms before the development of the vibrating dumbbell. Functional outcomes that specifically are important to manual wheelchair users, such as wheelchair propulsion and transfers have also not been examined. Although long term vibration training programs have been successful and feasible in other populations, many aspects of both short term, acute, training and long-term training programs still need to be investigated when using the vibrating dumbbell and in persons with SCI.

### 1.4.6 Upper Limb Vibration Training

Upper limb vibration has been used in a limited capacity, but with a variety of devices and populations. Previous studies have used devices ranging from custom made handle bars (Moras et al., 2010; Reyes et al., 2011; B. L. Tripp, Faust, & Jacobs, 2009), to commercially available devices for targeted upper limb vibration (Marín et al., 2012; B. Tripp, Eberman, & Dwelly, 2009). Additionally, several studies administered upper limb vibration by placing participants' hands or upper limbs on vibrating plates (Di Giminiani et al., 2014a; Gyulai, Rácz, Di Giminiani, & Tihanyi, 2012; J.-S. Lee, Kim, Kim, & rehabilitation, 2016). A variety of populations and outcomes have been studied. Results from a study by Reyes et al. found an increase in bone mass and grip force after 6 months of training with upper limb vibration in children with cerebral palsy (Reyes et al., 2011). Upper limb vibration also resulted in a positive impact on growth hormone and testosterone levels in trained gymnasts (Gyulai et al., 2012), but had no impact on testosterone levels in a sample of physically active young men (Di Giminiani et al., 2014b). In participants who were post stroke, upper limb vibration training resulted in increased grip strength and decreased spasticity (J.-S. Lee et al., 2016). Furthermore, upper limb vibration training was shown to increase shoulder range of motion in division 1 baseball pitchers (B. Tripp et al., 2009). Lastly, there have been a couple studies looking at muscle contraction using EMG with the use of upper limb vibration (Marín et al., 2012; Moras et al., 2010). A study by Moras et al. resulted in no differences in EMG activity between two different frequencies (Marín et al., 2012; Moras et al., 2010). Lastly, in a study with older adults, EMG activity of the biceps was increased following a session of upper limb vibration (Marín et al., 2012). However, these two studies that looked at EMG did not use the same implementation of upper limb vibration, which may have led to differences in results. None of the studies mentioned used the same dumbbell that was used in this dissertation work.

### 1.4.7 Designing a Vibration Protocol for Strength and Functional Outcomes

Several factors need to be taken into consideration when making a vibration protocol. The parameters that affect increases in strength and power, are not identical to the parameters that create benefits in other outcomes. When designing a study, the parameters should be chosen to achieve the primary outcome of the study. The International Society of Musculoskeletal and Neuronal Interactions, published recommendations for reporting and selecting parameters for WBV intervention studies (Rauch et al., 2010). The recommendations provided for the parameters selected and described below follow the suggestions made by the International Society of Musculoskeletal and Neuronal Interactions. The parameters that have been studied and established were done using whole body vibration and with vibration platforms. Not all these parameters may directly translate into training with targeted upper limb vibration.

Frequency is the most important parameter when designing a WBV intervention. Three frequency zones have been determined: 5-12Hz, 12-20Hz, and 20-40Hz (Rauch et al., 2010). Each frequency zone can accomplish different functional and performance goals. Frequencies in the 5-12Hz range, are used for muscle relaxation as a cool down mechanism and for improvements in proprioception/balance. The frequencies in the 12- 20Hz range are used primarily for improvements in flexibility, mobility, pain, spasticity and bone mineral density. The higher frequencies, 20-40Hz, are used for improving muscle strength and power. These frequency ranges apply to both WBV and targeted upper extremity vibration and the appropriate one should be chosen based off the desired outcome. Although studies have shown success with both vertical vibration platforms and sinusoidal platforms, vertical vibration is not a favorable option for upper extremity vibration. On the vertical platforms, the stimulus can travel much further through the lower extremities, into the spine, neck and head. This type of stimulus movement would not be tolerated when applied directly to the upper extremities, due to their proximity to the head. Making side alternating vibration the appropriate selection when using a vibrating dumbbell. Amplitude on sinusoidal plates is determined by the placement of the feet on the platform, however, with a dumbbell this parameter is unable to be adjusted because the placement of the hand can only be in one location and only one hand is being stimulated at a time. However, the literature indicates that although an adjustable and greater amplitude provides improved results, with a high frequency that is used for increasing strength and power the lack of adjustable amplitude may not be a large shortcoming of the dumbbell. This may be a greater shortcoming when lower frequencies are being used for improving balance, pain, spasticity etc. Compared to using the vibration plate, the concept of loading with vibration is different with the vibrating dumbbell. With the plate, no additional weight from the platform is present due to the stimulus being directly at the feet, however, with the dumbbell weight is already associated with it; leading to no true unweighted vibration. This weight is small compared to the additional weight that can be added and the idea of additional load can be applied to the dumbbell to see increased results in strength and performance. Like amplitude, the base weight of the dumbbell may have a greater impact on other outcomes such as pain, spasticity and balance. Other parameters, such as duration of and number of sessions of vibration, as well as postures are like that when using WBV. Exercises with the dumbbell should still be done in a static hold as this has shown to be more beneficial compared to the dynamic exercise with vibration. To achieve the best results, exercise should occur a minimum of three times per week with each exercise session not exceeding 9 total minutes of vibration per arm, with each bout being between 30-60 seconds and the rest period largely determined by the participant but should not exceed five minutes between each bout of vibration exposure. Ideally the training program would last at least a minimum of 12 weeks. Programs lasting less than 12 weeks, have shown mixed results on being successful. These are the ideal parameters, to achieve optimal success in increasing strength and power, however, due to participant tolerance and equipment availability, all the ideal parameters may not be achieved.

## 1.5 Specific Aims

Little research has been done with upper limb vibration, especially in persons with SCI. This research aimed to study targeted upper limb vibration training in manual wheelchair users with SCI; assessing the feasibility and effectiveness of this type of training for persons with SCI. Therefore, the specific aims are related to two research studies aimed at examining upper limb vibration as an exercise intervention. A third research study was conducted to examine the reliability of the protocols used to measure upper limb isokinetic strength. Because upper limb vibration is a new form of vibration, the same parameters of feasibility and acute training effects have not been established. Chapter 2 describes the results of a study examining the feasibility of upper limb vibration training and compares the differences in training outcomes between vibration training and dumbbell training. Chapter 3 describes a study that aimed to look at these feasibility parameters for training and the acute training effects compared to a standard dumbbell training program. The second vibration study described in chapter 4 aimed to examine the feasibility of implementing a 12-week training program with upper limb vibration. Additionally, the study aimed to look at changes in strength, power, pain and functional outcomes after training with vibration for 12-weeks. The specific aims and hypothesis for the two studies are as follows:

### 1.5.1 Specific Aims Study 1

Specific Aim 1) Assess the feasibility of a single session of upper limb vibration training

*Hypothesis 1)* The training will be feasible as measured by 80% of the participants being able to complete all seven exercises performed at 30Hz and a minimum hold time of 45 seconds.

Specific Aim 2) Assess participants ability to tolerate a single session of vibration exercise

*Hypothesis 2a)* Vibration will not exacerbate current levels of pain or cause new pain at the wrist, elbows and shoulders

*Hypothesis 2b)* Participants will self-report a positive perception about the vibration exercises. When surveyed on their interest and excitement about using vibration exercise, at least 80% of participants will report they are interested and excited to participate in a training program where vibration is used.

Specific Aim 3) Compare the acute physiological effects of a single session of upper limb vibration to a single session of standard dumbbell resistance training

*Hypothesis 3a)* Participants will show the following changes after completing the session of vibration exercise compared to the session of standard dumbbell resistance training:

- Greater power output on the Upper Extremity Wingate Test
- Increased blood lactate levels

*Hypothesis 3b)* Participants will show the following changes after completing each exercise with vibration compared to standard dumbbell training

- Increased changes in heart rate values
- Increased changes in RPE on the Borg Scale

Specific Aim 4) Compare the differences in muscle activity as measured by electromyography maximum voluntary contraction before and after vibration training.

*Hypothesis 43)* Muscle activity will be increased after completing the vibration training protocol compared to the values measured at baseline.

### 1.5.2 Specific Aims Research Study 2

Specific Aim 1) Assess the reliability of the Biodex upper limb strength protocol that is being used in the longitudinal vibration study to measure strength through six different movements.

*Hypothesis 1a)* There will be no significant differences in strength measurements between the two study visits for all movements

*Hypothesis 2a)* Strength measurements between the two study visits will be strongly correlated (R>.70) for all movements

*Hypothesis 3a)* Reliability between the two study visits will be rated with a minimum of "good" reliability (ICC value>.70)

### 1.5.3 Specific Aims Research Study 3

Specific Aim 1) Assess the feasibility of implementing a 12-week longitudinal exercise study using upper limb vibration assessed by demand, implementation, practicality, and acceptability.

•Demand will be measured the number of participants who express interest in participating in the research study and undergo screening procedures and informed consent and the number of participants expressing interest in continuing to train with vibration after the study has ended

•Implementation will be assessed by examining the number of training sessions completed, the weight progression for each exercise, the amount of time of vibration exposure for each exercise, reasons for not completing a training session, and retention of participants

•Acceptability will be measured by participant's satisfaction with the training program, perceived functional benefits, tolerance, perceived strength, excitement about the training program and desire to continue training collected at the end of the training program through a structured survey and open-ended questions.

*Hypothesis 1)* Implementing a 12-week longitudinal study using upper limb vibration will be feasible as measured by the following outcomes:

•The training program will be in demand as measured by at least eighty percent of study participants wanting to continue training with vibration exercise after the study ends

•The training program will be successfully implemented as measured by participants completing a minimum of 60% of the exercise training sessions; participants being able hold the dumbbell for 45-60s for each exercise and the weight of the dumbbell being progressed for each exercise, participants not completing a given training session due to scheduling conflicts or life related conflicts, not due to the development of pain or sustaining an injury; the study retaining 12 out of 16 participants that start the study (based on sample size calculations)

•The training program will be acceptable as measured by participants reporting a high satisfaction with the training program; participants reporting a perceived difference in their strength and functional abilities; participants reporting they have a desire and excitement to continue the training program after the study ends. High satisfaction being defined by the survey response rating of "very satisfied"

Specific Aims 2) Assess the effects of a 12-week longitudinal training program with upper limb vibration on improving strength, power, function and pain.

*Hypothesis 2)* Subjects will demonstrate the following changes over time

•Strength: increased peak isokinetic muscle torque output as measured using a Biodex machine of the shoulder internal rotators, external rotators, shoulder abductor/adductors, and shoulder flexion/extension, elbow flexion/extension, forearm pronation/supination, wrist flexion/extension, and hand grip at 6 weeks (mid-way into training) and 12 weeks (end of training) when compared to baseline.

•Power: increased power as measured by the Upper Limb Wingate Test at 12-weeks (end of the intervention) compared to baseline.

•Propulsion testing: Increased maximum speed and acceleration attained, peak force, and mechanical effective force measured using the SmartWheel during start-up propulsion over level and inclined surfaces at 12 weeks when compared to baseline.

•Transfer testing: Higher maximum and minimum attainable transfer heights to a height-adjustable transfer station at 12 weeks when compared to baseline.

•Reduced upper limb pain in the shoulder, elbow and wrist (as recorded on the Numerical Rating Scale (NRS) and shoulder pain reported during activities (Wheelchair Users Shoulder Pain Index (WUSPI)) at 6 weeks and 12 weeks when compared to baseline.

•Increased self-perceived aspects of health and function as measured using the Short Form SF-36 Walk Wheel scale at 6 weeks and 12 weeks when compared to baseline

## 2.0 Feasibility of training with upper limb vibration

### 2.1 Introduction

A large body of literature has looked at the feasibility and acute training effects of exercising with vibration using vibrating plates and platforms. Furthermore, appropriate training parameters for a desired physical or functional outcome have been established. Studies with able bodied persons including young men, older adults, elite athletes and menopausal women have shown mixed results with a variety of outcome measures. A single session of total body vibration has been shown to increase metabolic variables such as heart rate, blood pressure, blood lactate and $VO_2$ compared to baseline measurements (D. J. Cochrane et al., 2008; Rittweger, Beller, & Felsenberg, 2000). Also research has shown increases in muscle activity and strength after a single session of vibration (Mileva et al., 2006; Jörn Rittweger, 2010). Several studies have shown that muscle activation is greater as measured by EMG following one session of vibration training (Erskine, Smillie, Leiper, Ball, & Cardinale, 2007; Jörn Rittweger, Mutschelknauss, & Felsenberg, 2003). Flexibility also increased following a single session of vibration (D J Cochrane & Stannard, 2005). However, when it comes to performance results are mixed on whether one session of vibration of varying lengths can lead to changes in performance. Several studies have shown acute vibration improves jump height and power immediately following a bout of vibration, as well as up to 20 minutes following vibration (D. Cochrane, Stannard, Walmsely, & Firth, 2008; Cormie, Deane, Triplett, & McBride, 2006; Gerodimos et al., 2010). Contrastingly, many studies have found no improvement or a decrease in performance after one session of vibration (Jordan et al., 2010). Many of the studies did not use the same parameters for vibration and had different subject populations. Thus, when looking at the studies that did not find any changes, it is possible they were not using vibration parameters that were appropriate for inducing training effects.

Studying acute effects of vibration exercise has largely been to determine the mechanisms behind vibration as well as to determine the physiological effects. Additionally, the acute studies have been used to determine the appropriate vibration training parameters, adjustments and exposure times for optimal training to elicit the training effects that are shown with traditional exercise. The results of these onetime sessions are generally short lived, and the results are not permanent. However, they have shown to be useful in establishing guidelines for training that can be implemented in longer term training programs.

Although there has been some research conducted with vibration and SCI, the studies were conducted using plates. The same acute training parameters and parameters of feasibility still need to be established with the vibrating dumbbell. The training parameters that have been established for plates and platforms may not directly translate to the vibrating dumbbell. The dumbbell does not have a variable amplitude, but it does have a variable frequency. Additionally, the application of vibration at the hands is closer to the head compared when vibration is applied at the feet with a plate. Because of this, the stimulus may be more uncomfortable compared to the plates. Thus, participants' perceptions may be different compared to those of the vibrating plates. Therefore, the first aim of the study is to examine parameters related to feasibility of an upper limb vibration training protocol and to compare the short-term physiological training effects of an upper limb exercise protocol using a vibrating dumbbell compared to a standard dumbbell. Measures related to feasibility include the hold times for each exercise completed, the percentage of participants that can complete the exercises at the desired training parameters, and participant perceptions about the training protocol. Specific physiological measures being studied include, power output, blood lactate, heart rate and ratings of perceived exertion. The second aim of the study is to examine the mechanism behind vibration training by using electromyography to measure the maximum voluntary contraction of three muscle groups on the upper limbs before and after vibration training.

## 2.2 Methods

The study received approval from the VA Pittsburgh Healthcare Systems Institutional Review Board. Testing took place at the Human Engineering Research Laboratories (HERL) in Pittsburgh, PA (September 2018-May 2019) and the 38th National Disabled Veterans Wheelchair Games in Orlando, FL (August 2018). Recruitment at the Wheelchair Games took place in person primarily through word of mouth and IRB approved flier. Recruitment in Pittsburgh took place through a research registry maintained by HERL as well as through the Department of Physical Medicine and Rehabilitation research registry. A variety of community events and support groups were also sources of recruitment. The IRB-approved flyer for the study was posted in the SCI and rehabilitation-related hospitals and clinics, as well as on the HERL website. In response to the flyer, potential subjects directly contacted the research team if they were interested in participating.

### 2.2.1 Human Subjects

Adult manual wheelchair users with SCI were recruited for this study. The following criteria were met in order to participate:

*Inclusion Criteria*: (1) have a neurological impairment secondary to a SCI at T2 or lower (2) have a SCI which occurred over 6 months prior to the start of the study; (3) use a manual wheelchair as primary means of mobility (at least 30 hrs. per week but not necessarily always in motion); (4) be between 18 and 65 years of age; (5) be able to perform a transfer independently to and from a wheelchair; and (6) have normal range of motion in the upper limbs.

*Exclusion Criteria*: (1) History of fractures or dislocations in the shoulder, elbow and wrist from which the subject has not fully recovered (i.e. the subject may no longer experience pain or limited/altered function due to the injury) (2) upper limb pain that interferes with the ability to propel or transfer (3) recent hospitalization for any reason (within the past three months); (4) pregnant women (5) history of coronary artery disease, coronary bypass surgery or other cardiorespiratory events; and (6) Currently taking blood thinner medication.

### 2.2.2 Protocol Overview

The research study required two study visits. However, the second study visit was optional for testing that was conducted at the National Disabled Veterans Wheelchair Games. Because participants' schedules at the games are highly variable, some participants were not able to come back for their second visit. For this reason, participants tested at the NDVWG, all started with the vibration training program to increase the numbers of participants who were able to try the vibration training protocol. Participants that were tested at HERL had their visit order (exercise type) randomized. A random number generator was used to determine which training protocol, vibration training or dumbbell training, participants started with.

At the first study visit, all participants signed an informed consent form. Afterwards, they completed a demographics questionnaire asking about the frequency of their wheelchair usage, transfers, number of non-level transfers performed daily, basic demographics (age, gender, years since SCI, etc.), work history, history of medical problems, current medications, and alcohol and smoking consumption.

### 2.2.3 Outcomes Measures

After completing the demographics questionnaire, participants completed the following pain questionnaires and outcome measures:

#### 2.2.3.1 Pain Measures

Numerical rating scale (NRS): Participants completed this scale at the beginning and end of the training session, once for each upper limb joint (wrist, elbow, and shoulder). The participants were asked to rate their most severe wrist, elbow and shoulder pain at the time of study participation on an 11-point scale (i.e. 0-10) anchored at the ends by “no pain” and “worst pain ever experienced (Farrar, Young Jr, LaMoreaux, Werth, & Poole, 2001).”

WUSPI – Wheelchair User’s Shoulder Pain Index: The WUSPI is a 15-item, self-report instrument that measures shoulder pain intensity in wheelchair users during various functional activities of daily living, such as transfers, loading a wheelchair into a car, wheelchair mobility, dressing, bathing, overhead lifting, driving, performing household chores, and sleeping (Curtis et al., 1995a; Curtis et al., 1995b). This measure was completed at the beginning of the first training session.

#### 2.2.3.2 Power Output

Participants completed two Wingate Anaerobic upper body tests (P. L. Jacobs, E. T. Mahoney, & B. Johnson, 2003) to measure power. One was completed at the beginning of the visit after the paperwork had been completed, and the second was completed immediately after the exercise portion of the study had ended. Participants were familiarized with this test prior to completing it. The resistance on the ergometer was set constant at 3.5% of the participant's body weight (P.L. Jacobs et al., 2003). After a 5-minute warm up with no load and at a comfortable speed for the participant, he or she began cranking faster and with a moderate resistance. The total time of the test was one minute and thirty seconds. For the first 60 seconds, the participant cranked on the on the cycle with minimal resistance and maintained a speed between 55-65 rotations per minute (RPM's)'s. The resistance was then increased to a maximal level and participants cranked as hard and as fast as they were able to for the last 30 seconds of the test. After that the test was completed, the resistance was then returned to zero and the participants cycled at a comfortable pace to cool down.

#### 2.2.3.3 Electromyography

Bipolar electrodes of a 16-channel wireless surface EMG system (Noraxon Telmyo 2400T) were placed on 3 bilateral muscle groups of the upper extremities: the anterior deltoids, biceps brachii, and triceps brachii according to standards documented for EMG surface electrode placement. Sensors were worn for the study visit where participants completed the vibration training protocol at HERL. In order to prepare the skin for good contact with the electrodes, the areas where the electrodes were placed were cleansed with alcohol. Manual muscle tests were performed for each of the 3 bilateral muscle groups listed above to confirm correct electrode placement and to elicit MVCs. Muscle testing followed standardized procedures for each of the desired muscle groups (Basmajian, 1980). Muscle testing took place before and after vibration training. EMG data was not collected during the exercise training, but the participant wore the sensors for the duration of the training to ensure the placement was the same for both sets of manual muscle tests. Sensors were not worn, and data was not collected for the visit where participants completed dumbbell training.

#### 2.2.3.4 Physiological Measures

Heart Rate: All participants wore a heart rate monitor on their chest below the heart for the duration of the testing period. Participants' resting heart rate was measured prior to starting the training protocol and collected continuously throughout the testing. Data was collected using the Garmin app on an Apple iPad or with another Garmin device.

Blood Pressure: A resting blood pressure was measured prior to starting the exercise training. During the training session, blood pressure was measured at the end of each of the exercises and after the exercise training had concluded.

Blood Lactate: A LactatePro portable blood lactate monitor was used to analyze blood samples for blood lactate. The participants' finger was cleaned and sterilized with an alcohol wipe prior to blood collection. A finger prick was used to collect a small blood sample that was read into the monitor. The first drop of blood was wiped clean to avoid alcohol contamination and the second drop of blood was read into to the monitor. After a good sample was obtained and read into the monitor, the participant was given a cotton swab that was held over the finger until the bleeding has stopped. A band aid was also offered to the participant if there was still bleeding or if the participant wanted one. Measurements were taken at baseline and after the training session.

#### 2.2.3.5 Ratings of Perceived Exertion

Borg scale: Participants rated their level of perceived exertion (RPE) after completing each exercise. The Borg scale is a 6-20 scale with values ranging from no exertion (6) to maximal exertion (20) and was used to collect the ratings of perceived exertion (van der Scheer, Hutchinson, Paulson, Ginis, & Goosey-Tolfrey, 2018).

### 2.2.4 Data Collection

The dumbbell that was used in the study (Galileo Mano, StimDesigns, Carmel, CA) is a Class 1 exercise device that weighs approximately 5.7 pounds (2.6 kg) and has a variable frequency control (0-40 Hz in increments of 0.5 Hz) and a fixed amplitude of 2 mm (4 mm peak to peak) when vibration is active.

Prior to starting the exercise training all participants' one rep maximum (1RM) for each of the exercises to be performed in the training portion of the study were determined using a standard dumbbell in accordance with standard procedure [61]. Dumbbell weight was increased accordingly until the subject reached their 1RM. If a subject was not able to perform a 1RM that matched the weight of the dumbbell (5.7lbs) for a given exercise, that exercise was not performed for the vibration portion training protocol. The same protocol was followed for the standard dumbbell training. If a participant was not able to perform a 1RM that matched the weight of the lightest standard dumbbell weight (5lbs) for a particular exercise, then that exercise was also not performed for the dumbbell training portion of the study.

After the baseline measurements and 1RM's are determined participants will perform one of the Vibration or Dumbbell Exercise Training protocols described below.

*Vibration Exercise Training Protocol*

The following seven exercises (Figure 5) were completed in a static arm posture: side flies, straight arm rows, bicep curls, internal/external rotation, triceps, front raises, bent over rows. The point at which the movement was held was the point where the force generating output of the targeted muscle group is maximized. For each of the exercises, participants used 60% of the 1RM values that were previously obtained. If a participant's calculated value was less than the weight of the dumbbell (5.7lbs), they did not complete that exercise. For each of the exercises that were completed, participants were asked to try and hold the dumbbell at 30 Hz for 45-60s. If they were not able to do so, the exercise was stopped when they were no longer able to hold the dumbbell, they broke good form, or they communicated with the study team they were uncomfortable and needed to stop. The amount of time they were able to hold the dumbbell was recorded. Each exercise was completed on the left and right sides before moving onto the next exercise. Perceived exertion was measured after completing each exercise on both arms. Blood pressure was measured after the completion of one whole (left and right sides) exercise. Heart rate was collected and monitored throughout the entire trial. Participants rested for 1 minute between exercises.

*Dumbbell Exercise Training Protocol*

The same seven exercises were completed with a dumbbell that were completed with the vibrating dumbbell: side flies, straight arm rows, bicep curls, internal/external rotation, triceps, front raises, bent over rows. The participant again remained seated in their wheelchair for each exercise. For each set of exercises participants used 60% of their one RM that was previously obtained. Participants completed 1 set of 10 repetitions for each exercise, moving through the entire ROM. If they were not able to complete all 10 repetitions, they completed as many as they were able to. The number they were able to complete of each exercise was recorded. Each exercise was completed on the left and right sides before moving onto the next exercise. Perceived exertion using the same scale from the first visit was measured after completing each exercise and for each arm. Blood pressure and oxygen saturation level was measured after the completion of one whole (left and right sides) exercise. Heart rate was collected and monitored throughout the entire trial. Participants rested for at least 1 minute between exercises.

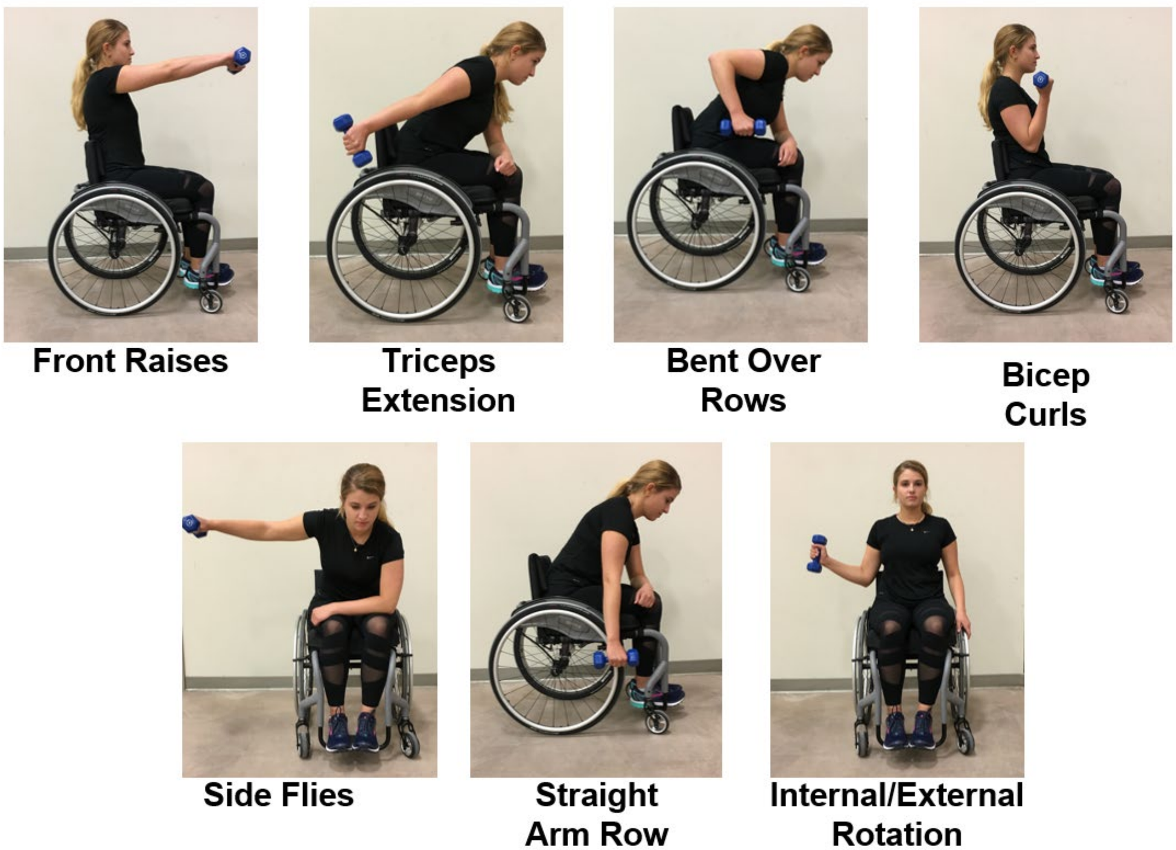



**Figure 5. Exercises compeleted during the vibration and dumbbell trianing protocols**

Immediately following the completion of the exercise protocol, post measurements of blood pressure and blood lactate were measured. After these measures were taken, participants completed a second Wingate test and a second set of manual muscles tests (vibration protocol only) following the same procedures that were used for the baseline testing. Lastly, participants completed the same pain questionnaires that were measured at baseline as well as a survey to get their feedback on their tolerance to the training, their perceptions of the training, the potential of the training to increase their strength, the potential of faster strength gains, their desire to train with vibration and their excitement to train with vibration.

*Second Study Visit*

If participants were randomized to the vibration training protocol first and could complete a minimum of five minutes of vibration, they were invited to participate in a second research study visit. For participants randomized to the dumbbell training protocol first, if they were able to complete five repetitions of half of the exercises in the dumbbell training protocol, they were asked to complete the second study visit. The second visit took place a minimum of 1 day and a maximum of 2-weeks after completion of the first study visit. This time frame was selected to give participants the flexibility when scheduling their second visit. Participants recruited at the wheelchair games had a condensed timeline in order to allow a second study visit, as the wheelchair games are only one weeklong. For participants tested at HERL, participants were ideally scheduled three to five days after their initial testing. However, additional time was given to accommodate participants' schedules as well as to account for the weekends and lab availability.

At the second visit, the same study protocol was followed as described above for the first study visit. Participants completed only the NRS pain scale prior to the exercise training. Additionally, participants completed the type of training, either vibration or dumbbell training, that was not completed in the first study visit. At the end of the visit they completed a questionnaire assessing the training protocol they completed during the study visit. The questionnaire that participants completed for dumbbell training and vibration training is in Appendix A.

### 2.2.5 Data Analysis

The total score for the WUSPI was calculated by summing the pain score for each item. Items not performed were not included in the total score. Total scores range from 0 (no pain at all) to 150 (maximal pain on all tasks), where the lower the score the less pain experienced. Two measures of heart rate were examined: 1) the maximum heart rate obtained during each exercise and 2) the percent change in heart rate from resting to the maximum heart rate achieved (equation 1 below). Heart rate date was collected continuously throughout both training programs and displayed using a Garmin Edge monitor. Peak heart rate values were determined by looking at the heart rate value displayed on the monitor after each exercise was completed. Peak power output was reported as weight normalized. Measures of satisfaction with the exercise intervention were aggregated for each question asked (e.g. tolerance, efficiency of training, etc.) across all the subjects within each group. Lastly, EMG was reported as the maximum voluntary contraction for each muscle group before and after vibration training. The raw EMG data was filtered through a fourth order Butterworth filter, demeaned, rectified, and down sampled. After this post processing, the MVC was calculated by extracting top ten peaks from MVC exercise. The MVC value was determined by taking the average of the ten peaks.

Tolerance was measured by looking at the time and frequency of which participants were able to hold the dumbbell, and the number of participants able to meet the minimum hold time of 45s for each exercise.

**Equation 1. Percent change in heart rate from resting calculation equation**

$$\frac{(Maximum\ achieved\ heart\ rate\ value - Resting\ heart\ value)}{Resting\ heart\ rate\ value} * 100\%$$

### 2.2.6 Statistical Analysis

All statistical analysis was performed using SPSS version 25 (SPSS Inc, Chicago). Demographics were reported in means and standard deviations as appropriate. EMG data were reported graphically due to the low participant numbers. A two-way repeated measures ANOVA was used to compare blood lactate and power output between the two different training programs and pre and post training for the participants who completed both training protocols. Post-hoc testing using Bonferroni correction was applied to significant results. A dependent samples t-test was used to compare heart rate and ratings of perceived exertion for each exercise between the two training programs. Also, a dependent samples t-tests was used to compare differences in blood lactate and power output before and after completing vibration training; analysis was completed with all participants enrolled in the study. The level of significance for all analysis was set at $\alpha$ = 0.05 or less.

### 2.2.7 Sample Size Calculations

Data from previous studies involving a single session of vibration training (Couto et al., 2013; Kvorning, Bagger, Caserotti, & Madsen, 2006; Jörn Rittweger et al., 2003) and using the smallest magnitude of change for outcomes of power output, heart rate, and blood lactate was used to determine the required sample size. Using an alpha = 0.05, power of 0.8, and a paired t-test, a minimum of 4 participants (powered off of lactate), 9 participants (powered off blood pressure), 6 participants (powered off HR) and 25 participants (powered off power) will be needed to detect within subject changes pre and post training session. Additionally, to determine the number of participants needed to see differences in the physiological training measures between the two training programs, a power analysis powering on blood lactate and power, using an alpha of .05, power 0.80 and a moderate effect size (.50-.70) and a repeated measures ANOVA was performed. The results showed that 16 participants will be needed to detect changes between and within participants on blood lactate and 22 participants would be needed to detect changes in power output.

To capture the feasibility data, we aimed to collect a larger sample size than what was needed to capture changes in the specific outcome measures. A variety of tolerances and responses to the vibration training program were anticipated. Thus overall, the study aimed to enroll 40 participants to capture these responses.

## 2.3 Results

Twenty-two participants in total enrolled in the study and signed informed consent forms. Seven participants did not complete both study visits, therefore, 15 participants were included in the analysis comparing the two training methods. All seven participants did not complete the second visit due to scheduling and time conflicts. Of the 22 participants, all 22 completed the vibration training. The EMG analysis was conducted only on participants collected at HERL and contains two participants.

### 2.3.1 Participants

Detailed demographics of the 22 participants enrolled in the study that completed the vibration training and that completed both training protocols can be seen below in Table 1. Level of injury of the participants reported in Table 1 was reported at high paraplegia (T6 and above) and low paraplegia (T7-T12). These classifications have been previously reported in the literature (Schmid et al., 1998; Teasell, Arnold, Krassioukov, Delaney, & rehabilitation, 2000). The autonomic nervous system controls heart rate leading to variations post SCI above T6 (Chiodo, Crane, Reyes, Song, & Klebine, 2015).

**Table 1. Detailed participant demographics for all participants that completed vibration training and participants that completed both training protocols**

| | Mean (standard deviation) or Counts (Percentages) | |
|---|---|---|
| | **Participants that completed vibration training (n=22)** | **Participants that completed vibration training and dumbbell training (n=15)** |
| **Gender** | 20 Men (91%)<br>2 Women (9%) | 14 Men (93%)<br>1 Women (6.7%) |
| **Race** | 13 Caucasian (59%)<br>7 African American (32%)<br>2 Hispanic or Latino (9%) | 9 Caucasian (60%)<br>5 African American (33.3%)<br>1 Hispanic or Latino (6.7%) |
| **Age (years)** | 47.7 (10.0) | 47.2 (11.0) |
| **Height (cm)** | 174.9 (6.7) | 173.7 (6.5) |
| **Weight (kg)** | 82.6 (14.4) | 85.4 (16.9) |
| **Complete/Incomplete** | Complete 9 (41%)<br>Incomplete 13 (59%) | Complete 8 (53.3%)<br>Incomplete 7 (46.7%) |
| **Injury Level** | T2-T6 7 (32%)<br>T7-L5 15 (68%) | T2-T6 4 (27%)<br>T7-L5 11 (73%) |
| **Handedness** | Left 3 (14%)<br>Right 18 (82%)<br>Both 1 (4%) | Left 3 (20%)<br>Right 11 (73.3%)<br>Both 1 (6.7%) |
| **Hours using wheelchair (per day)** | 12.9 (4.7) | 12.3 (4.8) |
| **Years using wheelchair** | 12.9 (8.2) | 10.9 (7.5) |
| **Number of level transfers per day** | 3.9 (3.4) | 3.5 (2.6) |
| **Number of non-level transfer per day** | 4.6 (3.2) | 4.4 (3.1) |
| **Currently participating in wheelchair sports** | Currently participating in wheelchair sports 20 (91%)<br>Not currently participating in wheelchair sports 2 (9%) | Currently participating in wheelchair sports 14 (93.3%)<br>Not currently participating in wheelchair sports 1 (6.7%) |

### 2.3.2 Feasibility of Completion and Hold Times

All participants were able to complete the exercises in the study at 30Hz. Overall, average hold times for five out of the seven exercises were greater than the desired hold time of 45s for the right and left sides (Table 2). For both the left and right arms, side flies and front raises were the two exercises with an average hold time less than 45s. However, for five out of the eight exercises on the right side and six out of the eight exercise on the left sides, less than 80% of participants were able to meet the minimum hold time of 45s. Bicep curls and internal/external rotation were the only three exercises where more than 80% of study participants were able to meet the minimum hold time of 45s on the right side. On the left side, internal/external rotation were the only two exercises where more than 80% of participants were able to hold the dumbbell for 45s.

**Table 2. Average hold times for each exercise and the number of participants that met the minimum hold times for each exercise on the left and right sides**

| | Right Side | | | Left Side | | |
|---|---|---|---|---|---|---|
| **Exercise** | Completed | Average (STD) Hold Time (s) | Number of Participants that Met Desired Time | Completed | Average (STD) Hold Time (s) | Number of Participants that Met Desired Time |
| Side Flies | 21 | 43.6 (11.7) | n = 11 (52%) | 21 | 37.4 (12.3) | n = 7 (33%) |
| Straight Arm Row | 21 | 50.1 (11.2) | n = 16 (76%) | 22 | 47.8 (11.0) | n = 13 (59%) |
| Bicep Curls | 21 | 55.3 (10.1) | n = 17 (81%) | 22 | 55.2 (9.8) | n = 17 (77%) |
| Internal Rotation | 21 | 58.3 (5.4) | n = 20 (95%) | 22 | 57.9 (6.7) | n = 20 (91%) |
| External Rotation | 21 | 57.6 (8.4) | n = 19 (90%) | 22 | 56.4 (9.4) | n = 20 (91%) |
| Triceps Extension | 21 | 49.1 (11.0) | n = 12 (57%) | 19 | 46.4 (12.1) | n = 12 (63%) |
| Front Raise | 21 | 37.9 (14.5) | n = 7 (33%) | 21 | 36.1 (15.3) | n = 7 (33%) |
| Bent Over Rows | 21 | 49.8 (11.4) | n = 13 (62%) | 22 | 47.0 (13.7) | n = 12 (55%) |

### 2.3.3 Physiological Results

Participants' overall had very little pain at the time of participating in the study. The average WUSPI score for all participants included in physiological study results was less than 1 (score = 0.74). Additionally, only two participants reported pain in any joints on the NRS, one before vibration training, and another before dumbbell training. After vibration training and dumbbell training both participants had decreased pain in the joints where pain was reported. Results from the ANOVA showed no significant interaction effects between the two training programs and time points for the measures of blood lactate ($p = .909$) and power output ($p = .838$). Additionally, for both blood lactate and power there were no significant main effects of time (BL $p = .399$, Power Output $p = .361$) or exercise type (BL $p = .132$, Power Output $p = .156$) in the model run with 15 participants. However, results from the dependent samples t-test run with all 22 study participants revealed a significant difference in blood lactate before and after vibration training ($p = .017$). There were no significant changes in power output before and after vibration training. Although they were no significant differences between the two training programs, there was an increase in blood lactate for both training programs after the training compared to the pre-training measurement as shown below in Figure 6. Furthermore, when looking at just the vibration training program there was a significant increase in blood lactate concentration.

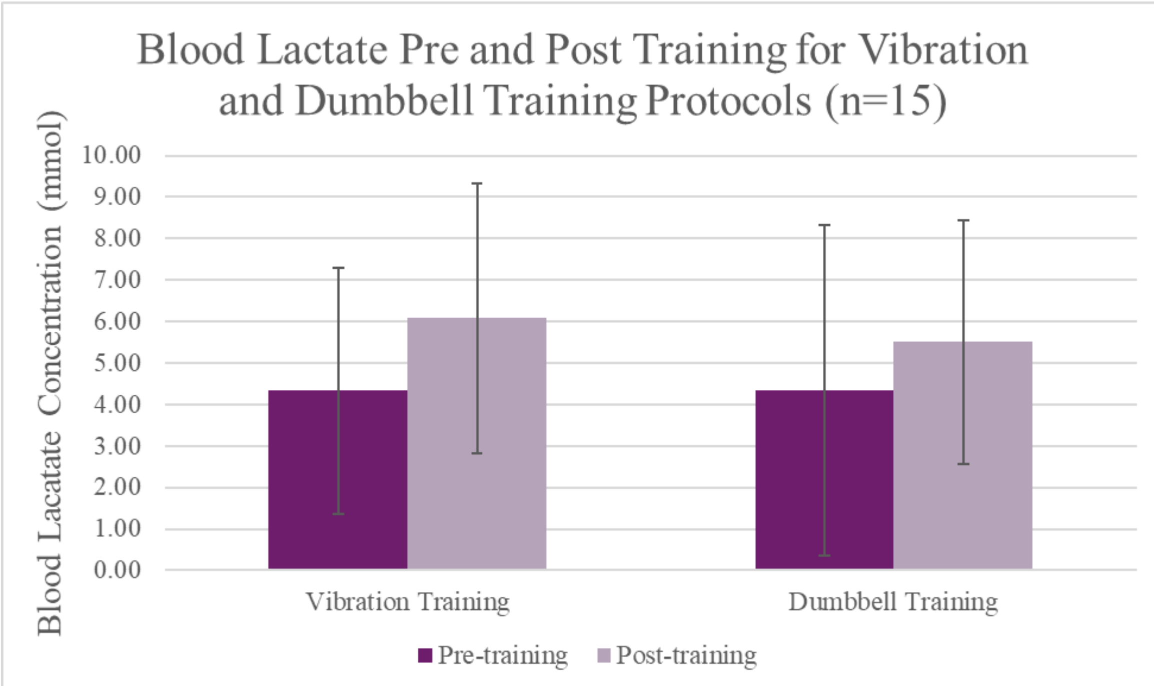



**Figure 6. Blood lactate concentration results**

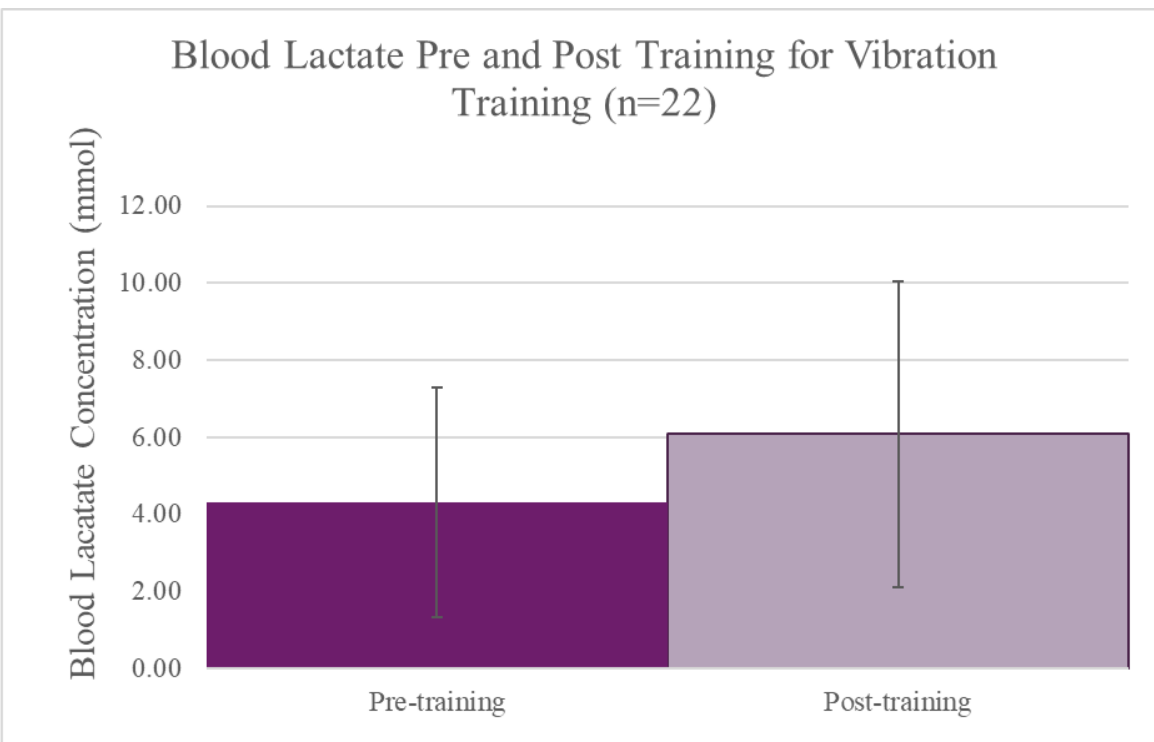



**Figure 7. Blood lactate concetration results for all study participants**

Additionally, although not significant, there was a trend in the power output data. The difference between the two trainings and the two timepoints was very small, but none the less both training protocols resulted in a decrease in power output post-training compared to pre-training, shown in Figure 8.

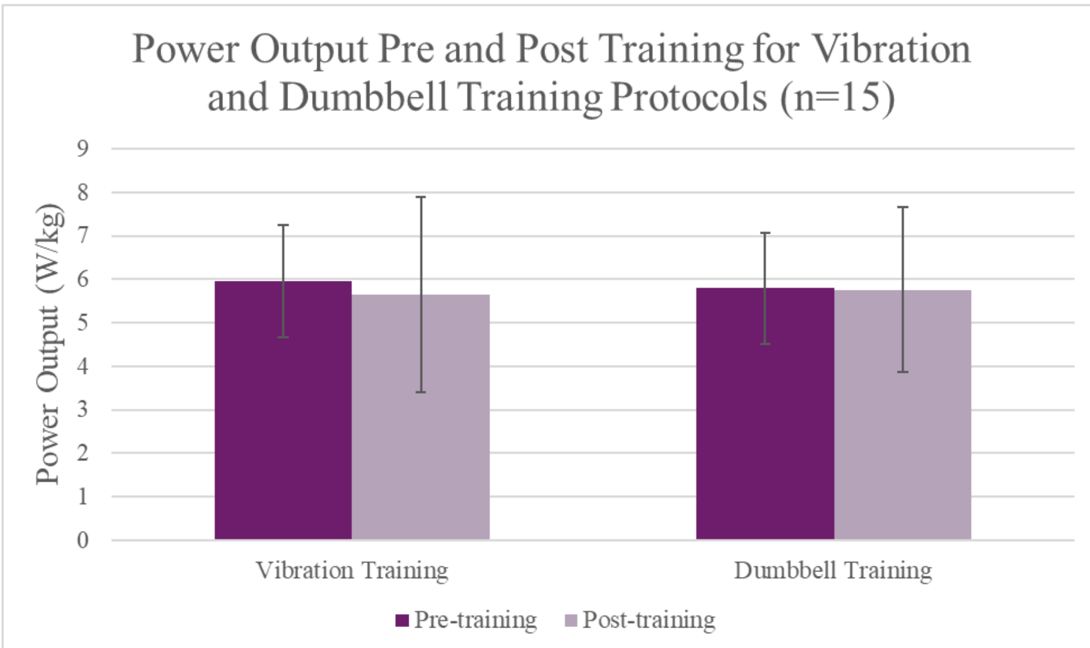



**Figure 8. Power output results**

There were no significant changes between the two training programs in the percent increase in heart rate from resting or the maximum achieved heart rate for each of the exercises. Although the results are not significant, vibration exercise overall elicited greater maximum heart rates overall for 4 out of the 7 exercises completed as shown below in Table 3. Additionally, 5 out of the 7 exercises had a greater increase in heart rate from resting heart rate for the exercises completed during vibration training compared to dumbbell training, shown in Table 4.

**Table 3. Maximum acheived heart rates for the exercises comleted in the two training protocols**

| Exercise | Mean (STD) (bpm) | | |
|---|---|---|---|
| | Vibration Training | Dumbbell Training | p-value |
| Side Flies (n=15) | 110.53 (27.6) | 112.20 (18.2) | .744 |
| Straight Arm Row (n=15) | 113.60(25.0) | 110.40 (19.4) | .504 |
| Bicep Curls (n=15) | 112.80 (19.6) | 112.93 (20.1) | .974 |
| Triceps Extensions (n=12) | 116.67 (21.6) | 109.83 (17.11) | .166 |
| Front Raise (n=14) | 119.50 (20.75) | 117.21 (17.04) | .648 |
| Bent Over Rows (n=15) | 123.33 (24.02) | 118.27 (18.92) | .267 |
| Internal/External Rotation (n=15) | 92.83 (22.14) | 99.80(21.40) | .378 |

*significant at p<.05

**Table 4. Percent increase in heart rate from baseline for each exercise completed for both training protocols**

| Exercise | Mean (STD) (%) | | |
|---|---|---|---|
| | Vibration Training | Dumbbell Training | p-value |
| Side Flies (n=15) | 38.4 (38.6) | 35.6 (26.9) | .738 |
| Straight Arm Row (n=15) | 42.30 (38.0) | 33.7 (29.0) | .277 |
| Bicep Curls (n=15) | 43.2 (31.0) | 36.7 (28.4) | .518 |
| Triceps Extensions (n=12) | 48.9 (36.5) | 40.4 (31.0) | .266 |
| Front Raise (n=14) | 48.9 (37.3) | 38.7 (25.3) | .238 |
| Bent Over Rows (n=15) | 31.9 (21.7) | 43.1 (27.2) | .092 |
| Internal/External Rotation (n=15) | 15.0 (21.7) | 20.8 (23.4) | .358 |

*significant at p<.05

There were significant differences between the two training protocols on RPE. Overall participants rated vibration training with significantly higher exertion compared to dumbbell training as shown below in Table 5. All of the exercises except for bicep curls and internal/external rotation had significant higher ratings of perceived exertion. Although they were not significant, bicep curls and internal/external rotation also had higher RPE values for vibration training compared to dumbbell training.

**Table 5. Ratings of perceived exertion for the exercises copmpleted for both training protocols**

| Exercise | Mean (std) | | p-value |
|---|---|---|---|
| | Vibration Training | Dumbbell Training | |
| Side Flies (n=13) | 14.0 (1.7) | 11.5 (1.6) | <.001* |
| Straight Arm Row (n=13) | 12.7 (2.9) | 10.7 (2.1) | .033* |
| Bicep Curls (n=13) | 13.1 (2.8) | 11.7 (2.2) | .153 |
| Triceps Extensions (n=13) | 13.3 (1.5) | 10.6 (1.5) | .002* |
| Front Raise (n=13) | 15.1 (2.7) | 11.8 (1.5) | <.001* |
| Bent Over Rows (n=13) | 13.7 (2.7) | 11.7 (2.0) | .018* |
| Internal/External Rotation (n=13) | 11.2 (2.4) | 10.4 (2.1) | .201 |

*significant at p<.05

### 2.3.4 Electromyography Results

EMG data was collected on two participants. The maximum voluntary contractions for the anterior deltoids, biceps and triceps were performed before and after completing vibration training. Figure 89 shows the MVC data right and left sides for P1 and Figure 10 shows the same for P2. P1 had lower muscle activation or the same muscle activation post training compared to pre training for all but one muscle. The only muscle that had greater muscle activation post training was the triceps. Participant P2 had more varied results regarding muscle activation. On the right side, the anterior deltoids had almost the same muscle activation post training while, the biceps had an increase in muscle activation post training. Contrastingly, the triceps had a decrease in muscle activation post training compared to pre training. On the left side the anterior deltoids had the same muscle activation pre and post training, whereas the biceps and triceps had a decrease in muscle activation post training.

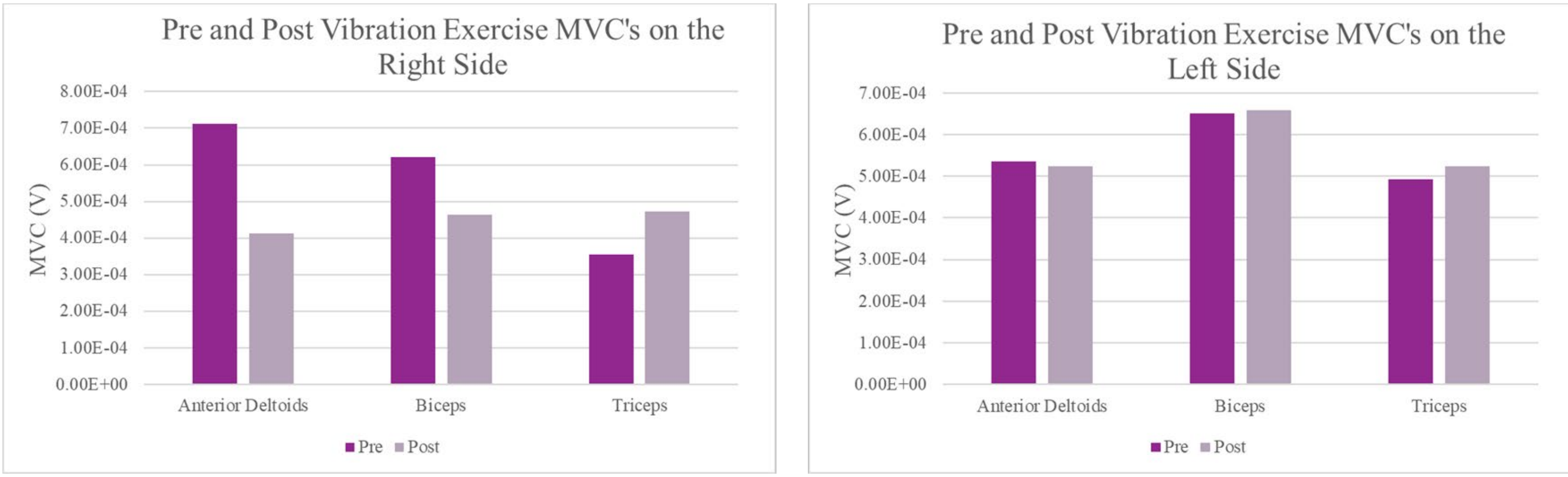



**Figure 9. EMG data pre and post vibrataion training for participant P1 for all three muscle groups on the (left) ritght side and (right) left side**

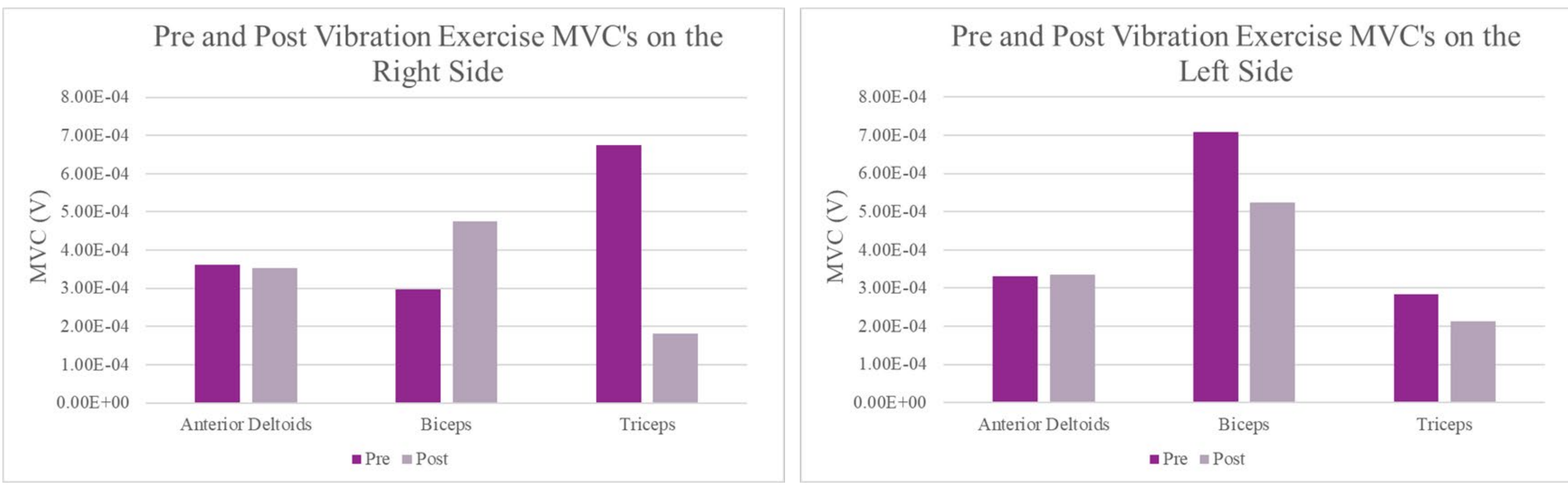



**Figure 10. EMG data pre and post vibrataion training for participant P2 for all three muscle groups on the (left) ritght side and (right) left side**

### 2.3.5 Tolerance

Participants' answers to the surveys collecting feedback on the two training programs can be seen below in Figures 11 and 12. Overall, participants had positive feedback related to their excitement and desire to train with vibration exercise in the future. Fifty nine percent of participants that completed the vibration training rated they were either moderately excited or very excited to train with vibration in the future. Also, 77% of the participants that completed the vibration training had a moderate or strong desire to train with vibration in the future. Furthermore, 77% of participants were either somewhat likely or very likely to participate in a 12-week training program with vibration and 77% of participants had a moderate or strong desire to participate in a 12-week training program with vibration. When surveyed about which training program participants preferred, 62% of participants that completed both training programs preferred the training with vibration over training with the dumbbells. Training with vibration was rated to be more difficult by almost all participants that completed both training programs. Participants' answers on which training program they enjoyed more were split more evenly. Forty three percent of participants rated they enjoyed vibration training more than dumbbell training, while 29% of participants said that both training programs were equally enjoyable and 29% said that training with the dumbbell was more enjoyable. Additional survey results can be seen in Appendix B.

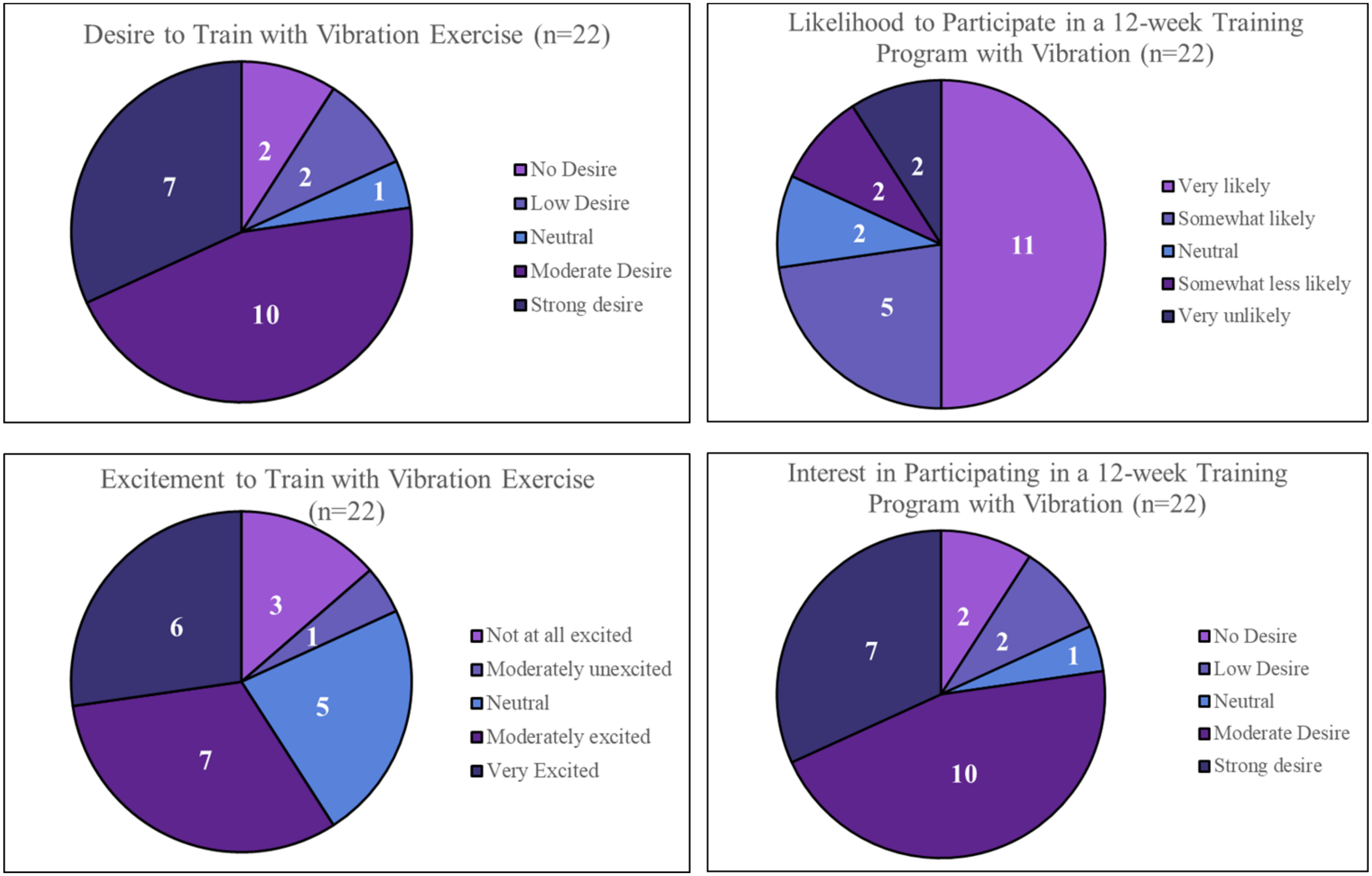



**Figure 11. Participants' answers to survey questions, (top left) Rate your desire to train with vibration exercise, (top right) rate your liklihood of participating in a 12-week training program with vibration exercise, (bottom right) rate your excitement to with training with vibration exericise, (bottom right) rate your interest in paticipainting in a 12-week training program with vibration exercise**

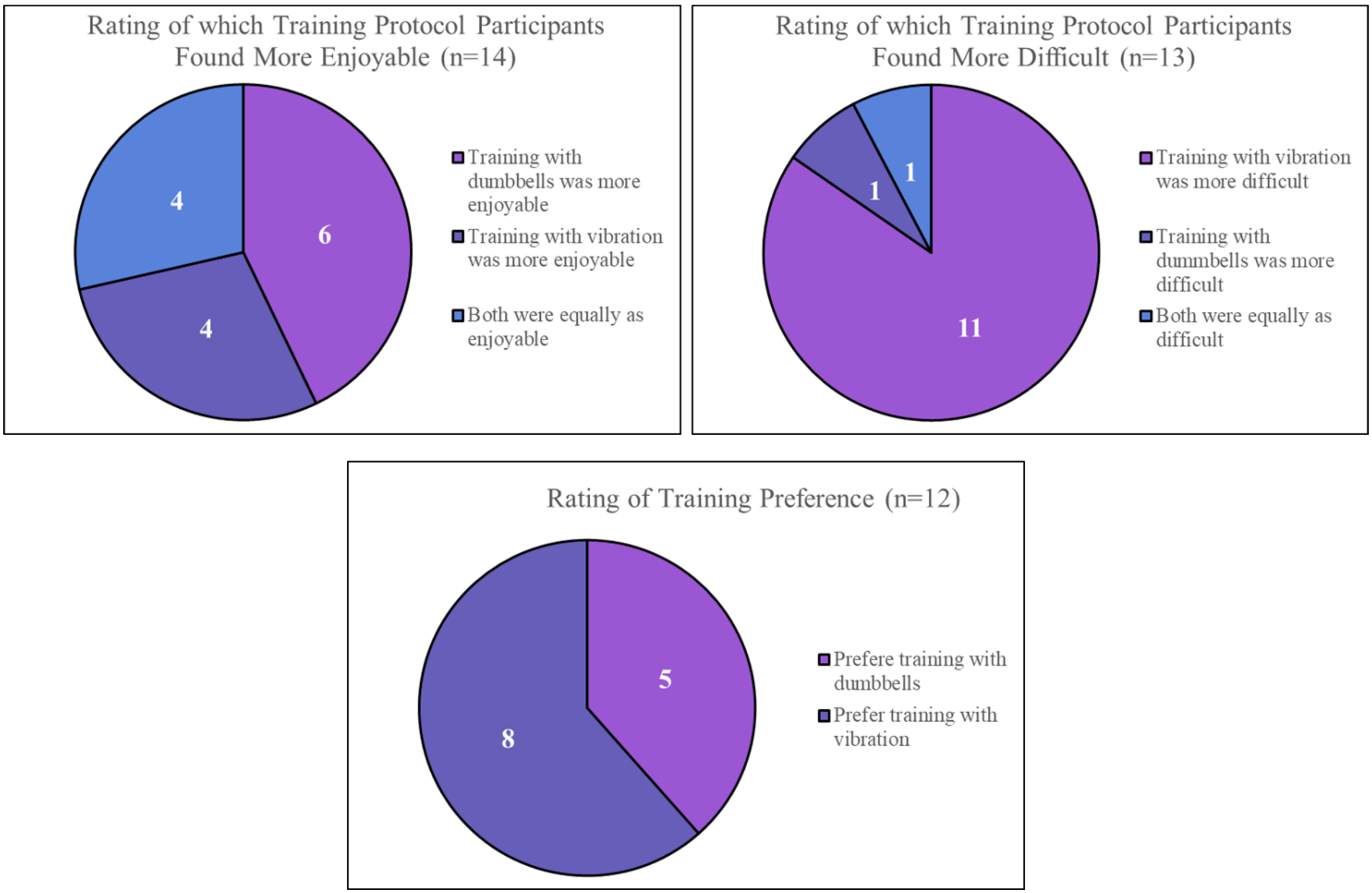



**Figure 12. Participants' answers to survey questions, (top left) rate which training program you found more enjoyable, (top right) rate which training program you found more difficult, (bottom middle) rate your excitement to with training with vibration exericise, (bottom right) rate your training preference**

Participants were asked open ended questions to gain additional feedback on what they liked the most and liked the least about training with vibration. Examples of the open-ended feedback can be seen in Table 6. Overall participants felt vibration training was more intense, required more exertion to complete and may lead to faster results. However, participants did not like certain aspects of training with vibration. Participants reported feeling uncomfortable with the training, feelings of itchiness and pain, and concerns about it vibrating their face which may cause headaches if used for a prolonged period.

**Table 6. Participants' open ended feedback on likes and dislikes of training with vibration**

| **Liked the Most About Vibration Training** |
| --- |
| "It felt like it was more intense" |
| "Feeling the different exertion from the standard dumbbell to the vibration" |
| "It was less painful" |
| "New, faster results" |
| "Feels like it works the muscle group twice as much than regular workouts" |
| "Makes exercise more strenuous, and may provide results quicker than standard dumbbell" |
| "Helped with muscle tiredness not as much of a burning feeling" |
| |
| **Like the Least About Vibration Training** |
| "Hurting my wrist" |
| "Boring, I got bored while doing the exercise" |
| "Certain positions I would just use regular dumbbells" |
| "Pain and itchiness" |
| "Made my face vibrate, not sure if it would give me headaches if I did it longer than 1" |
| "Made fingers and arms numb" |
| "Awkwardness if the unit, and uncertain of the grip while vibrating" |
| "Noise" |

## 2.4 Discussion

The results show overall the vibration training protocol was not feasible on an individual level with regards to minimum hold times however participants well tolerated the vibration training. Feedback overall was mostly positive, with participants providing a few comments on some of the aspects of the training that could be improved.

### 2.4.1 Feasibility to Complete and Hold Times

All participants were able to complete the exercises at 30Hz. This is the frequency that would be a minimum to start a long-term training program with based off previous literature that examined training frequency (Bedient et al., 2009; Lienhard et al., 2014; Petit et al., 2010; Turner, Sanderson, & Attwood, 2011). The desired hold time for participants was between 45-60s. Two exercises out of the seven (front raises and side flies) on the left and right sides did not have an average hold time that met the 45s minimum. Both side flies and front raises are completed in a position away from the body, with the arm extended to the side and front respectively. These exercises put the shoulder in an unstable position compared to the other exercises, making them more challenging to complete (Bedi, 2011). Given that these exercises are more challenging, it is not surprising participants were unable to meet the minimum hold time. However, on the right side, side flies were only 2 seconds away on average from the minimum hold time and the front raises were within 8 seconds. On the left side, the average hold times were not as close to the desired hold times. Most participants reported being right hand dominant. This could explain the difference in results seen between the left and right sides.

Although the average hold times for most of the exercises were greater than 45s, only 3 exercises on the right side and 2 exercises on the left side met the hypothesis that 80% of participants would be able hold the dumbbell for 45s. For the remainder of the exercises, less than 80% of study participants were able to hold the dumbbell for 45s. Participants used 60% of their 1RM for each exercise during the training. However, the 1RM was done dynamically whereas the training was completed isometrically. In an isometric hold, 60% may have been too heavy for most participants to complete the exercises. Given that most participants were unable to complete the majority of exercises at the desired hold time, the starting weight and weight progression should be evaluated and monitored if these exercises were to be used in a long-term training program. Given this study was the first of its kind, there are few guidelines on what the starting weight should have been, or what should be used in the future. When starting a training program with vibration each exercise should be completed with just the weight of the dumbbell first to assess participants' abilities to complete them with vibration. Each exercise would be assessed individually afterwards for weight progression. If participants can hold the dumbbell for 60s pain free and with a RPE of 13 or lower (on a 6-20scale), than the weight should be increased by 2-10% (Medicine, 2009). This assessment would then be repeated to find the ideal weight to be used for the training protocol and for progressing the training weight. The exercises completed are generally not completed in an isometric hold. The increased intensity of vibration training, through an isometric hold and heavy starting weight, may have contributed to the majority of participants not being able to complete most of the exercises at a minimum hold time of 45s.

### 2.4.2 Physiological Measures

Most of the physiological measures showed that vibration training was not more challenging than traditional dumbbell training. Only two participants reported pain at either visit. All but two participants reported participating in wheelchair sports and activities. Participating in wheelchair sports have been shown to help decrease pain, and to prevent the development of shoulder pain and injury (Mulroy et al., 2011a). The study population that completed the study may have been more athletic than the average manual wheelchair user with SCI. There were no significant differences in the maximum achieved heart rate or the percent increase in heart rate from baseline between the two training programs. Around 30% of our participants had injury levels that were at T6 or above. Injuries at these levels can result in altered cardiac function (Teasell et al., 2000). Furthermore, previous research found that persons with SCI at this level had heart rates that did not reach as high of values and did not change or increase as much during exercise as these other two groups (Schmid et al., 1998). It's possible that including participants with higher level injuries in our study may have therefore contributed to the lack of statistically different findings in heart rate between the two training protocols. However, participants rated vibration exercise with significantly more exertion for five out of the seven exercises compared to those same exercises completed with the dumbbell. In addition to the use of vibration added to the resistance training, the greater perceived exertion could be due to the implementation of the training. Vibration training is done in an isometric hold, whereas dumbbell training is typically done concentrically through the entire range of motion. Previous research has shown that during isometric and dynamic squatting there was greater muscle activation during the isometric squat than the concentric squat (Earl et al., 2001). Thus, regardless of the addition of vibration this type of training may be perceived as harder. This may be true especially for those exercises that require the participant to hold the dumbbell at a position away from the body as is done with front raises and side flies. An isometric hold is not typically done with standard resistance training because it requires training in multiple positions, whereas dynamic training accomplishes training throughout the entire range of motion (Carlson et al., 2014). Participants may have not been used to this type of training contributing to the higher ratings of perceived exertion that may not have been entirely attributed to vibration.

Furthermore, there were no significant changes in power output and blood lactate between the training methods. However, when looking just at the vibration training protocol there was a significant difference in blood lactate concentration before and after the training. Lactate concentrations were significantly larger after the training compared to baseline. Although blood lactate values with vibration training compared to dumbbell training were not significant, vibration training is still able to elicit physiological changes in this measure of exercise intensity. The Upper Limb Wingate test has some limitations when used in a test-re-test study design. The test itself is challenging; thus, even though vibration exercise has been shown to increase power, participants' may have been feeling the effects of fatigue when completing the test following both training sessions. Furthermore, in studies with vibration exercise, power is typically measured by jumping maneuvers and explosive power movements such as squats. These types of movements are not possible in manual wheelchair users with SCI. Thus, although the Wingate test has some limitations, methods of measuring power in this population are limited. Results from the blood lactate match those previously reported from using whole body vibration; values ranging from 2.0-8.0 mmol of blood lactate (Sartorio et al., 2011). The study however, compared vibration exercise to an isometric contraction (Sartorio et al., 2011). Although they found a significant difference between the two testing protocols, the stimulus of the isometric contraction is different than the dynamic exercises participants completed with the dumbbell in the current study which could attribute the non-significant findings. Additionally, the resting blood lactate values are higher than those generally found at rest; 0.5-1.0 mmol (Kenney, 2015). The values were measured after the Wingate test was completed. Although participants were given time to rest, while their heart rate and blood pressure values returned to resting, this may have not been enough time for the lactate to dissipate that was built up after completing the rest. These higher baseline values may have contributed to smaller changes in blood lactate concentration and non-significant findings between the two training programs. The results from the blood lactate testing and power output testing further support that although the vibration training was perceived as more challenging, physiologically both training programs were equally as challenging for most of the exercises. There were significant changes in blood lactate concentration after training with vibration and maximum achieved heart rate values were greater for vibration training compared to dumbbell training. As a result, vibration exercise may be a good training option for participants with limited ranges of motion in their upper limbs or who have pain when moving through the complete range of motion, due to the training being completed isometrically.

### 2.4.3 Electromyography

Overall results of the EMG analysis are inconclusive. Previous research has indicated that vibration increases muscle fiber recruitment, rate of firing and synchronization of firing (Darryl J. Cochrane, 2011; L. Griffin et al., 2001; Mischi & Cardinale, 2009). Furthermore, vibration training has been shown to lead to a lower inhibition of co-contraction. These have all been shown previously by EMG as indicated by changes in muscle activation (Darryl J. Cochrane, 2011; Pollock et al., 2012; Jörn Rittweger, 2010). The results of the present study do not match the results of these previous studies and do not support the idea that vibration can enhance muscle activation. Differences between the previous research and the current study are present. These studies were done with whole body vibration and with large muscles of the legs. Additionally, some of these studies did not use vibration with additional weight and the parameters in the studies are all different. The muscles in the lower limbs are larger than those in the upper limbs and are more resilient to fatigue (Neyroud et al., 2013). It is possible that vibration may have enhanced muscle activation, but it is likely instead the muscles may have been fatigued; a conclusion that was drawn from the power output results as well. With upper limb vibration there may be a lower threshold between enough vibration to increase strength and the point where muscles become fatigued.

### 2.4.4 Tolerance

Overall, participants provided positive feedback on the vibration training as well as the dumbbell training. Participants' found the vibration training to be enjoyable and expressed a desire to train with vibration exercise in the future. Although the hypothesis was not met with an 80% response rate of positive answers, many of the questions response rates were close to 80% with multiple questions being at 77%. Due to the limited research with targeted upper limb vibration and the newness of the exercise modality, participants' attitude toward the training are important in the success of a long-term training program. Previous research has indicated when participants reported a positive attitude toward vibration exercise, the training program was implemented more successfully, and the outcomes were improved (Kawanabe et al., 2007). When asked which training program participants preferred, 62% of participants preferred the vibration training. Again, this question didn't meet the desired response rate of 80%. However, the majority of study participants did rate they enjoyed vibration training more. Many comments from the open-ended feedback may be attributed to the participants' perceived ratings of exertion being higher for all exercises during vibration training compared to dumbbell training. There were several comments related to the vibration exercise feeling more intense, feelings of the muscles working harder and vibration making the exercise more strenuous. Like was mentioned previously, these feelings may also have been in part related to the vibration exercise being carried out in an isometric hold instead of dynamically in the manner of the dumbbell training. Some of the dislikes of the training may also be related to the higher ratings of perceived exertion reported during vibration training. Participants' comments included feelings of pain, itchiness, and feelings of numbness in the arms and fingers. The combination of the higher RPE and participant feedback support participants' perceptions of vibration training being harder to complete.

### 2.5 Limitations

The study enrolled fewer participants than desired based on initial power calculations and feasibility. Because participants were tested at the National disabled Veterans Wheelchair games, where they have a limited schedule, not all participants were able to complete the second visits. Even if they had, the study would likely have been under powered. This may have also contributed to there being no significant changes in the physiological measures. The study visit order was not randomized for participants that were tested at the wheelchair games. There may have been bias associated with the feedback provided by participants because participants were trying the vibration training first. This may have altered their opinions on one of the training protocols differently than if the visit order was randomized. This was done to test a high volume of study participants and to have more participants try the vibration protocol, however, the study team acknowledges the associated bias. The dosage of exercise between the two training programs is different. While both programs are using 60% of the one repetition max for each exercise, the vibration exercise is performed isometrically while the dumbbell exercise is isokinetic. Vibration exercise is typically performed in an isometric hold to maximize the benefits of training with it. However, standard dumbbell training is generally not done in an isometric hold. For this reason, completing repetitions with the dumbbell was chosen, although differences in the training intensity of the two protocols may not solely be to the addition of vibration to the training. Thus, a future study with equal doses will have to be done in order to determine if vibration is the contributing factor to the results that were observed or if it was simply training isometrically. Furthermore, some of the outcome measures have associated limitations. The upper limb Wingate test is generally not used for the application in which it was used. Previous studies that have looked at power output and vibration have used body weight maneuvers that are not possible in manual wheelchair users with SCI. The results from the power output testing may have been different if the test being used was more like those used in previous studies. Participants with SCI, in particular those above T6 have altered heart rate responses to exercise. Because of the level of the injury, generally their heart rate responses are not large and their heart rates do not go as high (Schmid et al., 1998). Even though one of the exercises may have been more physiologically demanding, it is possible because of the population and the nature of SCI this may not have been observed in the heart rate data. Lastly, all but two participants reported currently participating in wheelchair sports. However, most of the participants also reported that it was less than two times a week. The National Disabled Veterans Wheelchair Games are a competitive event that draws active participants. These participants may have already been too active to see a change in these physiological variables. The training may be better suited for participants that are not as active or currently training.

## 2.6 Conclusion

Overall the training did not prove to be feasible for most participants and exercises. However, participants' feedback on vibration training was overall positive with a majority of the participants being excited and interested to train with it in the future. Although physiologically the results did not show significant differences between the two training programs, the majority of the exercises with vibration training elicited greater maximum achieved heart rates compared to dumbbell training. Furthermore, participants' perceived exertion was greater for all seven exercises with vibration compared to dumbbell training, with five of them reaching significance. When looking at just the vibration training program, there was a significant increase in blood lactate results after completing the training. The EMG data did not support previous research indicating vibration is able to enhance muscle activation. Additional research to determine whether participants' perceptions of vibration training are physiologically supported by physiological markers of exertion and EMG need to be conducted. However, given the training sessions are the same amount of time, participants may get more out of training with vibration compared to training with a standard dumbbell for the same amount of time put into training. This may be true especially due to participants who perceived training with vibration exercise to be harder than traditional dumbbell exercise. Additional participants and studies are needed to confirm these results, as well as the use of vibration in a long-term training program to study the potential strength gains that may be achieved.

# 3.0 Reliability of an upper limb strength measurement protocol using the Biodex dynamometer

## 3.1 Introduction

Isokinetic strength measurements reliability has been extensively studied in the lower body and in a healthy population. However, for the upper limbs less evidence is available proving reliability of isokinetic strength measurements, especially in persons with SCI. This is in part, due to their inability to stabilize in an upright posture in a seated position from lack of trunk muscular strength and upper limb pathology. In addition, many of the positions needed to measure some motions such as shoulder flexion/extension may need to be modified compared to able-bodied persons (Sisto & Dyson-Hudson, 2007). The Biodex Dynamometer (Biodex Medical Systems, LLC, Shirly, NY) measures isokinetic and isometric strength in a variety of upper and lower limb muscles. Using a Biodex, or similar system, has been shown to be the most reliable way to measure upper limb strength compared to handheld dynamometry, and is considered the gold standard. Handheld dynamometry requires a high level of skill, training and physical strength. It has been shown to have mixed results in studies that looked at reliability (Kelln et al., 2008). Although many studies report a high level of reliability in the shoulder, elbow and wrist, the specific protocols used are rarely reported as well as the protocol set up (Edouard et al., 2011; Forthomme, Dvir, Crielaard, & Croisier, 2011; Plotnikoff & MacIntyre, 2002). Furthermore, no mention of how the set up may have been recreated and the proper data collected was reported. Each measurement has a variety of settings which are unique to the person, based on set up, anthropometrics, and range of motion. Many of the studies only looked at one aspect of the set up and make no mention of the other aspects (Caruso, Brown, & Tufano, 2012).

## 3.2 Methods

The research study required 2 visits, with at least 1 day in between each study visit, but no more than 7 days. All testing took place at the Human Engineering Research Laboratory. The study received approval from the University of Pittsburgh's Institutional Review Board. All participants signed informed consent forms before any testing procedures were performed.

### 3.2.1 Participants

A convenience sample of individuals employed at HERL was used to recruit participants for the research study. Testing took place between August 2017 and February 2018 and all testing took place at HERL. Recruitment took place entirely in person by word of mouth and with IRB approved text that was sent out over email. Ten able-bodied participants were recruited to test the Biodex protocol that is used to measure upper limb strength. Participants were included in the study if they had a normal range of motion in their upper limbs and did not have pain at the time of the study.

### 3.2.2 Data collection

To assist in obtaining reliable data a recording tool was developed to ensure participants are in in the same position as they were in for the initial testing session on the Biodex (data recording tool can be seen in Appendix C. The measurement tool was developed to verify that all the measurements needed to re-create the setup at a later visit were captured. Items related to set up such as the position of the chair, dynamometer, and arm as well as the range of motion participants move through were recorded.

*Study Visit 1*

After participants signed the consent form, isokinetic strength measures at a torque arm speed of 60deg/sec were recorded using the Biodex dynamometer. In order to ensure the maximal force production of the tested upper limb, participants were secured into the chair with three padded belts: two diagonally across their chest and one across their lap. This was done to isolate their upper limbs and to ensure little to no trunk movement. The order in which the movements were recorded were randomized. The following movements and targeted range motions were completed: shoulder flexion/extension (-30 to 50 degrees), shoulder abduction/adduction (10 to 70 degrees), shoulder internal/external rotation (0 to 45 degrees), elbow flexion/extension (0 to 90 degrees), forearm supination/pronation (-80 to 80 degrees) and wrist flexion/extension (-45 to 45 degrees). For each movement, two sets of 5 repetitions were collected. The first set of 5 repetitions served as practice repetitions and to get used to the movement. The second set of repetitions were used for data analysis. Each movement was collected on both the left and right sides before moving onto the next. At the first study visit, all aspects of the set up were recorded using the measurement tool. These measurements were used at the second visit to replicate the set up.

*Study Visit 2*

The same procedures were followed at the second visit as at the first visit. The movement order followed a new unique randomization order.

### 3.2.3 Data Analysis

Peak isokinetic torques were identified and averaged over the second set of five repetitions for each of the movements recorded at the shoulder, elbow and wrist. Peak torques were normalized by body weight for each person and are recorded in Nm-kg.

For all data left and right sides were conducted in separate models, giving a total of 12 tests being run per side.

### 3.2.4 Statistical Analysis

All statistical analysis was performed using SPSS Version 23 (SPSS Inc., Chicago). Means and standard deviations are reported for all values. Wilcoxon Signed Rank test was used to look at differences in strength measurements between the two time points for each of the movements involved. Spearman correlations were used to examine the association between the strength measurements taken at each time point. The non-parametric version of the tests were used because the data were not normally distributed. Lastly, Intraclass Correlation Coefficients and their 95% confidence intervals were used to test the test-retest reliability of the measurements. A two-way mixed model, with a single measurement and absolute agreement was used for the ICC analysis. For the Wilcoxon rank test and Spearman correlation, the level of significance was set at a p-value of 0.05 or less. For the ICC calculations values less than .50 are indicative or poor reliability, values between .5 and .75 indicate moderate reliability, values between .75 and .9 indicate good reliability and values greater than .9 indicate excellent reliability.

## 3.3 Results

Results from the Wilcoxon rank test for the right side showed no significant difference between the two testing visits for any of the movements. For the left sides, elbow extension and forearm pronation were significantly different between the two-time points, with other movements showing no significant difference between the two visits. These results can be seen in tables 7 and 8 for the right and left sides respectfully.

**Table 7. Wilcoxon rank test results for the right side**

| Movement | Mean | STD | P-Value |
|---|---|---|---|
| R Shoulder Flexion Visit 1 | 32.2 | 10.2 | .859 |
| R Shoulder Flexion Visit 2 | 32.1 | 9.5 | |
| R Shoulder Extension Visit 1 | 23.9 | 15.2 | .646 |
| R Shoulder Extension Visit 2 | 23.3 | 18.2 | |
| R Shoulder Abduction Visit 1 | 29.9 | 7.7 | .374 |
| R Shoulder Abduction Visit 2 | 32.2 | 7.6 | |
| R Shoulder Adduction Visit 1 | 21.7 | 13.9 | .953 |
| R Shoulder Adduction Visit 2 | 20.9 | 11.2 | |
| R Shoulder Internal Rotation Visit 1 | 12.9 | 6.6 | .260 |
| R Shoulder Internal Rotation Visit 2 | 11.9 | 5.4 | |
| R Shoulder External Rotation Visit 1 | 16.9 | 8.1 | .721 |
| R Shoulder External Rotation Visit 2 | 17.2 | 6.2 | |
| R Elbow Flexion Visit 1 | 27.3 | 14.3 | .959 |
| R Elbow Flexion Visit 2 | 26.5 | 10.1 | |
| R Elbow Extension Visit 1 | 15.1 | 5.4 | .441 |
| R Elbow Extension Visit 2 | 14.4 | 7.1 | |
| R Forearm Pronation Visit 1 | 3.7 | 1.1 | .284 |
| R Forearm Pronation Visit 2 | 3.4 | 1.4 | |
| R Forearm Supination Visit 1 | 5.9 | 1.3 | .126 |
| R Forearm Supination Visit 2 | 5.4 | 1.1 | |
| R Wrist Flexion Visit 1 | 2.2 | 1.0 | .154 |
| R Wrist Flexion Visit 2 | 1.7 | .50 | |
| R Wrist Extension Visit 1 | 3.5 | 1.5 | .645 |
| R Wrist Extension Visit 2 | 3.8 | 2.2 | |

**Table 8. Wilcoxon rank test results for the left side**

| Movement | Mean | STD | P-Value |
|---|---|---|---|
| L Shoulder Flexion Visit 1 | 33.3 | 10.6 | .508 |
| L Shoulder Flexion Visit 2 | 32.3 | 7.2 | |
| L Shoulder Extension Visit 1 | 23.5 | 17.2 | .959 |
| L Shoulder Extension Visit 2 | 23.5 | 21.4 | |
| L Shoulder Abduction Visit 1 | 29.3 | 6.1 | .285 |
| L Shoulder Abduction Visit 2 | 31.7 | 8.3 | |
| L Shoulder Adduction Visit 1 | 23.3 | 13.5 | .169 |
| L Shoulder Adduction Visit 2 | 20.1 | 10.1 | |
| L Shoulder Internal Rotation Visit 1 | 11.7 | 5.9 | .374 |
| L Shoulder Internal Rotation Visit 2 | 12.5 | 6.4 | |
| L Shoulder External Rotation Visit 1 | 17.7 | 7.9 | .153 |
| L Shoulder External Rotation Visit 2 | 16.5 | 5.5 | |
| L Elbow Flexion Visit 1 | 26.6 | 13.3 | .878 |
| L Elbow Flexion Visit 2 | 25.9 | 10.1 | |
| L Elbow Extension Visit 1 | 15.0 | 6.5 | .015* |
| L Elbow Extension Visit 2 | 13.2 | 5.3 | |
| L Forearm Pronation Visit 1 | 4.2 | 1.7 | .041* |
| L Forearm Pronation Visit 2 | 3.1 | 1.1 | |
| L Forearm Supination Visit 1 | 5.3 | 1.2 | .153 |
| L Forearm Supination Visit 2 | 5.0 | 1.1 | |
| L Wrist Flexion Visit 1 | 1.9 | .87 | .759 |
| L Wrist Flexion Visit 2 | 1.6 | .61 | |
| L Wrist Extension Visit 1 | 4.0 | 2.5 | .919 |
| L Wrist Extension Visit 2 | 3.7 | 1.7 | |

The Spearman correlations showed significantly positive relationships between the two study time visits for almost all the movements. On the right side only, shoulder abduction and wrist extension showed no significant association between the two visits. The left side showed comparable results, with all but forearm pronation showing a significant relationship between the two visits. Tables 9 and 10 show the results from the Spearman correlations for the right and left sides respectively.

**Table 9. Spearman correlation results for the right side**

| Movement | Mean | STD | $R^2$ Value | P-Value |
|---|---|---|---|---|
| R Shoulder Flexion Visit 1 | 32.2 | 10.2 | .770 | .009** |
| R Shoulder Flexion Visit 2 | 32.1 | 9.5 | | |
| R Shoulder Extension Visit 1 | 23.9 | 15.2 | .891 | .001** |
| R Shoulder Extension Visit 2 | 23.3 | 18.2 | | |
| R Shoulder Abduction Visit 1 | 29.9 | 7.7 | .685 | .029* |
| R Shoulder Abduction Visit 2 | 32.2 | 7.6 | | |
| R Shoulder Adduction Visit 1 | 21.7 | 13.9 | .527 | .117 |
| R Shoulder Adduction Visit 2 | 20.9 | 11.2 | | |
| R Shoulder Internal Rotation Visit 1 | 12.9 | 6.6 | .736 | .015* |
| R Shoulder Internal Rotation Visit 2 | 11.9 | 5.4 | | |
| R Shoulder External Rotation Visit 1 | 16.9 | 8.1 | .903 | <.001** |
| R Shoulder External Rotation Visit 2 | 17.2 | 6.2 | | |
| R Elbow Flexion Visit 1 | 27.3 | 14.3 | .661 | .038* |
| R Elbow Flexion Visit 2 | 26.5 | 10.1 | | |
| R Elbow Extension Visit 1 | 15.1 | 5.4 | .796 | .006** |
| R Elbow Extension Visit 2 | 14.4 | 7.1 | | |
| R Forearm Pronation Visit 1 | 3.7 | 1.1 | .668 | .035* |
| R Forearm Pronation Visit 2 | 3.4 | 1.4 | | |
| R Forearm Supination Visit 1 | 5.9 | 1.3 | .793 | .006** |
| R Forearm Supination Visit 2 | 5.4 | 1.1 | | |
| R Wrist Flexion Visit 1 | 2.2 | 1.0 | .675 | .032* |
| R Wrist Flexion Visit 2 | 1.7 | .50 | | |
| R Wrist Extension Visit 1 | 3.5 | 1.5 | .541 | .106 |
| R Wrist Extension Visit 2 | 3.8 | 2.2 | | |

**Table 10. Spearman correlation results for the left side**

| Movement | Mean | STD | $R^2$ Value | P-Value |
|---|---|---|---|---|
| L Shoulder Flexion Visit 1 | 33.3 | 10.6 | .867 | .001** |
| L Shoulder Flexion Visit 2 | 32.3 | 7.2 | | |
| L Shoulder Extension Visit 1 | 23.5 | 17.2 | .952 | <.001** |
| L Shoulder Extension Visit 2 | 23.5 | 21.4 | | |
| L Shoulder Abduction Visit 1 | 29.3 | 6.1 | .758 | .011* |
| L Shoulder Abduction Visit 2 | 31.7 | 8.3 | | |
| L Shoulder Adduction Visit 1 | 23.3 | 13.5 | .721 | .019* |
| L Shoulder Adduction Visit 2 | 20.1 | 10.1 | | |
| L Shoulder Internal Rotation Visit 1 | 11.7 | 5.9 | .855 | .002** |
| L Shoulder Internal Rotation Visit 2 | 12.5 | 6.4 | | |
| L Shoulder External Rotation Visit 1 | 17.7 | 7.9 | .869 | .001** |
| L Shoulder External Rotation Visit 2 | 16.5 | 5.5 | | |
| L Elbow Flexion Visit 1 | 26.6 | 13.3 | .939 | <.001** |
| L Elbow Flexion Visit 2 | 25.9 | 10.1 | | |
| L Elbow Extension Visit 1 | 15.0 | 6.5 | .985 | <.001** |
| L Elbow Extension Visit 2 | 13.2 | 5.3 | | |
| L Forearm Pronation Visit 1 | 4.2 | 1.7 | .445 | .197 |
| L Forearm Pronation Visit 2 | 3.1 | 1.1 | | |
| L Forearm Supination Visit 1 | 5.3 | 1.2 | .732 | .016* |
| L Forearm Supination Visit 2 | 5.0 | 1.1 | | |
| L Wrist Flexion Visit 1 | 1.9 | .87 | .729 | .017* |
| L Wrist Flexion Visit 2 | 1.6 | .61 | | |
| L Wrist Extension Visit 1 | 4.0 | 2.5 | .826 | .003** |
| L Wrist Extension Visit 2 | 3.7 | 1.7 | | |

Scatter plots are presented below for the movements that did not have significant spearman correlations. For right shoulder adduction, the linear $R^2$ value was moderate, showing a moderate percentage of variation between the two time points. One data point appears to on outlier compared to the other data points, which could be causing movement to not be significantly correlated.

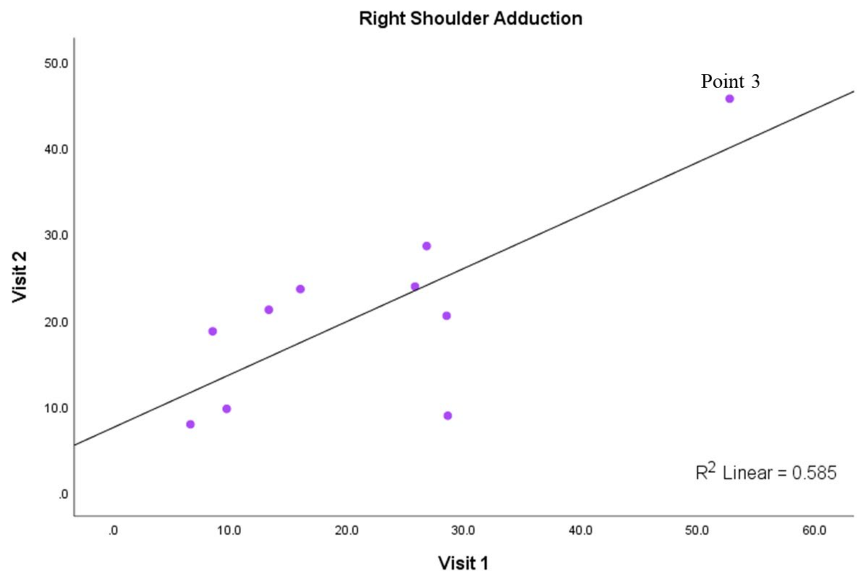



**Figure 13. Scatter plot for right shoulder adduction**

Further investigation into the one data point shows evidence to treat that point as an outlier. The box and whisker plot is shown below. Additionally, when looking at the outlier labeling rule developed by Tukey and Hoaglin , data point three (value 45.7) falls outside of the upper quartile value calculated as 43.34.

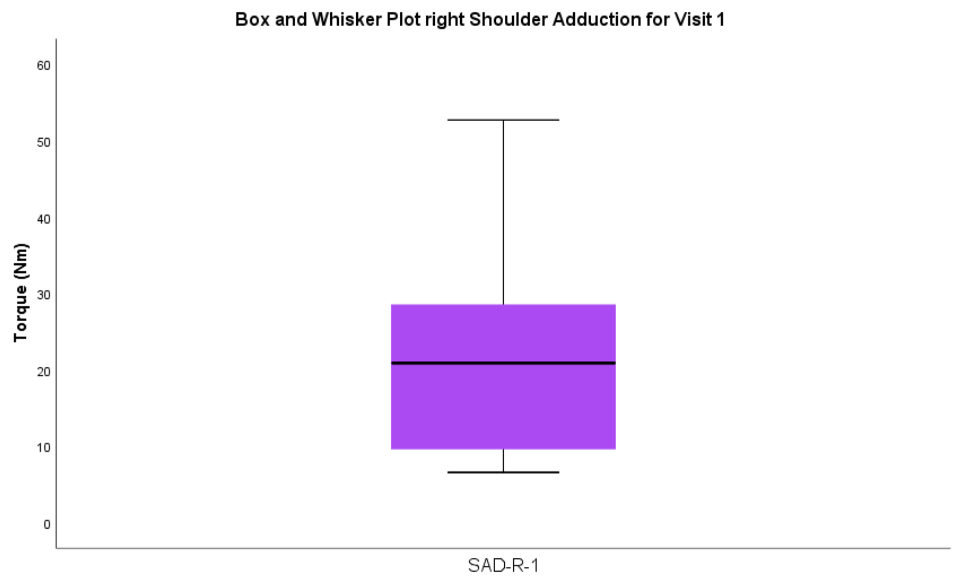



**Figure 14. Box and whisker plot for right shoulder adduction for visit 2**

A similar approach was taken for right wrist extension. The $R^2$ value was slightly higher, but still showed a high percentage of variation between the two time points. Again, looking at the scatter plot, there appears to be two points that could also be outliers, warranting further investigation.

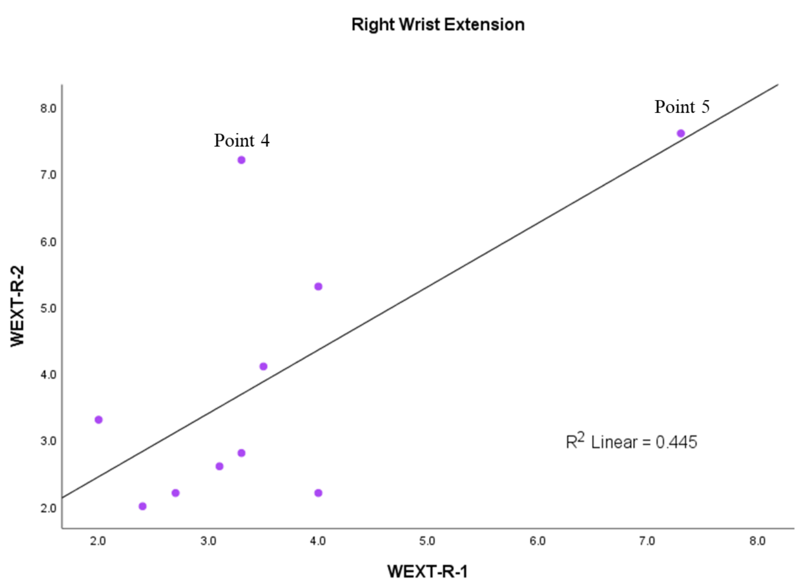



**Figure 15. Scatter plot for right wrist extension**

The box and whisker plots are presented below for right and left wrist extension. Looking at both of the plots, another point that could possibly be flagged as an outlier is present. Point five from visit 1 (value 7.3) was flagged on the box and whisker plot and point four from visit 1 (value 3.3) was not flagged. However, point five has similar values between the two time points, whereas point four shows a large difference between the two visits. Thus, looking at the points for just one time point, may give the whole explanation. Point 4 may still be treated as on outlier based off the difference between the two visits. When looking further at point 5, and looking at the outlier labeling rule, data point five falls outside of the upper quartile range of 7.025. This point could also then be considered an outlier.

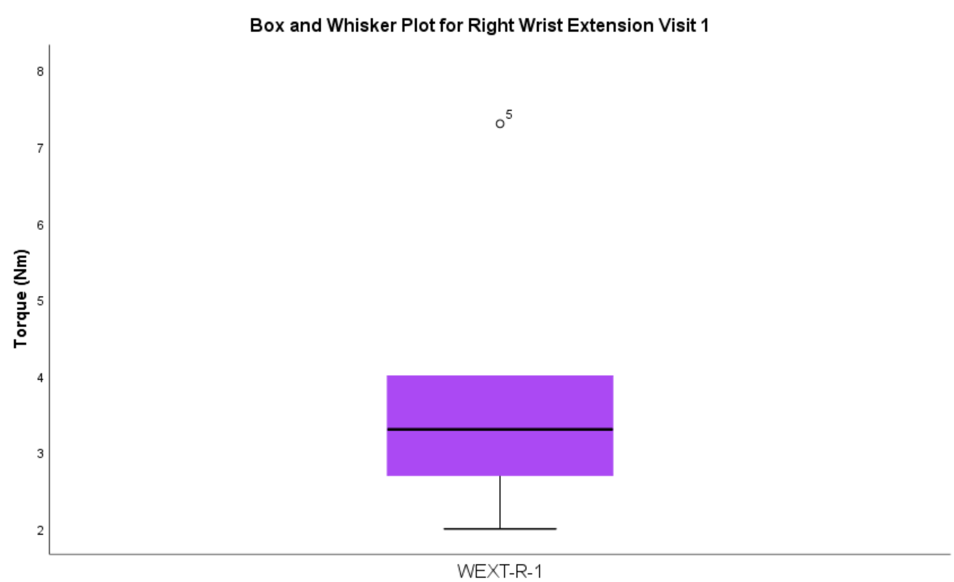



**Figure 16. Box and whisker plot for right wrist extension for visit 1**

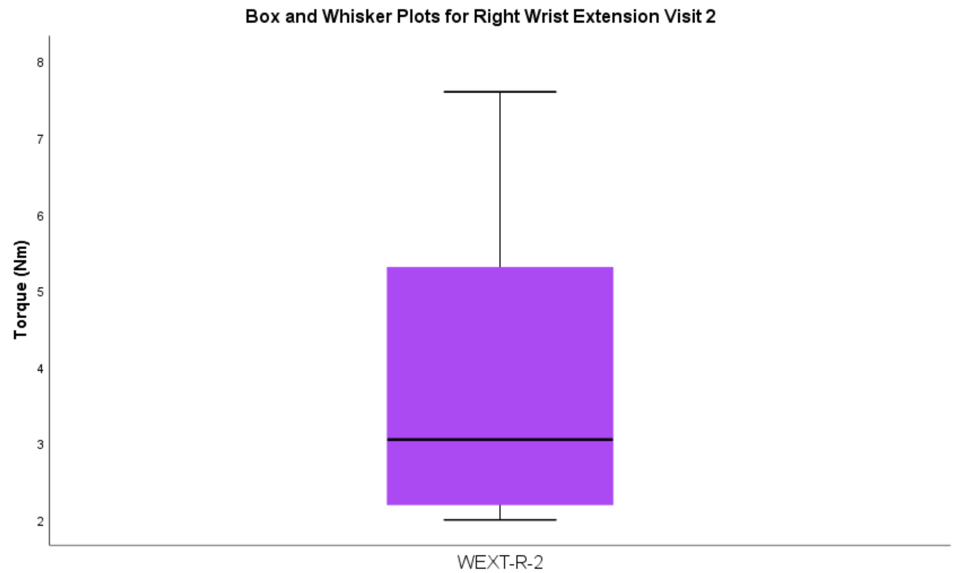



**Figure 17. Box and whisker plot for wrist extension for visit 2**

The scatter plot for left forearm pronation is presented below. The plot shows a very low R2 value and a high percentage of variation between the two time points. For this movement there appears to be no one outlier that could be affecting the results.

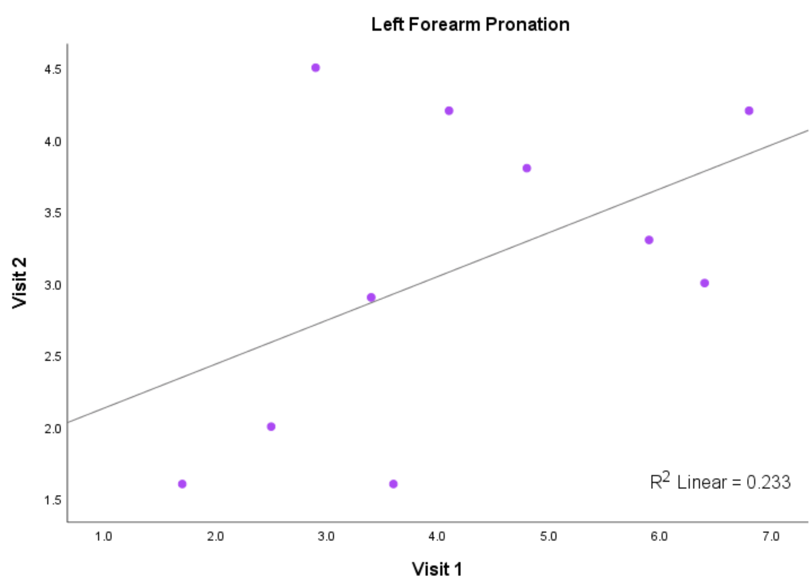



**Figure 18. Scatter plot for left forearm pronation**

The results of the ICC and 95% confidence intervals are presented in table 11 for the right side and table 12 for the left side. For the right side, all but one ICC value showed moderate or better reliability. The only movement to show excellent reliability is shoulder external rotation. Wrist flexion was the only movement on the right side to show poor reliability.

**Table 11. ICC and 95% confidence intervals for the right side**

| Movement | Mean | STD | ICC | 95% CI | |
|---|---|---|---|---|---|
| | | | | Lower Bound | Upper Bound |
| R Shoulder Flexion Visit 1 | 32.2 | 10.2 | .888 | .610 | .971 |
| R Shoulder Flexion Visit 2 | 32.1 | 9.5 | | | |
| R Shoulder Extension Visit 1 | 23.9 | 15.2 | .842 | .479 | .959 |
| R Shoulder Extension Visit 2 | 23.3 | 18.2 | | | |
| R Shoulder Abduction Visit 1 | 29.9 | 7.7 | .548 | .050 | .863 |
| R Shoulder Abduction Visit 2 | 32.2 | 7.6 | | | |
| R Shoulder Adduction Visit 1 | 21.7 | 13.9 | .765 | .288 | .937 |
| R Shoulder Adduction Visit 2 | 20.9 | 11.2 | | | |
| R Shoulder Internal Rotation Visit 1 | 12.9 | 6.6 | .887 | .631 | .970 |
| R Shoulder Internal Rotation Visit 2 | 11.9 | 5.4 | | | |
| R Shoulder External Rotation Visit 1 | 16.9 | 8.1 | .939 | .777 | .985 |
| R Shoulder External Rotation Visit 2 | 17.2 | 6.2 | | | |
| R Elbow Flexion Visit 1 | 27.3 | 14.3 | .733 | .217 | .927 |
| R Elbow Flexion Visit 2 | 26.5 | 10.1 | | | |
| R Elbow Extension Visit 1 | 15.1 | 5.4 | .797 | .376 | .945 |
| R Elbow Extension Visit 2 | 14.4 | 7.1 | | | |
| R Forearm Pronation Visit 1 | 3.7 | 1.1 | .562 | -.061 | .870 |
| R Forearm Pronation Visit 2 | 3.4 | 1.4 | | | |
| R Forearm Supination Visit 1 | 5.9 | 1.3 | .680 | .165 | .908 |
| R Forearm Supination Visit 2 | 5.4 | 1.1 | | | |
| R Wrist Flexion Visit 1 | 2.2 | 1.0 | .371 | -.220 | .787 |
| R Wrist Flexion Visit 2 | 1.7 | .50 | | | |
| R Wrist Extension Visit 1 | 3.5 | 1.5 | .637 | .064 | .895 |
| R Wrist Extension Visit 2 | 3.8 | 2.2 | | | |

The left side, like the right side, had all but one movement show moderate or higher reliability. Additionally, internal rotation, external rotation, and elbow extension showed excellent reliability. Forearm pronation was the only movement to show less than moderate reliability.

**Table 12. ICC and 95% confidence intervals for the left side**

| Movement | Mean | STD | ICC | 95% CI | |
|---|---|---|---|---|---|
| | | | | Lower Bound | Upper Bound |
| L Shoulder Flexion Visit 1 | 33.3 | 10.6 | .774 | .319 | .939 |
| L Shoulder Flexion Visit 2 | 32.3 | 7.2 | | | |
| L Shoulder Extension Visit 1 | 23.5 | 17.2 | .642 | .026 | .899 |
| L Shoulder Extension Visit 2 | 23.5 | 21.4 | | | |
| L Shoulder Abduction Visit 1 | 29.3 | 6.1 | .688 | .146 | .912 |
| L Shoulder Abduction Visit 2 | 31.7 | 8.3 | | | |
| L Shoulder Adduction Visit 1 | 23.3 | 13.5 | .778 | .365 | .939 |
| L Shoulder Adduction Visit 2 | 20.1 | 10.1 | | | |
| L Shoulder Internal Rotation Visit 1 | 11.7 | 5.9 | .913 | .706 | .997 |
| L Shoulder Internal Rotation Visit 2 | 12.5 | 6.4 | | | |
| L Shoulder External Rotation Visit 1 | 17.7 | 7.9 | .901 | .670 | .974 |
| L Shoulder External Rotation Visit 2 | 16.5 | 5.5 | | | |
| L Elbow Flexion Visit 1 | 26.6 | 13.3 | .904 | .664 | .975 |
| L Elbow Flexion Visit 2 | 25.9 | 10.1 | | | |
| L Elbow Extension Visit 1 | 15.0 | 6.5 | .923 | .306 | .985 |
| L Elbow Extension Visit 2 | 13.2 | 5.3 | | | |
| L Forearm Pronation Visit 1 | 4.2 | 1.7 | .353 | -.158 | .767 |
| L Forearm Pronation Visit 2 | 3.1 | 1.1 | | | |
| L Forearm Supination Visit 1 | 5.3 | 1.2 | .759 | .325 | .933 |
| L Forearm Supination Visit 2 | 5.0 | 1.1 | | | |
| L Wrist Flexion Visit 1 | 1.9 | .87 | .673 | .093 | .909 |
| L Wrist Flexion Visit 2 | 1.6 | .61 | | | |
| L Wrist Extension Visit 1 | 4.0 | 2.5 | .839 | .472 | .957 |
| L Wrist Extension Visit 2 | 3.7 | 1.7 | | | |

Additional statistics looking for outliers that could have potentially affect the outcome, were calculated on the data that did not show favorable results from the Wilcoxon, Spearman correlation and ICC analysis.

Left elbow flexion showed significantly different results from the two time points. However, looking at the remainder of the results, there was a strongly significant correlation and moderate reliability. Looking at the scatter plot below shows a good $R^2$ value and no apparent points as outliers. Looking further at the box and whisker plots and the outlier analysis, point four (value 57.4) is flagged as a potential outlier. However, that point still sits close to the trend line and has a value close to that of the first visit. Lastly, looking at the upper quartile value for outlier labeling rule of 68.225, the value of the potential outlier falls within that range. Based off of the previously stated evidence, it is reasonable to treat this point as a valid point and not an outlier. Therefore, additional analysis on this point was not performed.

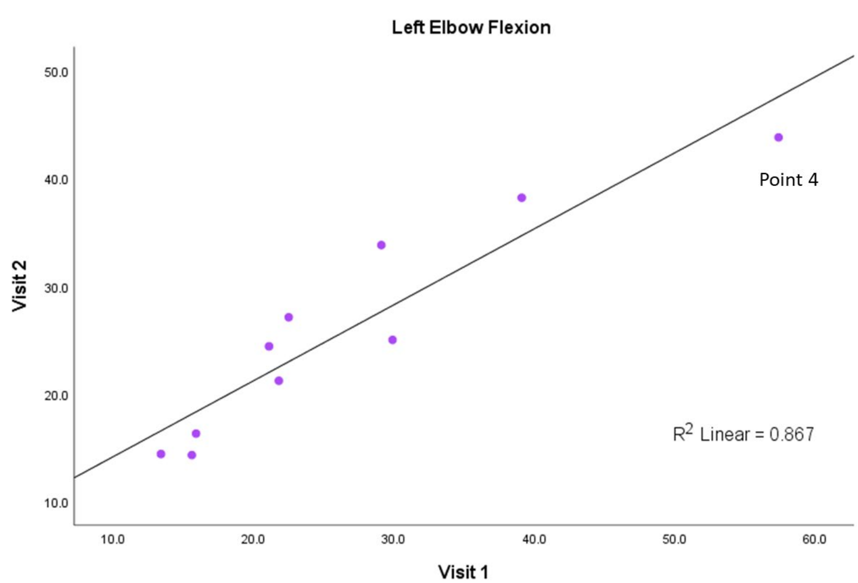



**Figure 19. Scatter plot for left elbow flexion**

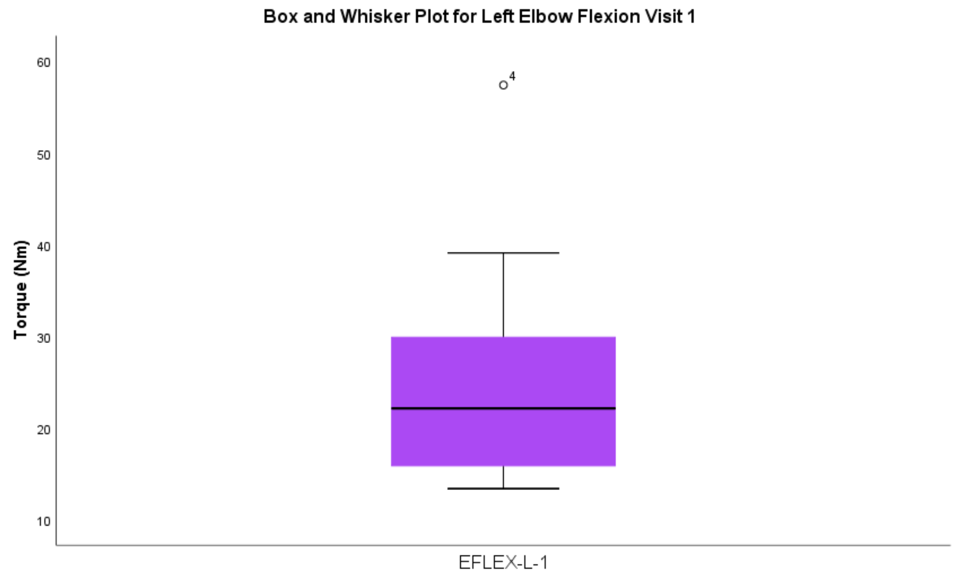



**Figure 20. Box and whisker plot for left elbow flexion for visit 1**

Right wrist flexion had a very low reliability coefficient but had a moderately significant correlation coefficient and a favorable Wilcoxon outcome. When looking at the scatter plot a couple of points could potentially be treated as outliers. Looking further at the box and whisker plots none of the points are identified as possible outliers. Furthermore, when looking at the upper quartile values of 5.715 (visit 1) and 4.775 (visit 2) for the outlier labeling rule none of the values fall above those values. Thus, these points can be treated as valid points and not treated as outliers.

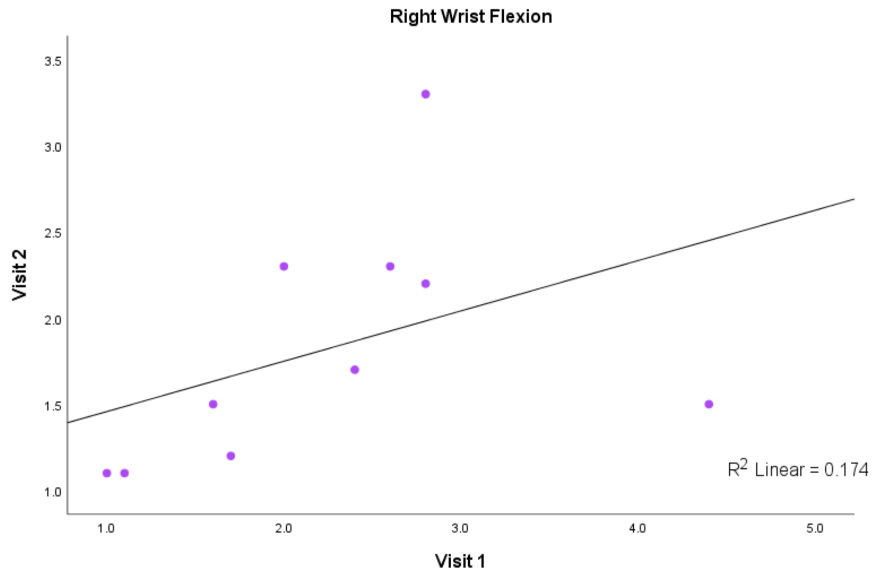



**Figure 21. Scatter plot for right wrist flexion**

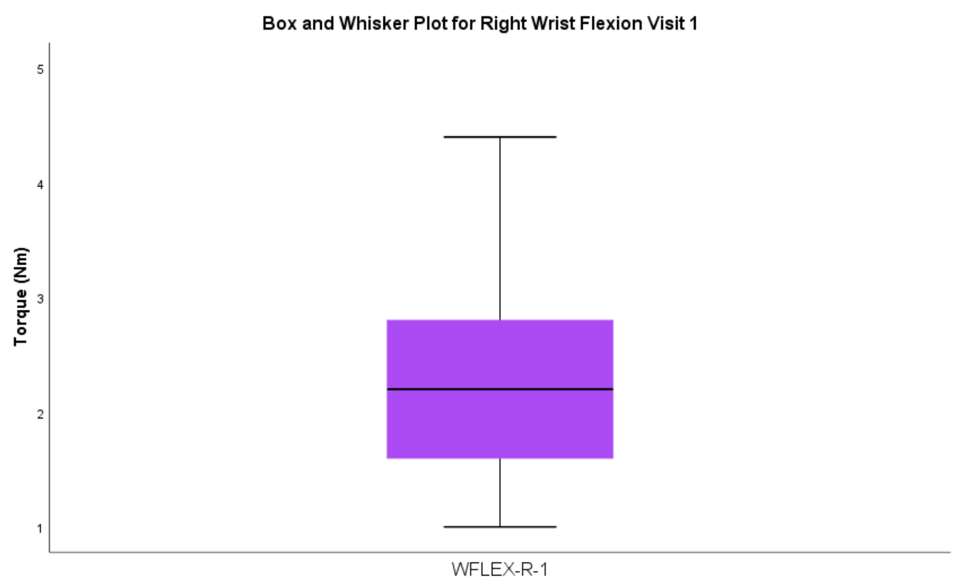



**Figure 22. Box and whisker plot for right wrist flexion visit 1**

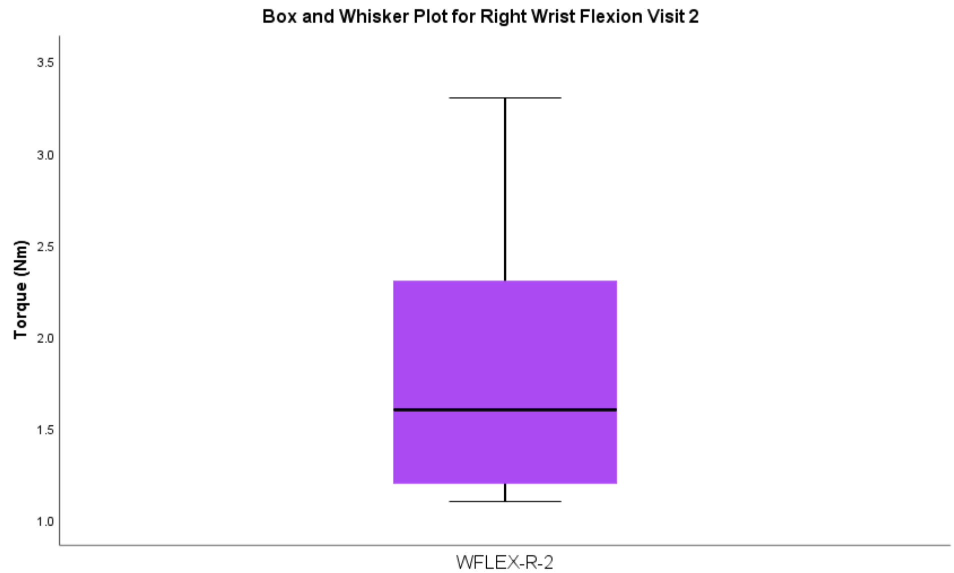



**Figure 23. Box and whisker plot for right wirst flexion visit 2**

Finally, the points from above that could be treated as outliers were removed and the statistics were run without those points. The results are presented in the table below.

**Table 13. Summary of re-run statistics without potential outliers**

| Movement | | Mean | STD | Wilcoxon p-value | Spearman Correlation Coefficient | Spearman p-value | ICC | Upper Bound | Lower Bound |
|---|---|---|---|---|---|---|---|---|---|
| Right Shoulder Adduction | R | 18.2 | 3.1 | .889 | .350 | .352 | .420 | -.375 | .837 |
| | L | 18.11 | 2.5 | | | | | | |
| Right Wrist Extension | R | 3.1 | .26 | 1 | .367 | .371 | .413 | -.457 | .853 |
| | L | 3.1 | .40 | | | | | | |

## 3.4 Discussion

The results indicate overall, the protocol being used is reliable for a majority of the motions tested and the parameters being collected on set-up are satisfactory in re-creating positioning at the second study visit. However, when looking at the ICC values the 95% confidence intervals are large. These large confidence intervals indicate a greater uncertainty that the ICC values obtained are accurate values. The sample size used in this study was small and likely contributed to the wide confidence intervals as the variability between participants was large. Further modifying the method of data collection to improve the process may help improve the precision of the ICC estimates. There are physical limitations to the set-up of some of the movements that cannot be adjusted without physical modification of the Biodex hardware. The ability to modify the system may reduce the variability in some of the measures, however, cost to do this may not improve the variability significantly. However, there were two other measures of reliability used to assess the protocol which indicated the protocol to be more reliable. Results from the Wilcoxon Rank Test and Spearman Correlations indicated better overall reliability. Some exceptions were observed for a few of the movements, however, based on the examination of the three tests used to examine reliability (Wilcoxon, Spearman and ICC) the protocol was shown to be reliable for most movements.

There were some tests with poor reliability. On the right side, shoulder abduction and wrist extension did not show a significant association between the two-time points. However, there was no significant differences between the means at the two-time points. The ICC was only barely over .5, showing moderate reliability. These results are somewhat contradictive and inconclusive. However, two out of the three results indicate the protocol is reliable. When looking at these tests on an individual basis, there were a few study participants' that had large jumps in their numbers between visits. This may be due to the randomization order. Each of the protocols was randomized, and its possible fatigue was a factor at one of the visits. This aspect will also be a possibility when testing participants with SCI and will have to be taken into consideration. Participants' may have also become more acclimated to the testing procedures by their second visit. Even though participants were given a set of five repetitions for each exercise as warm up/introduction it is still possible that at the second visit they had a great understanding and feeling for how the exercises were performed.

Wrist extension on the right side also did not have a significant association between the two visits as shown by the Spearman correlation. This movement also showed no significant differences in the means between the two visits and showed moderate reliability. Also, wrist flexion was the only joint on the right side that did not show moderate reliability. The wrist movement is challenging to set up on the Biodex and has some physical limitations for some participants. This may have impacted the results at the wrist. Additionally, this is a very challenging movement to complete. Many participants struggled to move through the normal wrist range of motion, with almost all having to shorten the range of motion. Given that participants with no upper limb pathology were unable to move through the entire range of motion for the wrist trials, it is possible that for the participants with SCI this will also be true. The range of motion may have to be adjusted for each participant as was done for the participants in the study. For this motion specifically, fatigue may have contributed to the differences found in the results. It is also possible, that at the second visit, participants were more aware of the movement being performed and were able to move through it more efficiently. These results are consistent to what has been found previously on the Biodex, although little research has been done on the wrist compared to the shoulder and knee (Caruso et al., 2012).

The results on the left side are more consistent than the results on the right. Elbow extension was found to have a significant difference between the means of the two visits. However, the results were highly associated with one another and showed excellent reliability. The difference in the means could be attributed to error from performing multiple tests. Lastly, forearm pronation was the only movement to be consistently unreliable. There was a significant difference in the means, as well as no significant relationship between the two visits and a low coefficient of reliability. Like wrist flexion/extension, this movement is challenging to set up and recreate a second time due to physical limitations of the setup. It is also a difficult movement to complete; like wrist flexion/extension, depending on the randomization order of the movements fatigue may have also been a factor for this movement as well. Other factors related to range of motion and awareness of the movement at the second visit, as explained for wrist flexion and extension may also help to explain the results found for forearm pronation/supination. For this movement, we must closely monitor the set up, but the physical limitations of the Biodex we are not able to overcome.

Finally, removing the potential outliers that could have been affecting the outcome of the correlation analysis ended up not impacting the results. After removing them, the Spearman correlation coefficients are still not significant. Thus, the original analysis and conclusions drawn from that can be used.

Although the wrists showed results that were not as reliable as the other protocols, these movements are still of interest because the wrist joint is an important joint for persons with SCI. The wrists are highly susceptible to injury from high loading activities such as transfers and repetitive tasks such as wheelchair propulsion (Nyland et al., 2000). Upper limb strength, including forearm strength, can assist in preventing these injuries and can help support the elbow and shoulder joints as well (A. M. Koontz et al., 2011). Therefore, although individual tests showed a lack of reliability, some of the individual tests showed good reliability. There is still an interest to measure these movements in future studies with participants with SCI because of the pathologies at the wrist that are commonly developed.

The participants tested in the study were able bodied participants, while the participants that will be tested in the future regarding strength measurements will be those with SCI. Generally, if the same set up procedures are used for the persons with SCI as were used for the able-bodied participants and they are set up in the Biodex the same way each time, the protocol should be reliable. Additional factors that are unique to persons with SCI will need to be accounted for. The participants with SCI may have pain or overuse injuries in their upper limbs from daily wheelchair usage and completion of ADL’s and IADL’s. This could cause them to have a more limited or variable range of motion when completing the protocols. Particularly between sessions depending on their levels of pain at a given testing session. Additionally, the presence of pain or injury may not allow the participants to move through the motions as hard or as fast as the able-bodied participants. This may lead to inconsistencies in the data, or in the ability of participants to be able to complete all five testing repetitions. Additionally, the participants with SCI, depending on the level of injury may have less trunk control compared to the able-bodied participants tested. There is no way to measure the ‘tightness’ of the straps that are used to secure participants to the seat. Although, the movement is related to the upper limbs if the trunk is more tightly secured to the seat at one session compared to another this may allow for greater forces to be generated compared to when the straps are loose. Given that persons with SCI may have limited trunk control this may be an important variable to control for in future testing.

## 3.5 Limitations

This study used participants who are able-bodied although the exercise study in which this protocol will be used will use participants with SCI. Although testing persons with SCI would have been most ideal, access to this population is extremely limited and the study needed to be performed and issues could be identified, and procedures refined prior to completion of a longitudinal study. Furthermore, the ranges of motion selected were based on those that were most often used however, most of these studies used able-bodied participants. Some of the ranges of motion such as the one for the shoulder and elbow have previously been used in persons with SCI as well as in the able-bodied population (Kakebeeke, Lechner, & Handschin, 2005; Mayer, Horstmann, Kranenberg, Röcker, & Dickhuth, 1994; Souza et al., 2005). The wrist measurements however, have been largely studied in the able-bodied population, thus the values being used for range of motion were taken from that literature (Poulis et al., 2003). Participants with SCI may not be able to complete the entire range of motion for these two movements. The limitations of set-up with the Biodex are going to be present with participants with SCI as well. Many of these set up limitations are due to participant anthropometrics and the lack of adjustability in some set-ups. These for the most part are factors that cannot be changed without modification of the equipment itself. The knowledge of these set-up limitations has been noted and will be used with future participants. Lastly, the 95% CI for the majority of movements was large, indicating uncertainty around the accuracy of the ICC values that were obtained. The sample size for the study was small and there was large inter-subject variability in the values for some of the movements which likely contributed to the larger than desired confidence intervals.

## 3.6 Conclusion

The upper limb strength protocol was shown to be reliable for most of the movements on two out of the three measures for reliability when using the set-up data collection tool. In particular, the movements at the shoulder (flexion/extension, abduction/addiction and internal/external rotation) and the elbow (flexion/extension) were shown to be more reliable movements compared to the wrist. Although the movements at the forearm (pronation/supination) and wrist (flexion/extension) were not reliable, the data collection set-up tool likely helps to reduce measurement error to some extent.

## 4.0 Feasibility and implementation of a 12-week upper limb vibration training program

### 4.1 Introduction

The previous upper limb vibration study showed vibration training for the most part to be feasible to implement in a single training session as well as illicit some physiological changes in ratings of perceived exertion. Furthermore, most of the exercises were able to be completed by more than half of the study population at the minimum training requirements. In a variety of populations, using vibration for recurring sessions, was shown to lead to more significant changes in performance and more permanent neuromuscular adaptations. There is Compelling evidence suggests vibration exercise needs to be performed for longer than six weeks to prove effective with the number of vibration exercise sessions playing a vital role in performance measures. Studies that last longer than six weeks have shown to increase both strength and power, as measured by lower limb isometric strength testing and ground reaction forces respectively (Roelants, Delecluse, Goris, & Verschueren, 2004; Russo et al., 2003; S. M. P. Verschueren et al., 2004). Increases in testosterone, growth hormone and cortisol , indicators of muscle growth, as well as increases in bone mineral density and decreases in fat mass have been shown in programs lasting longer than 6-weeks. Additionally, training programs that last 6-weeks or longer show improved results when 2 or more training sessions were performed per week (C. de Ruiter et al., 2003).

These parameters for longitudinal training programs were established for vibration training with plates and platforms. Also, the physiological changes in strength and power have been demonstrated in a variety of populations, with and without disabilities. These same parameters and findings need to be established in participants with SCI as well as with the vibrating dumbbell.

Therefore, the first aim of this study was to examine the feasibility of implementing a 12-week in home exercise training program with upper limb vibration. The home was chosen to eliminate some of the barriers with exercising for persons with SCI. Furthermore, there have been studies that have shown that supervised in home training and rehabilitation programs are successful and are viewed favorably by persons with SCI (Van Straaten et al., 2014). The second aim of the study was to examine the changes in strength, power and pain after completing the 12-week training program with upper limb vibration. This aim included examining the effects of training with vibration on the functional outcomes of wheelchair propulsion and wheelchair transfers. These two outcomes are very important to manual wheelchair uses but have not been studied thus far in relation to potential improvements after training with vibration.

## 4.2 Methods

The study received approval from the University of Pittsburgh's Institutional Review Board. In-lab testing took place at HERL (January 2016-January December 2018) and exercise testing took place at the participants' home or other agreed upon location. Recruitment efforts took place through HERL's research registry, the Clinical and Translational Sciences Institute and local community groups. These groups include the SCI peer support group held at UPMC Mercy hospital, Three Rivers Adaptive Sports, and the Steelwheelers basketball team. The study team worked with therapists at the Center for Assistive Technology and seating clinicians at the VA to recruit participants from the two seating clinics. Other sources of participants were utilized include the Physical Medicine and Rehabilitation registry, Vocational Rehab, and the Harmarville Health South Rehab clinic. Participants were recruited in person at the Center for Assistive Technology and the Mercy Outpatient SCI clinic. At these two locations participants were directly screened for participation in the research study.

### 4.2.1 Human Subjects

Adult manual wheelchair users with SCI were recruited for this study. The following criteria were met in order to participate:

*Inclusion Criteria*: (1) have a neurological impairment secondary to a SCI, disease or dysfunction at T2 or lower (2) have a SCI which occurred over 6 months prior to the start of the study; (3) use a manual wheelchair as primary means of mobility (at least 30 hrs. per week but not necessarily always in motion); (4) be between 18 and 65 years of age; (5) be able to perform a transfer independently to and from a wheelchair; (5) Provide a signed medical release by primary care physician to engage in a high-intensity resistance training exercise program; (6) live within 60 minutes driving time from the Human Engineering Research Laboratory and (6) have normal range of motion in the upper limbs.

*Exclusion Criteria*: (1) History of fractures or dislocations in the shoulder, elbow and wrist from which the subject has not fully recovered (i.e. the subject may no longer experience pain or limited/altered function due to the injury) (2) upper limb pain that interferes with the ability to propel or transfer (3) recent hospitalization for any reason (within the past three months); (4) pregnant women and (5) history of coronary artery disease, coronary bypass surgery or other cardiorespiratory events.

### 4.2.2 Protocol Overview

Participants were asked to come to HERL three times over a 12-week study period for three different study visits: baseline, mid-training visit (approximately 6-weeks into the study) and end of the training (ideally within 1 week of the last training visit after the 12-week training protocol). During these visits, the following activities took place a) Pain and Health Surveys (Baseline and Weeks 6, 12), b) Muscle Strength Testing (Baseline and Weeks 6, 12), c) Functional Testing (Baseline and Week 12), and Pre-Training Assessment and Instructions (Baseline). The 12-week training period began after the first baseline visit and ended with a study visit at the end of the training period. The timeline and outcome measures being competed at each visit can be seen below in Figure 24.

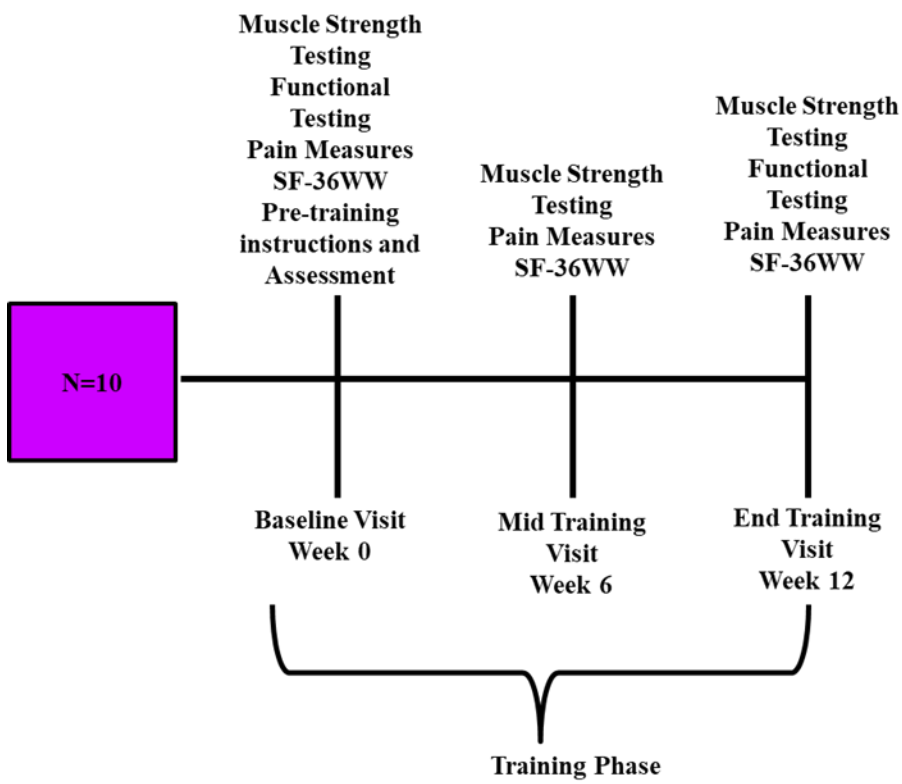



**Figure 24. Study flow chart**

After signing informed consent, all subjects completed the same demographics questionnaire that was completed in the previous study (chapter 2). Prior to initiation of study procedures, all participants were screened for their tolerance to vibration. Every participant held the dumbbell at 25Hz for 30 seconds with their arm at a forty-five-degree angle away from their bodies (position like a bicep curl). If they were unable to complete the assessment, they were not permitted to continue the study.

### 4.2.3 Outcome Measures

Once the demographics questionnaire and vibration screening were completed, the following outcome measures were collected.

#### 4.2.3.1 Pain Measures

Numerical rating scale (NRS): Participants were asked to rate their most severe wrist, elbow and shoulder pain during the past 24 hours using an 11-point scale (i.e. 0-10) anchored at the ends by "no pain" and "worst pain ever experienced (Farrar et al., 2001)." This scale was completed at all three study visits (baseline, 6-weeks and 12-weeks).

WUSPI (Wheelchair User's Shoulder Pain Index): The WUSPI is a 15-item, self-report instrument that measures shoulder pain intensity in wheelchair users during various functional activities of daily living, such as transfers, loading a wheelchair into a car, wheelchair mobility, dressing, bathing, overhead lifting, driving, performing household chores, and sleeping (Curtis et al., 1995a; Curtis et al., 1995b). This measure was completed at all three study visits (baseline, 6-weeks and 12-weeks).

Carpal Tunnel Syndrome Self-Assessment Questionnaire: This self-report instrument includes two scales: A Symptom Severity Scale consisting of 11 questions and a Functional Status Scale evaluating 8 different activities. This instrument is reproducible, internally consistent, and responsive to clinical changes in symptoms (Levine et al., 1993b). Participants completed this measure at all three study visits (baseline, 6-weeks and 12-weeks).

#### 4.2.3.2 General Health and Function

The 36-Item Short Form Health Survey Walk Wheel (SF-36 WW) is a slightly modified version of the original SF-36 that has been validated for persons with SCI (B. Lee et al., 2009). The SF-36 is a brief, multi-dimensional, self-report health questionnaire that measures eight concepts - Physical Functioning, Role limitation due to Physical problems, Bodily Pain, General Perception of Health, Vitality, Social Function, Role limitation due to Emotional problems, and Mental Health. The domain scales ranges from 0 (worst possible health state measured by the questionnaire) to 100 (best possible health state). Like the previous pain scales described and carpal tunnel assessment scales, the SF-36 was completed at all three study visits (baseline, 6-weeks and 12-weeks).

#### 4.2.3.3 Muscle Strength Testing

Isokinetic strength measurements, at a torque arm speed of 60 deg/sec were recorded using an instrumented dynamometer (Biodex Medical System, New York, USA) (Sisto & Dyson-Hudson, 2007). Isokinetic muscle strength is more correlated with the performance of physical activities when compared to isometric strength (Brown & Weir, 2001); thus it was chosen for this study. The torque measurements were recorded using the standardized setup and testing protocol as described previously in the Biodex Reliability Study (chapter 3). Each exercise was performed in randomized fashion for both arms for the following test movements: shoulder flexion/extension (-30 to 50 degrees), shoulder abduction/adduction (10 to 70 degrees), shoulder internal/external rotation (0 to 45 degrees), elbow flexion/extension (0 to 90 degrees), forearm supination/pronation (-80 to 80 degrees) and wrist flexion/extension (-45 to 45 degrees) and grip strength. Two practice repetitions for each movement tested were completed prior to data collection. In order to ensure the maximal force production of the tested upper limb, subjects were secured into the chair with three padded belts: two diagonally across their chest and one across their lap. Two sets of five repetitions were recorded for each movement with at least five minutes of rest in between muscle groups tested.

After the final movement was measured participants transferred back to their wheelchair for the grip strength measurements. A handheld dynamometer was used to measure grip strength. Three trials were collected for each arm. A fourth trial was collected if one of the trials was not within 5N of the other trials.

Based off the strength testing reliability study, the wrist measurements were shown to not be as reliable compared to the shoulder and elbow movements. Additionally, able-bodied participants were unable to move through the entire range of motion for the wrist measurements indicating this may also be a challenge with participants with SCI. The wrist measures were still tested during the study because the wrist in general is of interest to persons with SCI and improvement in these results was still of interest to the study team. Furthermore, participants were instructed to move within the range of motion in which they feel comfortable and pain free. Participants' had sufficient time to rest in between movements as well as before the next outcome measure.

#### 4.2.3.4 Power Output

Participants completed an Upper Extremity Wingate Test (P.L. Jacobs et al., 2003) using a Lode Ergometer (Lode Movement and Performance, Groningen, Netherlands) to measure power. The test was completed after the strength testing. The resistance on the ergometer was set constant at 3.5% of the participant's body weight (P.L. Jacobs et al., 2003). Participants positioned themselves such that they were in a comfortable cranking position and there was a slight bend in their elbows at full extension. The height of the ergometer was adjusted as needed. Participants were required to secure their wheel locks and wheelchair blocks were placed around their rear wheels. After a 5-minute warm up with no load and at a comfortable speed, the test was initiated. The total time of the test was one minute and thirty seconds. For the first 60 seconds, the participants cranked on the on the cycle with minimal resistance (10W) and maintained a speed between 55-65 RPM's. The resistance was then increased to a maximal level and participants cranked as hard and as fast as they were able to for the last 30 seconds of the test. After that the test was completed, the resistance was then returned to zero and the participants cycled at a comfortable pace to cool down. Peak power normalized by body weight was calculated.

#### 4.2.3.5 Wheelchair Propulsion Assessment

Each subject's wheelchair was fit with a SmartWheel (Three Rivers Holdings, Mesa, AZ), an instrumented wheel that measures forces and moments applied to the pushrim, on the non-dominant side of the participants' wheelchair. A dummy wheel with matching inertial properties to the SmartWheel was placed on the dominant side. Participants propelled down a level hallway that is 5 feet wide by 250 feet long. Participants started from a dead stop with their front castors at the beginning of the hallway and propelled their wheelchairs up to a maximum velocity until they reached the end of the hallway. At the end of the hallway, participants were asked to turn and propel as fast as they were able in order to return to the starting point. The total time of the trial, from the starting point to returning to the starting point, was recorded. Participants' rating of perceived exertion were measured after each trial using the Borg Scale (van der Scheer et al., 2018). Participants also propelled up three different ramp grades (3, 5 and 8 degrees) at a comfortable pace. The 3-degree ramp is 5 feet wide by 15ft long. The 5-degree and 8-degree ramps are 4 feet wide by 10 feet long with a 4 by 4-foot landing platform at the top. The total time of the ramped trials as well as participants' ratings of perceived exertion were measured. A ramped trial started at the bottom of the ramp and ended when the rear wheels were on the landing platform. Three propulsion trials on the level surface and for each ramp slope were collected. Participants were given sufficient time to rest in between trials.

#### 4.2.3.6 Wheelchair Transfer Assessment

Participants were asked to transfer to a custom height adjustable transfer station. The platform on the station contains a 24-inch-wide by 16-inch-deep cushioned seat and has an adjustable height range from 10 inches to 43 inches above the floor in 1-inch increments. The participants first transferred to and from the platform set at level height with their wheelchair seat using their habitual methods. Afterwards the platform was raised to a level that participants felt would be the maximum height they were able transfer; participants then performed a transfer to and from the elevated platform. Participants were spotted by study personnel for all transfers. If a participant experienced difficulty making the transfer or required any help from the spotters, the platform was lowered, and the participant was offered a second attempt at a lower height. If after the transfer was completed and participants felt as if they were able to transfer higher, the platform was raised, and they were given another attempt. Participants were instructed to perform transfers in this protocol only if they felt comfortable and safe in performing. Repeated attempts were completed until participants' maximum transfer heights were completed with success (e.g. defined by requiring no spotting assistance and by landing safely and securely on the target surface). The same procedure was used to determine how low participants were able to transfer. The maximum transfer heights high/low that were attainable were recorded. This protocol has been used successfully in previous work to measure transfer ability (A. M. Koontz, Bass, Kulich, & Cooper, 2019; Toro et al., 2013).

### 4.2.4 Data Collection

The dumbbell that was used in the study is a Class 1 exercise device that weighs approximately 5.7 pounds (2.6 kg) and has a variable frequency control (0-40 Hz in increments of 0.5 Hz) and a fixed amplitude of 2 mm (4 mm peak to peak) when vibration is active; the same dumbbell that was previously used in the vibration feasibility study (chapter 2).

After all outcome measures were collected participants completed a 1 repetition max (1RM) test for the exercises that were completed during in-home training sessions. The 1RM's were determined with standard dumbbells in accordance with standard procedure (Medicine, 2013). Dumbbell weight was increased accordingly until the participant reached their 1RM. If a participant was not able to perform a 1RM that matched the weight of the dumbbell for a given exercise, they started their training protocol with a lower weight than the vibrating dumbbell for that exercise until they were able to hold it for 30 seconds (Fleck & Kraemer, 2014; Medicine, 2013). This was carried out with a standard dumbbell with the exercises still held in an isometric contraction.

#### 4.2.4.1 Pre-training Assessment and Instructions

After the standard 1RM test, participants were given instructions on the use of the vibrating dumbbell and were able to experience how it feels. Participants were also given a pair of lifting gloves to aid in maintaining a strong firm grip during the in-home training sessions. They started out holding the dumbbell at a moderate frequency (25 Hz) and experienced how the effects of the vibration on the arm and body change with differing arm positions and grips. Using a biceps curl as an example, participants held the exercise in the static training posture (90 degrees of elbow flexion at 60% of their 1 RM) while the frequency was progressively increased to 40 Hz. They were asked to hold the position for 30-60s. Participants were able to try out 40Hz of vibration for each of the exercises. If a participant was unable to tolerate 40 Hz for any one of the exercises, they started that exercise in their first training session at 30 Hz, the minimum frequency for training upper limb muscle force and power (Bosco et al., 1999). For participants that started the training at 30 Hz, the frequency was reassessed at each training session to progressively increase the training frequency to 40Hz.

#### 4.2.4.2 In-home Training

Each participant was scheduled for a minimum of two training sessions per week in their home for 12 consecutive weeks. The home was chosen for the training setting to make it easier on participants to comply with the training program. The training equipment is portable and can be easily setup and broken down after each session. All the training sessions were supervised and administered by a study team member who was well trained in exercise safety and dumbbell training. He/she traveled to the home and guided the participant through each training session. For each of the exercises, the trainer monitored the participants' form. A visual depiction of proper form and at what point the form breaks down to the extent of ending the exercise was used as a guide during training (Appendix D).

Sessions were ideally scheduled with one day in-between to allow time for muscles to rest and rebuild in between training sessions. However, if participants' schedules required back to back training sessions, they were scheduled at different times of the day (e.g. one morning session followed by an afternoon session). To start the training, participants, completed a warm-up (approximately 5-10 minutes) and stretching routine. The warm-up consisted of non-resisted arm movements that parallel motions of the resistance exercises  and forward and backward arms circles. The stretches included an open book stretch for the chest, cross body horizontal adduction stretches (posterior shoulder joint capsule), shoulder extension stretches (anterior shoulder joint capsule), upper trapezius stretch (Mulroy et al., 2011a; Van Straaten et al., 2014) and biceps and triceps stretches (holding each stretch for 20-30 seconds). An overview of the resistance training protocol that participants completed can be seen in Table 14.

**Table 14. Overview of the vibraiton trainng protocol**

| |
|---|
| Dumbbell weight = 60% 1 RM obtained during standard protocol |
| 2 sets of 1 static (30-45 second) hold at the end ROM (exception biceps) with 40Hz vibration |
| Intensity increased based off of maximum static hold time to pain-free exhaustion:<br>• If able to hold for 15 second or less, the weight will be decreased for the next session<br>• If able to hold for 60 seconds the weight will be increased for the next session |

Participants completed nine exercises during the training. The exercises were chosen based on training the muscle groups that are highly active (> 50% MVC) during wheelchair propulsion  and transfers (Gagnon et al., 2009). Muscles trained for propulsion were the posterior and anterior deltoids, rhomboids, rotator cuff (infraspinatus, supraspinatus, subscapulus, teres minor), serratus anterior and biceps (Mulroy et al., 1996; Van Drongelen et al., 2005). Muscles trained for transfers were the triceps, latissimus dorsi and lower trapezius(Gagnon et al., 2009). The pectoralis major muscle is intensely active during both propulsion and transfers. The exercises were performed in the following order in an attempt to avoid fatiguing the same muscle groups: butterflies, serratus punches, side flies, straight arm rows, bicep curls, internal/external rotation, triceps, front raises, bent over rows. The butterflies and serratus punches were performed on a mat table or other surface suitable for exercising. All of the other exercises were performed in the participants' wheelchairs. Each of the exercises were completed twice on the left and right sides. The exercises were completed on the left and right sides before moving onto the next exercise. The second set was completed after all of the exercises in the first set were completed.

#### 4.2.4.3 Training Intensity and Adjustment

Training intensity was adjusted progressively with add-on dumbbell weights. During the second set of exercises, participants were asked to hold onto the vibrating dumbbell tightly for as long as they were able to for each exercise. If they were unable to hold onto the dumbbell for at least 15 seconds, the weight for the next session was decreased by 1-2 pounds, whereas if they were able to hold onto the dumbbell for greater than 60 seconds, the trainer stopped the exercise and the dumbbell weight was increased by 1-2 pounds for the next session.

### 4.2.5 Trunk Stabilization Strategies

Participants were not able to complete each of the exercises during the training in the same manner as able-bodied persons due to a lack of trunk stability and possible limited shoulder range of motion. Participants with SCI, depending on level of injury have a variety of trunk muscle control and the ability to stabilize their core. For seated exercises, the ability to stabilize the trunk to maintain form is crucially important. During the first training session for each participant, every exercise was evaluated to see how participants completed it and strategies to compensate for lack of trunk control were determined as needed. If a participant wanted a belt or strap to stabilize their trunk, and their wheelchair configuration was able to accommodate it, one was provided to them. If they did not want to use a belt/strap or their wheelchair did not accommodate it, other trunk stabilization strategies were used. A visual depiction of these strategies can be seen below in Appendix E.

### 4.2.6 Data Analysis

#### 4.2.6.1 Key Variables

Demand: the percentage of participants who were enrolled in the research study after expressing interest and being screened eligible, and the number of participants who expressed interest in continuing to train with vibration after the study ended was reported.

Implementation: the number of training sessions completed by each participant, the weight progression of the exercises for each participant, the length of time participants were able to hold the dumbbell for each exercise, the number of participants retained and the reasons for participants' not completing training sessions. Weight progression was looked at by looking at the change in weight compared to baseline.

Acceptability: participants' perceptions of the training program, their perceived changes in strength and functional abilities and their excitement to continue training with vibration were recorded.

Strength*:* Peak isokinetic torques were identified and averaged over the second set of five repetitions for each of the movements recorded at the shoulder, elbow and wrist. The peak torques were normalized by body weight for each person and reported in Nm-kg.

Power Output**:** peak power was normalized by body weight and reported in W/kg.

Wheelchair Propulsion: The time to complete level propulsion trials was used to determine the velocity across each trial. Velocity across the three level trials were averaged along with participants' ratings of perceived exertions. Time to complete ramped trials and RPE's were reported. The general success with the ramp trials (e.g. could or could not ascend) was also noted. Variables related to stroke specific force values and velocity were analyzed using the following methods. Peak velocity (m/s), average velocity ($m/s^2$), peak force (N), mean tangential force (the component of the total force that contributes to forward propulsion in N) and mechanical effective force (percentage of force exerted tangentially relative to the overall force) during the three trials over level ground and on each ramped trial were determined from the SmartWheel. Variables taken from the SmartWheel were averaged across five strokes and over the three trials for the level surface and the 3-degree ramp. The five strokes were chosen from the middle of the trial to ensure steady state propulsion. Generally, participants completed start up after 4-5 strokes, thus the five strokes were chosen after start-up was complete. The 5 degree and 8-degree ramps were shorter, and participants were only able to complete 2-3 stokes per trial. Thus, start up for these ramps was not avoided and is included in the strokes that were analyzed. The variables for these ramps were averaged over the strokes completed and over the three trials. The variables of interest were averaged across the three trials.

Wheelchair Transfers: The relative height differences (difference between the subjects' maximum attainable high/low heights and their own wheelchair seat to floor height) was determined. Additionally, the absolute height (the height from the ground to the top of the transfer station) was also determined. Both of these values were reported inches.

Pain and Health Measures: Total scores for the Carpal Tunnel Assessment (Levine et al., 1993a), WUSPI (Curtis et al., 1995a) and SF-36WW (John E. Ware & Sherbourne, 1992) were computed. The total score for the WUSPI was calculated by summing the pain score for each item. Items not performed were not included in the total score. It ranges from 0 (no pain at all) to 150 (maximal pain on all tasks), where the lower the score the less pain experienced. From the Carpal Tunnel Assessment, a functional status and symptom severity score was calculated. Each score was calculated by taking the average across the items included in the category. Both scales have a score ranging from 0 to 5, where zero represents no symptoms on the severity score and no difficulty on the functional score and 5 represents severe symptoms and cannot perform a task on the severity score and functional score respectively. Average scores for each of the scales within the SF-36 were calculated using pre-defined methods (John E. Ware & Sherbourne, 1992). Scores range from 0-100, where 0 represents poor health and 100 represents excellent health.

#### 4.2.6.2 Statistical Analysis

The analysis followed recommendations outlined by Moore et al. for pilot studies and studies with a small sample sizes (Moore et al., 2011). Each participant was treated as a case study, and general trends were examined between the participants for which data is presented. Data was presented for each participant for the primary outcomes of interest: strength, pain and power output as well at the secondary interests of wheelchair propulsion and transfers. Where appropriate plots were used to visually represent the data.

Feasibility was assessed by looking at the outcomes related to completion of the training protocol. The three categories of interest mentioned above in the key variables were: demand, implementation and acceptability. Like the variables for strength function and pain, a graphical approach was used to look at the variables of interest when appropriate.

### 4.2.7 Sample Size Calculation

A sample size calculation was performed prior to initiation of the study to determine the number of participants that would be needed to detect changes in strength. Based on a previous study involving 12-weeks of circuit training in men with paraplegia (Nash, van de Ven, van Elk, & Johnson, 2007) and using the smallest magnitude change found for upper limb strength, an alpha = 0.05, power of 0.8, and a paired t-test, six participants were needed to detect within subject changes between the three time points. Given the primary outcome of the study is feasibility of implementing the training program using vibration, our goal was to enroll more participants than needed because of SCI being a heterogenous population. The study aimed to enroll 16 participants and factoring a 20% attrition rate 12 participants were desired for the analysis.

### 4.2.8 Clinically Meaningful Values

Given the small sample size that resulted, statistical analysis was unable to be performed. Alternatively, change values and clinically meaningful values were used to evaluate each outcome measure. Meaningful differences for strength data were calculated with data collected in chapter 3 assessing the protocol used evaluate upper limb strength. A previous study conducted with manual wheelchair users with SCI that completed an in-home exercise training program used the Minimal Detectable Difference (MDD) to set a meaningful threshold for strength values (Van Straaten et al., 2014). Furthermore, the 95% confidence interval was used to determine whether the values are clinically meaningful. Changes in strength outside of the MDD value and outside of the 95% confidence interval were defined as being clinically meaningful. The MDD values and 95% confidence intervals computed for each exercise on the left and right sides can be seen in tables 15 and 16. Minimal clinically important difference (MCID) values from the literature were used for measures of power output, pain and quality of life. Clinically relevant values related to wheelchair propulsion velocity and wheelchair transfers that have been previously established were used in place of MCID values.

**Table 15. Meaningful detectable difference values used to assess meaningful changes in strength data for the right side movements**

| Movement | Minimal Detectable Difference Values (Nm/kg) |
|---|---|
| Right Shoulder Flexion | 9.14 |
| Right Shoulder Extension | 18.48 |
| Right Shoulder Abduction | 14.5 |
| Right Shoulder Adduction | 11.27 |
| Right Shoulder Internal Rotation | 5.59 |
| Right Shoulder External Rotation | 4.93 |
| Right Elbow Flexion | 17.7 |
| Right Elbow Extension | 7.99 |
| Right Forearm Pronation | 2.27 |
| Right Forearm Supination | 1.95 |
| Right Wrist Flexion | 2.03 |
| Right Wrist Extension | 1.56 |

**Table 16. Meaningful detectable difference values used to assess meaningful changes in strength data for the left side movements**

| Movement | Minimal Detectable Difference Values (Nm/kg) |
|---|---|
| Left Shoulder Flexion | 11.99 |
| Left Shoulder Extension | 32.21 |
| Left Shoulder Abduction | 11.3 |
| Left Shoulder Adduction | 15.56 |
| Left Shoulder Internal Rotation | 5.04 |
| Left Shoulder External Rotation | 5.9 |
| Left Elbow Flexion | 10.16 |
| Left Elbow Extension | 4.57 |
| Left Forearm Pronation | 3.21 |
| Left Forearm Supination | 1.56 |
| Left Wrist Flexion | 1.21 |
| Left Wrist Extension | 2.11 |

Minimal clinically important differences for the Numerical Rating Pain Scale Range from 1.0 -1.74 points. Farrar et al. found an MCID of 1.74 in persons with chronic pain (Farrar et al., 2001) and Tashjian reported a value or 1.4 for patients being treated for rotator cuff disease (Tashjian et al., 2009). Hawker et al. reported a value of 1.37 with patients who reported pain due to knee osteoarthritis (Hawker et al., 2011) and Salaffi reported an MCID value of 1 with participants with chronic musculoskeletal pain. Mulroy et al. (Mulroy et al., 2011b) conducted a study with SCI and used an MCID value of 1.4, whereas Villinger at al. (Villiger et al., 2013) also conducted a study with SCI participants and used an MCID of 1.74 to detect clinically meaningful change. A value of 1.4 was chosen for use in interpreting the NRS scores.

For the Wheelchair Users Shoulder Pain Index (WUSPI) Curtis et al. reported a value of 5.1 points to detect a minimally clinically important difference in shoulder pain for participants with SCI.

Two different MCID values were reported for the Carpal Tunnel Assessment Scale, one value for each of the sub-scales. Values for the symptom severity scale ranged from .47 to 1.55. Amirfeyez reported a MCID value of .47 for patients following carpal tunnel release surgery (Amirfeyz et al., 2009). Baker et al. also used this value in patients with carpal tunnel looking at two different non-surgical treatments. Kim at al. reported a value of 1.14 also following carpal tunnel release surgery. Lastly, Ozer et al. reported values of 1.55 and 1.45 for participants with and without diabetes. For the functional status score, values ranged from .47 to 2.05 as reported by the same studies mentioned above. Values of 1.14 and 1.45 were used for the symptom severity score and functional status score respectively.

Values for the SF-36 are reported for each of the 8 subscales on the assessment. The ranges can be seen below in table 15 for each of the subscales. Populations used to determine these values include participants with knee osteoarthritis , knee replacement , and hip replacement (Quintana et al., 2005).

Upper limb power output as measured by the Wingate test research is limited, with little to no literature being published on clinically meaningful values. Therefore, values used for lower extremity power output will be used. A study published by Younes at al (Hachana et al., 2012). looked at lower extremity power using the lower extremity Wingate test in young athletes reported a value of 1.72 W/kg. A second study looking at older adults with lower limb impairments reported MCID values ranging from 18.0-23.1 W (Kirn et al., 2015). The value being used for the study is 1.72 W/kg.

**Table 17. Outcome measures and clinically meaningful values for scale data and power output**

| Outcome Measure | MCID Value Ranges | MCID Value Used | Source |
|---|---|---|---|
| Numerical Rating Scale (NRS) | 1.0-1.74 | 1.4 | Villiger (Tashjian et al., 2009) |
| Wheelchair User Shoulder Pain Index (WUSPI) | 5.1 | 5.1 | Curtis (Curtis et al., 1995c) |
| Carpal Tunnel Syndrome Self-Assessment Questionnaire-Symptom Severity Scale | .47-1.5 | 1.14 | Kim (Kim & Jeon, 2013) |
| Carpal Tunnel Syndrome Self-Assessment Questionnaire-Functional Status Scale | .47-2.05 | 1.45 | Ozer (Kagan Ozer et al., 2013) |
| SF-36 -Physical Functioning | 18.99-19.5 | 18.99 | Quintana (Quintana et al., 2005) |
| SF-36 -Role Limitations Due to Physical Health | 22.71-26.97 | 22.71 | Quintana (Quintana et al., 2005) |
| SF-36 -Role Limitations Due to Emotional Problems | 24.19-30.33 | 30.33 | Quintana (Quintana et al., 2005) |
| SF-36 -Energy/Fatigue | 29.84-31.35 | 31.35 | Quintana (Quintana et al., 2005) |
| SF-36 -Emotional Well-Being | 23.3-28.52 | 23.3 | Quintana (Quintana et al., 2005) |
| SF-36 -Social Functioning | 41.23-42.05 | 42.05 | Quintana (Quintana et al., 2005) |
| SF-36 -Pain | 37.91-38.09 | 38.05 | Quintana (Quintana et al., 2005) |
| SF-36 -General Health | 27.4-27.7 | 27.73 | Quintana (Quintana et al., 2005) |
| Power Output | 1.72 (W/kg)<br>18.0-23.1 (W) | 1.72 (W/kg) | Younes (Hachana et al., 2012) |

Previous studies have shown that for wheelchair users transfers that 2 inches higher or lower than their wheelchair seat height allows participants to access more surfaces in their home and in community and the ability to transfer an additional inch further above or below level transfer height is clinically meaningful (A. M. Koontz et al., 2019). Current accessibility standards recommend transfer surfaces in the community be between 17 and 19 inches for transfer benches and toilets (Board, 2015). Additional standards related to amusement park rides, park benches, boating areas and playgrounds have standards for transfers ranging from 14 to 24 inches. These standards will be used as the comparison values for wheelchair transfers, as they are transfer heights that participants need to complete for community engagement. For wheelchair propulsion previous research had indicated a velocity of 1.06 m/s as a clinically meaning velocity for level ground propulsion in the community (Cowan et al., 2008). This value was based off the gait speed required to cross a crosswalk while ambulating in the community; also, an essential for wheelchair users for community participation. Meaningful changes in wheelchair propulsion velocity were also taken from the literature related to ambulation and gait speed. These same values are unavailable specifically related to wheelchair propulsion. A study looking at persons with SCI that can ambulate reported a value of .13 m/s as a clinically meaningful change in gait speed (Lam et al., 2008). This value along with the previously mentioned value will be used to assess clinically meaningful changes for wheelchair propulsion. Ramp propulsion will be assessed by participants' ability to complete the trials.

## 4.3 Results

### 4.3.1 Participants

In total 10 participants were screened and eligible to participate in the study. Five of the participants who were screened did not complete a single study visit. The study team received signed physicians release forms for all these participants. Of these participants who had signed release forms, two were scheduled for their first visit but did not come to complete them. When contacted to reschedule, they did not return communication. The other three participants with signed release forms did not get back into contact with the study team after multiple attempts at contacting them. In total 5 participants were enrolled in the study and completed at least one study visit. One participant completed only the baseline in lab study visit and did not complete any exercise training sessions. Although this participant passed the vibration screening at the baseline visit, at their first in-home training visit they decided they did not want to train with vibration and dropped out of the study. An additional participant completed the baseline study visit and 6 weeks of the exercise training. However, this participant did not complete the 6-week midpoint visit due to elbow pain. After consultation with a physician and the study physical therapist, the participant was unenrolled from the study due to the development and diagnosis of tennis elbow. The remaining three participants enrolled in the study completed all three study visits as well and the training.

The specific demographics for each participant that completed all study visits are seen below in Table 18. At the time of the study, all three participants reported participating in some type of athletic activities. Participant 1 reported participating in adaptive kayaking during the summer months, 1-2 days per week for 30 minutes to an hour. He was not participating at this frequency at the time of the study. Participant 2 at the time of the study reported going to the gym 1-2 days per week for less than 30 minutes, as well as walking laps in the hallway. Lastly, participant 3 reported completing lower limb exercises at the gym 1-2 days per week for 30 minutes to an hour. Additionally, participant 1 was a full-time student at the time of the study participation. Participants 2 and 3 had volunteer responsibilities, in addition to participant 3 having family responsibilities watching his granddaughter 3 days per week.

**Table 18. Demographics for the three research participants who completed all study visits**

| | Participant 1 | Participant 2 | Participant 3 |
|---|---|---|---|
| Age (years) | 41 | 55 | 56 |
| Height (inches) | 70 | 53 | 58 |
| Weight (lbs.) | 155 | 167 | 225 |
| Gender | Male | Female | Male |
| Injury Level | T-8 Incomplete | T-12 Incomplete | T7-Incomplete |
| Race | Caucasian | African American | Caucasian |
| Length of time using a wheelchair (years) | 3.96 | 12 | 5 |
| Number of transfers per day | 10 | 30 | 6 |

### 4.3.2 Feasibility Results

The results presented below address the variables related to the feasibility of implementing an exercise training intervention using upper limb vibration.

#### 4.3.2.1 Demand

Of the 10 participants who were screened and eligible for the study, only 5 of them completed a single study visit, the informed consent process and were enrolled in the study. Of the three participants that completed the exercise intervention, one participant expressed interest in continuing to train with vibration in the future and was very likely to recommend training with vibration to other persons with SCI. The other two participants expressed they were very unlikely to continue exercising with vibration after the study. Furthermore, these two participants rated they were very unlikely to recommend vibration exercise to other persons with SCI.

**4.3.2.2 Implementation**

Participant 1 completed 20 of the 36 sessions (56%), participant 2 completed 19 of the 36 sessions (53%) and participant 3 completed 21 of the 36 sessions (58%). Participants' were not able to schedule a third session each week generally due to scheduling conflicts and the need for time in between training sessions to recover. The weight progression for each participant can be seen in Appendix F. Each participant was able to increase their training weight over the course of the study for most of the exercises. Participant 3 was able to increase the weight he used more so compared to the other two participants. The other two participants were able to increase their training weight for most exercises but reached a plateau towards the end of the training. Overall participants were unable to start most of the exercises at 60% of their 1RM at 40Hz. To help participants maintain the training frequency of 40Hz and hold the dumbbell between 45-60s, a lower starting weight was used to start the training if needed. Participant 1 completed fewer training visits in the weeks following the mid-point laboratory visit. He developed wrist pain at that point in the study. Training was slowed to one session per week and the weight was not increased during that time period.

The total amount of vibration exposure for each of the exercises performed as well as the average hold time for each exercise is shown below in Table 19. Participant 1 was able to hold the dumbbell for an average time of at least 45 seconds for 6 and 5 exercises on the right and left sides respectively. He had an average hold time less than 45 seconds for side flies, straight arm rows, front raises and bent over rows on both the left and right sides, and triceps extensions on the left side. However, bent over rows were very close, at 44.5 seconds average hold time on both sides and 44.7s average hold time for triceps extensions on the left side. Contrastingly, participant 2 was unable to meet the 45s average hold time for any of the exercises completed. She was consistent with the majority of her hold times, averaging between 35-40s for most exercises. Side flies was the only exercise where she was not able to hold the dumbbell for at least 35 seconds on average. Participant 3 obtained an average hold time greater than 45s for all of the exercises completed except for straight arm rows on the left side. However, he was close to the 45s mark with an average hold time of 44.4s.

The cumulative total time of vibration exposure was 621.3 minutes, 471.2 minutes and 760.8 minutes for participants 1, 2 and 3 respectively. Participants were generally consistent with the exposure for each exercise and were generally symmetrical between the left and right sides. Participant 2 experienced lower exposure times compared to the other exercises for external rotation, however the remainder of the exercises were closer in exposure time.

**Table 19. Total time of vbiration exposure and average hold time for each exercise and each participant**

| | Participant 1 | | | | Participant 2 | | | | Participant 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Right Total Time (s) | Left Total Time (s) | Right Average Time (s) | Left Average Time (s) | Right Total Time (s) | Left Total Time (s) | Right Average Time (s) | Left Average Time (s) | Right Total Time (s) | Left Total Time (s) | Right Average Time (s) | Left Average Time (s) |
| Butterflies | 1885 | 1885 | 47.1 | 47.1 | 1400 | 143 | 36.8 | 38.2 | 2129 | 2097 | 50.7 | 49.9 |
| Serratus Punch | 2005 | 2005 | 50.1 | 50.1 | 1367 | 1330 | 38.0 | 37.0 | 2390 | 2390 | 56.9 | 56.9 |
| Side Flies | 1776 | 1744 | 44.4 | 43.6 | 1412 | 1375 | 37.2 | 36.2 | 2235 | 2130 | 50.8 | 48.4 |
| Straight Arm Row | 1665 | 1628 | 41.6 | 40.7 | 1442 | 1445 | 38.0 | 38.0 | 2562 | 1952 | 58.2 | 44.4 |
| Bicep Curls | 2035 | 2035 | 50.9 | 50.9 | 1511 | 1544 | 39.8 | 40.6 | 2375 | 2395 | 54.0 | 54.4 |
| Internal Rotation | 1990 | 1990 | 49.8 | 49.8 | 1335 | 1392 | 35.1 | 36.6 | 2345 | 2328 | 55.8 | 55.4 |
| External Rotation | 1990 | 1990 | 49.8 | 49.8 | 1230 | 1235 | 32.7 | 32.5 | 2353 | 2365 | 56.0 | 56.3 |
| Front Raise | 1770 | 1708 | 44.2 | 42.7 | 1496 | 1498 | 39.4 | 39.4 | 2227 | 2200 | 50.6 | 50.0 |
| Triceps Extension | 1800 | 1789 | 45 | 44.7 | 1365 | 1423 | 35.9 | 37.4 | 2260 | 2213 | 51.3 | 50.2 |
| Bent Over Rows | 1796 | 1795 | 44.9 | 44.9 | 1510 | 1508 | 39.7 | 39.7 | 2355 | 2350 | 53.5 | 53.4 |

#### 4.3.2.3 Acceptability

The exercise evaluation form completed by participants to assess the training can be seen in Appendix G. Overall participants 1 and 2 did not rate the vibration training favorably. Both participants reported they were somewhat uncomfortable with the vibration and overall were dissatisfied with using vibration as an exercise modality. Participant 1 noted seeing small increases in strength and a small improvement in wheelchair propulsion after completing the training program. Participant 2 reported seeing no changes in strength and no improvements in wheelchair propulsion. Both participants 1 and 2 rated seeing no improvements in their transfer ability and no change in overall health. Lastly, both expressed it was very unlikely they would continue to train with vibration and very unlikely to recommend to other persons with SCI. Contrastingly, participant 3 rated training with vibration highly. Overall, he was satisfied with vibration and found it to be somewhat comfortable to use. He reported he perceived large increases in strength, and improvements in wheelchair transfers, propulsion and overall health. Also, he reported he was very likely to train with vibration in the future and very likely to recommend using vibration for others with SCI.

Although not all participants enjoyed using vibration, all participants rated the stretching and warm up phases highly as well as the training they received at the first study visit. Participants felt sufficiently warmed up after completing the stretching and warm up phase. Participants 1 and 2 felt as if the 12-week time period was too long, while participant 3 felt the length of time was appropriate. However, he did mention that the study should have provided more compensation. All three participants were very satisfied with exercising in their home and felt the length of the in-home training sessions were appropriate. Lastly, participants were satisfied with exercising in their wheelchairs.

### 4.3.3 Pain Results

Results from the WUSPI and NRS are shown below in Figures 25-27. As shown in Figure 25, participant 1 reported minor pain at baseline based on the total WUSPI score. Primary tasks contributing to the pain were pushing up ramps, performing household chores and sleeping. An increase in shoulder pain was reported at 6-weeks compared to baseline. Lifting items from a shelf and wheelchair transfers also contributed to pain at 6-weeks. At 12-weeks, participant 1 reported double the amount of shoulder pain at 12-weeks compared to 6-weeks and 19 points greater compared to baseline; a clinically meaningful increase in shoulder pain. At the final visit, he had pain on all items of the WUSPI except for transferring from his bed to his wheelchair. Participant 2 rated having no pain on the WUSPI at any time point throughout the study. Participant 3 also reported some pain at baseline, with tasks contributing to his pain being the same as mentioned above for participant 1. At 12-weeks he rated only having minor pain while performing activities of daily living and household chores; also, a clinically meaningful decrease in shoulder pain.

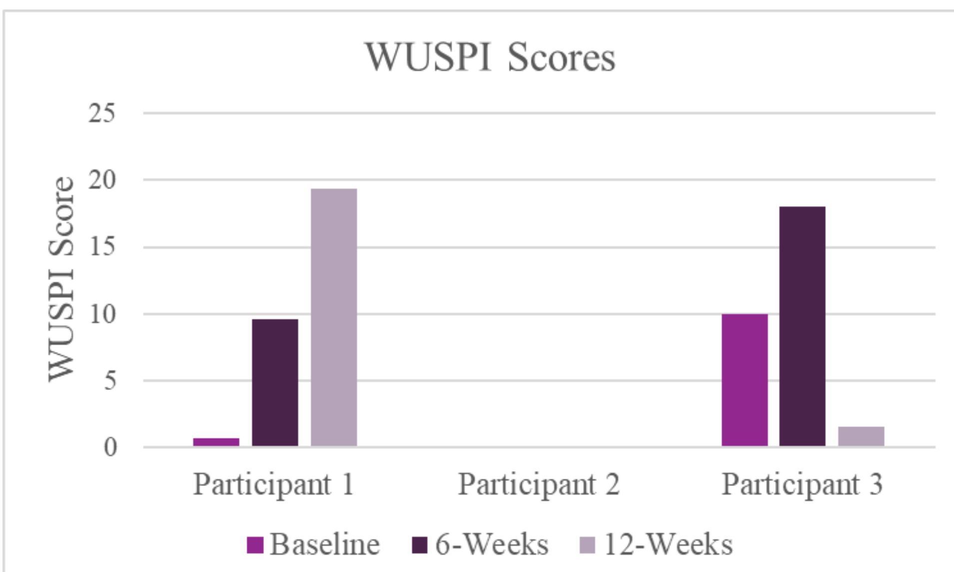



**Figure 25. Total scores for the wheelchair users shoulder pain index (WUSPI) for all three visits**

Data from the NRS for participants 1 and 3 are shown below in figures 26 and 27 respectively. Participant 1 reported equal or less pain in all six joints at 12-weeks compared to baseline. The decreases in pain at 12-weeks compared to baseline were not clinically meaningful. Like the WUPSI, participant 2 did not have any pain on the NRS throughout the study. Participant 3 reported pain in the shoulders throughout the entire study, however this pain was minor. The pain level remained the same at the right shoulder at all three time points. The increase in pain at 6-weeks is a clinically meaningful change in pain.

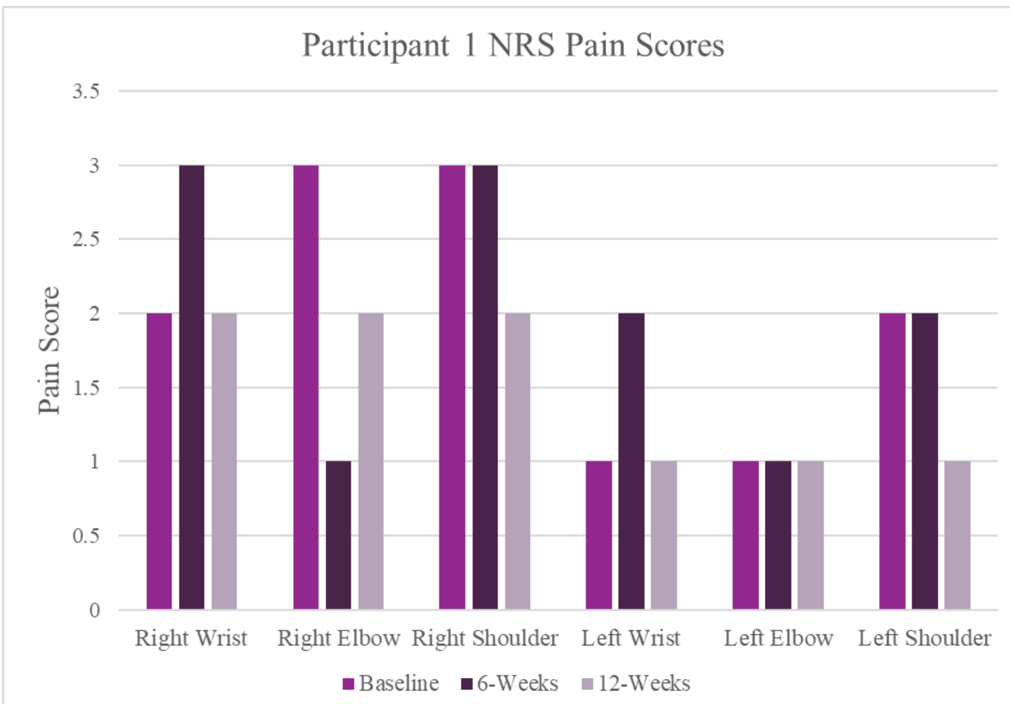



**Figure 26. NRS scores at all three time points for participant 1**

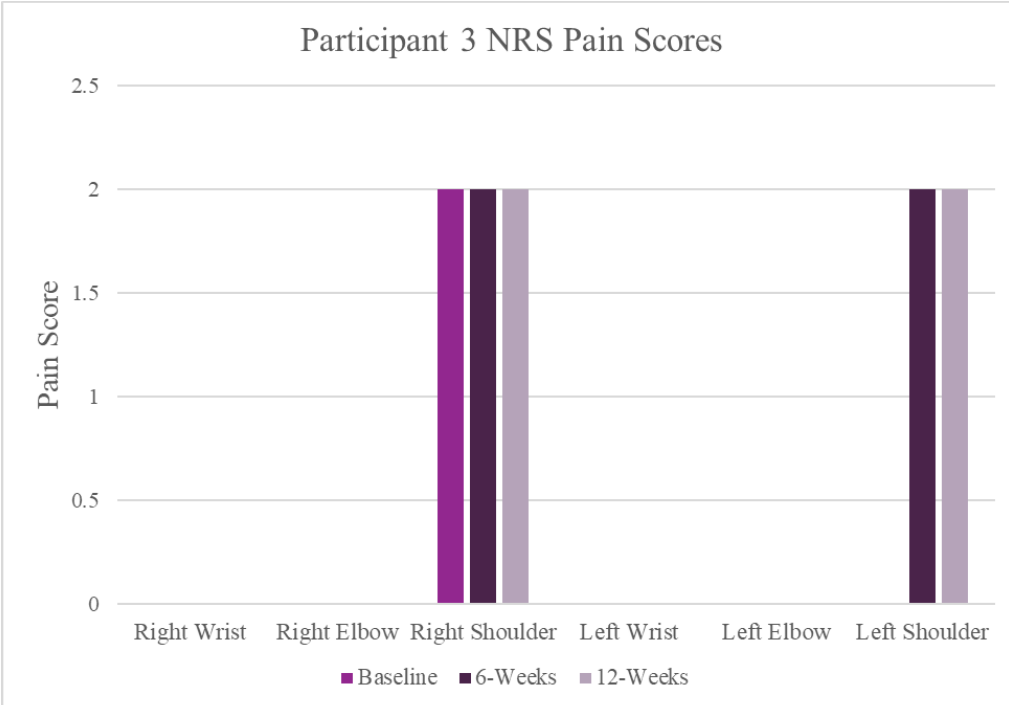



**Figure 27. NRS scores at all three time points for participant 3**

### 4.3.4 Carpal Tunnel Assessment

All three participants' scores on both the carpal tunnel symptom severity scale and the functional status scale remained relatively stable throughout the study. The scores for each scale can be seen below in Figures 28 and 29. Scores on the severity of carpal tunnel symptoms at 12-weeks were slightly increased compared to baseline. Whereas, participant 3 reported a slight increase at 6-weeks but returned almost to baseline at the 12-week's visit. On the functional status score participant 1 reported a decrease in the functional status score, but then reported an increase at 12-weeks compared to baseline and 6-weeks. However, these changes were small. Participant 2's functional status scores were stable at baseline and 6-weeks and were decreased at 12-weeks. Scores for participant 3 were stable at baseline and 6-weeks with an increase in functional status score observed at 12-weeks. All observed changes were very small and not clinically meaningful.

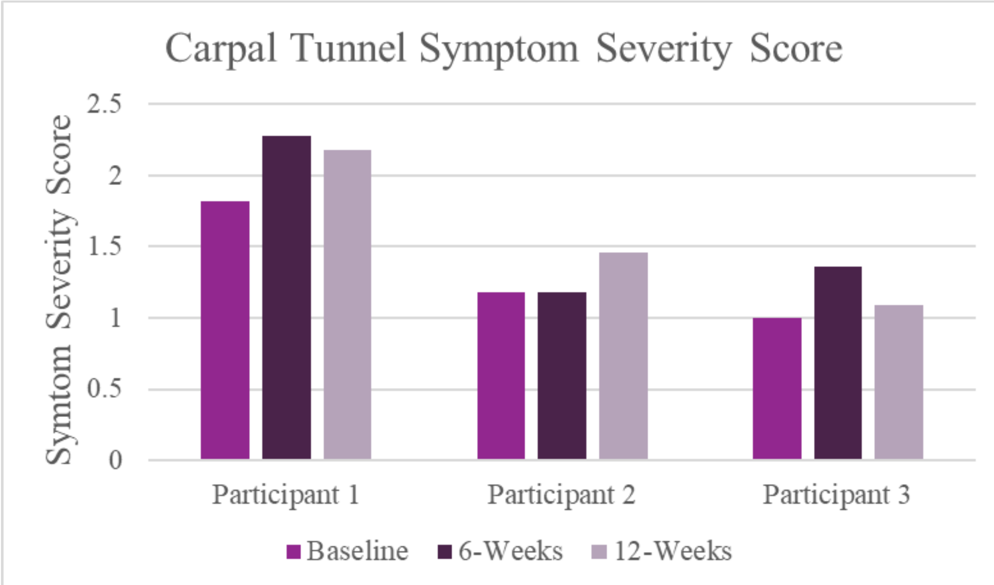



**Figure 28. Carpal tunnel symptom severity scores for all three visits for each participant**

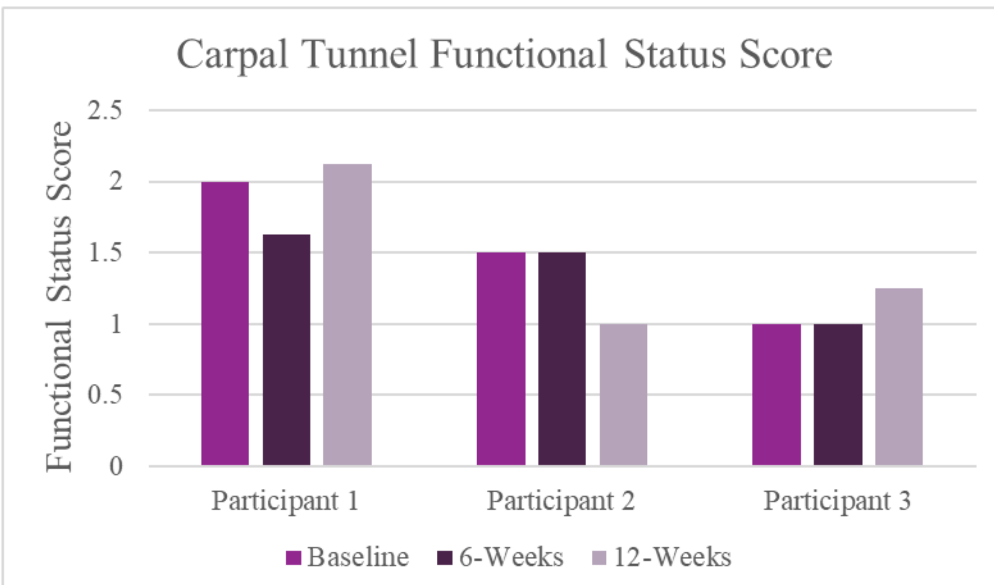



**Figure 29. Carpal tunnel funcational status scores for all three timepoints for all participants**

### 4.3.4.1 Quality of Life

The total score for each of the seven categories of the SF-36 can be seen in Tables 20, 21 and 22 for participant 1, participant 2 and participant 3 respectively. At baseline, participant 1 had a moderately good quality of life in most of the seven categories. However, he had a decrease in quality of life scores at 12-weeks for almost every category except for emotional wellbeing, which improved from baseline, but decreased compared to 6-weeks. However, of these changes only the change in score for role limitations due to physical health was clinically meaningful. Participant 2 had a very high perceived quality of life at baseline in almost every category except for social functioning. At 12-weeks, all categories remained at the same high level of quality of life except for social functioning, which improved to an excellent quality of life and physical functioning which decreased slightly. Both changes were clinically meaningful. In comparison to participants 1 and 2, participant 3 had a variety of quality of life scores across the seven categories. Pain, physical functioning and role limitations due to physical health all had very low quality of life scores at baseline representing poor quality of life. Emotional wellbeing had a moderate quality of life score, whereas role limitations due to emotional problems, social functioning and general health had very good quality of life scores. At 12-weeks, almost every category had improved quality of life scores or maintained quality of life scores. For pain and role limitations due to physical health he went from having very poor quality of life scores to having good and very good quality of life scores respectively. Physical functioning was the only score at 12-weeks that didn't improve. However, the score did improve from a poor quality of life score at baseline to a moderate quality of life score at 12-weeks. Almost all changes scores were clinically meaningful except for energy/fatigue, social functioning and general health.

**Table 20. Participant 1 Quality of Life Scores**

| | Baseline | 6-Weeks | 12-Weeks |
|---|---|---|---|
| Physical Functioning | 50 | 55 | 45 |
| Role Limitations Due to Physical Health | 25 | 0 | 0 |
| Role Limitations Due to Emotional Problems | 100 | 100 | 100 |
| Energy/Fatigue | 55 | 50 | 40 |
| Emotional Well-Being | 52.5 | 72 | 64 |
| Social Functioning | 75 | 32.5 | 45 |
| Pain | 67.5 | 67.5 | 67.5 |
| General Health | 50 | 65 | 40.6 |

**Table 21. Participant 2 Quality of Life Scores**

| | Baseline | 6-Weeks | 12-Weeks |
|---|---|---|---|
| Physical Functioning | 100 | 80 | 80 |
| Role Limitations Due to Physical Health | 100 | 100 | 100 |
| Role Limitations Due to Emotional Problems | 100 | 100 | 100 |
| Energy/Fatigue | 100 | 100 | 100 |
| Emotional Well-Being | 100 | 100 | 100 |
| Social Functioning | 50 | 100 | 100 |
| Pain | 100 | 100 | 100 |
| General Health | 90 | 90 | 90 |

**Table 22. Participant 3 Quality of Life Scores**

| | Baseline | 6-Weeks | 12-Weeks |
|---|---|---|---|
| Physical Functioning | 35 | 25 | 55 |
| Role Limitations Due to Physical Health | 0 | 100 | 100 |
| Role Limitations Due to Emotional Problems | 100 | 66.67 | 100 |
| Energy/Fatigue | 50 | 80 | 80 |
| Emotional Well-Being | 65 | 100 | 100 |
| Social Functioning | 87.5 | 90 | 80 |
| Pain | 22.5 | 70 | 77.5 |
| General Health | 80 | 77 | 95 |

### 4.3.5 Strength Results

Tables 23 and 24 show the movements for each participant that were meaningful changes at 12-weeks compared to baseline for the right and left sides respectively.

**Table 23. Meaningful changes in strength data for the right side**

| | Direction of strength results at 12-weeks compared to baseline | | |
|---|---|---|---|
| | Participant 1 | Participant 2 | Participant 3 |
| Shoulder Flexion | ↑ | ↑ | ↑ |
| Shoulder Extension | ∅ | ∅ | ∅ |
| Shoulder Abduction | ∅ | ∅ | ∅ |
| Shoulder Adduction | ∅ | ↓ | ↓ |
| Shoulder Internal Rotation | ∅ | ↑ | ∅ |
| Shoulder External Rotation | ∅ | ↑ | ↑ |
| Elbow Flexion | ∅ | ∅ | ∅ |
| Elbow Extension | ∅ | ∅ | ↑ |
| Forearm Pronation | ∅ | ∅ | ∅ |
| Forearm Supination | ∅ | ∅ | ∅ |
| Wrist Flexion | ∅ | ∅ | ∅ |
| Wrist Extension | ∅ | ↓ | ∅ |

↑-Meaningful increase in strength at 12-weeks compared to baseline
↓-Meaningful decrease in strength at 12-weeks compared to baseline
∅ - Non-meaningful increase or decrease in strength at 12-weeks compared to baseline

**Table 24. Meaningful changes in strength data for the left side**

| | Direction of strength results at 12-weeks compared to baseline | | |
|---|---|---|---|
| | Participant 1 | Participant 2 | Participant 3 |
| Shoulder Flexion | ∅ | ∅ | ∅ |
| Shoulder Extension | ∅ | ∅ | ∅ |
| Shoulder Abduction | ∅ | ∅ | ∅ |
| Shoulder Adduction | ∅ | ∅ | ∅ |
| Shoulder Internal Rotation | ∅ | ∅ | ∅ |
| Shoulder External Rotation | ∅ | ∅ | ∅ |
| Elbow Flexion | ∅ | ↓ | ∅ |
| Elbow Extension | ∅ | ∅ | ∅ |
| Forearm Pronation | ∅ | ∅ | ∅ |
| Forearm Supination | ∅ | ↓ | ↑ |
| Wrist Flexion | ∅ | ∅ | ↑ |
| Wrist Extension | ∅ | ↓ | ↑ |

↑-Meaningful increase in strength at 12-weeks compared to baseline
↓-Meaningful decrease in strength at 12-weeks compared to baseline
∅ - Non-meaningful increase or decrease in strength at 12-weeks compared to baseline

The results for the strength data output in Nm/kg can be seen below in tables 25 and 26 for the right and left sides respectively. On the right side, participant 1 had a meaningful increase in shoulder flexion. All other changes were not meaningful by the defined parameters. Participant 2 also only had a few more movements with meaningful change. At 12-weeks, shoulder adduction and wrist extension decreased compared to baseline. Shoulder flexion and shoulder internal/external rotation increased in strength at 12-weeks compared to baseline. Lastly, on the right side, participant three had a meaningful change in strength in shoulder flexion, shoulder extension and elbow extension, as well as a decrease in shoulder adduction.

On the left side, participant 1 had no meaningful changes in strength. Participant 2 had a meaningful decrease in strength in elbow flexion, forearm supination and wrist extension. All other changes in strength were not considered meaningful based on the outlined criteria. Lastly, participant 3 had a meaningful increase in strength in forearm supination, wrist flexion and wrist extension.

**Table 25. Strength results for all participants and timepoints on the right side**

| | | Peak Torque (Nm/kg) | | |
|---|---|---|---|---|
| Measure | | Baseline | 6-Weeks | 12-Weeks |
| Shoulder Flexion | Participant 1 | 41.4 | 34.9 | 50.8 |
| | Participant 2 | 10.7 | 35.8 | 30.2 |
| | Participant 3 | 51.4 | 63.7 | 70.1 |
| | | | | |
| Shoulder Extension | Participant 1 | 10.5 | 10.9 | 8 |
| | Participant 2 | 3.8 | 33 | 13 |
| | Participant 3 | 63.6 | 52.5 | 64 |
| | | | | |
| Shoulder Abduction | Participant 1 | 40.6 | 45 | 45.1 |
| | Participant 2 | 34.3 | 42.1 | 22.6 |
| | Participant 3 | 44.4 | 60.3 | 41.9 |
| | | | | |
| Shoulder Adduction | Participant 1 | 10.3 | 17.4 | 8.5 |
| | Participant 2 | 36.6 | 33.7 | 9.8 |
| | Participant 3 | 67.6 | 77.2 | 44.2 |
| | | | | |
| Shoulder Internal Rotation | Participant 1 | 6.3 | 5.5 | 5.9 |
| | Participant 2 | 7.6 | 25.1 | 13.9 |
| | Participant 3 | 42.9 | 45.9 | 41.3 |
| | | | | |
| Shoulder External Rotation | Participant 1 | 23.6 | 24.7 | 20.6 |
| | Participant 2 | 11.1 | 22.8 | 16.2 |
| | Participant 3 | 24.6 | 40 | 41.4 |
| | | | | |
| Elbow Flexion | Participant 1 | 41.6 | 44.1 | 30.2 |
| | Participant 2 | 27.6 | 34.2 | 22.7 |
| | Participant 3 | 35.4 | 36.8 | 44.5 |
| | | | | |
| Elbow Extension | Participant 1 | 11.3 | 15.8 | 10.7 |
| | Participant 2 | 15.9 | 34 | 23.2 |
| | Participant 3 | 27.6 | 33.8 | 38.1 |
| | | | | |
| Forearm Pronation | Participant 1 | 7.4 | 8.7 | 7.2 |
| | Participant 2 | 3.6 | 3.3 | 3 |
| | Participant 3 | 11.2 | 10.7 | 9.9 |

**Tabel 25 contd. Strength results for all participants and timepoints on the right side**

| | | Baseline | 6-Weeks | 12-Weeks |
|---|---|---|---|---|
| Forearm Supination | Participant 1 | 4.4 | 5.3 | 5.4 |
| | Participant 2 | 7.6 | 8.5 | 6.3 |
| | Participant 3 | 10.2 | 13.1 | 11 |
| | | | | |
| Wrist Flexion | Participant 1 | 2 | 1.8 | 4.1 |
| | Participant 2 | 4.7 | 4.5 | 3.3 |
| | Participant 3 | 8.8 | 8.6 | 9.3 |
| | | | | |
| Wrist Extension | Participant 1 | 4.9 | 8.2 | 5.5 |
| | Participant 2 | 5.3 | 5.7 | 3.7 |
| | Participant 3 | 10.8 | 7.7 | 12.3 |

**Table 26. Strength results for all participants and timepoints on the left side**

| | | Peak Torque (Nm/kg) | | |
|---|---|---|---|---|
| Measure | | Baseline | 6-Weeks | 12-Weeks |
| Shoulder Flexion | Participant 1 | 46.2 | 42.9 | 46.1 |
| | Participant 2 | 31.2 | 29.1 | 23.2 |
| | Participant 3 | 53.8 | 60.2 | 64.2 |
| | | | | |
| Shoulder Extension | Participant 1 | 9.7 | 11.6 | 10.2 |
| | Participant 2 | 28.3 | 19.4 | 12.2 |
| | Participant 3 | 53.7 | 62 | 71.6 |
| | | | | |
| Shoulder Abduction | Participant 1 | 46.2 | 50.2 | 42.8 |
| | Participant 2 | 44.3 | 42.5 | 24.9 |
| | Participant 3 | 42.9 | 56.2 | 49.4 |
| | | | | |
| Shoulder Adduction | Participant 1 | 8.8 | 15 | 9.1 |
| | Participant 2 | 37.5 | 48.5 | 24 |
| | Participant 3 | 62.9 | 71.3 | 70 |
| | | | | |
| Shoulder Internal Rotation | Participant 1 | 4.6 | 13 | 6.7 |
| | Participant 2 | 9.9 | 15.2 | 13.1 |
| | Participant 3 | 40.8 | 50.2 | 39.7 |
| | | | | |
| Shoulder External Rotation | Participant 1 | 23.7 | 24.6 | 25.6 |
| | Participant 2 | 15.6 | 15.9 | 14.6 |
| | Participant 3 | 30.9 | 39.4 | 31.4 |
| | | | | |
| Elbow Flexion | Participant 1 | 39.2 | 37.6 | 31.9 |
| | Participant 2 | 28.1 | 34.6 | 16.7 |
| | Participant 3 | 41 | 41.9 | 49.3 |
| | | | | |
| Elbow Extension | Participant 1 | 12.1 | 12.6 | 13 |
| | Participant 2 | 11.6 | 27.9 | 9.1 |
| | Participant 3 | 39.8 | 41.4 | 37.4 |

**Table 26 contd. Strength results for all participants and timepoints on the left side**

| | | Baseline | 6-Weeks | 12-Weeks |
|---|---|---|---|---|
| Forearm Pronation | Participant 1 | 5.8 | 7.2 | 3.6 |
| | Participant 2 | 4 | 3.5 | 1.6 |
| | Participant 3 | 7.5 | 10.9 | 10.6 |
| | | Baseline | 6-Weeks | 12-Weeks |
| Forearm Supination | Participant 1 | 6.7 | 5.8 | 5.7 |
| | Participant 2 | 9.2 | 6.6 | 5.9 |
| | Participant 3 | 9.6 | 13.9 | 11.9 |
| | | | | |
| Wrist Flexion | Participant 1 | 1.2 | 2.5 | 2.3 |
| | Participant 2 | 4.5 | 7.2 | 3.3 |
| | Participant 3 | 6.5 | 9.1 | 10.3 |
| | | | | |
| Wrist Extension | Participant 1 | 7.5 | 10.3 | 6.9 |
| | Participant 2 | 6.4 | 7.3 | 3 |
| | Participant 3 | 4.2 | 7.7 | 11.1 |

### 4.3.6 Power Output Results

Results from the upper limb Wingate test for all three participants at baseline and the end of the exercise intervention can be seen below in Figure 30. Participant 1 decreased their power output by 0.1 W/kg at 12-weeks compared with baseline. This change was not clinically meaningful. Contrastingly, participants 2 and 3 were able to increase their weight normalized power output at 12-weeks compared to baseline. Participant 2 had increase of 1 W/kg, while participant 3 had almost a 3 W/kg increase and clinical meaningful result at 12-weeks.

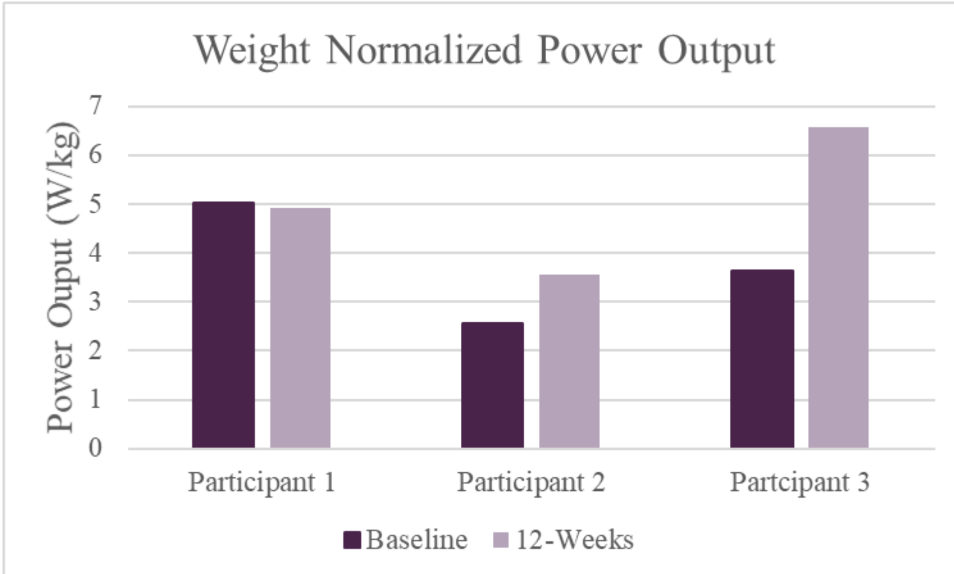



**Figure 30. Weight normalized power output results for all three participants at baseline and 12-weeks**

### 4.3.7 Transfer Ability

Participants' transfer ability as measured by relative transfer height and absolute transfer height for maximum and minimum obtainable transfers are depicted below in Tables 27-30. Additionally, participants' ratings of perceived exertion are shown in the tables for each type of transfer that was completed. Overall participants were able to improve their transfer ability or reported less exertion to complete their maximum and minimum height transfers. Participant 1 was able to transfer higher at 12-weeks compared to baseline relative to his wheelchair seat height. However, he reported a higher rating of perceived exertion to achieve a higher transfer. Participant 2 did not see a change in how high they were able to transfer. Furthermore, they reported a higher rating of perceived exertion at 12-weeks to achieve the same transfer. Participant 3 was also able to transfer higher at 12-weeks compared to baseline and rated the transfer to their wheelchair with less exertion. All three participants obtained the same minimum transfer height relative to their wheelchair seat height at 12- weeks compared to baseline and the same exertion or less exertion to complete the transfer. All participants were able to transfer at a clinically meaningful height above and below their wheelchair seat height. The results from the absolute transfer height match those results of the relative transfer height.

**Table 27. Relative maximum height tranfers acheived and ratings of percieved exertion for both time points**

| | Baseline | | | Endpoint (12-Weeks) | | |
|---|---|---|---|---|---|---|
| | Transfer Height (in) | RPE TO | RPE FROM | Transfer Height (in) | RPE TO | RPE FROM |
| Participant 1 | 5.5 | 14 | 10 | 6.5 | 15 | 8 |
| Participant 2 | 2 | 8 | 7 | 2 | 13 | 13 |
| Participant 3 | 10 | 8 | 7 | 12 | 8 | 6 |

**Table 28. Relative minimum height tranfers acheived and ratings of percieved exertion for both time points**

| | Baseline | | | Endpoint (12-Weeks) | | |
|---|---|---|---|---|---|---|
| | Transfer Height (in) | RPE TO | RPE FROM | Transfer Height (in) | RPE TO | RPE FROM |
| Participant 1 | 13 | 12 | 14 | 13 | 10 | 13 |
| Participant 2 | 12 | 6 | 6 | 12 | 6 | 6 |
| Participant 3 | 10 | 11 | 7 | 10 | 6 | 7 |

**Table 29.Absolute maximum height tranfers acheived and ratings of percieved exertion for both time points**

| | Baseline | | | Endpoint (12-Weeks) | | |
|---|---|---|---|---|---|---|
| | Transfer Height (in) | RPE TO | RPE FROM | Transfer Height (in) | RPE TO | RPE FROM |
| Participant 1 | 28.5 | 14 | 10 | 29.5 | 15 | 8 |
| Participant 2 | 24 | 8 | 7 | 24 | 13 | 13 |
| Participant 3 | 30 | 8 | 7 | 32 | 8 | 6 |

**Table 30. Absolute minimum height tranfers acheived and ratings of percieved exertion for both time points**

| | Baseline | | | Endpoint (12-Weeks) | | |
|---|---|---|---|---|---|---|
| | Transfer Height (in) | RPE TO | RPE FROM | Transfer Height (in) | RPE TO | RPE FROM |
| Participant 1 | 10 | 12 | 14 | 10 | 10 | 13 |
| Participant 2 | 10 | 6 | 6 | 10 | 6 | 6 |
| Participant 3 | 10 | 11 | 7 | 10 | 6 | 7 |

### 4.3.8 Wheelchair Propulsion Results

Wheelchair propulsion velocity for the level data as well as the participants' ratings of perceived exertion are presented in Table 31. Table 32 shows the average time to complete each ramped trial and RPE's for the three ramped conditions. Force and velocity variables from the SmartWheel, averaged across three trials, for each participant and across all three conditions are shown in Appendix I. Plots for the propulsion variables can be seen below in Appendix J. Participant 2 was unable to complete the propulsion trials at baseline due to time constraints with the participants' transportation. Additionally, data from the SmartWheel was not collected for participant 3 on the 8-degree ramp trial at the 12-week visit due to technical issues encountered with the wheel. After several attempts at trouble shooting the wheel, the trials were completed without collecting SmartWheel data to not increase the length of testing too much and to be cognizant of the participants' time.

Participants 1 and 3 both propelled with a slower velocity at 12-weeks compared to baseline, however these changes are small and not clinically meaningful. Additionally, although the values were slower, all level propulsion velocities at baseline and 12-weeks were above 1.06 m/s. Participant 1 at baseline and 12-weeks was able to complete all ramped propulsion trials. Although they did not complete the baseline trials, participant 2 was unable to complete the 8-

degree ramp trials at 12-weeks. Participant 3 was unable to complete the 8-degree ramped trials at baseline without assistance but was able to complete them at 12-weeks. He was able to complete all other ramped trials at baseline and at 12-weeks.

**Table 31. Averge velocity and ratings of perceived exertion for level ground propulson trials**

| | **Participant 1** | | | | **Participant 2** | | | | **Participant 3** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Velocity (m/s) | | RPE | | Velocity (m/s) | | RPE | | Velocity (m/s) | | RPE | |
| | Mean | STD | Mean | STD | Mean | STD | Mean | STD | Mean | STD | Mean | STD |
| **Level** | | | | | | | | | | | | |
| Baseline | 2.48 | .090 | 8 | 0 | | | | | 2.02 | .035 | 8 | 0 |
| 12-Weeks | 2.37 | .026 | 13 | 0 | 1.72 | .30 | 6.7 | .81 | 1.95 | .024 | 7 | 0 |

**Table 32. Timing to complete propulsion trials and ratings of perecieved exertion averaged across three trials**

| | **Participant 1** | | | | **Participant 2** | | | | **Participant 3** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time (s) | | RPE | | Time (s) | | RPE | | Time (s) | | RPE | |
| | Mean | STD | Mean | STD | Mean | STD | Mean | STD | Mean | STD | Mean | STD |
| **3 Degrees** | | | | | | | | | | | | |
| Baseline | 7.2 | .63 | 10.3 | .47 | | | | | 10.51 | .24 | 8.33 | .47 |
| 12-Weeks | 7.8 | .76 | 14 | 0 | 13.1 | .78 | 7.33 | .94 | 11.3 | .47 | 8 | 0 |
| **5 Degrees** | | | | | | | | | | | | |
| Baseline | 2.2 | .03 | 10 | 0 | | | | | 4.49 | .56 | 7 | 0 |
| 12-Weeks | 3.57 | .15 | 12 | 0 | 5.3 | 1.1 | 6 | 0 | 4 | .82 | 6 | 0 |
| 8 **Degrees** | | | | | | | | | | | | |
| Baseline | 4.13 | .46 | 13 | 0 | Did not complete | | | | Did not complete | | | |
| 12-Weeks | 5.14 | .46 | 14 | 0 | Did not complete | | | | 9.7 | 1.7 | 9 | 0 |

## 4.4 Discussion

The results of this study are mixed both in participant opinion and data related to strength, power and pain. Participants' had varying opinions on vibration training. Furthermore, participants had increases, decreases and no changes in all of the outcomes collected.

### 4.4.1 Feasibility

The demand for the study was low. The study enrollment period lasted approximately two years and extensive efforts were made to recruit individuals with SCI yet only 10 responded with interest and were screened for the study. Of those 10, 5 participants (50%) completed one study visit and three participants (30% of those screened) completed the entire study One reason is the need to obtain a physician's release form prior to scheduling the first study visit. For many participants this was a long process and may have contributed to the loss of contact with participants. Additionally, some physicians never sent the release form back to the study team. Second, the study involved a twelve-week time commitment, which may have led to a low interest/demand in participating in the study. Lastly, the vibrating dumbbell itself may have turned off some participants who would have otherwise participated in the study if there was a different modality used for the training. More detailed information on challenges with recruitment and retention is shown below in section 4.6.

In addition, demand was measured by the number of participants who would be interested in continuing to train with vibration after the study ended. Only 1 of the three participants (33%)

said he would be likely to train with vibration after the study. The sample size that was screened and participated in the study makes it difficult to draw conclusions about the true demand for the training.

Overall, some aspects of the study met the hypothesis for implementation, while others did not. All three participants completed less than 60% of the training visits. In general, participants were unable to schedule a third training session due to scheduling conflicts with work, school, volunteer duties, family responsibilities and medical appointments. However, all three participants noted they needed time in between training to recover. Additional information on intervention delivery and retention is shown below in section 4.7.

A second aspect of implementation related to the amount of time participants were able to hold the dumbbell. Participants 1 and 3 were able to complete each exercise on both the left and right sides for the desired hold times. Participant 2 was unable to hold the dumbbell for 45s for all exercises completed. Ideally, participants would hold the dumbbell for 60s as that has been shown to be the optimal time for the most improvements, however as little as 30s has also been shown to be effective (Adams et al., 2009). Participant 2 also had the least total time of vibration exposure throughout the study because overall, they were unable to hold onto the dumbbell as long as the other two participants. Not surprisingly participant 3 had the greatest total time of vibration exposure due to being able to hold onto the dumbbell the longest out of the three participants. The overall body of literature suggests that the greater the total time of vibration exposure the better overall result as long as a single bout of vibration exposure isn't longer than 60s (Da Silva-Grigoletto et al., 2011). For the vibrating dumbbell, the implementation of these parameters may not be appropriate for all participants. The parameters for vibration timing were determined using plates and platforms. Although the timing is an important determining factor in seeing improvements in strength, the practicality of the timing guidelines may not be possible for all persons when using the dumbbell. Additionally, literature related to the length of vibration exposure during longitudinal training programs is lacking. The training protocols in longitudinal studies varies greatly, with many of the protocols using training that increase in time or intensity throughout the training. Total amount of vibration training per session ranges from 3-22 minutes and training sessions 2-3 times per week (Machado, García-López, González-Gallego, & Garatachea, 2010; Martínez et al., 2013; Roelants et al., 2004; Torvinen et al., 2003). These parameters have also largely been based off the parameters that have been successful in the acute studies, but these studies do not provide evidence for the training adjustments or intensities that are made in a longitudinal training program. Generally, previous studies have not reported the additive total time of vibration exposure throughout the study, but only the amount of vibration exposure per bout. Furthermore, the studies in general do not report the number of training sessions each participant completed, or the training protocol completed for those visits. This makes it challenging to determine the total amount of vibration exposure that participants have completed in previous studies. There may be a point at which participants over the course of the training have had too much vibration exposure that it has detrimental effects which has yet to be explored.

Compared to the other two participants, participant 3 was able to increase the weight being used throughout the training more steadily. Furthermore, he was able to do this without sacrificing the amount of time he held the dumbbell for each of the exercise. Weight for participants' 1 and 2 was increased slowly in the beginning but then plateaued for the reminder of the study. For these two participants', the amount of time of vibration exposure, the amount of time holding the dumbbell, was determined to be more important based off of previous literature (Adams et al., 2009; Da Silva-Grigoletto et al., 2011; Da Silva-Grigoletto et al., 2009; Dabbs et al., 2011). In order to optimize the amount of time participants 1 and 2 were able to hold the dumbbell, the weight was not increased as much. This was especially true for participant 2. She was unable to meet the minimum desired hold time of 45s for any of the exercises completed during the training. Ultimately this may have impacted the lack of improvements in the strength and functional outcomes found for participants 1 and 2.

Although the participants did not participate in strength training at the time of the study, generally speaking it has been established that women do not have the same upper body strength as men (Frontera et al., 1991). Furthermore, it has also been established that as people age they lose muscle mass and strength at well (Goodpaster et al., 2006). This combination of factors may have meant the parameters established were not appropriate for participant 2. Studies with older females using the vibrating plates, have used a variety of parameters, but most do not use loading with vibration (Machado et al., 2010). This participant may have been able to hold the dumbbell longer if there was less weight or no weight added to the dumbbell. However, the evidence doesn't dictate which of these parameters is more important when determining increased strength.

The study desired to recruit 16participants and retain12 of those 12 (75%) participants. The study did not retain the desired number of participants, in addition to not enrolling the desired number of participants. Extensive efforts were made to recruit participants including efforts over the phone through research registries, in person recruitment at SCI clinics and local groups, and the use of social media outlets such as Twitter and Facebook. Even after extensive recruitment the target numbers for enrollment fell short. More detailed information on recruitment efforts and challenges is described below in section 4.6. Of the participants that were enrolled 3 out of the 5 (60%) completed the study. Although the number of participants enrolled was low, the number of participants retained matches that of previously conducted longitudinal exercise studies with spinal cord injuries. These studies have had retention rates that ranges from 51%-94% retention for interventions lasting 3-9 months (Bakkum et al., 2015; Crane, Hoffman, & Reyes, 2017; Kilkens et al., 2005; Nash, van de Ven, van Elk, Johnson, & rehabilitation, 2007; Pelletier, De Zepetnek, MacDonald, & Hicks, 2015). The one participant that dropped out at 6 weeks liked the training and would have continued if they had not developed elbow pain. At the end of the intervention, the implementation of the study only met a few of the hypotheses that were established. Overall, the main factors involved in the difficulty of implementation of the study were challenges with recruitment, the lack of interest in vibration training and the low number of completed sessions.

Two thirds of the participants did not find the training to be acceptable. Previous studies have indicated that vibration can be uncomfortable and annoying, and cause itchiness and numbness (Hadi et al., 2012). Furthermore, participants in these studies were using plates and platforms. Participants 1 and 2 expressed the same feelings with using the upper limb vibration. Because the vibration is administered at the hand, the feelings at the head and neck are amplified potentially leading to additional discomfort. Further measures of acceptability regarding the length of the training program and the recommendation of vibration to other persons with SCI can overall be explained by the participants' discomforts and dislike of the training. Participants 1 and 2 felt the training was too long and did not perceive any strength or functional benefits to the training. The participants' negative perceptions on the training may have impacted their perceptions on the rest of the training and potential benefits of the training. In a previous study with vibration, participants attitude toward vibration directly impacted outcomes (Kawanabe et al., 2007).

### 4.4.2 Pain

Pain decreases on the NRS for participant 1 were small and not clinically significant. However, the increase in pain on the WUSPI for participant 1 was larger, almost 19 points, and was clinically significant. Pain was reported on more tasks at 12-weeks compared to baseline. The presence of shoulder pain while completing more tasks is also not a desired outcome. The ability to complete these tasks is essential for independence, role functioning and participation in the community (ML. et al., 2005). Having pain while performing these activities may limit a person's participation and independence. The development of shoulder pain may be attributed to the increase in physical activity and may not be attributed to vibration training directly.

Results from the pain scores for participants 2 and 3 were overall more positive than negative. Participant 2 reported having no pain at any of the visits on either the WUSPI or NRS. Because she did not have any pain at baseline, it cannot be determined whether vibration training had any effect on pain. However, she did not develop pain over the course of the study which is still a positive outcome. Results from the NRS and WUSPI were both clinically meaningful for participant 3. At 12-weeks the participant was able to complete ADL's and IADL's with less pain and they were able to perform some ADL's that were previously not performed such as household chores and cooking with no pain. The ability to perform a variety of ADL's and IADL's without pain may lead to an overall improvement in his independence and community participation (ML. et al., 2005). Participant 3 also had a clinically meaningful increase in pain on the NRS, however this pain was still considered mild. The development of pain was at 6-weeks in the left shoulder; although this pain was clinically meaningful, it was not picked up on the WUSPI. Thus, the overall positive pain results are more meaningful for him.

None of the changes in the carpal tunnel scores for both the symptom severity score and the functional status score were clinically meaningful. These changes were small and likely had no impact on carpal tunnel symptoms, pain or functioning. Additionally, these changes may be attributed to measurement error in the scale. Given that manual wheelchair users with SCI are at risk for development of carpal tunnel, the training was able to keep carpal tunnel symptoms stable and prevent them from getting any worse. Furthermore, this type of training may be beneficial long term for preventing development of carpal tunnel.

### 4.4.3 Quality of Life

At baseline participant 1 had moderate to low quality of life in almost all domains except for role limitations due to emotional problems. Although there were decreases and increases in quality of life scores for the various categories, only the category of role limitations due to physical health was clinically significant; with the score being lower at 12-weeks compared to baseline. Physical functioning has repeatedly been identified as a theme impacting quality of life in persons with SCI (Manns & Chad, 2001). Decreased physical functioning has been shown to cause decreased participation and independence in completing activities of daily living (Manns & Chad, 2001). Although the physical functioning quality of life score decreased and was clinically meaningful, overall his quality of life remained at a moderate level throughout the study. Thus although exercise both with and without vibration has been shown to improve quality of life (Anneken et al., 2010; Sañudo Corrales et al., 2010), he did not see those effects and his quality of life did not benefit from the training program.

For almost all categories on the SF-36, participant 2 had high quality of life scores at baseline and at 12-weeks. The two categories that had reported change at 12-weeks compared to baseline, physical functioning and social functioning, were both clinically meaningful changes. Although the score for physical functioning decreased and was clinically meaningful, this score was still indicative of a very good quality of life score. Overall quality of life was excellent at the beginning of the study and remained excellent at the end of the study even though one of the scores had a clinically meaningful decrease. The exercise intervention did not improve quality of life, but it also did not alter it negatively such that they had an overall decrease in quality of life; this still being a positive outcome.

Like participant 1, participant 3 had a variety of quality of life scores for each of the 8 categories at baseline. However, at 12-weeks changes in all of the categories except for three, energy/fatigue, social functioning and general health, were clinically meaningful. The quality of life score in all the categories that were clinically meaningful increased in score at 12-weeks compared to baseline. Increased quality of life has been shown to lead to increased participation, social functioning, and self-efficacy (Middleton et al., 2007). This result also matches previous studies using whole body vibration, that training with vibration improves quality of life (Sañudo Corrales et al., 2010; P. Wang et al., 2016). Overall his quality of life was improved which may lead to other improvements that have been associated with improvements in quality of life.

### 4.4.4 Strength

Participants' 1 and 2 from a strength perspective benefited the least. Participant 1 overall saw a meaningful increase in strength in shoulder flexion on the right side. Furthermore, participant 2 only had meaningful decreases in strength on both the left and right sides. Overall, participant 3 had the greatest strength benefits out of the three participants. He had meaningful increases in strength for multiple movements on the right and left sides.

All three participants had decreases in right shoulder adduction at 12-weeks compared to baseline. The exercises completed in the training protocol targeted the shoulder abductors specifically (Durán, Lugo, Ramírez, Lic, et al., 2001). However, the adductors may not have been trained as intensely as the shoulder abductors due to the exercise being completed isometrically. Furthermore, compared to the other shoulder protocols, this movement had only moderate reliability as was shown in the reliability study testing the study protocol. This may also have contributed to all three participants seeing a decrease in right shoulder adduction at 12-weeks compared to baseline.

Many of the changes in strength fell within the measurement error of the measurement protocol. Based on the reliability parameters, large changes in strength are needed to be detected by the protocol. The method for measuring strength in previous studies with vibration training are varied. Some use the Biodex or similar dynamometer systems. Others use handheld dynamometry or 1RM testing to determine changes in strength. The Biodex or similar dynamometry system is considered the gold standard for measuring strength. Although previous studies have found strength increases after vibration training, it is difficult to compare across measurement tools with varying psychometric properties.

The protocol that was designed was consistent with guidelines that have been previously developed for WBV for seeing improvements in strength (Da Silva-Grigoletto et al., 2011; Lienhard et al., 2014; Martínez-Pardo, Romero-Arenas, & Alcaraz, 2013; Ramona Ritzmann et al., 2013). Training with WBV at least 2 times per week has been found to increase strength however in these studies participants trained for a longer time period; most ranging between 18-24 weeks (Roelants et al., 2004; S. M. Verschueren et al., 2004). Furthermore, based on strength training guidelines, all three participants should have gotten stronger from completing the training, however, this was not what the results showed. Exercise guidelines for SCI were updated and released in 2018. These guidelines recommend 3 sets of 10 repetitions at a moderate intensity for each of the major muscle groups 2 times per week ("Sceintific exercise guidelines for adults with spinal cord injury," 2017). Previous guidelines have used the following description to inform persons with SCI on what is meant by a moderate intensity. A resistance weight should be used that is heavy enough that one can barely, but safely finish the set of 10 repetitions on the last set (Ginis et al., 2011). Both the 2011 guidelines (Ginis et al., 2011) and updates to the guidelines made in 2018 ("Sceintific exercise guidelines for adults with spinal cord injury," 2017) present these recommendations for fitness benefits and cardiorespiratory and muscle strength benefits respectively. The current study protocol aimed for participants to train with vibration 2 times per week however all of the subjects fell short of this goal and in fact none of them averaged the recommended two sessions per week over the 12 week study duration (e.g. Participants 1, 2 and 3 completed 20, 19 and 21 sessions respectively out of 24). Thus, it is possible that the reason significant strength gains were not seen across all muscle groups for all subjects may be because they did not do enough work.

Although participants did not complete an average of two training visits per week, the intensity of the vibration training and duration of the training were probably higher than the guidelines recommend, thus they may not have needed additional training visits to see increases in strength. A repetition of a standard dumbbell exercise takes about 2-3 seconds to complete (Folland, Hawker, Leach, Little, & Jones, 2005; Knapik, Mawdsley, & Ramos, 1983). At the end of each repetition there is short rest period when the muscles can relax prior to starting the next repetition. In isometric training there is no break in contraction until the hold is completed. Three sets of ten repetitions for one major muscle group means the muscle would be actively working for about 60-90s. Interestingly, the hold times for participant 2 fell within this range for the completed exercises. However, for participants 1 and 3 their hold times for the two sets were longer than the recommended guidelines. Furthermore, the desired hold time of 60s per exercise for 2 repetitions with vibration exceeds the recommended guidelines. This is something to keep in mind when developing future vibration training protocols. The addition of vibration to resistance training at or above 60% of participants 1RM as well as completion of the exercises isometrically likely increased the intensity beyond the moderate level recommended in the guidelines. The combination of a higher intensity with longer durations means that our participants likely experienced a much higher than recommended volume of exercise per session compared to the training volume in the guidelines.

Due to the higher training volume experienced per session the participants in the study may have been over trained. Furthermore, participants 1 and 2 may have been more predisposed to over training compared to participant 3, who presented with less signs of over training. Over training has been defined as a plateauing and/or a decrease in performance that results from failure to tolerate or adapt to a training load (Stone et al., 1991). Plateauing was observed in the load progression plots for both participants 1 and 2. Participant 2's performance on four of the strength measures deceased at 12-weeks for some of the movements and remained the same for other movements. Additionally, participants 1's performance on the Wingate test decreased slightly compared to baseline. Symptoms of over training include, fatigue, decrease in performance, feeling tired or a lack of energy, mild soreness and pain among other symptoms (Hartmann & Mester, 2000; Stone et al., 1991). Participant 1 developed pain over the course of the study and reported decreased quality of life related to the physical domain at 12-weeks compared to baseline.

Furthermore, taking into consideration the survey responses, it is likely participants 1 and 2 did not adapt to the training as well as participant 3.

Lastly, there may have been other physiological processes contributing to the results. Poor nutrition and dysfunction of the bowel and bladder can lead to the body absorbing fewer nutrients. This makes it more challenging to gain muscle and improve strength. Bowel and bladder dysfunction are common secondary complications of SCI. Furthermore, participants' nutrition was not monitored in our study. Although this may not have been the primary factor that contributed to the study results, it is likely a factor, that in combination with other factors may have played a role.

In summary, the training did not benefit participants 1 and 2 for most movements, showing little meaningful differences in strength outcomes at 12-weeks compared to baseline. Participant 3 did see more meaningful changes in strength at 12-weeks compared to baseline. None of the participants averaged two training sessions per week, thus it is possible they did not receive enough vibration exposure to see gains in strength. However, vibration training is more intense thus they may not have needed to complete as many training sessions. Furthermore, the training protocol was more intense and higher volume compared to the recommended guidelines. This may have led to overtraining and a lack of results improved strength. These results are largely inconclusive and additional studies need to be performed to address the potential causes for minimal to no increases in strength.

### 4.4.5 Power Output

The increase in power from participant 3 was clinically meaningful when compared to the values obtained from lower extremity Wingate test. In manual wheelchair users, previous studies have found a strong correlation between anaerobic upper extremity tasks such as car transfers and wheelchair sprint test (Patrick L Jacobs et al., 2003). Although no clinically meaningful values were reported for these specific tasks, increases in power may lead to improvements in wheelchair propulsion and transfers for manual wheelchair users. Participant 3 was able to improve their transfer ability and propel up a steeper ramp at baseline compared to 12-weeks. Both functional outcomes may have been improved by the increases in power output.

### 4.4.6 Wheelchair Transfers

The ability to transfer higher and lower than level wheelchair seat height is functionally important for wheelchair users for independence in the community (A. M. Koontz et al., 2019). Although it is recommended to complete level transfers when possible, this is not always feasible in the built environment (ML. et al., 2005). The American with Disabilities Act-Architectural Barriers Act (ADA-ABA) Standards put out by the U.S Access Board outlines and specifies height requirements for surfaces related to transfers (Board, 2015). Standards for areas such amusement parks, recreational facilities and boating areas set a maximum transfer height at 24 inches. Although participants may not access some of the specialty areas often being able to access these areas may allow participants to more fully engage in recreational activities. All participants at baseline and 12-weeks were able to transfer to this height, giving them a greater access to transferring in the community. Although already over the clinically meaningful value, participants

1 and 3 were able to transfer higher at 12-weeks compared to baseline. Participant 2 maintained the same transfer height; just at the transfer height of maximum of some allowable surfaces. She was not able to transfer higher, but the ability to maintain this transfer height is still meaningful; giving her greater access to transfers in the community. The same can be seen with the minimum height transfers. Seats, benches, medical exam tables and toilets all have a recommended standard range of 17-19 inches as outlined in the standards (Board, 2015). Toilets and seats/benches are encountered in almost every public place in the built environment. Furthermore, being able to access medical exam tables, is vitally important to receiving good medical care. Being able to transfer to this height is vitally important for wheelchair users. All three participants were able to transfer to the lowest transfer height on the station, which is well below that of the standards. Again, this allows participants greater access and participation in the built environment.

A flooring effect with the station was present, as the minimum height of the station is 10 inches. This has been seen in previous studies where the station was involved (A. M. Koontz et al., 2019). Wheelchair transfers to floor and floor to wheelchair transfers are an essential wheelchair skill that is commonly performed compared to transfers above a participants wheelchair (Morgan et al., 2017). Even if the station had gone to the floor, it is likely that participants would have been able to complete the transfer. However, participants did perceive aspects of the transfer required less exertion at 12-weeks compared to baseline.

In addition to the absolute transfer height, the transfer maximum and minimum transfer height obtained relative to level seat height has also shown to be important for wheelchair transfers. Previous research has indicated that most participants are only able to transfer 1 inch above their level wheelchair seat height (A. M. Koontz et al., 2019; Toro et al., 2013). Furthermore, the number of participants that can transfer outside of that range by 1 inch decreases by 12% and 2 inches decreases by 25% (A. Koontz et al., 2012). Level seat height for most manual wheelchair users is between 21-22 inches. Therefore, the ability to transfer greater than 1 inch above or below level seat height gives participants greater access to transfers in the community and the ability to transfer just one inch further improves this ability. All three participants were able to transfer greater than or equal to 2 inches above and below their level wheelchair seat height at baseline and 12-weeks. Additionally, participants 1 and 3 were able to increase their maximum achieved wheelchair transfer height at 12-weeks compared to baseline. Although at baseline these participants were already able to transfer 2 inches over their level wheelchair seat height, after the training they were able to maintain their level of transfer ability or improve their transfer ability. This further provides participants the opportunity to transfer in a variety of community settings.

### 4.4.7 Wheelchair Propulsion

Wheelchair propulsion is one of the most important functional activities for manual wheelchair users for community participation and functional independence (Chaves et al., 2004). Previous research outlined the ability to cross a crosswalk as an important functional task to successful community participation from the viewpoint of wheelchair propulsion. A value of 1.06 m/s was the speed determined to walk across the crosswalk, and was set as the threshold value as the minimum speed at which wheelchair users would need to propel to cross the street (Cowan et al., 2008). Additionally, a clinically meaningful change in wheelchair propulsion velocity of .13m/s was determined based off gait speed with persons with SCI who can ambulate. These values were used to assess whether the results from the wheelchair propulsion trials were clinically meaningful for the level ground propulsion results. The ability to traverse ramps is also an important measure of community participation. The successful ascent of these surfaces is necessary for community function regardless of the time it took to complete them. The ADA-ABA standards outline the steepest allowable ramp is just over 7 degrees (Board, 2015). If participants can complete an 8-degree ramp, then they would be able to ascend the steepest ramps encountered in the community. For the two participants that completed the propulsion trials at baseline and 12-weeks, both were able to complete the propulsion trials with a velocity greater than 1.06 m/s. Although both participants propelled with a slower velocity at 12-weeks compared to baseline, they were still above the threshold and the decreases in velocity were not clinically meaningful. Participant 2 completed the propulsion trials 12-weeks and was able to propel over this desired velocity. Although propulsion velocity decreased, the decrease likely would not affect their ability to function in the community.

At baseline and 12-weeks participant 1 was able to complete all the ramped trials of varying steepness's. Improvements in propulsion ability were difficult to assess for Participant 2 due to missing these measures at baseline but at 12 weeks was unable to ascend the 8-degree ramp. At baseline, participant 3 was unable to complete the 8-degree ramp trials without assistance but was able to complete these trials at 12-weeks which may be attributed to the gains in strength and power. The ability to ascend a steeper ramp may allow this participant to access a part of the community or their home, which he was previously unable to do.

### 4.4.8 Success of the training protocol

Participants 1 and 2 overall had less benefit from the vibration training compared to participant 3 based on all the outcome measures presented. Participant 1 had a few positive outcomes, but still most of the outcome measures did not show a positive result. He had increased pain and decreased quality of life. An increase in right shoulder flexion strength was the only meaningful increase in strength at 12-weeks. He also had the same power output at 12- weeks as at baseline. However, he did see some improvements on the functional outcome measures, obtaining a higher maximum height transfer and maintained functional aspects of wheelchair propulsion on level and ramped surfaces. He also did not enjoy the training and would not recommend it. Participant 2 benefitted the least from the training. Overall, she saw little improvement in any of the outcomes except for an increase in power. She had no pain at the beginning of the study but did not develop any over the course of the study, which is still a positive outcome. However, she hardly saw an improvement in strength. Only one of the movements had a meaningful increase in strength, whereas a handful of movements had a meaningful decrease in strength at 12-weeks compared to baseline. While there was no improvement in transfers, she was able to maintain the transfer ability at 12-weeks; an important functional outcome for community participation. She only completed the propulsion trials at the 12-week's visit, so this outcome measure could not be assessed fully but she was able to propel over the meaningful velocity measure. Lastly, she did not enjoy the training and would not recommend it to other manual wheelchair users with SCI. Participant 3 had the most success out of the three participants as well as enjoyed the training overall and would recommend it other manual wheelchair users with SCI. He had a clinically meaningful decrease in pain and increase in quality of life. Also, he was the only participant to see clinically meaningful increases in power as well as meaningful increases in strength. On the functional movements he was able to transfer higher and complete the 8-degree ramped trail at 12-weeks, which was not obtainable at baseline., These improvements in functional outcomes may benefit his participation and independence in the community. Overall based on the first three participants the program has mixed results.

### 4.5 Future Vibration Training Protocol Considerations

The development of pain by two of the study participants and the findings related to no changes and decreases in strength warrants changes to the vibration training protocol to make it safer and beneficial to participants.

#### 4.5.1 Intensity and Loading

There is little to no guidance on how to administer additional loading into vibration training. However, there is an extensive body of literature using whole body vibration that has examined using additional load. Compared to the present study protocol, these studies did not use a percentage of a 1RM squat for example, but used a percentage of the participants' body weight (Y Osawa & Oguma, 2013; J. Rittweger, G. Beller, & D. Felsenberg, 2000; Jörn Rittweger et al., 2003; Ramona Ritzmann et al., 2013). In these studies the percentages ranged from 10-40% of participants body weight as the additional load (D. J. Cochrane et al., 2008; Garatachea et al., 2007; J. Rittweger et al., 2000). Other studies used a percentage of lean body mass rather than a percentage of total body weight (J Rittweger et al., 2002; Tapp & Signorile, 2014). These percentages overall are much smaller in weight than using 60% of a 1RM for a given lift. For example, a 135 female may be able to back squat 250lbs. Comparing 40% of her body weight (54lbs) to 60% of her 1RM (150lbs), the value of the 1RM is much larger than the percentage of body weight. The addition of vibration to 60% of the 1RM would likely increase the intensity of training to a level where over training would be a concern. Additionally, for the most part, the other parameters of these studies matched those of the current training protocol (40Hz vibration, 60s bout of vibration), with the exception that the current study was using greater loads and smaller muscle groups. The training frequency and time per bout of vibration remained the same in these studies even though additional load was used. The percentage of body weight as a way to determine the loading does not directly translate to training with upper limb vibration. However, it is an indication that the loads used in the current study were likely too great for vibration training and lead to a training volume which may have been prohibitive of strength increases. Future studies could be used to calculate these percentages. For example, based on participants abilities to complete a given exercise with a load under the criteria determined for starting weight and weight progression these percentages could be determined.

The potential that high-intensity vibration added to a participants' 60% 1RM could approach a person's maximum training threshold is very possible. Adding vibration to a starting weight of 60% 1RM likely equates to weight training with much more weight than what is actually on the dumbbell. Research on the topic is limited. Marin et al.'s study aimed to equate vibration training at different frequencies during a semi-squat exercise to the same exercise using a loaded barbell resting on the participants shoulders (Marín, Santos-Lozano, Santin-Medeiros, Delecluse, & Garatachea, 2011). Intensity of the two types of training were measured with surface EMG (sEMG) on the lower limbs. During the protocol, sEMG was measured while participants held a semi-squat position on a vibration platform for 15s or with a load on their shoulders using a Smith machine. Vibration frequency conditions ranged from 25-45Hz (increasing in increments of 10Hz) and weighted conditions ranged from 20kg-70kg (increasing in increments of 10kg). Results of the study showed that the sEMG values with a vibration frequency of 20Hz was equivalent to the sEMG values while completing the semi-squat with 20kg of weight on the shoulders. Furthermore, there was positive linear relationship between the frequency of vibration training and weight participants held on their shoulders on the sEMG measurements. While the study was conducted using WBV and a lower body exercise the primary finding that training with vibration of increasing frequencies is the equivalent to training with additional shoulder loads can be related to the current study. Furthermore, the upper limbs are smaller muscle groups and are not as robust to large increases in weight as the lower limbs. The effects of vibration with loading may be felt more extensively on the upper limbs than the lower limbs. Additionally, the duration of hold times in the current study were much longer that the Marin et al. study. A study like the one conducted on the lower limbs should be conducted with the upper limbs. Training loads with upper limb vibration and progression of training weight would be better informed if we knew the added effect of vibration to weight training on the upper limbs. Furthermore, information as to how this relates to percentage of a 1RM or body weight could also help inform training loads and weight progression with an upper limb vibration training protocol.

When looking at how much training is too much training, previous research has related the upper limit of vibration exposure to ISO Standards for hand transmitted vibration (Jörn Rittweger, 2010). These guidelines lay out the amount of vibration exposure that is permissible before damage to the limbs can occur (M. J. Griffin, 2004). The standards outline the upper limit of vibration exposure in terms of the time and acceptable acceleration ($a_{rns}$) values for the given time of exposure. The $a_{rms}$ value can be calculated based on the vibration frequency and amplitude (Jörn Rittweger, 2010). Based on the standards and training parameters used in the current study, the amount if vibration exposure is under the exposure limit value for one minute of vibration exposure (M. J. Griffin, 2004). Regarding the aspect of recommended loads used during vibration training, there are no guidelines when using vibration with resistance training. Previous studies have used loading with vibration, but official training guidelines have yet to be made.

Given the above information on loading used in previous studies with WBV and the likely indication that training with vibration increases the intensity beyond the training weight, it is likely that the training volume in this study was close to or above the recommended training volume to see improvements in strength. Furthermore, given that the participants had some decreases or no changes in strength at 12-weeks compared to baseline, suggests that participants may have been exercising at a training volume that was prohibitive of additional strength gains because they were over trained.

### 4.5.2 Suggested Protocol Modifications

Several modifications to the protocol are suggested to make the program safer as well as address the issues noted above associated with the intensity of vibration training. One suggestion would be to decrease the total number of exercises and focus on ensuring the volume and intensity of the training is appropriate. During vibration training, all muscles of the arms and back feel the stimulus, regardless of what position the arm is in. Along with the co-contraction experienced by antagonist muscles during vibration training (C De Ruiter, R Van Der Linden, M Van der Zijden, A Hollander, & A De Haan, 2003; R. Ritzmann, Kramer, Gollhofer, & Taube, 2013), the number of exercises can be reduced. The number of exercises could potentially be reduced to five exercises: side flies, front raises, bicep curls, bent over rows and butterflies. These exercises still accomplish training the muscle groups of interest but are not double or tripling the exercises that train specific muscle groups. While side flies and front raises put the upper limbs in a potentially compromised position, they are key exercises for working muscles of the shoulder and upper back. In order to make these two exercises safer, the position in which the arm could be held could be changed to 45° flexion for front raises and 45° abduction for side flies, rather than the 90° positions that were previously used. These positions put the upper limbs in a better position, not stressing the shoulder, elbow and wrist joints as much but still working the shoulder muscles.

Additionally, the volume and intensity of the training should be changed, as well as building in a mechanism for individual responses to vibration. The response to the training was different for each of the participants, indicating the need to evaluate individual participants more carefully in terms of making training parameter adjustments. Adjustments to the training protocol would aim to more slowly build in intensity, while maintaining the number of sets and hold times. Previous research with vibration training and loading was done using WBV and the lower limbs. The upper limbs may not be as robust as the lower limbs to the use of high-frequency vibration and loading during training, thus further supporting that the application of vibration should be done more slowly and gradually. In addition, the starting percentage was too heavy and should be evaluated more carefully in a future training protocol with a more structured assessment process than what was used in this study. Because this study is the first of its kind there are no guidelines for what an appropriate weight percentage is to start at. Instead of using 60% of participants' 1RM to start, all participants should start training by completing all the exercises with just the dumbbell to assess their ability to complete the exercises with vibration. For exercises where participants can hold the dumbbell for 60s with no pain and a moderate difficulty (e.g. RPE < 13), the weight would be increased. The weight progression could be modeled after the DAPRE Technique for strength training (Knight, 1985). This technique uses the number of repetitions completed to dictate the weight that is used for future training sessions (Knight, 1985). For the vibration training protocol, the criteria outline above could be used as the conditions that need to be met in order for the weight to be progressed. Exercises that did not meet these outlined parameters would remain at same weight. For exercises that met all the conditions, the weight of the dumbbell would be increased 2-10% (Medicine, 2009). These are the recommended percentages by the ACSM and are based on the same principle as the DAPRE protocol. They suggest increasing weight when certain criteria are met related to the number of repetitions that are completed during the final set of a training session (Medicine, 2009). The dumbbell does not have the same adjustments as standard dumbbells so the weight adjustments would be close to the target range but may not be exact. Furthermore, because this type of training is new with little known about training intensity adjustment, starting out with smaller percentage increases in weight would keep the training volume manageable for participants at the beginning but give them an opportunity to build. Moving forward the weight of the dumbbell would only be increased if the parameters for progression are once again met. In the current protocol, the starting weight was likely too heavy, and the weight progression was likely too fast and also too heavy, which likely contributed the development of pain. Both aspects of the training would be made safer based on the suggested training.

### 4.6 Limitations

In addition to the study limitations discussed in chapter 2, this study presents additional limitations. A large limitation is the small sample size. The data was only able to be presented in a case study format. Because of the limited sample inferential statistics were not used, thus none of the findings can be interpreted as significant different. Instead of using statistical significance, threshold values were used to determine if results are clinically meaningful. The threshold values were selected to be as close as possible to those that have been used in a SCI population. However, for some of the measures there was not an exact threshold value in a SCI population. The best value was chosen based off the available information, but some may not have had the best fit. Additionally, there was no control group in the study. Thus, any differences that are found cannot directly be attributed solely to the vibration aspect of the training.

There were several limitations with the outcome measures used in the study. The upper limb Wingate test is the equivalent to the lower extremity Wingate test used for able bodied persons. Although this is the gold standard method for measuring power output, the majority of the studies that used whole body vibration did not use the Wingate test as a measure of power. Instead these studies used jumping and other body weight maneuvers as measures of power. These movements are not feasible for persons with SCI. Limited information is available with vibration research that used a Wingate test to act as a direct comparison for power output results. Also, although the Biodex Upper Limb protocol that was used was tested for reliability, error was still present in the protocol. The same set up variables were used at 12-weeks as were used at baseline; however, the settings were adjustable depending on how the participants were feeling at the visit. If they had pain or discomfort while performing any of the exercises the settings were adjusted to make sure these symptoms were mitigated. Each participant was given the same instructions when performing the exercises but if a participant was tired or fatigued, they may not have moved through the movements as hard and as fast as they were able to. Participants 2 and 3 have an incomplete data set for the propulsion trials and SmartWheel data due to time constraints and issues with the wheel. Thus, when looking at the whole of wheelchair propulsion, only one participant can be examined. From the Biodex reliability study that was conducted (Chapter 3), the two wrist protocols were shown to lack the reliability of the other protocols. The study team chose to leave these two protocols in the strength testing because they are still of interest. However, the reliability of the strength values obtained is a limitation. Issues directly related to recruitment and retention are explained below.

## 4.7 Challenges with Recruitment

There were several challenges related to recruitment of study participants. Recruitment efforts were extensive and took place in a variety of settings. Efforts took place through the Human Engineering Research Lab's research registry, the Clinical and Translational Sciences Institute and local community groups. These groups include the SCI peer support group held at UPMC Mercy hospital, Three Rivers Adaptive Sports, and the Steelwheelers basketball team. We also worked with therapists at the Center for Assistive Technology to recruit participants from the seating clinic. Other sources of participants that were used to recruit include the Physical Medicine and Rehabilitation registry, opportunities to connect with persons through Vocational Rehab, and the Harmarville HealthSouth Rehab clinic. Participants were recruited in person at the Center for Assistive Technology and the Mercy Outpatient SCI clinic. Social media was also used as a source of recruiting. The flier for the study was posted through the HERL Facebook page as well as through the CTSI and Pitt+Me social media pages including Facebook and twitter. However even with all of the recruitment efforts, there was still a lack of participants for the study. From these efforts approximately 100 potential participants were approached in person or on the phone, with approximately 85 of those 100 being approached on the phone. Of the participants that were approached, half of the participants were never reached. Participants either had disconnected phone numbers, never returned a phone call or had moved/changed their phone number. There were a group of participants recruited who did not meet the inclusion criteria either due to medical reasons or living farther than one hour away from the lab. Lastly, there were a group of participants recruited that were not interested in participating in the study. Thus, although recruitment efforts were extensive,10 participants were screened eligible for the study and ultimately 5 participants were enrolled. One possible roadblock in recruitment was the need for a physician's release form. There were several participants who were never scheduled for a study visit or enrolled into the study during the process of obtaining the physicians release form. Several participants were screened, and their physicians never returned the release form. Efforts were made to contact the physician's office as well as sending additional release form. It is possible physicians were skeptical about receiving a phone call from a graduate student from a research laboratory they were unfamiliar with. The physicians may have felt more comfortable with signing the form if they were receiving a phone call from another physician and may have felt more of an obligation to sign the form if they were asked by a fellow physician or peer. Additionally, the participants were encouraged by the study team to contact their physician to see if they would be able to request the form be completed, but none of the participants chose to do this. However, after these efforts the forms were still not obtained. There were also several participants who the study team lost contact with after their release forms were obtained. These participants were contacted after their release forms were obtained, but their phone numbers were not in service or the participants did not return phone messages after several attempts at contact. There may have been more participants enrolled in the study and complete at least one study visit if they did not need a signed release form prior to scheduling the first study visit. In order to mitigate the need for a physician's release form, the questions asked on the screening script could have been worded differently or expanded to make sure study team members were addressing potential health complications that could have been contraindications for study participation. Furthermore, the study team could have worked with the physiatrist at the laboratory to do an exam at the first study visit to act in place of the physician's release form. In addition, when recruiting many participants expressed skepticism about the vibrating dumbbell and had preconceived notions about it due to the presence of imitation devices. Participants were concerned about the amount of time commitment to the study, stating that 12-weeks was too long, and they did not want to commit to a study for that long. This initial skepticism with the long-time commitment added to the recruitment challenges of the study.

### 4.8 Challenges with the Intervention Delivery and Retention

There were several challenges related to retention and the intervention delivery. One of the primary issues was with the number of sessions completed and scheduling issues related to the training session. The study team members worked with the participants to accommodate their schedules and lifestyles as best as they were able to. Preferred methods of communication by the participant were used to ensure participants ease of communication. Scheduling conflicts still arose with each of the participants. All the participants were active members of the community, having jobs, classes, volunteer responsibilities, medical appointments and family obligations. Participants in general were able to fit in two training sessions per week. However, there were some weeks where participants only trained one time. These were attributed mostly to scheduling conflicts with the participant and scheduling conflicts with the study team member doing the training There were weeks where the study team member doing the training and the participant could not find a time for training. Also, the study team was unavailable for one week of training due to being out of the lab. An attempt was made to make up the training before and after the week away, but it was not possible for all participants to schedule these extra visits. Participant 3 missed two training sessions due to family vacation. Additionally, for participant 1, a couple of sessions were not completed due to the participant reporting having wrist pain. There were several weeks where only one training session was completed to give him an opportunity to rest.

Furthermore, participants expressed needing time to recover from the exercise sessions and that trying to fit in a third visit may not have been possible. Manual wheelchair users are required to use their arms all day in order to complete activities of daily living as well as propelling and transferring to and from their wheelchair . Training sessions were scheduled with 2-3 days in between to give participants enough time to recover however, participants were only able to complete 2 visits per week of the training program. Additionally, there were interruptions in training due to development of wrist pain (participant 1). Exercise guidelines generally recommend strength training 3 times per week for effective results. Therefore, participants may not have completed enough training session to see an increase in strength or power.

There were also challenges in intervention delivery related to space in the participants home. Participants 2 and 3 had limited space in their homes to complete the exercises; in particular having challenges related to setting up the mat table. Both participants did not have room to set up the mat table without moving furniture. The set up that was used for training remained in place for the entirety of the study, however this may have been seen as an inconvenience for the participants.

Lastly two of the participants that were enrolled did not complete the training and study visits for reasons that were likely related to the training. Even though efforts were made to space out the training sessions, one participant was not able to complete the 6-week study visit after having completed 6 weeks of exercising due the development of an elbow injury. A second participant completed the first training visit but did not complete any training. At the first visit they decided to not continue participation in the study due to the vibration training. They had the opportunity to try the vibration at the first study visit but then changed their mind when it came to the actual training.

## 4.9 Conclusion

The feasibility of implementing a 12-week vibration training protocol and the effects on strength, pain and functional outcomes were explored in this study. The demand for the study was low and did not meet all of the desired criteria for implementation. Participants were unable to meet the desired number of training visits but were able to progressively increase the weight they trained with. Only one participant enjoyed the training, while the other two participants noted not liking the training and not wanting to use vibration for future training. When examining the secondary outcome measures results were also varied with only some of the hypotheses being met. One participant did not have pain throughout the study, but the other two participants were split on their pain scores. One participant had a clinically meaningful increase in pain, while the other participant had a clinically meaningful decrease in pain. Only one participant had a meaningful increase in strength at 12-weeks compared to baseline, for more than a few movements. The other two participants had fewer meaningful results. Of the two participants that increased their power output at 12-weeks, only one participants results were clinically meaningful. The functional outcomes overall had improved results. Two of the participants were able to improve their wheelchair propulsion outcomes and complete trials they were unable to complete at baseline. Two of the three participants were able to transfer higher at 12-weeks compared to baseline, while all three were able to maintain their ability to transfer to the lowest transfer high the station allowed.

Overall results are varied amongst participants, along with participants' feedback on the training, demand to participate and improvement in the outcomes measures. With a limited sample size, the benefits of training with vibration for persons with SCI are unknown. However, with further research and additional participants completing the training with vibration, different conclusions may be drawn about whether or not it is a useful form of training for persons with SCI.

# 5.0 Conclusion

The work presented in this dissertation aimed to determine if targeted upper limb vibration is a feasible and effective form of exercise for manual wheelchair users with SCI. Previous research with whole body vibration training, as well as with a variety of populations from athletes, menopausal women to children with cerebral palsy and adults with MS have had success at increasing strength. Functional benefits of decreased pain and spasticity, as well as increased bone mineral density have also been reported. All of these benefits are of interest to persons with SCI. However, the literature presents mixed results in terms of whole-body vibration due to differences in study design, vibration parameters and participants. Limited research has been done with targeted upper limb vibration and in persons with SCI.

The first research study (Chapter 2) aimed to assess the feasibility of completing a single session of vibration training and to compare the physiological differences between training with vibration and training with standard dumbbells. Manual wheelchair users with SCI were recruited to assess the study aims. The vibration training protocol was shown to be feasible for three exercises on the right side and only 2 exercises on the left side. Side flies and front raises in particular were the two exercises where most participants were unable to hold the dumbbell for the desired minimum hold time of 45s at 30Hz. All participants were able to complete the training at 30Hz. Overall the study showed that physiologically the two training protocols were the same. There were no significant differences in heart rate variables, blood lactate, and power output between the two training programs. However, vibration exercise did elicit greater overall heart rates for more than half of the exercises, as well as larger overall increases in blood lactate. Contrastingly to the physiological results, participants rated vibration training with significantly higher exertion compared to dumbbell training for the majority of the exercises. Vibration exercise also did not support previous research that has indicated its ability to enhance muscle activation. Lastly, participants for the most part enjoyed the vibration training protocol and were interested and excited to train with vibration in the future.

The second research study aimed to test the upper limb strength measurement protocol with the Biodex for reliability. Able bodied participants without shoulder pain were enrolled to test the upper extremity strength protocol. A data collection tool was developed to ensure the settings related to the set-up for each exercise were being collected so the set-up could be recreated at a future study visit. Movements at the shoulder (flexion/extension, abduction/adduction and internal/external rotation) and elbow (flexion/extension) were shown to be reliable. Movements at the forearm (pronation/supination) and the wrist (flexion/extension) did not meet all the criteria of reliability. Although the movements at the forearm (pronation/supination) and wrist (flexion/extension) were not reliable, the data collection set-up tool likely helps to reduce measurement error to some extent.

The last research study aimed to test the feasibility of implementing a 12-week training program using upper limb vibration and to assess its impact on strength, function and pain in persons with SCI. Three participants completed the 12-week training program and all three assessment visits. Overall, there were challenges with recruitment and retention of participants. Demand for the study was low, and two out of the three participants would not be interested in continuing to train with vibration exercise at the end of the study. The three participants were only able to complete two training sessions per week, but all three were able to increase the weight they used progressively throughout the study. Two out of the three participants did not enjoy the training and would not recommend it to other manual wheelchair users with SCI. Only one participant found the training to be enjoyable. For two of the three participants, training with vibration did not have a positive impact on strength, with several movements seeing a decrease in strength at 12-weeks compared to baseline. Contrastingly, power increased for two participants and remained the same for the third participant. Pain increased or stayed the same for all three participants, while quality of life also stayed the same or decreased for two of the participants and only increased for one participant. Participants had more success on the functional outcomes compared to the other measures. Both participants where SmartWheel data was collected saw an improvement in one or more of the propulsion variables leading to improved propulsion. Additionally, two out of the three participants were able to transfer higher after the training period, while all participants maintained the ability to transfer to the minimum height of the station.

The research studies presented provided insight into the use of vibration exercise for manual wheelchair users with SCI and its potential to be used in an exercise training program. Overall, results were mixed for the two research studies. More of the hypothesis were accepted than refuted in the first study (chapter 2) compared to the second study (chapter 4). Although there was minimum physiological change, the first study did not show vibration training was preferred by a majority of users over standard dumbbell training. The second study was also inconclusive on the benefits of a longitudinal training program with vibration. However, information was obtained about the training parameters related to upper limb vibration and how they likely need to be different from whole body vibration applied to the lower limbs. The number of exercises should be limited and the total volume and intensity of the exercise needs to be taken under closer consideration in future studies. Insight was gained into participants perceptions on the training, and their desires to train with vibration. With further refinement of the vibration parameters, and future research, vibration exercise may still be a useful form of training for manual wheelchair users with SCI.

# 6.0 Future Work

Future work includes testing of additional participants for both research studies. Participants rated the vibration training to be harder than the dumbbell training and objective physiological measures were inconclusive. Enrolling additional participants may give more insight into whether physiologically  a true difference exists with vibration training. Furthermore, participants need to be tested who are not active and participating in wheelchair sports or weightlifting at the time of completing the study. In order to gain further insight into whether vibration is making an impact on the training, a study with a direct comparison needs to be completed. Rather than completing repetitions with the standard dumbbell, participants should hold the vibrating dumbbell in an isometric hold without the vibration turned on. This would give insight into the effect vibration alone is having with the two training programs being comparable. Whole body vibration exercise has been studied on a variety of populations; within the SCI community there may also be a subset of the population who would benefit more from this type of training than others. Additional research is needed to determine the types of participants that would be most receptive and responsive to using vibration.  A shorter training program (e.g. 6-weeks in duration) should be completed first to see if participants are able to tolerate the new methods proposed for assessing the starting weight as well as the assessment and progression of the training weight. Furthermore, these training weights can be used to determine tolerable training percentages of 1RM's; providing additional evidence of the loading that should be used with upper limb vibration training. . Additionally, the training program should focus more on targeting specific muscle groups and not completing as many exercises during each bout of vibration. Lastly, should these other studies show promising results, a study comparing vibration training to a control group would have to be performed to show that vibration exercise is better than what is currently being recommended to persons with SCI.

## Appendix A Survey Administered to Participants to Assess the Vibration and Dumbbell Training Protocols

Exercise Evaluation Form (Standard Dumbbells)

How much did you **enjoy** exercising with the standard dumbbell?

- Very Enjoyable
- Somewhat Enjoyable
- Neutral
- Somewhat Unenjoyable
- Not Enjoyable

Comments: ______________________________________________________

Rate your overall **difficulty** level in performing the exercises:

- The exercises were very easy to perform
- The exercises were moderately easy to perform
- Neutral
- The exercises were moderately difficult to perform
- The exercises were very difficult to perform

Comments:_______________________________________________________

Rate the **ease of use** of using the standard dumbbell

- Very Easy
- Somewhat Easy
- Neutral
- Somewhat Difficult
- Very Difficult

Comments:_______________________________________________________

Rate your overall **comfort** level using the standard dumbbell for exercise

- Very Comfortable
- Somewhat Comfortable
- Neutral
- Somewhat Uncomfortable
- Very Uncomfortable

Comments:______________________________________________

Rate your **desire** to train with dumbbells in the future

- Strong Desire to Train with Dumbbells in the future
- Moderate Desire to Train with Dumbbells in the future
- Neutral
- Low Desire to Train with Dumbbells in the future
- No Desire to Train with Dumbbells in the future

Comments:______________________________________________

Rate your **excitement** to train with dumbbells in the future

- Very Excited to Train with Dumbbells in the future
- Moderately Excited to Train with Dumbbells in the future
- Neutral
- Moderately Unexcited to Train with Dumbbells in the future
- Not at All Excited to Train with Dumbbells in the future

Comments:______________________________________________

What is the likelihood that you will use dumbbell training as an exercise modality in the future?

- Very Likely
- Somewhat Likely
- Neutral
- Somewhat Unlikely
- Very Unlikely

Comments:______________________________________________

Did you previously complete an exercise training session with **vibration exercise**?

- Yes
- No

If **YES** please answer the following questions:

Compared to training with vibration training, how much did you **enjoy** the dumbbell training?

- Training with vibration was more enjoyable than dumbbell training
- Training with the dumbbells was more enjoyable than training with vibration
- Both were equally enjoyable
- Both were equally unenjoyable

Comments:___________________________________________________________

Compared to training with vibration, rate the **difficulty** of the dumbbell training:

- Training with vibration was more difficult than dumbbell training
- Training with the dumbbells was more difficult than training with vibration
- Both were equally as difficult
- Both were equally not difficult

Comments:___________________________________________________________

Which form of exercise would you prefer if you were to complete a 12-week exercise protocol?

- I would prefer training with vibration for a 12-week protocol
- I would prefer training with the dumbbells and no vibration for a 12-week protocol
- I would not use either for a 12-week protocol

Comments:___________________________________________________________

Are there any other comments you would like to make about exercising with dumbbells?

Exercise Evaluation Form (vibration exercise)

Was the length of the training session long enough for you to form a solid opinion about vibration exercise?

- O The length of the training session was appropriate
- O The training session was too long
- O The training session was too short (please explain)

Comments:____________________________________________________

How much did you **enjoy** exercising with the vibrating dumbbell?

- O Very Enjoyable
- O Somewhat Enjoyable
- O Neutral
- O Somewhat Unenjoyable
- O Not Enjoyable

Comments: ___________________________________________________

Rate your overall **difficulty** level in performing the exercises:

- O The exercises were very easy to perform
- O The exercises were moderately easy to perform
- O Neutral
- O The exercises were moderately difficult to perform
- O The exercises were very difficult to perform

Comments:____________________________________________________

Rate your overall **comfort** level using the vibration for exercise

- Very Comfortable
- Somewhat Comfortable
- Neutral
- Somewhat Uncomfortable
- Very Uncomfortable

Comments:________________________________________________

Rate the **ease of use** of the vibrating dumbbell

- Very Easy
- Somewhat Easy
- Neutral
- Somewhat Difficult
- Very Difficult

Comments:________________________________________________

Rate your **desire** to train with vibration in the future

- Strong Desire to Train with Vibration in the future
- Moderate Desire to Train with Vibration in the future
- Neutral
- Low Desire to Train with Vibration in the future
- No Desire to Train with Vibration in the future

Comments:________________________________________________

Rate your **excitement** to train with vibration in the future

- Very Excited to Train with Vibration in the future
- Moderately Excited to Train with Vibration in the future
- Neutral
- Moderately Unexcited to Train with Vibration in the future
- Not at All Excited to Train with Vibration in the future

Comments:______________________________________________

What is the likelihood that you will use vibration as an exercise modality in the future?

- Very Likely
- Somewhat Likely
- Neutral
- Somewhat Unlikely
- Very Unlikely

Comments:______________________________________________

What is the likelihood you would recommend vibration exercise to other wheelchair users?

- Very Likely
- Somewhat Likely
- Neutral
- Somewhat Unlikely
- Very Unlikely

Comments:______________________________________________

Do you think this type of training has the potential to increase your strength?

- High Potential to Increase Strength
- Moderate Potential to Increase Strength
- Neutral
- Moderate Potential to NOT Increase Strength
- High Potential to NOT Increase Strength

Comments:__________________________________________________________

Do you think this type of training has the potential to increase your strength faster than traditional dumbbell training?

- High Potential to Increase Strength Faster
- Moderate Potential to Increase Strength Faster
- Neutral
- Somewhat Unlikely to Increase Strength Faster
- Not At All Likely to Increase Strength Faster

Comments:__________________________________________________________

How interested would you be in participating in a 12-week vibration exercise training program (training with the dumbbell 2-3 days/week)?

- Very Interested
- Somewhat Interested
- Neutral
- Somewhat Not Interested
- Not Interested

Comments:__________________________________________________________

How likely would you be to participate in a 12-week vibration exercise training program if you could do it at home versus at a gym, clinic or other setting?

- Most Likely
- Somewhat More Likely
- Neutral
- Somewhat Less Likely
- Very Unlikely

Comments:______________________________________________________

Did you previously complete an exercise training session with **dumbbell exercise**?

- Yes
- No

If **YES**:

Compared to training with the dumbbell, how much did you **enjoy** training with vibration?

- Training with vibration was more enjoyable than dumbbell training
- Training with the dumbbell was more enjoyable than training with vibration
- Both were equally enjoyable
- Both were equally unenjoyable

Comments:______________________________________________________

Compared to training with the dumbbells, rate the **difficulty** of the training with vibration:

- Training with vibration was more difficult than dumbbell training
- Training with the dumbbell was more difficult than training with vibration
- Both were equally as difficult
- Both were equally not difficult

Comments:____________________________________________________________

Which form of exercise would you prefer if you were to complete a 12-week exercise protocol?

- I would prefer training with vibration for a 12-week protocol
- I would prefer training with the dumbbells and no vibration for a 12-week protocol
- I would not use either for a 12-week protocol

Comments:____________________________________________________________

What did you like most about this form of exercise?

____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________

What did you like least about this form of exercise?

____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________

Are there any other comments you would like to make about exercising with vibration?

____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
____________________________________________________________________________
_______________________________________________

# Appendix B Survey Responses

Additional survey responses assessing vibration training and dumbbell training, as well as comparing the two trainings from chapter 2 are shown below in figures 29 and 30.

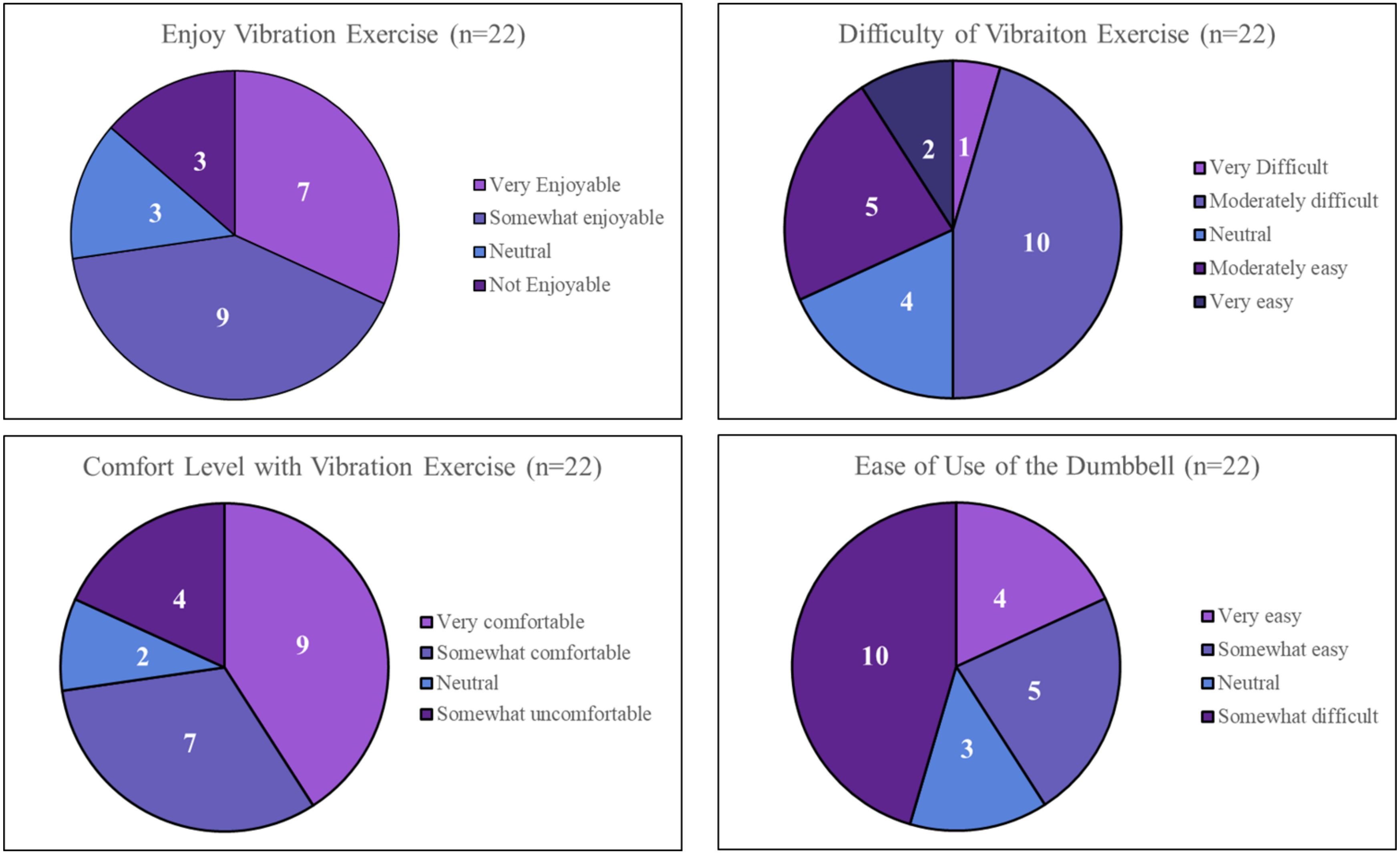



**Figure 31. Participants answers to survey questions, (top left) Rate how enjoyable it was training with vibration exeriercise, (top right) rate your difficulty in training with vibration exercise, (bottom right) rate your comfort level training with vibration exericise, (bottom right) rate your ease of use of the dumbbell while training with vibration exercise**

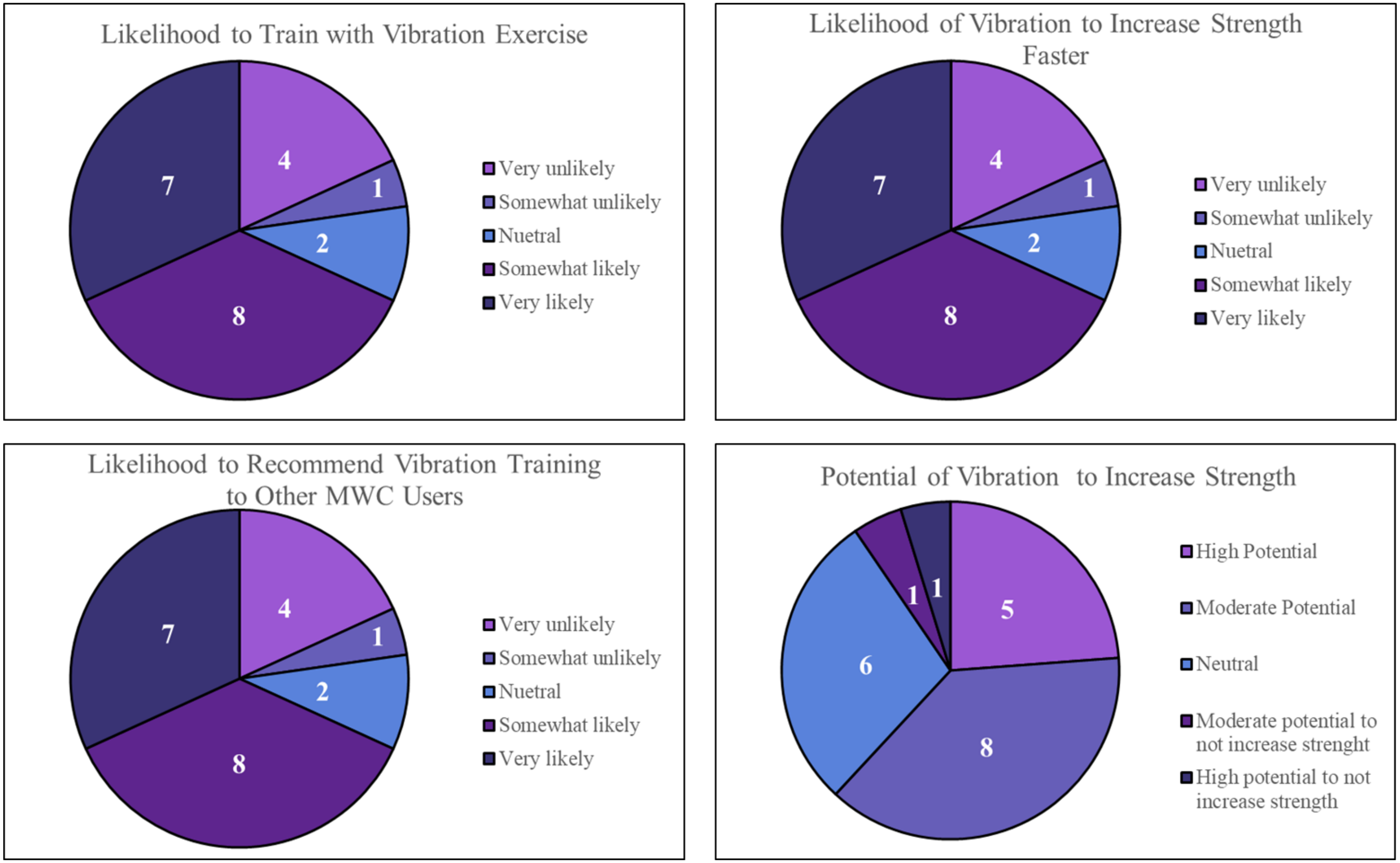



**Figure 32. Participants answers to survey questions, (top left) Rate your likelihood to train with vibration exeriercise in the future, (top right) rate your thoughts on vibration exercise to increase strength faster, (bottom right) rate your likelihood to recommend vibration training to other MWC users, (bottom right) rate your thoughts on whether vibration has the potential to increase strength**

## Appendix C Biodex Measurements From

The following form was used to collect the set-up related variables during the Biodex reliability study as well as with the longitudinal exercise study.

| **Shoulder Flexion/Extension** | |
|---|---|
| **Target ROM** | -30 to 50 degrees |
| **Dynamometer** | 0 degrees |
| **Dynamometer Tilt** | 0 degrees |
| **Seat Angle** | 15 degrees |
| **System Measurements** | |
| *Seat Height* | |
| Right | |
| Left | |
| *Back Rest Setting* | |
| Right | |
| Left | |
| *Chair Location* | |
| Right | |
| Left | |
| *Dynamometer Location* | |
| Right | |
| Left | |
| *Dynamometer Height* | |
| Right | |
| Left | |
| *Armrest Height* | |
| Right | |
| Left | |
| *Attachment Length* | |
| Right | |
| Left | |
| *Towards Angle* | |
| Right | |
| Left | |
| *Away Angle* | |
| Right | |
| Left | |
| **Total ROM** | |
| Right | |
| Left | |

| Shoulder Abduction/Adduction | |
|---|---|
| **Target ROM** | 10 to 70 degrees |
| **Dynamometer** | 0 degrees |
| **Dynamometer Tilt** | 10 degrees |
| **Seat Angle** | 75 degrees |
| **System Measurements** | |
| *Seat Height* | |
| Right | |
| Left | |
| *Back Rest Setting* | |
| Right | |
| Left | |
| *Chair Location* | |
| Right | |
| Left | |
| *Dynamometer Location* | |
| Right | |
| Left | |
| *Dynamometer Height* | |
| Right | |
| Left | |
| *Armrest Height* | |
| Right | |
| Left | |
| *Attachment Length* | |
| Right | |
| Left | |
| *Towards Angle* | |
| Right | |
| Left | |
| *Away Angle* | |
| Right | |
| Left | |
| **Total ROM** | |
| Right | |
| Left | |

| Shoulder Internal/External Rotation | |
|---|---|
| **Target ROM** | 0 to 45 degrees |
| **Dynamometer** | 20 degrees |
| **Dynamometer Tilt** | 50 degrees |
| **Seat Angle** | 0 degrees |
| **System Measurements** | |
| *Seat Height* | |
| Right | |
| Left | |
| *Back Rest Setting* | |
| Right | |
| Left | |
| *Chair Location* | |
| Right | |
| Left | |
| *Dynamometer Location* | |
| Right | |
| Left | |
| *Dynamometer Height* | |
| Right | |
| Left | |
| *Armrest Height* | |
| Right | |
| Left | |
| *Attachment Length* | |
| Right | |
| Left | |
| *Towards Angle* | |
| Right | |
| Left | |
| *Away Angle* | |
| Right | |
| Left | |
| **Total ROM** | |
| Right | |
| Left | |

| Elbow Flexion/Extension | |
|---|---|
| **Target ROM** | 0 to 90 degrees |
| **Dynamometer** | 30 degrees |
| **Dynamometer Tilt** | 0 degrees |
| **Seat Angle** | 0 degrees |
| **System Measurements** | |
| *Seat Height* | |
| Right | |
| Left | |
| *Back Rest Setting* | |
| Right | |
| Left | |
| *Chair Location* | |
| Right | |
| Left | |
| *Dynamometer Location* | |
| Right | |
| Left | |
| *Dynamometer Height* | |
| Right | |
| Left | |
| *Armrest Height* | |
| Right | |
| Left | |
| *Attachment Length* | |
| Right | |
| Left | |
| *Towards Angle* | |
| Right | |
| Left | |
| *Away Angle* | |
| Right | |
| Left | |
| **Total ROM** | |
| Right | |
| Left | |

| | |
|---|---|
| **Wrist Flexion/Extension** | |
| **Target ROM** | -45 to 45 degrees |
| **Dynamometer** | 0 degrees |
| **Dynamometer Tilt** | 0 degrees |
| **Seat Angle** | 0 degrees |
| **System Measurements** | |
| *Seat Height* | |
| Right | |
| Left | |
| *Back Rest Setting* | |
| Right | |
| Left | |
| *Chair Location* | |
| Right | |
| Left | |
| *Dynamometer Location* | |
| Right | |
| Left | |
| *Dynamometer Height* | |
| Right | |
| Left | |
| *Armrest Height* | |
| Right | |
| Left | |
| *Attachment Length* | |
| Right | |
| Left | |
| *Towards Angle* | |
| Right | |
| Left | |
| *Away Angle* | |
| Right | |
| Left | |
| **Total ROM** | |
| Right | |
| Left | |

| Forearm Pronation/Supination | |
|---|---|
| **Target ROM** | -80 to 80 degrees |
| **Dynamometer** | 0 degrees |
| **Dynamometer Tilt** | -5 degrees |
| **Seat Angle** | 90 degrees |
| **System Measurements** | |
| *Seat Height* | |
| Right | |
| Left | |
| *Back Rest Setting* | |
| Right | |
| Left | |
| *Chair Location* | |
| Right | |
| Left | |
| *Dynamometer Location* | |
| Right | |
| Left | |
| *Dynamometer Height* | |
| Right | |
| Left | |
| *Armrest Height* | |
| Right | |
| Left | |
| *Attachment Length* | |
| Right | |
| Left | |
| *Towards Angle* | |
| Right | |
| Left | |
| *Away Angle* | |
| Right | |
| Left | |
| **Total ROM** | |
| Right | |
| Left | |

## Appendix D Operational Definitions of Proper Form for Study Exercises

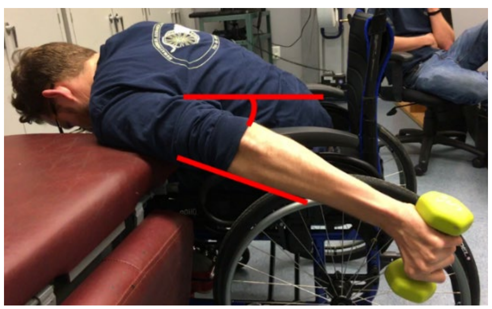
For each of the exercises completed during the in-home training session, the trainer made sure participants were using proper form. Each exercise was held in an isometric hold. When participants form began to break down, they were cued to get back to proper form. If they were unable to do so, the exercise was stopped. For practicality, was difficult to measure exactly how much a participants form had to break prior to stopping the exercise. Without measuring the angle that their arm was at, a visual depiction was needed to make that determination. The following table shows the proper form for each of the exercises that were completed in the study and the visual depiction of the point in which the exercise was stopped. This material was to the training sessions as a guide for the trainer as well as reference for the participant.

For certain exercises, participants were not able to maintain proper form for bicep curls and bent over rows as they are typically performed in a seated position. Some participants would rest their elbow on their leg, wheelchair frame of wheelchair tire during the biceps curl. Even after cuing, they would return their elbow to a supported position. Additionally, some participants were unable to achieve the proper shoulder position for bent over rows, either due to lack of shoulder mobility, wheelchair setup, trunk stability or a combination of those listed and other factors. For these participants, alternative positions were used. Bent over rows was completed in a prone position on the mat table. This was option for participants that were comfortable laying in that position. Additionally, biceps curls were performed with the elbow on the mat table. The alternative positions, and the proper form that was the standard for these positions can be seen in table 2.

**Table 33. Visual depiction of proper form and breaking point for each exercise completed during the in-home training sessions**

| | Proper Form | Point at which form breaks down and the exercise is stopped | |
|---|---|---|---|
| **Side Flies** |  |  Arm dropped too far below parallel | |
| **Front Raises** |  |  Arm dropped too far below parallel | |

| | | | |
|---|---|---|---|
| **Bicep Curls** |  |  Elbow resting on the tire | |
| **Straight Arm Row** |  |  Arm dropped too far below parallel | |

| | | | |
|---|---|---|---|
| **Bent over rows** |  | <br>Arm dropped too far below parallel | |
| **Triceps Extension** |  | <br>Elbow is not straight and arm dropped below parallel too far | |

| | | | |
|---|---|---|---|
| **Serratus Punch** |  | <br>Shoulder is on the mat table | |
| **Butterflies** |  | <br>Arm is parallel witht the ground | <br>Angle from the horizontal is too large |

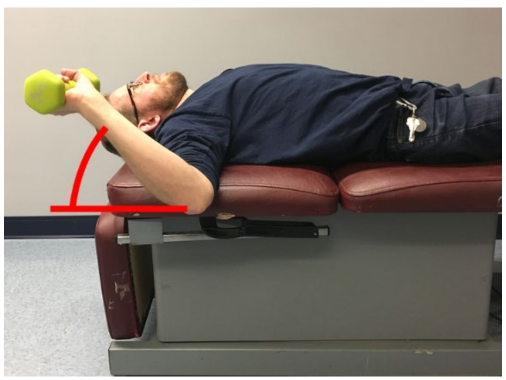
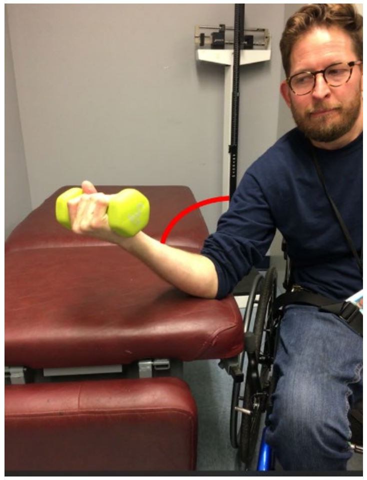
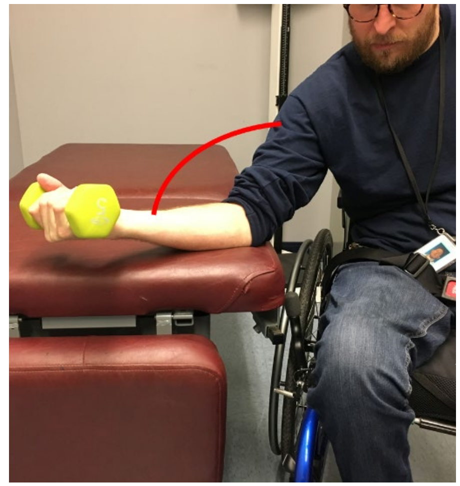
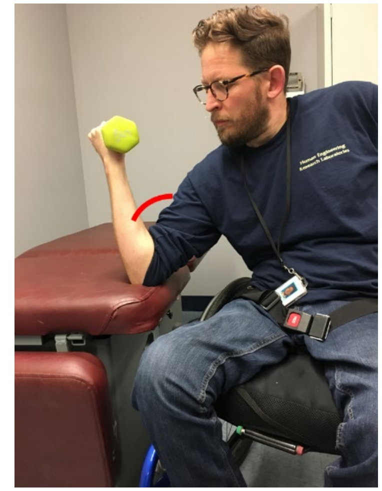
| | | | |
|---|---|---|---|
| **Internal Rotation** |  | <br>Too much internal rotation | <br>Too little internal rotation |
| **External Rotation** |  | <br>Too much external rotation | <br>Too little external rotation |

**Table 34. Visual depiction of proper form and breaking point for the alternative positions for bicep curls and bent over rows**

| | Proper Form | Point at which form breaks down and the exercise is stopped | |
|---|---|---|---|
| **Bicep Curls** |  |  Elbow angle is too large |  Elbow angle is too small |
| **Bent Over Rows** |  |  Arm dropped too far below parallel | |

## Appendix E Trunk Stabilization Strategies

Trunk stabilization was important for the successful completion of the exercises. For the exercise where the dumbbell was held away from the body, stabilizing the trunk was necessary to not compromise the shoulder. For participants who wanted to wear a belt or strap to stabilize their trunk for the exercises one was provided to them if their wheelchair set up was accommodating of its use. For those who did not want to use a belt/strap, or their wheelchair did not accommodate one, other strategies were used.

For side flies and front raises, two exercises that required the participant to be upright, strategies included using the opposite hand that was being trained as a brace on the opposing wheel or the wheelchair frame. Some participants also found it more comfortable to use their other hand to balance on their lap. Additionally, for front raises, participants found that moving forward in their chair and bracing their back on the backrest was helpful for stabilizing. Also depending on the participants wheelchair configuration, participants who had side guards or arms rests were able to use those for stabilization. Many participants used a combination of the strategies or used different ones until they found one that suited them. Figures 31 shows stabilizing options for the side flies and figure 32 shows stabilizing options for front raises.

**Figure 33. (left) Using the opposite hand to brace on the armrest to stabilize the trunk during side flies, (right) Using the opposite hand on the wheel to stabilize the trunk during side flies**

**Figure 34. (left) Using the opposite hand to brace on the lab for trunk stabilization during front raises, (middle) Using the opposite hand on the wheel to stabilize the trunk during front raises, (right) bringing the backside forward and leaning back against the backrest during front raises**

Like front raises and side flies, the opposite hand was used on the wheel or the armrest for bicep curls. If the wheelchair didn't have arms rests, participants also used side guards in their place. Figure 33 depicts how those strategies were accomplished for bicep curls.

**Figure 35. (left) Using the opposite hand to brace on the wheel to stabilize the trunk during bicep curls, (right) Using the opposite hand on the armrest to stabilize the trunk during bicep curls**

The main strategy used for straight arms rows was to use their opposite hand on their lap to stabilize. This exercise required trunk flexion, making the lap a comfortable position to stabilize on. Stabilizing on the arms rests and side guards was also an option for this exercise, however, most of the participants did not chose this option. Lastly, some participants used the front of their wheelchair frame to stabilize. Bracing on their lap or the front of the wheelchair frame were the two most popular strategies and can be seen below in figure 34.

**Figure 36. (left) Using the opposite hand to brace on the lap to stabilize the trunk during straight arm rows, (right) Using the opposite hand on the side guard to stabilize the trunk during straight arm rows**

For bent over rows, the same position for stabilizing as straight arm rows was used. Due to the nature of the exercise, most participants found supporting themselves on their lap was the most comfortable. Figure 35 shows what this strategy looks like for bent over rows.

**Figure 37. Using the opposite hand to brace on the lap to stabilize the trunk during bent over rows**

Lastly, for the exercises that were completed on the mat table in the supine position including serratus punches, butterflies and internal/external rotation, the primary means of stabilization was to hold onto the opposite side of the mat table. Figure 36 give examples for two of the exercises how the participant stabilized for the mat table exercises.

**Figure 38. (left) Using the opposite hand to brace on the lap to stabilize the trunk during straight arm rows, (right) Using the opposite hand on the side guard to stabilize the trunk during straight arm rows**

## Appendix F Weight Progression Plots

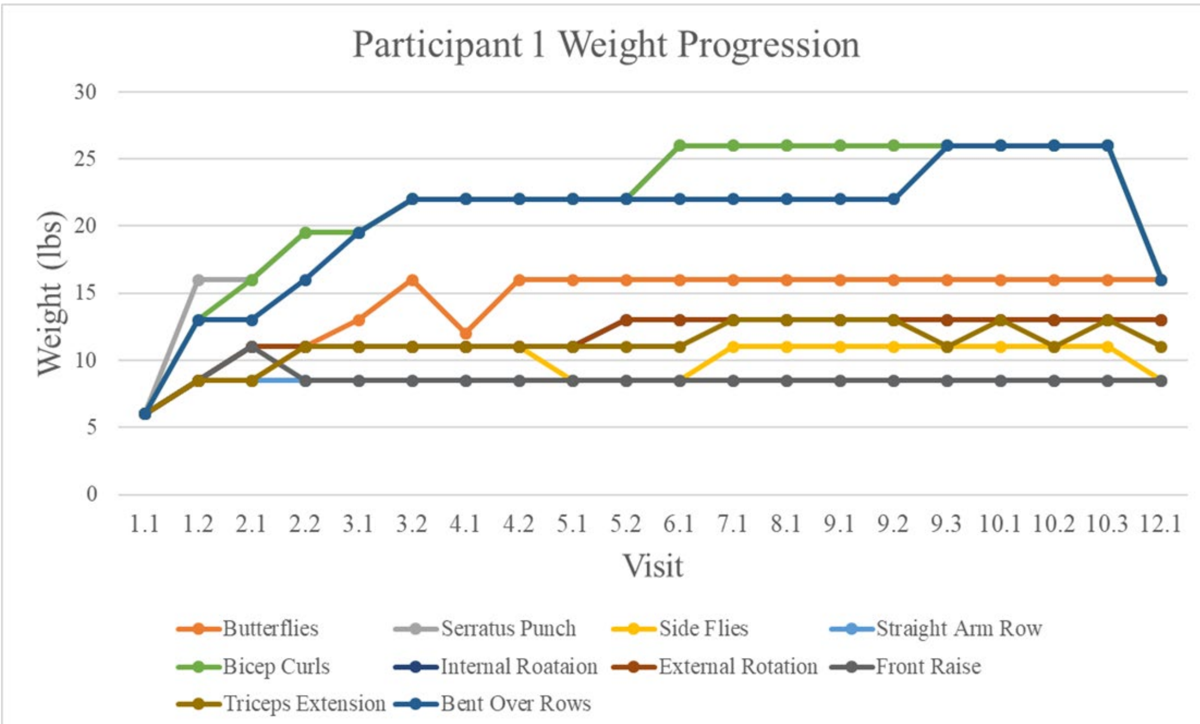



**Figure 39. Participant 1 weight progression throughout 12-week program**

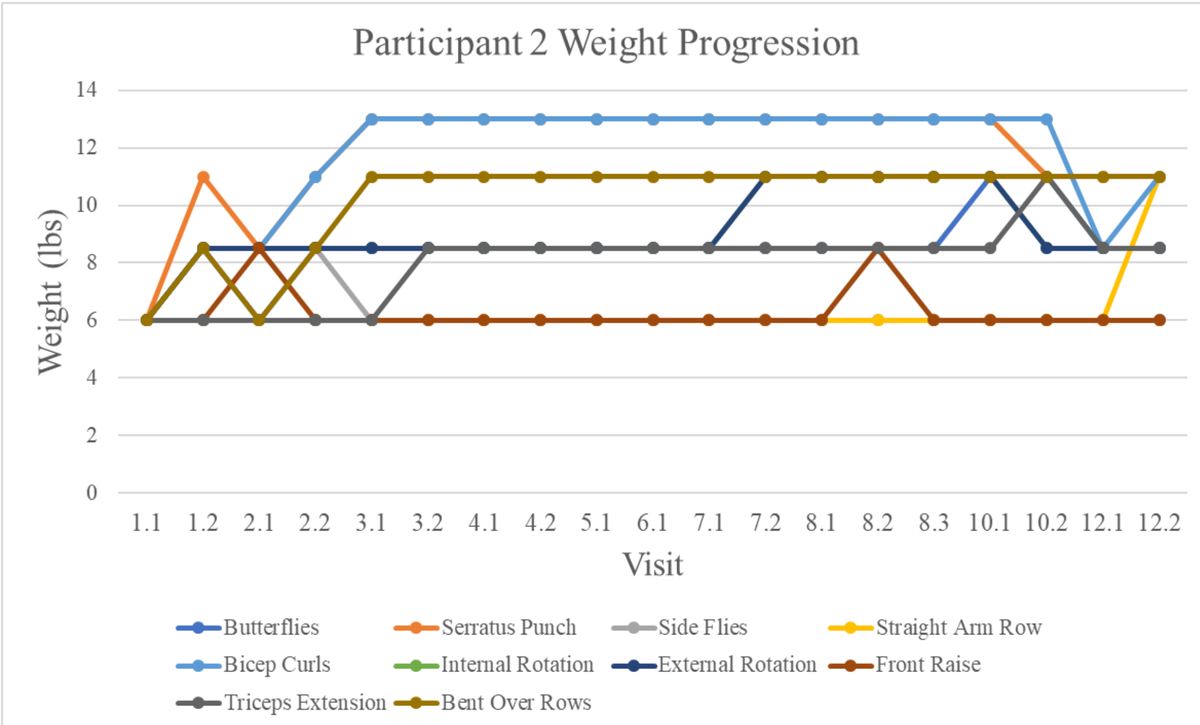



**Figure 40. Participant 2 weight progression throughout 12-week program**

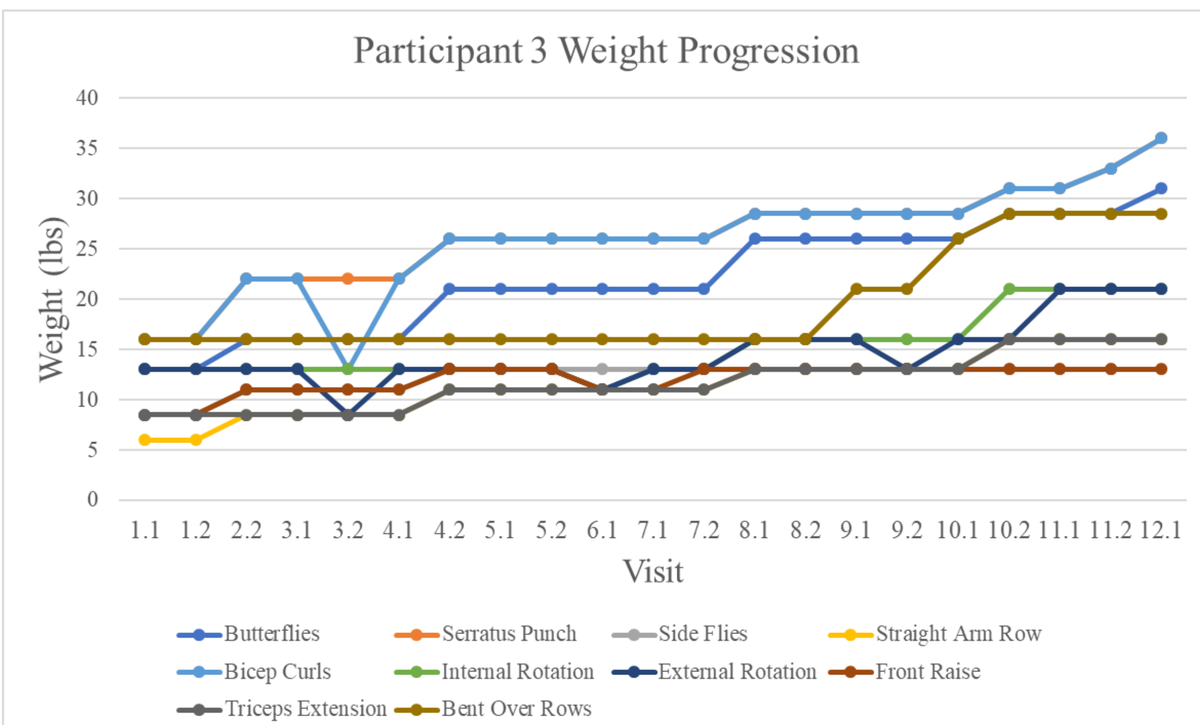



**Figure 41. Participant 3 weight progression throughout 12-week program**

## Appendix G Vibration Exercise Evaluation Form

Exercise Evaluation Form

The following questions relate to the pre-exercise training:

How satisfied are you with the pre-exercise training?

- Very Satisfied
- Somewhat Satisfied
- Neutral
- Somewhat Dissatisfied
- Very Dissatisfied

Do you feel the training was sufficient in preparing you for the exercise intervention?

- The training was sufficient in preparing me for the exercise intervention
- The training was not sufficient preparation for the exercise intervention and additional training or material needs to be made available
- The training was more than sufficient in preparing me for the exercise intervention

Was the length of the training appropriate?

- The length of the training was appropriate
- The training was too long
- The training was too short

Was the level of detail of the training appropriate?

- The level of detail was appropriate in preparing me for the exercise intervention
- The training was too vague and did not provide enough information
- The training was overly detailed and provided extra information that wasn't needed for the exercise intervention

Is there anything else about the training that can be improved?

______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________
_________________________________________________

<u>The following questions are about the exercise intervention:</u>

How satisfied are you with the exercise portion of the study?

- Very Satisfied
- Somewhat Satisfied
- Neutral
- Somewhat Dissatisfied
- Very Dissatisfied

Was the length of time for the warm-up phase appropriate?

- The length of the warm-up phase was appropriate
- The warn-up phase was too long
- The warm-up phase was too short

Were the stretches performed appropriate for the exercise intervention?

- The stretches were very appropriate for the exercise intervention
- The stretches were somewhat appropriate for the exercise intervention
- Neutral
- The stretches were somewhat inappropriate for the exercise intervention
- The stretches were very inappropriate for the exercise intervention

Were you sufficiently warmed up after the stretching phase?

- I was warmed up sufficiently enough to complete the exercise intervention
- I was warmed up sufficiently, but additional warm up would have been helpful
- I was not sufficiently warmed up to complete the exercise intervention
- Additional warm up was needed prior to starting the exercise intervention

Is there anything else about the stretching and warm up phase that you would change?

______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________
______________________________________________________________________________
_______________________________________________

<u>Rate the exercise portion of the study</u>

Rate you overall experience with the exercise intervention

- Very Satisfied
- Somewhat Satisfied
- Neutral
- Somewhat Dissatisfied
- Very Dissatisfied

Was the length of the total 12-week exercise intervention appropriate?

- The length of the exercise intervention was appropriate
- The exercise intervention was too long
- The exercise intervention was too short

Was the length of each home exercise session appropriate?

- The length of the home session was appropriate
- The home session was too long
- The home session was too short

Rate your overall difficulty level in performing the exercises:

- The exercises were very easy to perform
- The exercises were moderately easy to perform
- Neutral
- The exercises were moderately difficult to perform
- The exercises were very difficult to perform

Rate your overall experience exercising in the home

- Very Satisfied
- Somewhat Satisfied
- Neutral
- Somewhat Dissatisfied
- Very Dissatisfied

Rate your experience exercising while seated in your wheelchair

- Very Satisfied
- Somewhat Satisfied
- Neutral
- Somewhat Dissatisfied
- Very Dissatisfied

Is there anything that you would change about the exercise portion of the study?
_____________________________________________________________________________________________________________________________________________________________________________________________________________________________________________________________________________________________________

<u>Vibration Exercise</u>
Please rate your experience using vibration as an exercise modality

Rate you overall experience with vibration as an exercise modality

- Very Satisfied
- Somewhat Satisfied
- Neutral
- Somewhat Dissatisfied
- Very Dissatisfied

Rate your overall comfort level using the vibration for exercise

- Very Comfortable
- Somewhat Comfortable
- Neutral
- Somewhat Uncomfortable
- Very Uncomfortable

Rate the ease of use of the vibrating dumbbell

- Very Easy
- Somewhat Easy
- Neutral
- Somewhat Difficult
- Very Difficult

Have you seen a difference in your strength from the use of vibration exercise since the start of the exercise intervention?

- Large increase in strength
- Small increase in strength
- No change in strength
- Small decrease in strength
- Large decrease in strength

Have you seen a change in your wheelchair propulsion since the beginning of the exercise intervention?

- Large improvement in wheelchair propulsion
- Small improvement in wheelchair propulsion
- No change in wheelchair propulsion
- Small decline in wheelchair propulsion
- Large decline in wheelchair propulsion

Have you seen a change in your transfer ability since the beginning of the exercise intervention?

- Large improvement in transfer ability
- Small improvement in transfer ability
- No change in transfer ability
- Small decline in transfer ability
- Large decline in transfer ability

Have you seen any changes in your overall health since the beginning of the exercise intervention?

- Large improvement in overall health
- Small improvement in overall health
- No change in overall health
- Small decline in overall health
- Large decline in overall health

What is the likelihood that you will use vibration as an exercise modality in the future?

- Very Likely
- Somewhat Likely
- Neutral
- Somewhat Unlikely
- Very Unlikely

What is the likelihood you would recommend vibration exercise to other wheelchair users?

- Very Likely
- Somewhat Likely
- Neutral
- Somewhat Unlikely
- Very Unlikely

Are there any other comments you would like to make about exercising with vibration?

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

____________________________________________________________________________

______________________________________________

# Appendix H Biodex Strength Results Plots

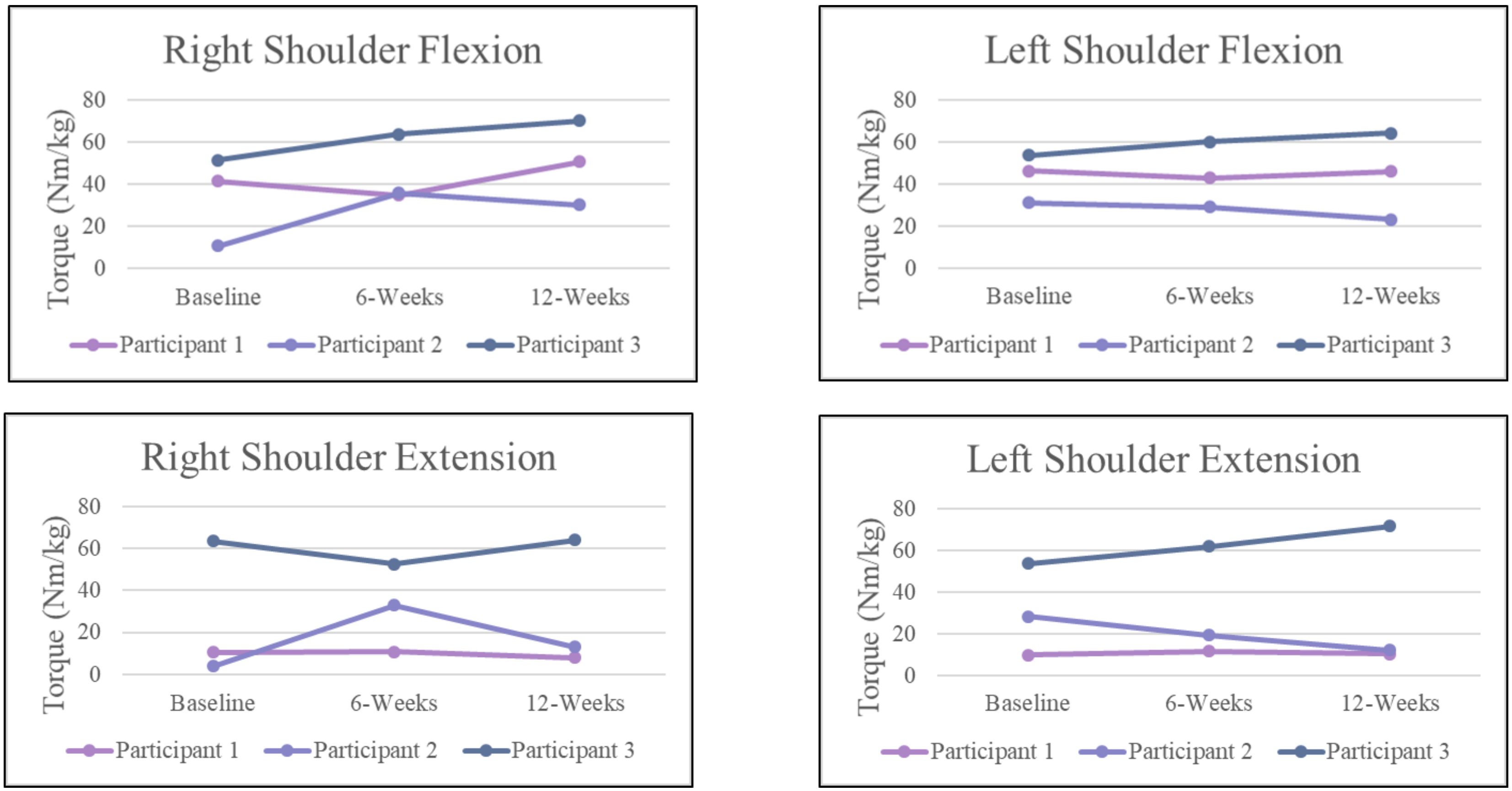



**Figure 42. (top right) Right shoulder flexion results for all participants and timepoints, (top left) Left shoulder flexion results for all participants and timepoints, (bottom left) Right shoulder extension results for all participants and timepoints, (bottom left) Left shoulder extension results for all participants and timepoints**

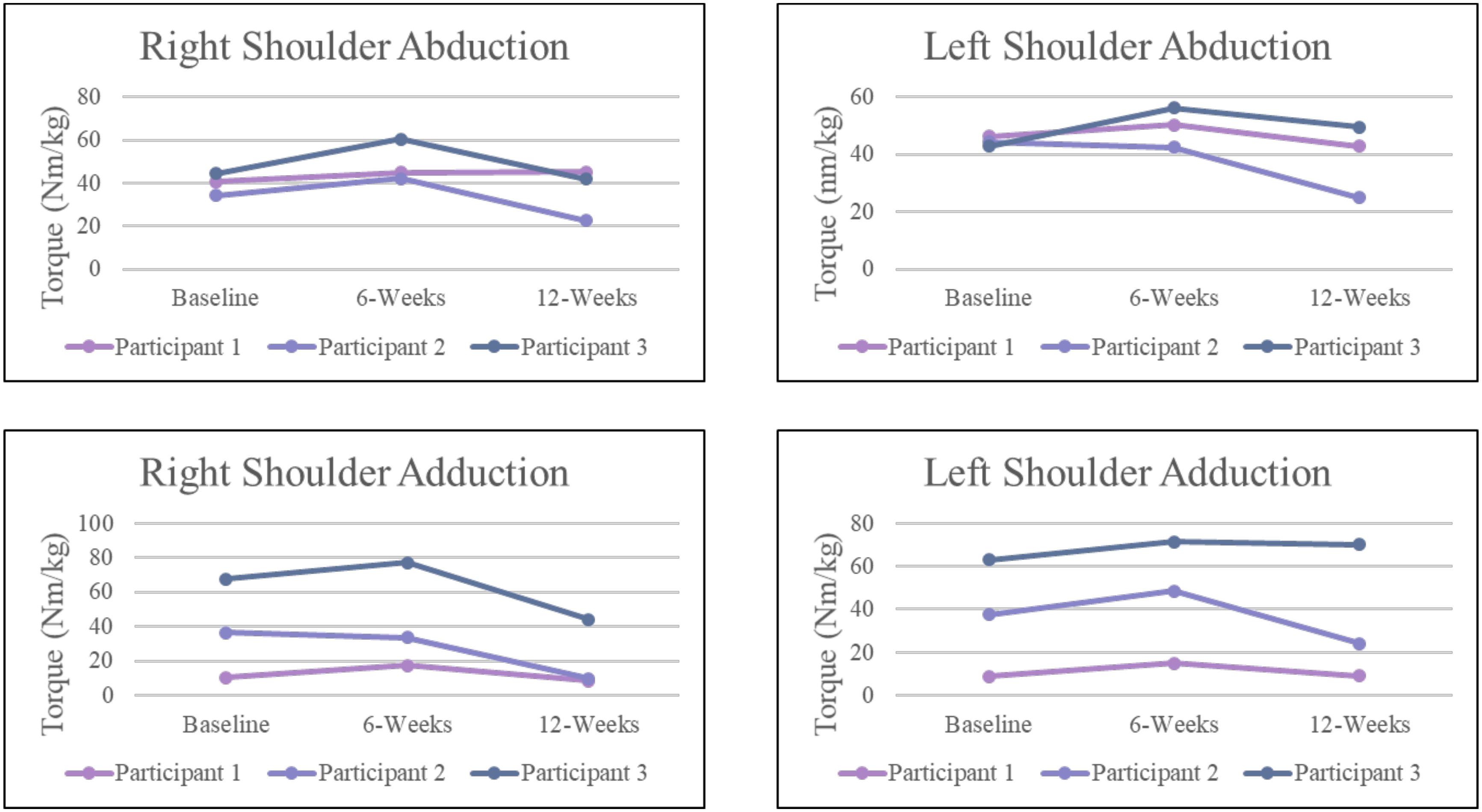



**Figure 43. (top left) Right shoulder abduction results for all participants and timepoints, (top right) Left shoulder abduction results for all participants and timepoints, (bottom left) Right shoulder adduction results for all participants and timepoints, (bottom right) Left shoulder adduction results for all participants and timepoints**

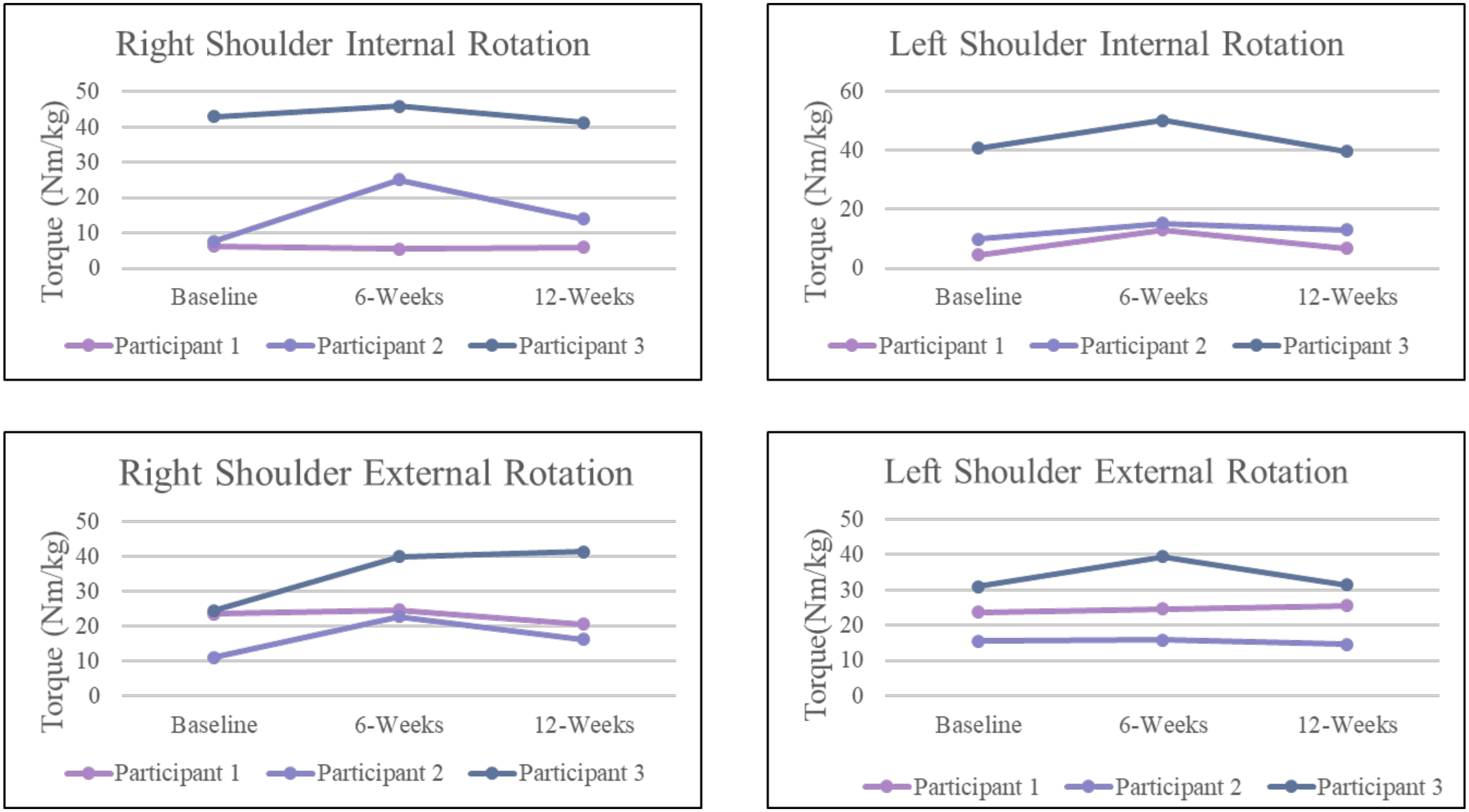



**Figure 44. (top left) Right shoulder internal rotation results for all participants and timepoints, (top right) Left shoulder internal rotation results for all participants and timepoints, (bottom left) Right shoulder external rotation results for all participants and timepoints, (bottom right) Right shoulder external rotation results for all participants and timepoint**

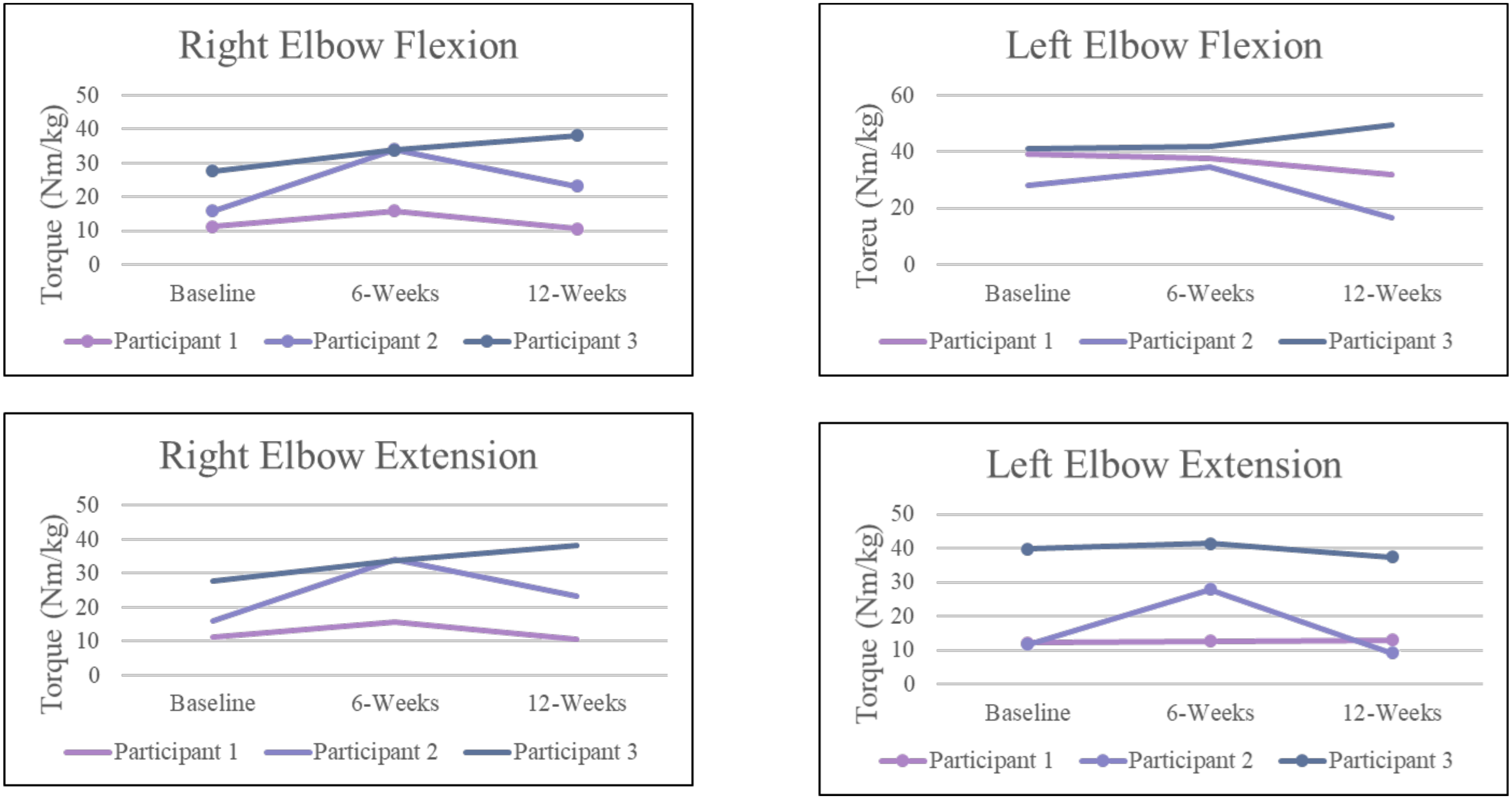



**Figure 45. top left) Right elbow flexion results for all participants and timepoints, (top right) Left elbow flexion results for all participants and timepoints, (bottom left) Right elbow extension results for all participants and timepoints, (bottom right) Left elbow extension results for all participants and timepoints**

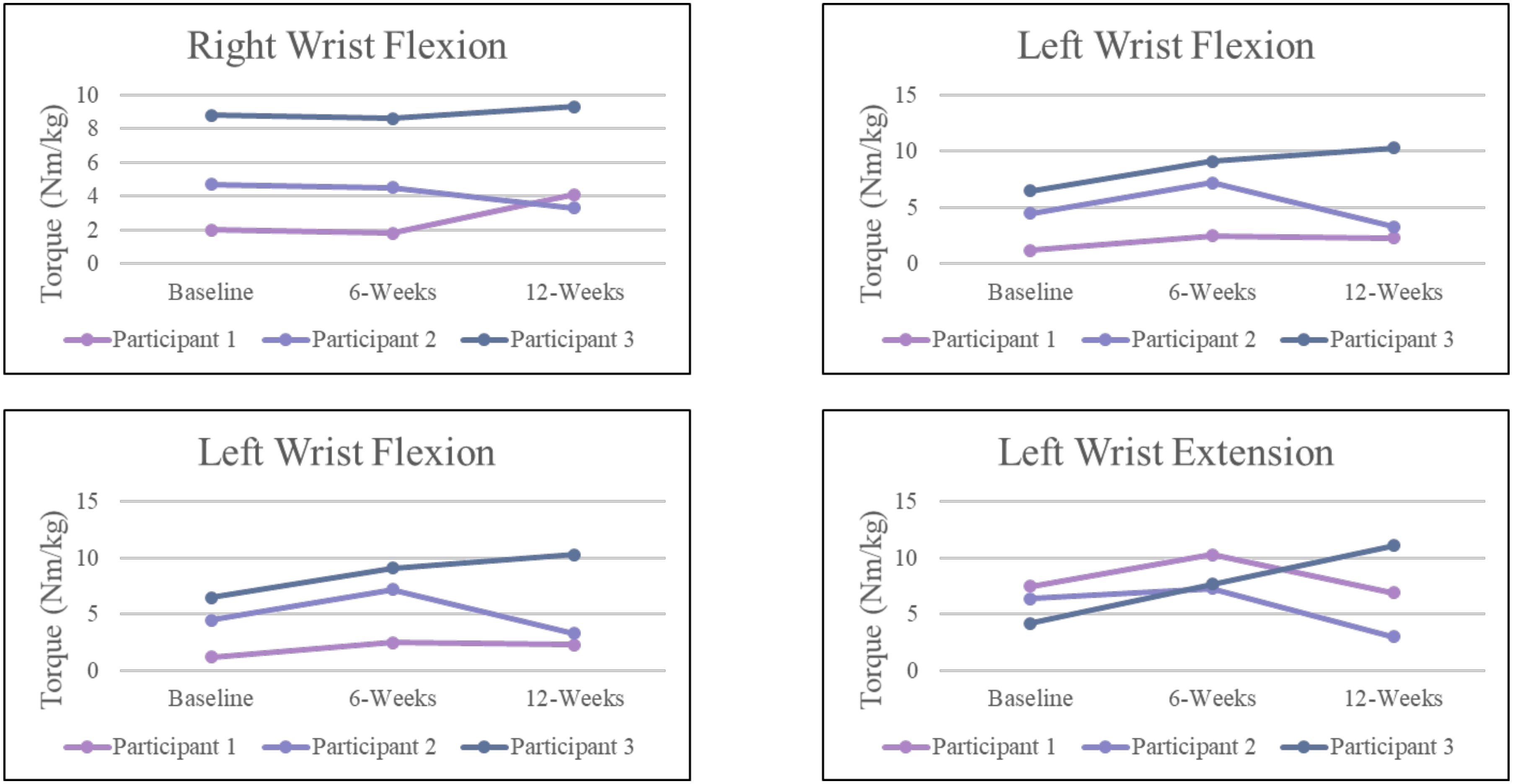



**Figure 46. (top left) Right wrist flexion results for all participants and timepoints, (top right) Right wrist flexion results for all participants and timepoints, (bottom left) Right wrist extension results for all participants and timepoints, (bottom right) Left wrist flexion results for all participants and timepoints**

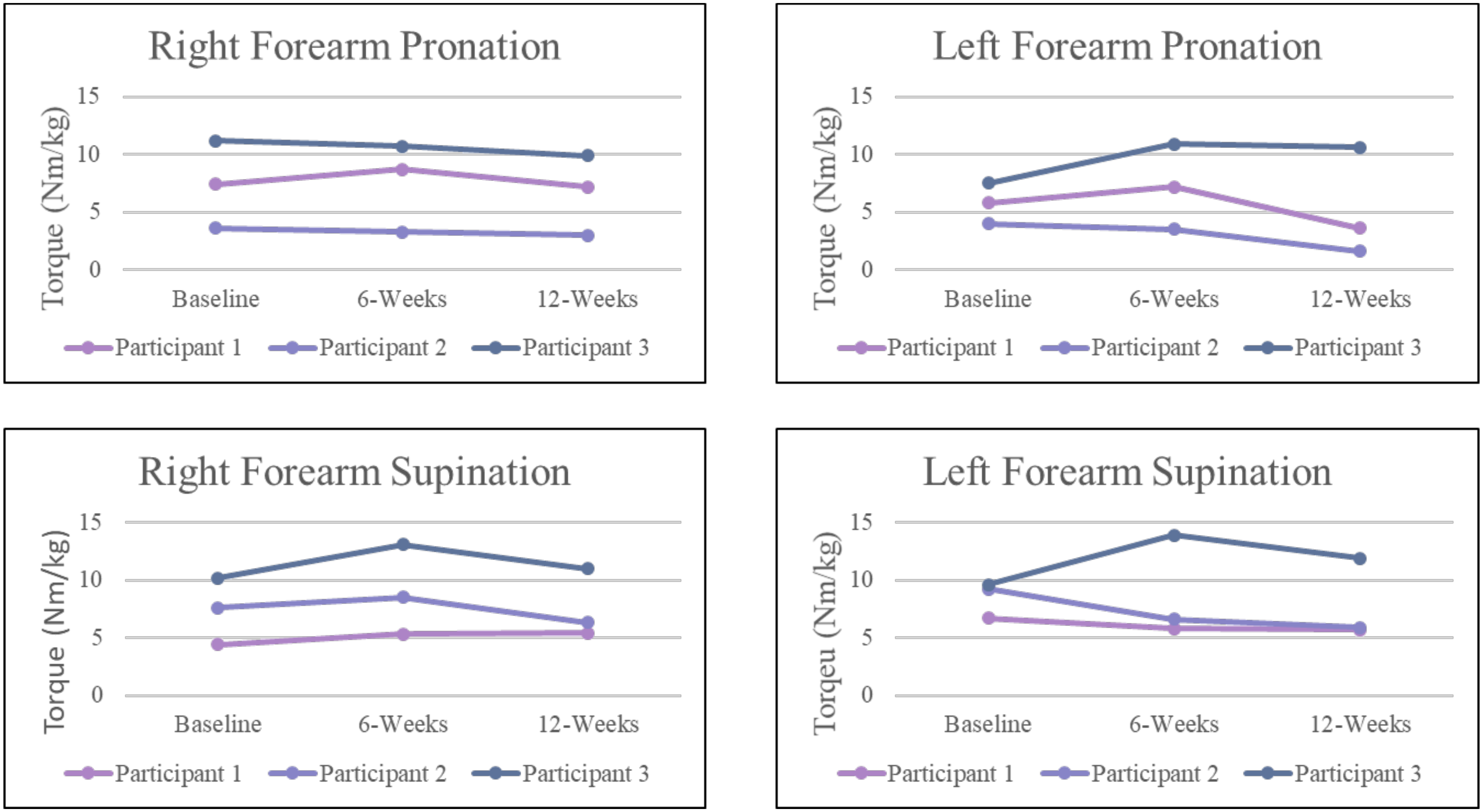



**Figure 47. (top left) Right forearm pronation results for all participants and timepoints, (top right) Left forearm pronation results for all participants and timepoints, (bottom left) Right forearm supination results for all participants and timepoints, (bottom right) Left forearm supination results for all participants and timepoints**

## Appendix I Force and Velocity Data From the SmartWheel for all Three Participants

| | Peak Total Force (MFtot) (N) | | Mean Tangential Force (MFt) (N) | | Mean Effective Force (MEF) | | Average Velocity (AVel) (m/s) | | Maximum Velocity (MVel) (m/s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean (Std) | | Mean (Std) | | Mean (Std) | | Mean (Std) | | Mean (Std) | |
| | Baseline | 12-Weeks | Baseline | 12-Weeks | Baseline | 12-Weeks | Baseline | 12-Weeks | Baseline | 12-Weeks |
| **Level** | | | | | | | | | | |
| Participant 1 | 110.03 (16.3) | 109.88 (11.44) | 61.21 (7.86) | 78.82 (11.36) | .328 (.044) | .510 (.906) | 2.54 (.119) | 1.91 (.356) | 2.60 (.134) | 2.01 (.284) |
| Participant 2 | | 41.20 (5.88) | | 21.81 (4.64) | | .217 (.062) | | 1.43 (.212.) | | 1.52 (.156) |
| Participant 3 | 111.1 (20.5) | 131.38 (6.28) | 86.43 (19.81) | 96.90 (18.01) | .516 (.108) | .463 (.132) | 1.52 (.274) | 1.75 (.289) | 1.616 (.238) | 1.825 (.240) |
| **3 Degrees** | | | | | | | | | | |
| Participant 1 | 153.69 (12.55) | 136.47 (11.38) | 98.45 (8.38) | 90.7 (6.90) | .355 (.0443) | .420 (.079) | 1.82 (.143) | 1.68 (.068) | 1.912 (.123) | 1.790 (.059) |
| Participant 2 | | 58.33 (5.79) | | 25.25 (3.52) | | .186 (.051) | | .942 (.040) | | 1.121 (.049) |
| Participant 3 | 125.99 (17.42) | 127.61 (13.79) | 105.51 (13.54) | 103.49 (13.33) | .713 (.191) | .602 (.183) | 1.09 (.160) | 1.10 (.109) | 1.256 (.104) | 1.227 (.117) |
| **5 Degrees** | | | | | | | | | | |
| Participant 1 | 139.81 (25.26) | 139.25 (11.61) | 102.43 (16.53) | 103.96 (6.93) | .504 (.089) | .487 (.092) | .949 (.195) | .705 (.159) | 1.197 (.286) | 1.106 (.108) |
| Participant 2 | | 71.33 (11.34) | | 30.31 (3.75) | | .139 (.019) | | .305 (.056) | | .488 (.079) |
| Participant 3 | 120.08 (20.11) | 131.79 (26.32) | 107.70 (14.37) | 116.64 (12.66) | .0849 (.171) | .835 (.206) | .481 (.058) | .572 (.572) | .640 (.074) | .726 (.102) |
| **8 Degrees** | | | | | | | | | | |
| Participant 1 | 142.66 (18.72) | 147.57 (11.48) | 103.16 (9.19) | 105.18 (6.53) | .633 (.102) | .628 (.097) | .536 (.273) | .47 (.124) | .808 (.204) | .929 (.244) |
| Participant 2 | | | | | | | | | | |
| Participant 3 | | | | | | | | | | |

## Appendix J Visual Representation of the Propulsion Variables

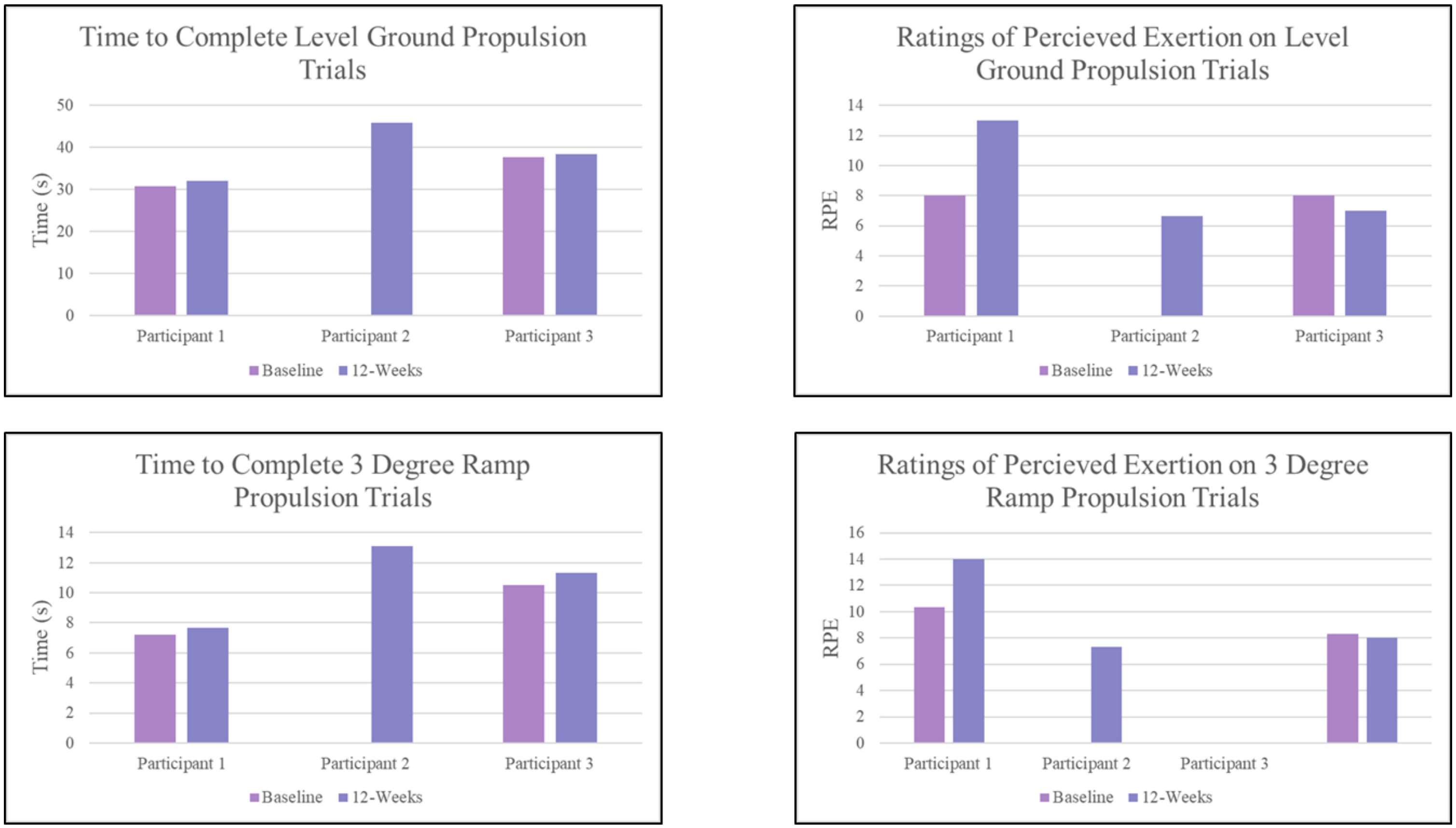



**Figure 48. (top left) Time to complete level ground propulsion trials for all participants timepoints, (top right) Ratings of perceived exertion for level ground propulsion trials for all participants and timepoints, (bottom left) Time to complete 3-degree ramp propulsion trials for all participants timepoints, (bottom right) Ratings of perceived exertion for 3-degree ramp propulsion trials for all participants and timepoints**

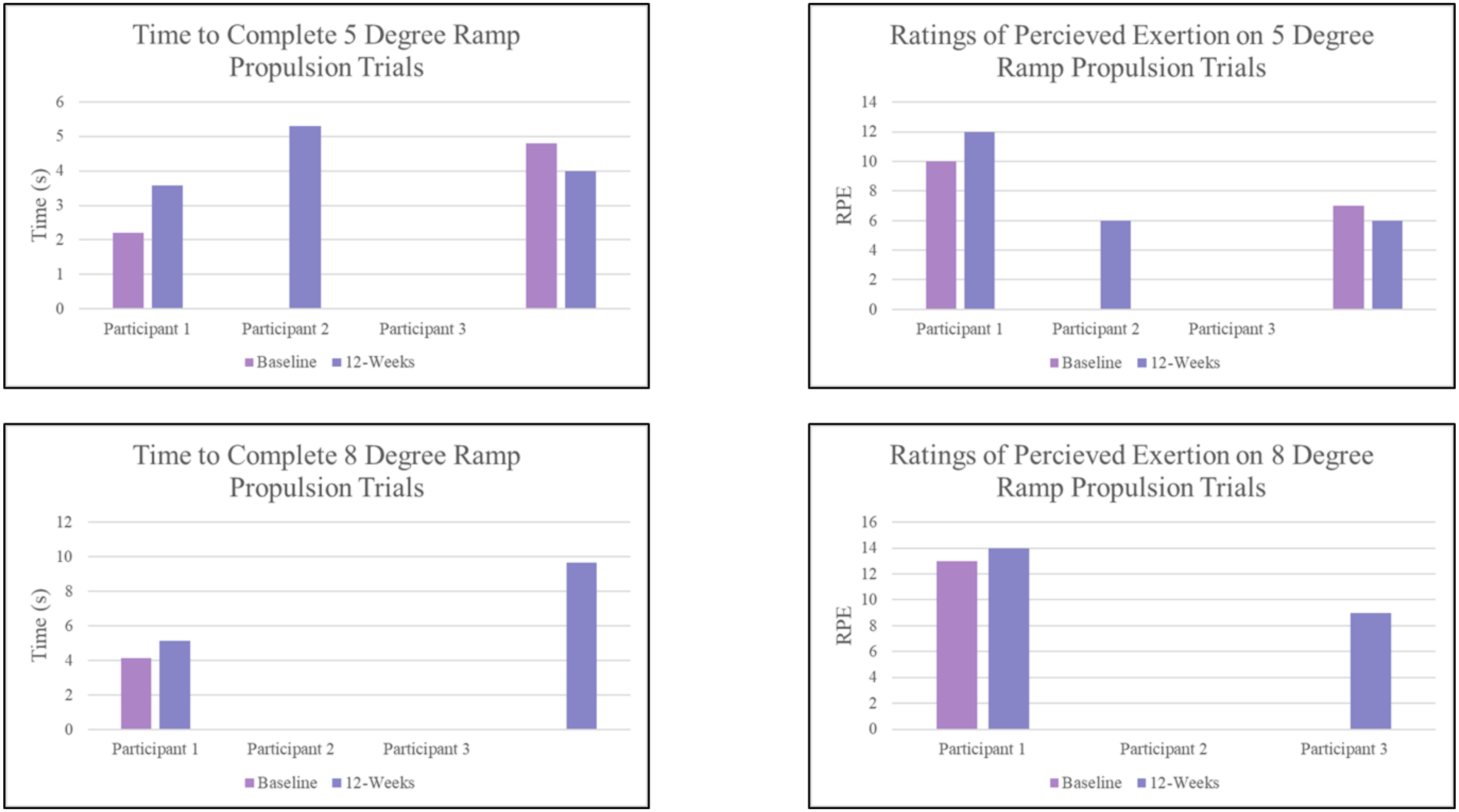



**Figure 49. (top left) Time to complete 5 degree ramp propulsion trials for all participants timepoints, (top right) Ratings of perceived exertion for 5 degree ramp propulsion trials for all participants and timepoints, (bottom left) Time to complete 8 degree ramp propulsion trials for all participants timepoints, (bottom right) Ratings of perceived exertion for 8 degree ramp propulsion trials for all participants and timepoints**

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