NEURAL ADAPTATIONS TO RESISTANCE TRAINING

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ABSTRACT

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Ageing-related alterations in neuromuscular system was the main interest in the current study. Muscle strength decrement may be one of the most evident changes. The impairment in strength through aging may lead to functional impairments, such as falling. In order to prevent functional loss, performing strength training has been reported to be one of the effective ways to preserve or even improve muscular strength. Except for the muscular system, the nervous system may contribute to strength gain as well. The current study aimed to compare the difference in corticospinal excitability and inhibition following resistance training and detraining between young and older adults.

Transcranial magnetic stimulation was the main methodology used and corticospinal tract was the targeted tract in the present study. Accompanied with surface electromyography, right rectus femoris muscle contractions in response to the transcranial stimulation was recorded. Under the same stimulation intensity and condition, the study assessed corticospinal excitability and inhibition mechanism differences following the resistance training and detraining period. In addition, both static and dynamic muscle strength tests were involved as performance indicators following the training and detraining period.

The main findings of the study implied a significant muscle strength change following resistance training and detraining without evident neural adaptations in both young and older adults. The dynamic muscle strength change was more prominent than the change in the static muscle strength in both young and older adults, which may be associated with the training specific effects. Therefore, the study supports the effects of resistance training on both young and older adults.

Keywords: Corticospinal excitability, Cortical silent period, Transcranial magnetic stimulation, Neural adaptation, Resistance training, Aging.

ABBREVIATIONS

CMEP	cervicomedullary motor-evoked potential
CNS	central nervous system
cSP	cortical silent period
CST	corticospinal tract
DCML	dorsal column medial lemniscus
HTS	heavy strength training
HYT	hypertrophy training
ICF	intracortical facilitation
MEP	motor evoked potential
MVC	maximal voluntary isometric contraction
PNS	peripheral nervous system
TMS	transcranial magnetic stimulation
RM	repetition maximum
RF	rectus femoris
sEMG	surface electromyography
SICI	short-interval intracortical inhibition
1 RM	one repetition maximum

CONTENTS

1 INTRODUCTION

Resistance training is one of the recognized methods to improve muscle strength and induce muscle hypertrophy (Bompa, 2009; Schoenfeld et al., 2019). Research has been done to investigate neuromuscular responses to different resistance training modes. For instance, static/isometric training (Nuzzo et al., 2017), and dynamic/isokinetic training (Jensen et al., 2005; Latella et al., 2018). Each training mode owns specific characteristics. Generally, one of purposes of resistance training is to improve muscle strength (Bompa, 2009).

Adaptation is defined as human system responses to environmental stimulation and is believed to be necessary for human beings to survive (Bompa, 2009). Resistance training, as a training stimulus, elicits adaptation in various human body systems and the adaptive effects are suggested to be task specific (Gardiner, 2011; Jensen et al., 2005; Siddique et al., 2020). Muscle strength gain is an example of neuromuscular adaptation to resistance training (Bompa, 2009).

Generally, strength generation is associated with muscle contraction mechanism. The sliding filament theory, muscle fiber types, muscle attachment, architecture and the pennation angle are all crucial contributors to force generation (Enoka, 2015; Houglum & Bertoti, 2012). Following resistance training, muscle adaptation occurs and is reported to be influential to strength gain (Akima et al., 1999; Blazevich et al., 2007).

Apart from the muscular system, the nervous system has a role in strength and movement generation as well (Enoka, 2015; Houglum & Bertoti, 2012). Anatomically, the nervous system is divided into two subsystems: the central nervous system (CNS) and the peripheral nervous system (PNS) (Houglum & Bertoti, 2012; Moore et al., 2014). CNS is composed of the brain, the spinal cord, and all the neurons connecting each other within this area (Houglum & Bertoti, 2012; Moore et al., 2014). PNS includes cranial nerves, afferent sensory nerves, and efferent motor neurons (Houglum & Bertoti, 2012; Moore et al., 2014). Functionally, muscle contraction is caused by the motor commands sent from the primary motor cortex (M1 region) to the PNS, consequently, activating motor units (Houglum & Bertoti, 2012; Moore et al., 2014). With resistance training, muscle strength improvement without significant muscle size increase is observed, which leads to the study of neural adaptation to training stimuli (Moritani & deVries, 1979).

Transcranial magnetic stimulation (TMS) and surface electromyography (sEMG) are the main methodologies to such studies (Enoka, 2015; Zewdie & Kirton, 2016). With different TMS procedures (i.e.: single-pulse and paired-pulse procedure), cortical and intracortical facilitation and inhibition can be measured by motor evoked potential (MEP), cortical silent period (cSP), intracortical facilitation (ICF), short-interval intracortical inhibition (SICI), and so on (Enoka, 2015). In the brain anatomy, the pyramidal cells are situated at the fifth layer of the cortex. The corticospinal tract (CST) is the only descending motor pathway that originates from pyramidal cells to spinal motor neurons, and the connection between pyramidal cells and spinal motor neurons are mono synapses. Pyramidal cells are modulated by excitatory and inhibitory interneurons from other cortical layers. Motor cortical output activated by TMS is an integral effect. It elicits interneurons, activates pyramidal cells, and the corticospinal tract (Komi, 2011). The present study applies TMS to assess neural adaptation to resistance training.

2 NEUROMUSCULAR SYSTEM CONTROL OF VOLUNTARY CONTRACTION

2.1 Nervous system

The nervous system plays an important role in motor control. Motor control includes dynamic postural and movement regulation. It is a result of a complicated neurological, physical, and behavioral process (Houglum & Bertoti, 2012). A well-functioning motor system depends on proper motor control, resulting from a proper coordination of neuromuscular, respiratory, cardiovascular, and digestive systems (Houglum & Bertoti, 2012). In other words, intact cortical motor center, ascending and descending spinal cord transmissions, peripheral nerve, neuromuscular junction, muscle fibers and tendons, Golgi tendon organ, muscle spindles are important (Houglum & Bertoti, 2012). Respiratory, cardiovascular, and digestive systems are necessary as well because they supply energy sources for muscle contraction (Houglum & Bertoti, 2012). One of the main motor outputs is through the corticospinal tract (CST), which originates from the motor cortex (Houglum & Bertoti, 2012; Komi, 2011).

2.1.1 Motor cortex and corticospinal tract

The motor cortex is the highest voluntary movement generation center that manages motor plans (Enoka, 2015). The involvement of primary somatic sensory cortex, primary motor cortex, premotor cortex, supplementary motor area, and parietal cortex are also important for voluntary movement production (Enoka, 2015). Motor command generated at the cortex level and the pyramidal neuron projections descend from the motor cortex to the spinal cord (Enoka, 2015; Houglum & Bertoti, 2012).

The corticospinal tract (CST) originates from pyramidal cells in the fifth layer of the cerebral cortex and over 60% of the tract fibers originate from the primary motor cortex, supplementary motor area, and premotor cortex. The projection fibers descend through the internal capsule, midbrain, pons, medulla, and the spinal cord. This projection tract is known as CST, which is mainly responsible for voluntary movement control (Houglum & Bertoti, 2012). The CST is composed of two tracts with distinct control regions. The anterior CST travels to the peripheral ipsilaterally, terminates at cervical and upper thoracic spinal cord level, and controls trunk muscles (Houglum & Bertoti, 2012). On the other hand, the lateral CST crosses to the opposite side of the nervous system at medulla and propagates the command toward peripheral system

contralaterally. The lateral CST primarily control voluntary movement of contralateral limbs (Houglum & Bertoti, 2012) (FIGURE 1).

CST is believed to be a neural pathway that can precisely control individual muscle groups (Houglum & Bertoti, 2012). Within the tract, upper motor neurons descend action potential from the cortex to the spinal cord, and they synapse with lower motor neurons in the anterior horn gray matter of the spinal cord (Enoka, 2015; Houglum & Bertoti, 2012). Collectively, movement generation, coordination, proper strength production, and even motor plan execution is highly relied on the proper functioning of primary motor cortex and the CST (Enoka, 2015).

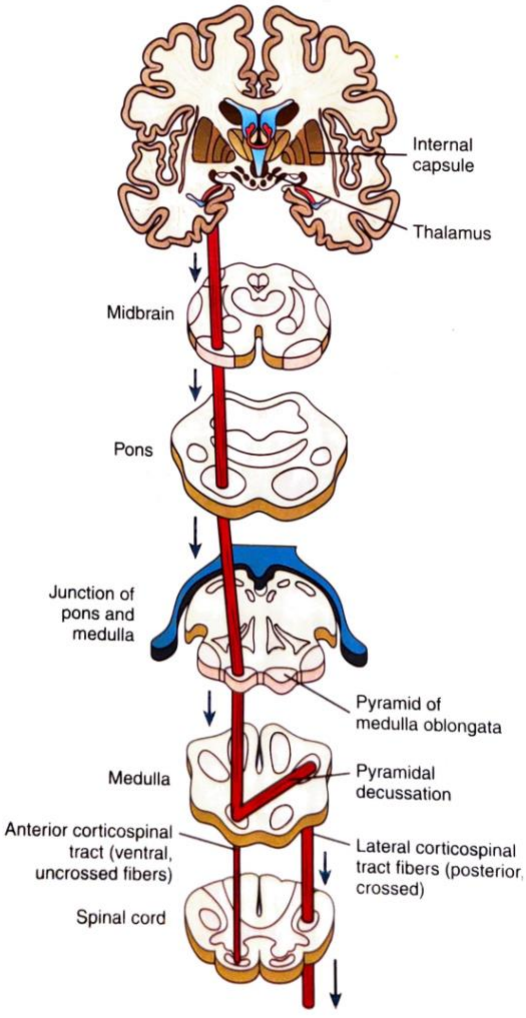


FIGURE 1. Corticospinal tract (Houglum & Bertoti, 2012).

2.1.2 Sensory feedback

Regardless of motor output through CST, sensory feedback has a determinant role in motor function. Through dorsal root, sensory information enters spinal dorsal horn, and the sensory neuron innervates motor neurons directly to form a reflex route or ascend ipsilaterally in dorsal column medial lemniscus (DCML) tract (Houglum & Bertoti, 2012). The tract crosses to the opposite side of the nervous system at the medulla, then the sensory information is sent through thalamus and terminates at primary sensory cortex. The sensory cortex syncs the sensory feedback and command the motor cortex to respond (Houglum & Bertoti, 2012) (FIGURE 2).

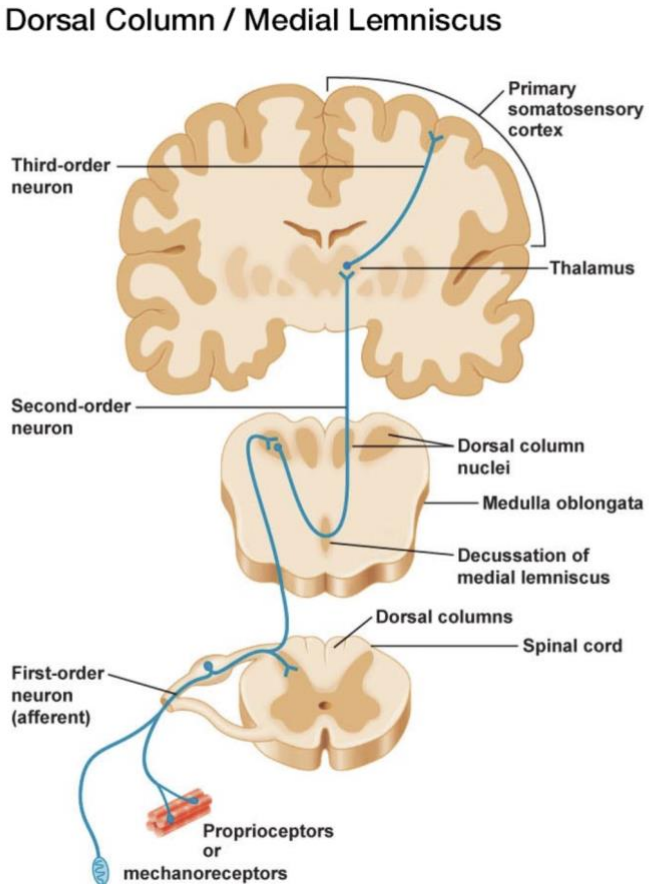


FIGURE 2. Dorsal column medial lemniscus tract (Houglum & Bertoti, 2012).

2.1.3 Motor unit behaviour

Except for the CNS, PNS and undamaged neuromuscular system play important roles in muscle contraction and motor output (Gardiner, 2011; Houglum & Bertoti, 2012). Motor neurons receive descending potential from supraspinal levels, through to alpha-motoneurons, and the potential activates all innervated muscle fibers, leading to muscle contraction (Enoka, 2015; Gardiner, 2011). Therefore, the motor unit, a functional unit of muscle contraction, is defined as a motor neuron and all the muscle fibers that it innervates, contributing to muscle contractions. Motor unit behavior is influenced by central neuronal drive, subsequently, having impacts on muscle strength generation (Enoka, 2015; Gardiner, 2011; Houglum & Bertoti, 2012; Moore et al., 2014). Motor unit behavior generally follows the size principle, and the recruitment and firing rate are two aspects associated with muscle force generation (Enoka, 2015; Gardiner, 2011; Houglum & Bertoti, 2012).

The size principle was first introduced by Henneman (Enoka, 2015; Gardiner, 2011). Stretch reflex of a decerebrated cat experiment was performed. During the experiment, motoneuron action potential were elicited by muscle stretching. Action potential was recorded in the ventral root (Gardiner, 2011). As the increase of the stretch amplitude, an increased action potential amplitude was observed. Larger action potential size implies that larger neurons are recruited (Enoka, 2015; Gardiner, 2011). In addition, a larger neuron with bigger axon diameter is beneficial to fast transmission speed (Enoka, 2015; Gardiner, 2011). The orderly recruited motoneuron phenomenon is known as Henneman's size principle (Enoka, 2015; Gardiner, 2011; Houglum & Bertoti, 2012).

Motor unit recruitment follows the principle (Enoka, 2015; Gardiner, 2011; Houglum & Bertoti, 2012). The hillock, located at the initial part of the axon, is the most excitable part of a motoneuron, which sums all the synaptic potential from dendrites and the soma (Gardiner, 2011). As long as the integral potential hits the excitability threshold of a motoneuron, an action potential is formed and propagates along the axon to the next neuron or to muscle fibers. The threshold varies among motoneurons (Gardiner, 2011). It represents a motoneuron's intrinsic property, also known as its excitability. Following the size principle, smaller motoneurons have lower firing threshold, are perceived to be more excitable, and are recruited before larger ones (Gardiner, 2011). Moreover, motor units follow the principle as well, and typically, small motor

units (those with fewer muscle fibers per nerve) innervate type I muscle fibers whereas large motor units innervate type II muscle fibers (Houglum & Bertoti, 2012).

Motor unit firing rate is the other factor related to force production. It is reported that the level of motor unit firing rate depends on the descending central drive (Aagaard et al., 2002; Enoka, 2015; Gardiner, 2011; Houglum & Bertoti, 2012). Research had shown a positive relation between input current intensity and motoneuron firing rate (Gardiner, 2011). It is suggested that the small motor units have lower firing rates whereas the larger ones show higher rates. Hence, force production per small motor unit is lesser than per large units. In other words, compared to larger motor units, more small motor units that have lower thresholds and firing rates are required to be activated to reach a given force level (Houglum & Bertoti, 2012). If smaller ones could not reach a specific force level, larger ones, having higher recruitment thresholds and firing rates, would be recruited afterwards to help (Gardiner, 2011; Houglum & Bertoti, 2012). Collectively, muscle force production is subjected to both motor unit recruitment and firing rate. Moreover, motor units follow the size principle.

2.2 Muscular system

In addition to the nervous system, the muscular system is related to muscle strength generation as well. Anatomically, the smallest unit of a muscle fiber is a sarcomere (Enoka, 2015; Houglum & Bertoti, 2012). A sarcomere is composed of thick and thin filaments, which slide through each other, leading to muscle contraction. This is known as the sliding filament theory (Enoka, 2015; Houglum & Bertoti, 2012). (FIGURE 3)

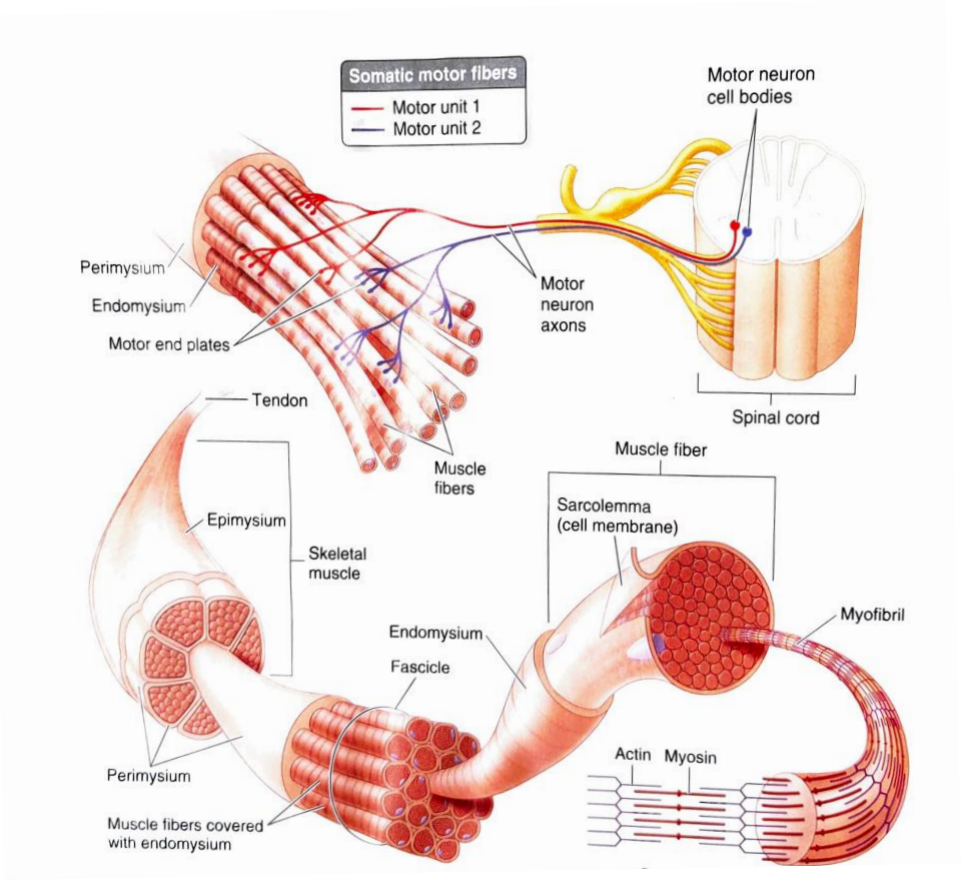


FIGURE 3. Muscle anatomy (Houglum & Bertoti, 2012).

Three muscle types are involved in the muscular system: skeletal muscle, cardiac striated muscle, and smooth muscle (Moore et al., 2014). Skeletal muscle is essential to human motor function (Moore et al., 2014), and it is composed of contractile and noncontractile portion. The contractile portion mainly contains skeletal striated muscle. In a more microscopic way, the myofilaments. On the other hand, the noncontractile portion is mostly comprised of collagen bundles, such as tendon, aponeuroses, and cytoskeleton (Enoka, 2015; Moore et al., 2014). The contractile structure is described as the active component while the noncontractile structure is the passive component (Moore et al., 2014). Both components contribute to voluntary movement and muscle strength production (Moore et al., 2014).

Muscle contraction produces muscle force and segmental movement. In terms of contraction, skeletal muscle function is based on two anatomical aspects: muscle fiber types and muscle attachment (Houglum & Bertoti, 2012; Moore et al., 2014). Muscle fiber types are categorized

mainly into two: type I (slow-twitch) and type II (fast-twitch) fibers (Enoka, 2015; Houglum & Bertoti, 2012). Muscle attachment provides information to describe a specific muscle and movement (Houglum & Bertoti, 2012). Consequently, contraction type can be put into isometric, isotonic, and isokinetic contraction (Enoka, 2015; Houglum & Bertoti, 2012). Furthermore, muscle size is one of the important factors for muscle force. (Bompa, 2009; Houglum & Bertoti, 2012; Moore et al., 2014).

2.2.1 Muscle fiber types

Type I and type II muscle fiber are two main fiber types (Bompa, 2009; Houglum & Bertoti, 2012; Moore et al., 2014). With distinct physiologically features, they respond differently to training stimulations. Plus, different types of muscle fibers are targeted with distinct training modes (Bompa, 2009; Houglum & Bertoti, 2012; Moore et al., 2014). Type I muscle fibers are the slow twitch fibers, which contains a greater number of mitochondria and myoglobin (Houglum & Bertoti, 2012). Therefore, they are thought to have higher oxygen consumption rates (Bompa, 2009). Type II muscle fibers contain less mitochondria and myoglobin, which is known as the fast twitch fibers (Houglum & Bertoti, 2012). Morphologically, muscle fiber type and their composition influence muscle strength output (Bompa, 2009). The composition of fiber types is believed to be associated with an athlete's maximal muscular strength and power production (Bompa, 2009; Hall et al., 2021). It is suggested that athletes with greater type I fiber percentage perform better in prolonged exercises whereas those with more type II composition have better ability in power production (Hall et al., 2021).

2.2.2 Muscle attachment and architecture

In order to precisely describe a movement caused by muscle contraction, knowing muscle attachment and its architecture is crucial. The proximal attachment is known as the origin of a muscle while the distal attachment is the insertion (Houglum & Bertoti, 2012; Moore et al., 2014). The action of a muscle (either the distal attachment moving toward a fixed proximal one, or reversely) determine its functional activity, which is characterized by different contraction types (Houglum & Bertoti, 2012). Typically, isotonic contraction (includes concentric and eccentric contraction), isometric contraction, and isokinetic contraction are three contraction types (Houglum & Bertoti, 2012).

Isotonic contraction refers to muscle length changes while the external load remains constant (Enoka, 2015; Houglum & Bertoti, 2012; Moore et al., 2014). Traditionally, force-velocity relationship of a muscle was measured with isotonic contraction. Scientists detached one end of the muscle and attached it to a load (Enoka, 2015). Then, stimulations were given to evoke muscle contraction, with the maximal contraction force and velocity being measured (Enoka, 2015). Muscle length changes in isotonic contraction can either be lengthening or shortening, which is termed as eccentric and concentric contraction separately (Enoka, 2015; Houglum & Bertoti, 2012; Moore et al., 2014). For example, as the proximal attachment of biceps brachii is fixed, the muscle shortens while bringing the distal segment toward proximal part, resulting in a concentric contraction (Houglum & Bertoti, 2012). Contrarily, under the same circumstance but the muscle elongates and brings the distal segment away from the proximal part, leading to an eccentric contraction (Houglum & Bertoti, 2012).

Other than isotonic contraction, an isometric contraction occurs when both ends are fixed. The initial isometric contraction causes muscle shortens and tendon elongates. Once the force has been generated, the whole muscle tendon unit length, joint angle, as well as the force level stay constant (Enoka, 2015; Houglum & Bertoti, 2012; Moore et al., 2014). In the experimental setting, maximal voluntary isometric contraction force (MVIC) is commonly used as an outcome measure for isometric contraction performance. In practical context, it could be a method helping patients and athletes improving joint stability by training isometrically contract muscles around or cross a joint (Houglum & Bertoti, 2012).

Isokinetic contraction refers to constant movement rate (Enoka, 2015; Houglum & Bertoti, 2012). It is challenging for humans to produce constant rate contraction without external assistance. In other words, both movement rate and range of motion can be controlled better with devices or external cues (Carroll et al. 2002; Siddique et al., 2020). Therefore, applying a metronome, a potentiometer, or a computer-controlled exoskeleton while an individual is performing isokinetic contraction would favorable (Enoka, 2015; Houglum & Bertoti, 2012).

Functionally, human movement production is contributed by more than one single muscle. It is supposed to be the product of fine coordination of different muscle contraction resulting from: (1) a closed kinetic chain, (2) contraction types, (3) gravity force that impact on distal segment movement, and (4) collaboration of distinct muscles (Houglum & Bertoti, 2012).

2.2.3 Muscle size

Muscle size is determined based on width and length (Houglum & Bertoti, 2012). Muscles with greater width tend to have more fibers arranged in parallel whereas with greater length as fibers align in series (Enoka, 2015; Houglum & Bertoti, 2012). Muscle with greater width has larger cross-sectional area, which is beneficial for producing higher force. Greater contractile speed is, contrarily, observed in longer muscles (Enoka, 2015; Houglum & Bertoti, 2012). Therefore, hypertrophy training aims to increase in contractile protein content, consequently, enlarging muscle width and cross-sectional area, leading to muscle force improvement (Bompa, 2009; Enoka, 2015; Gardiner, 2011; Houglum & Bertoti, 2012). Typically, muscle hypertrophy can be recognized by ultrasound system, magnetic resonance imaging, muscle biopsies, and circumferential measurements (Enoka, 2015; Houglum & Bertoti, 2012; Latella et al., 2012). Converse to hypertrophy, muscle atrophy is characterized by losing contractile protein resulting in the decrease of cross-sectional area of muscle fibers (Enoka, 2015; Houglum & Bertoti, 2012). Plus, pennation angle, defined as the angle between the orientation of the muscle fibers and the long axis of the muscle, is associated with muscle force modulation as well (Enoka, 2015; Gardiner, 2011). The greater the angle, the greater force production (Enoka, 2015).

3 RESISTANCE TRAINING

Muscle strength gain following resistance training has been observed (Nuzzo et al., 2017; Schoenfeld et al., 2019). It is suggested that resistance training leads to evident changes to the contractile machinery, neuromuscular system, and bioenergetic or metabolic pathways (Bompa, 2009). Studies reported that resistance training may benefit subjects by improving MVC (Carroll et al., 2002; Christie & Kamen, 2014; Griffin & Cafarelli, 2007; Kidgell & Pearce, 2010; Latella et al., 2017; Nuzzo et al., 2017), repetition maximum performance (RM, reflects dynamic contraction force) (Latella et al., 2012), or both (Jensen et al., 2005; Tran et al., 2006). Some suggested that the training effect could be task specific. For instance, a significant increase MVC following isometric training whereas 1RM value improves through dynamic contraction were observed (Jensen et al., 2005; Kidgell & Pearce, 2010; Siddique et al., 2020).

3.1 Elements in resistance training

Several elements should be considered for a resistance training program: training volume, intensity, density, and complexity (Bompa, 2009; Gamble, 2012). Training volume refers to a quantified sum of work performed within a given training time (Bompa, 2009). For example, repetition is a parameter to quantify volume and it refers to the amount of an exercise within one single set. Additionally, repetition is related to the percentage of 1RM. The more repetition within a set implies higher training volume (Bompa, 2009). Apart from repetitions, number of sets within a given training period is also influential to training volume. Greater work capacity and endurance can be achieved with greater number of sets. Last, "sets×repetitions×lifted load in kilograms" is a way to present volume load, which is another method to define training volume (Bompa, 2009). However, it has been criticized because it is influenced by the absolute lifted load and is perceived to be too simplified (Ogasawara et al., 2013).

Intensity within a resistant training program is usually quantified in kilograms (kg). Based on the training purposes, various training load can be applied. For example, studies have shown that training with light load, but high repetition is beneficial to endurance improvement. In contrast, a program comprising heavy load and low repetition has shown to be effective in muscle strength enhancement (Anderson & Kearney, 1982; Campos et al., 2002). It had also been reported that muscle hypertrophy could be elicited with different load and repetition

adjustment in a training program. Training with increasing load and fixed repetitions or reversely were suggested to be favourable to improving muscular adaptation (Plotkin et al., 2022)

Training density is associated with frequency which is defined as the repetitions in a series of work per unit of time (Bompa, 2009). For example, a subject trains three times a week has greater training density than the one trains twice per week. Training complexity refers to the extent of difficulty of a biomechanical skill. By adding additional factors to the movement, such as having faster, unstable, and unilateral multi-segment movements involved, will increase the complexity. Increasing training complexity is beneficial to integrated physical fitness component to be trained and to balancing with strength gain (Bompa, 2009; Gamble, 2012).

3.2 Resistance training modes

Various training modes have been discussed, including heavy strength training (HST), hypertrophy training (HYT), isometric/static strength training, and isokinetic/dynamic strength training (Latella et al., 2018; Latella et al., 2017; Nuzzo et al., 2017; Ruotsalainen et al., 2014). Depending on the training purpose, one particular training mode or combined modes could be applied.

Training with high intensity load but lower repetition, HST is beneficial to improve muscle strength. It is recommended to train with a load up to 80% of 1RM with 1-6 reps for HST (American College of Sports Medicine, 2009; Bompa, 2009). HYT refers to a training mode with lower intensity load but greater repetitions, which aims at increasing muscle mass, especially in early training phase (Bompa, 2009). It is suggested to be 67-75% of 1RM with 6-15 repetitions (Bompa, 2009). Additionally, training with lighter load accompanied with greater repetitions in one set is reported to be a viable way to improve muscle endurance (Anderson & Kearney, 1982; Campos et al., 2002).

Isometric resistance training refers to static muscle contraction training. Such training benefits the subject with improved not only static muscle strength but also joint stability (Houglum & Bertoti, 2012). Isokinetic training (Bompa, 2009) requires the subject to perform contraction exercises at a constant angular velocity. Typically, the subject relies on external cues under

such training mode (Siddique et al., 2020). Such training mode has been applied to both athletes and patients with neurological disorder. Horwath et al. (2019) had pinpointed that the combination of isokinetic and eccentric overload is beneficial for young ice hockey players in improving muscle hypertrophy. In addition, isokinetic strength training had been reported to be potentially positive in enhancing motor and functional improvement post-stroke hemiplegia patients (Kerimov et al., 2021).

4 INFLUENCES OF AGING ON NEUROMUSCULAR SYSTEM

Having adequate muscle strength to manage daily life is important. As age advances, the neuromuscular function degrades, including poorer muscular strength and power output (McNeil & Rice, 2007), decreased joint proprioception, leading to poorer postural control and balance, changing gait patterns, having greater fall and injury risks (Toosizadeh et al., 2018).

The nervous system mediates strength output. As observed, aged population shows a decrease in muscle strength (Keller & Engelhardt, 2014). The nervous system is potentially one of the contributors (Kamen and Knight, 2004; Oliviero et al., 2006). To my knowledge, there is a limited amount of research comparing neural influences on muscle force output between young and older adults. Some research observed changes in voluntary activation (Stevens et al., 2003), discharge rate (Kamen & Knight, 2004), motor cortex excitability and inhibitory mechanisms (McGinley et al., 2010; Oliviero et al., 2006), and nerve conduction velocity (Palve & Palve, 2018). Even though the mechanism of nervous system alteration is unclear now, it is suggested that deteriorated nervous system function could be one of the contributors to age-related losses in muscular strength. However, resistance training seems to be effective for older adults to gain muscle strength. Christie & Kamen (2014) investigated neural adaptation to resistance training among the older population by applying TMS. They reported that short-term resistance training results in muscle strength gain in both young and older populations without prominent corticospinal excitability change. But a significant corticospinal inhibition decreased following training was observed in both population groups, suggesting that strength gain and neural adaptation to resistance training occurs in older population as well.

Apart from the neural factors, the reduction in muscle mass is also influential to voluntary muscle strength output. Keller & Engelhardt (2014) concluded that muscle mass and muscle strength decline is associated with aging process. To a certain extend of muscle strength decline, sarcopenia could be diagnosed for older populations. According to European Working Group on Sarcopenia in Older People (EWGSOP) 2018, sarcopenia is a progressive skeletal muscle disorder that is associated with increased likelihood of adverse outcomes including falls, fractures, physical disability, and mortality (Cruz-Jentoft et al., 2019). Therefore, proper strength training will be beneficial to maintain muscle strength, which is thought to be positively influence elder population’s daily life function.

5 NEUROMUSCULAR ADAPTATIONS TO RESISTANCE TRAINING

Adaptation is the mechanism that human body responses to stimuli. In sports context, adaptation occurs when an individual is exposed to training stimuli (Bompa, 2009). Following resistance training, research had suggested that muscle strength enhancement may result from both neural and muscular factors (Bompa, 2009; Gardiner, 2011; Moritani & deVries, 1979). With an observation in evident muscle strength improvement without significant muscle size change, neural adaptation to resistance training has been studied (Akima et al., 1999; Gardiner, 2011; Griffin & Cafarelli, 2007; Latella et al., 2012; Mason et al., 2020).

5.1 Neural adaptations

Neural system modulation in response to training stimuli is known as neural adaptation (Gardiner, 2011). Studies had suggested that neural adaptation is potentially one factor regulating muscle strength in early training phase (around 2-6 weeks) (Akima et al., 1999; Latella et al., 2012; Mason et al., 2020; Moritani & deVries, 1979). In the nervous system, strength improvement is expected to be associated with increased excitability, decreased inhibition, or both, leading to an increased net excitatory drive from the central (Colomer-Poveda et al., 2020; Griffin & Cafarelli, 2007; Kidgell & Pearce, 2010; Latella et al., 2012; Latella et al., 2017; Mason et al., 2020; Mason et al., 2017; Mason et al., 2019; Sale & Semmler, 2005; Siddique et al., 2020). Additionally, neural adaptation may happen at any site within CST, some research explored the sites that contributes the most to adaptation (Carroll et al., 2002; Kidgell & Pearce, 2010; Nuzzo et al., 2017). However, no consensus was confirmed. Carroll et al. (2002) concluded that following an isokinetic resistance training program (3 times per week for 4 weeks), synaptic circuitry in the spinal cord changes its organization instead of having significant changes in the M1 functional properties. Conversely, compared to untrained subjects, Nuzzo et al. (2017) suggested isometric resistance training (three times per week for four weeks) leads to greater voluntary activation with the lack of significant cervicomedullary motor-evoked potentials (CMEPs) changes. Thus, suggesting that voluntary output from M1 increases the ability to excite motor neurons rather than the corticospinal transmission and motoneuron excitability were affected by resistance training.

5.1.1 Neural adaptation research methodology and mechanism

Transcranial magnetic stimulation (TMS) has been a common way to assess CST adaptation following resistance training. With different TMS procedures, not only pathway and circuit identification can be studied, but also measurement and modulation of neural plasticity (Zewdie & Kirton, 2016). Two main procedures are applied to assess excitatory and inhibitory response within CST: single- and paired-pulse stimulation. Single-pulse stimulation is a procedure assessing net corticospinal excitability (motor evoked potential response) (Colomer-Poveda et al., 2020; Latella et al., 2018; Latella et al., 2012; Latella et al., 2017; Mason et al., 2020; Ruotsalainen et al., 2014; Zewdie & Kirton, 2016) and the CST inhibitory outcome, cortical silent period (cSP) (Colomer-Poveda et al., 2020; Latella et al., 2018; Latella et al., 2012; Latella et al., 2017; Ruotsalainen et al., 2014; Zewdie & Kirton, 2016). Paired-pulse stimulation, based on different interstimulus time interval (ISI) (Enoka, 2015; Zewdie & Kirton, 2016), is an assessment procedure for intracortical responses, such as intracortical facilitation (ICF) (Colomer-Poveda et al., 2020; Latella et al., 2018; Latella et al., 2017; Mason et al., 2020; Zewdie & Kirton, 2016) and short- and long-interval intracortical inhibition (SICI and LICI, respectively) (Latella et al., 2018; Latella et al., 2017; Mason et al., 2020; Siddique et al., 2020; Zewdie & Kirton, 2016).

Before carrying out TMS, we need to define a specific stimulation intensity for each subject. The resting motor threshold (rMT) and active motor threshold (aMT) can both be chosen as a reference of stimulation intensity (Zewdie & Kirton, 2016). The rMT is measured without muscle activation whereas the aMT acquires a low level of muscle activation. The rMT is usually defined as the minimum TMS intensity to elicit reproducible MEP responses at least 50μV in about 50% of 5-10 consecutive trials and the aMT is defined as the minimum TMS intensity to elicit repeatable MEP response at least 200μV in about 50% of 5-10 consecutive trials (Zewdie & Kirton, 2016). Since the muscle is under voluntarily active condition when taking aMT, some of the motor units have already been activated, aMT is usually lower than rMT.

With the application of single-pulse procedure, accompanied by sEMG placed on the target muscle, TMS descending volleys can be quantified by the elicited muscle twitch (Enoka, 2015). The resultant EMG response is termed as motor evoked potential (MEP) (Enoka, 2015; Ruotsalainen et al., 2014; Zewdie & Kirton, 2016). The MEP amplitude and latency are two

variables representing the function of upper motor neurons. Following stimulation, the largest positive and negative peak subtracting from EMG signals, peak-to-peak amplitude, is one of the ways to assess MEP whereas the time duration between the stimulation trigger and the start of MEP is the latency (Enoka, 2015). It is suggested that the greater the stimulation intensity, the larger peak-to-peak MEP amplitude (Enoka, 2015). However, peak-to-peak MEP amplitude showed high variability, and research had recommended to increase measurement trials up to 20 trials to get a better reliability (Brownstein et al., 2018; Hashemirad et al., 2017). Currently, some research normalized Peak-to-peak MEP amplitude to M_{max} to improve reliability, which also improves the comparability between studies (Latella et al., 2018; McGinley et al., 2010). In general, MEP response stands for excitatory output from the CST (Zewdie & Kirton, 2016). Greater MEP response following resistance training was reported by several studies, suggesting strength gain may be a result of increased central neuronal drive descending to the motor neuron pool, and subsequently, the peripheral part of the neuromuscular system (Griffin & Cafarelli, 2007; Mason et al., 2020).

Single-pulse procedure can also measure corticospinal inhibitory mechanism. Stimulate under voluntary muscle contraction background, a temporary break of EMG signal is observed following a MEP, which is known as cortical silent period (cSP) (Enoka, 2015; Latella et al., 2012; Ruotsalainen et al., 2014; Zewdie & Kirton, 2016). Typically, cSP is the duration from the onset of the MEP to the restoration of EMG signal (Zewdie & Kirton, 2016). Nonetheless, some studies define it as the period between the TMS artifact and the EMG restoration (Colomer-Poveda et al., 2020; Tazoe et al., 2007), or between MEP offset and EMG signal return (Oliviero et al., 2006). Research had revealed that γ-Aminobutyric acid (GABA) neurotransmitters play an important role in the inhibition mechanism and the output from M1 is weakened under GABA regulation (Colomer-Poveda et al., 2020). Cortical silent period lasts for roughly 200 ms and it has been established that the initial part (~50ms) is spinal oriented, including after-hyperpolarization and activation of recurrent inhibition of activated motoneurons. The later part (>50ms) is most likely due to intracortical inhibitory mechanisms (Cantello et al., 1992; Chen et al., 1999; Inghilleri et al., 1993). Working as a counterbalance system, alteration of MEP amplitude and the cSP following training is thought to be an excitation-inhibition balance shift (Kidgell & Pearce, 2010). Christie & Kamen (2014) and Latella et al. (2012) suggested that inhibitory mechanisms play a major role in modulating strength gain after resistance training.

For the paired-pulse procedures, correct conditioning with right amount of ISI is important for studying intracortical responses (Enoka, 2015; Zewdie & Kirton, 2016). Giving a subthreshold conditioning stimulus following a suprathreshold test stimulus, with 1-6ms and 6-25ms ISI, SICI and ICF can be observed. Moreover, LICI is evoked by suprathreshold conditioning stimulus and test stimulus with 50-200ms ISI (Zewdie & Kirton, 2016). At spinal and peripheral level, nervous excitability can be assessed with H-reflex and M-wave (Beck et al., 2007; Christie & Kamen, 2014; Enoka, 2015). Because the intracortical response regulates strength output as well, several studies had investigated these responses following resistance training. Mason et al. (2020) assessed progressive M1 region alteration following every resistance training session across two weeks of training period. They concluded with an increase in strength and MEP response, accompanied with a decrease in cSP and SICI, suggesting a net increase from central output was perhaps attributed to strength improvement. Latella et al. (2017) had done an acute cortical and intracortical neural response to resistance training research. The results showed an increase in MEP, ICF, and SICI, with concurrent cSP decreases, which was suggested a compensatory effect to offset peripheral fatigue.

5.1.2 Potential factors influencing neural adaptations

Several factors may be accounted for the adaptations, including training-related factors (training volume, intensity, modality, training exercise selection), subject-related factors (experienced and non-experienced subjects, young and elder populations), target muscles, and testing protocols (stimulation intensities, muscle activation level when giving stimulation, the reliability and validity of a test) (Latella et al., 2017; Mason et al., 2020).

Various training modes, volume, and intensity were used among studies. Some subjects were trained three times per week for four weeks (Carroll et al., 2002; Jensen et al., 2005; Kidgell & Pearce, 2010; Nuzzo et al., 2017), some did a single session (Colomer-Poveda et al., 2020), others received an eight-week training program (Latella et al., 2012). Within a single training session, some executed three sets (Christie & Kamen, 2014; Kidgell & Pearce, 2010) for one movement while others perform more sets (Carroll et al., 2002; Griffin & Cafarelli, 2007; Jensen et al., 2005; Kidgell & Pearce, 2010; Nuzzo et al., 2017). Additionally, training mode varied. HST (Latella et al., 2017), HYP (Latella et al., 2017), dynamic isokinetic strength training (Carroll et al., 2002; Siddique et al., 2020), isometric strength training (Christie & Kamen, 2014; Griffin & Cafarelli, 2007; Jensen et al., 2005; Kidgell & Pearce, 2010; Nuzzo et

al., 2017) were mentioned and applied in different studies. According to several study results, various training modes might lead to distinct results because of the idea of task-specific adaptation (Gardiner, 2011; Jensen et al., 2005; Kidgell & Pearce, 2010; Siddique et al., 2020). In addition to training-related factors, the subjects and the target muscle groups had impacts on the varied results as well. In most of the studies, subjects were limited to those who are younger than thirty-five. For the target muscle groups, both lower and upper limb muscle groups were studied, including rectus femoris (Latella et al., 2012), tibialis anterior (Griffin & Cafarelli, 2007), biceps brachii (Jensen et al., 2005; Nuzzo et al., 2017), flexor carpi radialis (Mason et al., 2020), and first dorsal interosseous muscle (Carroll et al., 2002; Kidgell & Pearce, 2010). The high variety study protocols and designs make it challenging to compare results between one another.

5.2 Muscular adaptations

Neural adaptation has been studied to be accounted for strength gain without significant muscle size change after resistance training in early phase (Latella et al., 2012; Moritani & deVries, 1979). Except for neural influence, muscular adaptation to resistance training is still inevitable and it contributes to strength gain (Bompa, 2009; Moritani & deVries, 1979). Based on task specificity principle, training mode can be determined to the extent of muscular adaptations (Akima et al., 1999; Beck et al., 2007; Bompa, 2009; Enoka, 2015; Jensen et al., 2005; Kidgell & Pearce, 2010; Siddique et al., 2020).

Muscle strength improvement is related to muscle mass. In response to resistance training, muscle hypertrophy, defined by the increase in cross-sectional area, had been reported (Bompa, 2009; Enoka, 2015; Gardiner, 2011). With resistance training, type II muscle fiber are more sensitive than Type I fiber to be hypertrophied, so adaptations occur mostly in type II fibers (Bompa, 2009). Similarly, atrophy is observed in type II fibers through detraining (Bompa, 2009). Typically, ultrasound system is used to assess muscle thickness (Latella et al., 2012). Aside from muscle hypertrophy, an increase in pennation angle is suggested to be related to greater force production (Gardiner, 2011).

6 PURPOSE OF THE STUDY

Understand aging effects on motor performance is favorable to fall and disease prevention. TMS is one of the methods to gain more understanding on the neuromuscular aspect of aging. Connecting to current study, it is conducted by comparing the neural responses between the young and older adults. Nonetheless, as much as I know, most studies examining neural adaptations to resistance training via TMS were limited to younger subjects, and such comparison has not been widely studied yet. Thus, the purpose of the study is to compare the difference in corticospinal excitability (MEP amplitude) and inhibition (cSP) following resistance training and detraining between young and old subjects.

The research question of the present study was: following resistance training and detraining, how does the corticospinal excitability response, inhibitory mechanism, and muscle strength performance change in young and older adults?

The hypothesis are as following: (1) both groups have an increase in corticospinal excitability after training and a decrease after detraining, and the young group has higher response compared to the older group at all testing time points; (2) both groups have a decrease in corticospinal inhibition after training and an increase after detraining, and the young group has longer inhibition period compared to the older group at all testing time points; and (3) both MVC and 1RM performance increase after training and decrease after detraining. The young group has greater muscle strength than the older group at all testing time points and 1RM performance change in both groups would be greater than the change in MVC.

7 METHODS

7.1 Subjects

Twenty-one subjects were recruited on a voluntary basis. In terms of age, subjects were divided into two groups: the young group (M=5; F=6) and the older group (M= 4; F= 6). The average age in the young group was 26.8 years old (height: 74.1±10.2 cm; weight: 82.7±24.0 kg) while the older group was 71.2 years old (height: 165.8±5.7 cm; weight: 74.6±9.4 kg). All recruited subjects had no resistance training for more than six months. All subjects had signed a written informed consent with a thorough explanation of the experiment, a TMS screening form, and a health questionnaire. The experiment was approved by the university ethics committee of the University of Jyväskylä, which was performed according to the Declaration of Helsinki.

7.2 Experimental design and protocols

The study consisted of four testing session (control, pre-training, post-training, and detraining). After control and pre-training testing sessions, subjects joined a seven-week resistance training program. A week after the last training session, a post-training testing session was performed. The detraining period lasted for four weeks. During then, there were no training for the subjects. The last testing session occurred after the detraining period. FIGURE 4 presents timeline of the experiment.

All subjects participated in a familiarization session. In the familiarization session, subjects experienced the experimental protocols, including all the stimulations they would get from the study. EMG electrodes were placed on the right rectus femoris (RF), the target muscle, assessing MVC, maximal compound wave (M_{max}), and single-pulse TMS responses.

In each testing sessions, testing order was as following: (1) M_{max}, which was acquired with supramaximal electrical stimulation on femoral nerve (2) MVC, (3) finding the hotspot, (4) defining active motor threshold (AMT), and (5) delivering single-pulse TMS with 120%, 140%, or 160% AMT at 20% and 60% MVC in a random order. Prior to all the measurements, EMG electrodes were placed based on SENIAM protocol (Hermens et al., 1999). The subject was positioned on the chair with 90° hip and knee joint angle. The dynamometer strap was tied 2

cm above from the medial malleoli. Then, we adjusted the belt and shoulder straps to fix the subject on the seat properly. A screen was set in front of the subject, providing them with visual feedback while performing the test. 1RM was tested with a commercial knee extensor machine with individualized adjusted back pad and knee pad. Collectively, MVC, 1RM performance, corticospinal excitability (normalized MEP) and corticospinal inhibition mechanism (cSP) were main outcome measures in current study.

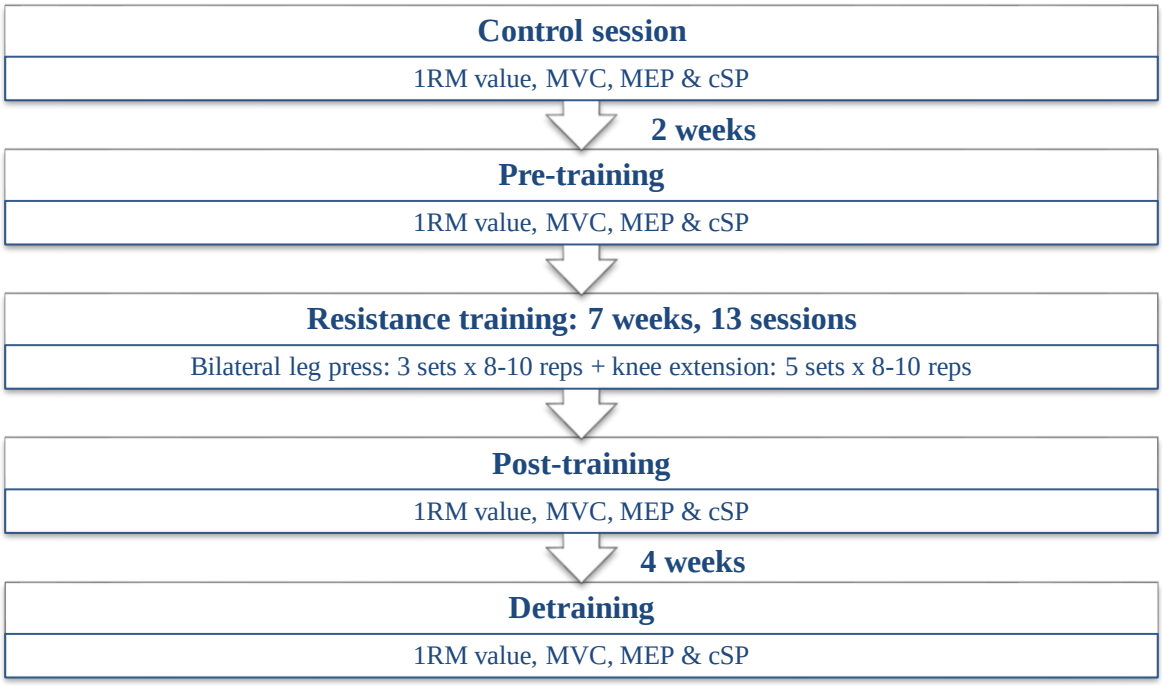


FIGURE 4. Measurement and training timeline

7.3 Resistance training

Thirteen training sessions spread through seven weeks. Training schedule is presented in FIGURE 5. With two warm-up sets at ten and five repetitions separately, 3-5 RM test was performed at pre-training testing session to determine loads for the training. The 3-5 RM test was counted as the first training session due to the movements performed in the test were identical to the training program.

During training sessions, ten minutes warm-up was done in the beginning. The subject cycled for five minutes and did dynamic movements with body weight (ten squats and ten lunges) for

the other five minutes. Then, five countermovement jumps were performed. Subjects were instructed with jumping techniques and were encouraged to jump as high as possible. Followed by warm-up exercises and countermovement jumps, bilateral leg press and knee extension training were executed on commercial machines. Bilateral leg press at 3 sets×8-10 reps while knee extension was done at 5 sets×8-10 reps. There were two minutes break between sets. Subjects were instructed to control the movement that eccentric phase lasted for two seconds, and concentric phase should be as fast as possible. No pause between eccentric and concentric phases. Full range of motion was required in both training exercises. The load was adjusted if needed. The whole training session was supervised by at least one member on the research team.

FIGURE 5. Training timeline.

7.4 Transcranial magnetic stimulation (TMS)

With subjects seated in the dynamometer chair, TMS (Magstim Bistim^2 Stimulator) was applied to the left motor cortex through a double cone coil (with posterior-anterior current). The coil was held by one of the master's degree students and it was placed firmly on the subject's scalp. The resultant MEP and cSP were recorded from the right RF muscle.

7.4.1 Motor evoked potential (MEP)

The hotspot was the optimal stimulation site for RF muscle. It was determined by 50%-70% of stimulator output, moving the coil slightly with each stimulus until the location had produced the largest MEP response in the RF muscle was determined. We marked the hotspot with a marker on the subject's scalp. Once the hotspot was located, aMT for the RF muscle was determined. The threshold was defined as the lowest intensity that evoked at least 200μV MEP

peak-to-peak amplitude in three out of five consecutive stimulations under 10% MVC. The threshold was retested in every testing session and adjusted if necessary. Followed by aMT determination, subjects were asked to produce either 20% or 60% of their MVC while delivering TMS pulse over the motor cortex at 120%, 140%, or 160% aMT, evoking MEP responses in the RF muscle. Each stimulation set consisted of 10 stimuli and all stimulation sets within each testing session were randomized. Visual feedback was provided to guide the subject contracting the muscle at the correct force level.

7.4.2 Cortical silent period (cSP)

After determining MVC for the knee extensors, subjects were asked to produce either 20% or 60% of their MVC. While contracting, the TMS pulses were delivered over the motor cortex, at 120%, 140%, or 160% aMT to evoke silent period in the RF muscle. Ten trials of TMS pulse on both muscle contraction levels were completed and all stimulation sets within each testing session were randomized. The duration of cSP was calculated as the period between stimulation artifact and the restoration of EMG signals.

7.5 Peripheral nerve stimulation: maximal compound wave (M_{max})

M_{max} is produced by supramaximal intensity peripheral nerve stimulation that maximally recruited entire motor neuron pool. Transcutaneous electrical stimulation of the femoral nerve (32 mm cathode/anode arrangement; Polar Neurostimulation Electrodes, Espoo, Finland) was performed to elicit M_{max} in RF 1 ms pulse duration (Digitimer DS7AH, Hertfordshire, UK). Electrodes were placed 2 cm apart and placed at each side of the femoral nerve, located by palpation and identification of the femoral artery. M_{max} was elicited by gradually increasing stimulator output intensity until the EMG response plateaued. The stimulation started with 20 mV. To ensure supramaximality, this intensity was further increased by 50 mV.

7.6 Surface electromyography (sEMG)

sEMG was recorded for the right RF muscle. The signal was amplified to 1000 times, bandpass filtered (16–1000 Hz) and sampled online at 3000Hz using CED 1401 A/D converter

(Cambridge Electronic Design Ltd, Cambridge, UK). Electrode placement and skin preparation were all based on SENIAM recommendation for the muscle. Skin preparation was performed near the electrode placement area, including hair removal, dead skin rubbing with sandpaper, and skin cleaning with 70% isopropyle alcohol. Electrodes were placed following skin preparation. A pair of self-adhesive Ag-AgCl electrodes (BlueSensor N, N-00-S/25, Ambu A/S, Denmark) were placed on RF muscle belly, which is located at half distance on the line from the anterior spinal iliac superior to the superior edge of patella. Interelectrode distance was 20 mm. Additionally, a ground electrode was placed on the patella bone. Signal checking with a volt-ampere-ohmmeter was done with an upper impedance limit of 2kΩ. To keep the placement consistent, we marked the placement with a marker. Following the placement, tapes were applied over the electrodes. Placement measurement and skin preparation were done in each testing session before the measurements started.

7.7 Muscle strength: 1 repetition maximum & maximal voluntary contraction

Both 1RM performance and MVC were tested throughout four testing time points. 1RM performance was assessed with leg extension commercial machine. The measurement was performed by trained master's students. Prior to the measurement, our subjects had a ten-minute warm-up. At a self-selected intensity, they cycled for five minutes. Subsequently, they performed dynamic warm-up exercises with their body weight for the other five minutes, including ten squat and ten lunges.

Bilateral knee extension 1RM performance was measured followed by the warm-up. A ten-repetition and a five-repetition set were done before the 1RM performance test. The subject sat at a commercial knee extensor machine with individualized adjusted back pad and knee pad. The subject was instructed to fully extend the knee every single time. The subject was first asked about an estimation that he/she could lift for ten- and five-repetition separately, and the weight was set according to it. There was a one-minute rest after the ten- and five-repetition set. Further, we attempt to acquire 1RM performance within 3-5 trials. The initial weight for 1RM performance test was adjusted based on his/her performance for the ten and five repetition. If the trial was successful, the weight increased by 2.5kg accordingly. The procedure continues until the subject could no longer complete one repetition, and the prior successful trial served as the 1RM knee extensor strength. The highest load (kg) for 1RM performance was recorded.

Unilateral knee extension MVC measurement was carried out with a dynamometer. Subjects were positioned and fixed with belt and harness on the chair with 90° hip and knee joint angle, the dynamometer strap was tied 2 cm above from the medial malleoli. A screen in front of the subject provided them with visual feedback while performing the test. A warm-up session was performed before the MVC performance test. The subject was asked to perform a perceived 50% MVC without countermovement for three times, with 10-20 seconds of rest interval. Before the actual measurement started, we adjusted the force level cursor to an estimated 80% MVC according to the warm-up set, serving as visual feedback. The subject was instructed to extend the knee "as fast and as hard as possible" without any countermovement for three trials. The duration of the contraction is roughly 2-3 seconds, separated by 1 minute of rest interval. The greatest MVC attempt among three trials was marked as a MVC performance (N).

7.8 Data analyses

MEP size and cSP were analyzed with Matlab. With our Matlab script, we manually marked down the onset of a MEP and the end point of cSP. For each subject, the median MEP and cSP values from ten trials at each intensity were taken, and those below or above 2.5 standard deviation (SD) were eliminated. The purpose of the elimination was to avoid the influence from the outliers. MEP response was defined by the peak-to-peak amplitude of each response and was normalized to the M_{max}. The period between the stimulation artifact to the EMG signal recovery accounted for cSP. Performance indicators included MVC and 1RM value, and the best trial was recorded.

7.9 Statistical analyses

All statistical analysis was performed with IBM SPSS Statistics version 28. All data were screened with Shapiro-Wilk test and were found to be normally distributed ($P>0.05$) except for the cSP at 20% MVC with 140% AMT, MEP and cSP at 60% MVC with 160% AMT. Two-way repeated measures analysis of variance (ANOVA), Friedman's two-way analysis, and independent-samples Mann-Whitney U test were used. Bonferroni's post hoc analysis was applied to determine differences between cells when significant main effects were observed. In

all cases, an alpha level of 0.05 or less was accepted as a significant difference. All data are presented as mean ± standard deviation (SD).

8 RESULTS

Results for corticospinal excitability and inhibition responses and muscle strength performances are elaborated separately below. Baseline condition refers to the statistical comparison between control and pre-training testing sessions within each group.

8.1 Motor evoked potential (MEP/M_{max})

8.1.1 Maximal compound wave: M_{max}

All the M_{max} from both groups across four time points were normally distributed. No significant TIME effect (p=0.881) and TIME×GROUP effect (p=0.447) was detected. Significant GROUP effect (p<0.001) was found at all testing time points. (TABLE 1 & FIGURE 6)

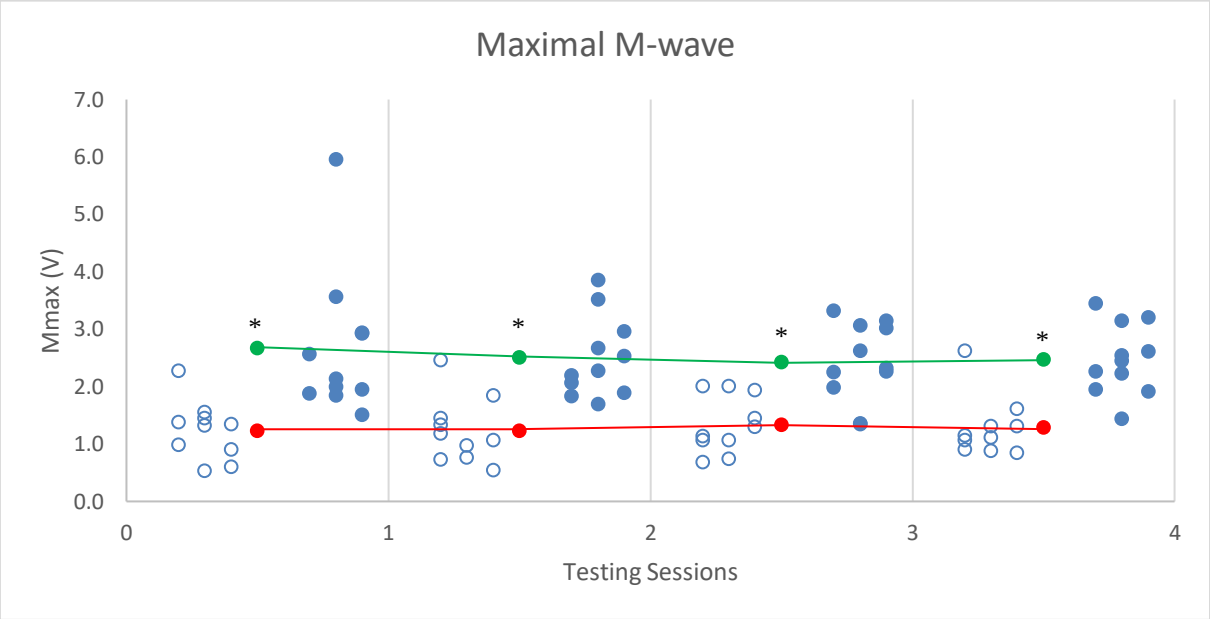
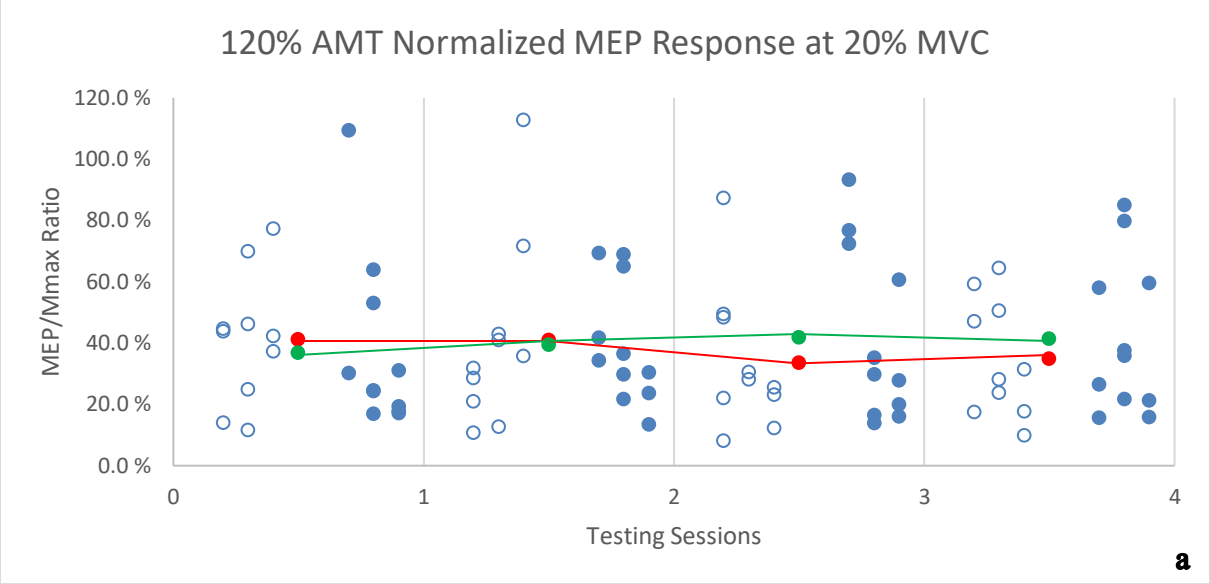


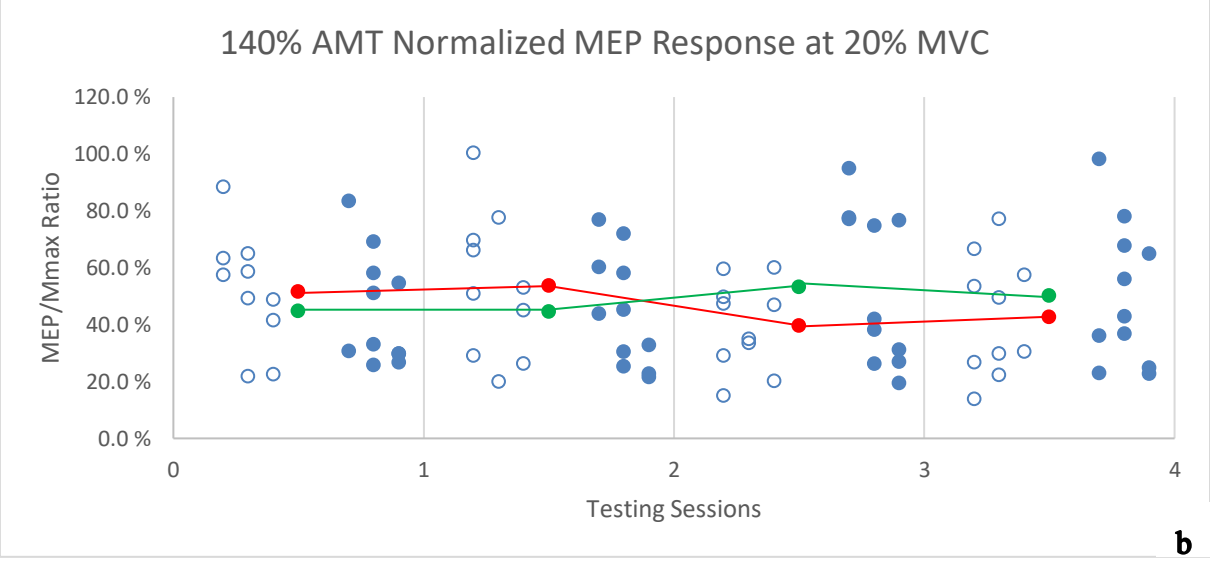
FIGURE 6. Maximal M-wave (M_{max}) changes throughout four testing time points (**open circles**: older group; **filled circles**: young group; **red filled circles**: mean for the older group; **green filled circles**: mean for the young group).

**: significant group difference at a given testing time point.*

8.1.2 At 20% MVC

All variables were normally distributed. No baseline difference was detected within group at all intensities. Statistics showed that only TIME×GROUP effect was observed at 140% (p=0.016) and 160% (p=0.034) aMT. However, Bonferroni post-hoc analysis did not detect pairwise difference. TABLE 1 and FIGURE 7 presented the response changes throughout four testing time points at all intensities.





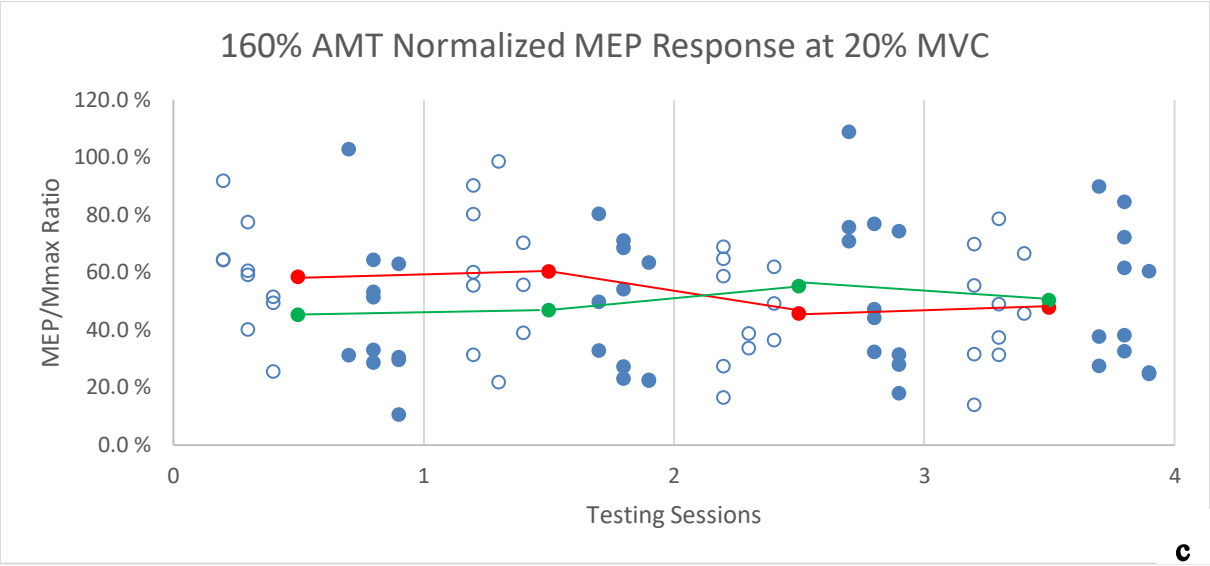
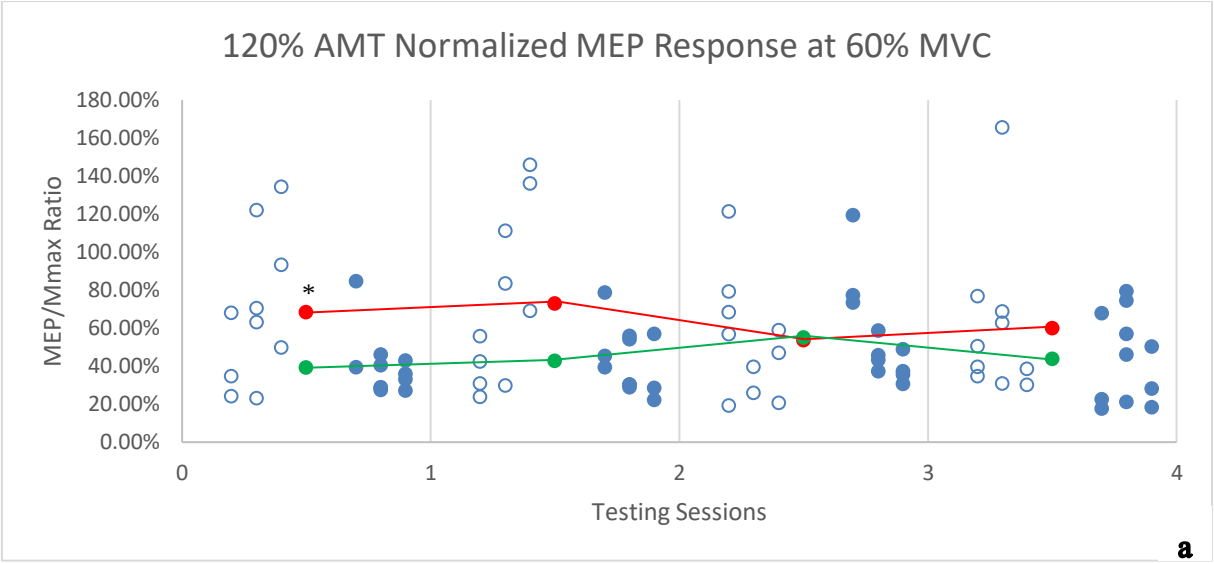
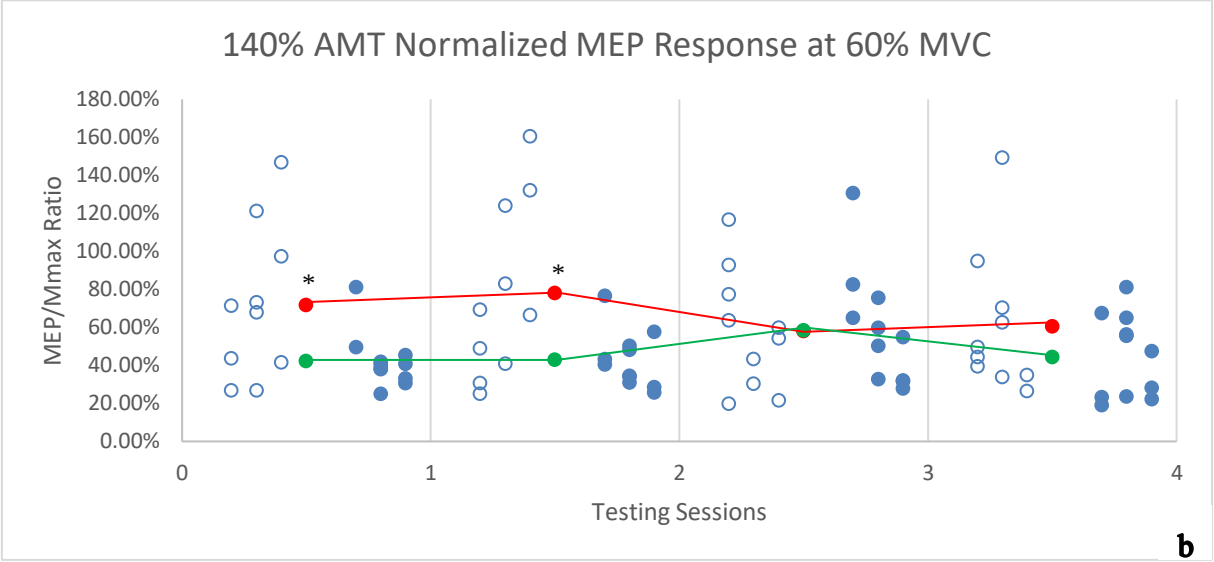


FIGURE 7. At 20% MVC, MEP response changes throughout four testing time points at 120% (a), 140% (b), and 160% (c) aMT **(open circles**: older group; filled **circles**: young group; red filled **circles**: mean for the older group; green filled **circles**: mean for the young group).

8.1.3 At 60% MVC

Except for the intensity at 160% aMT, all other variables were normally distributed. No baseline difference within group was detected at all intensities. Statistics showed significant TIME×GROUP effect at 120% (p=0.003) and 140% (p=0.002) aMT. Post-hoc analysis revealed that both groups had significant group difference at 120% (p=0.049) and 140% (p=0.049) aMT at control testing session; at 140% aMT, significant group differences were found at pre-training testing session as well (p=0.038). Non-parametric test revealed significant TIME effect (p=0.007) in the older group at 160% aMT. Post-hoc analysis showed neither a significant change between pre- and post-training testing nor a significant change between post- and de-training testing session. TABLE 1 and FIGURE 8 presented the response changes throughout four testing time points at all intensities.


120% AMT Normalized MEP Response at 60% MVC
MEP/Mmax Ratio
180.00%
160.00%
140.00%
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
0
1
2
3
4
Testing Sessions
*
a


140% AMT Normalized MEP Response at 60% MVC
MEP/Mmax Ratio
180.00%
160.00%
140.00%
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
0
1
2
3
4
Testing Sessions
*
*
b

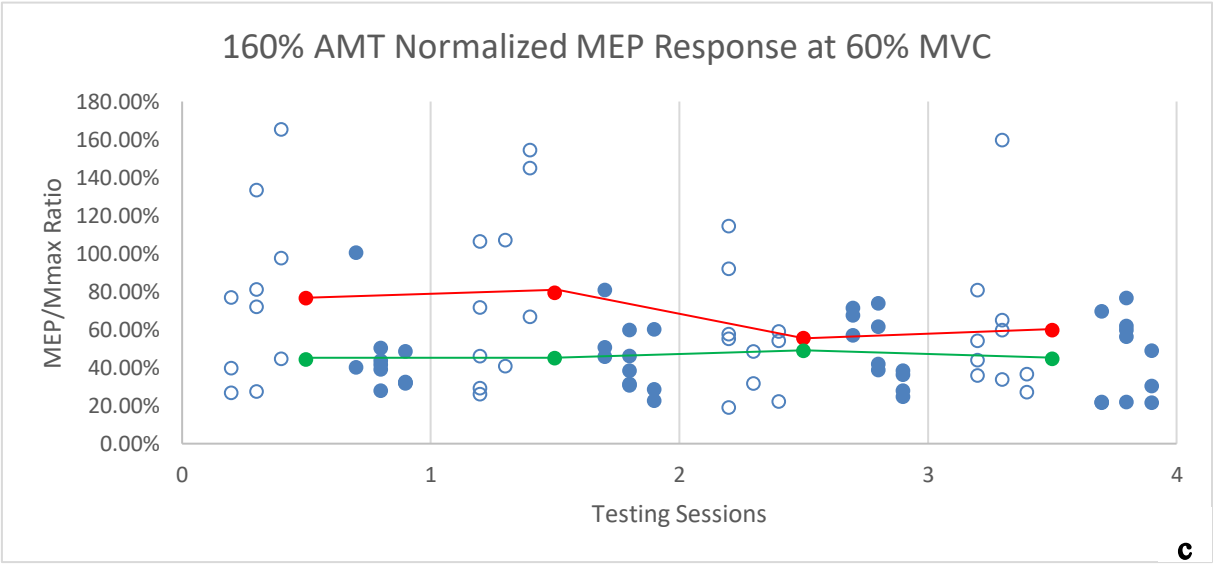
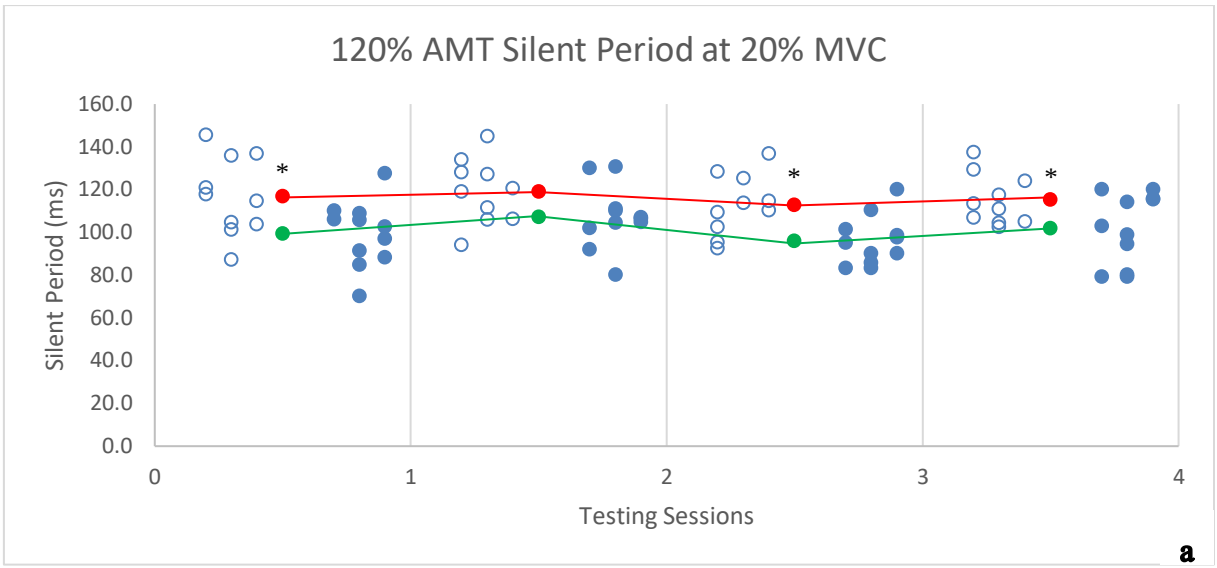

160% AMT Normalized MEP Response at 60% MVC
MEP/Mmax Ratio
180.00%
160.00%
140.00%
120.00%
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
0
1
2
3
4
Testing Sessions
c

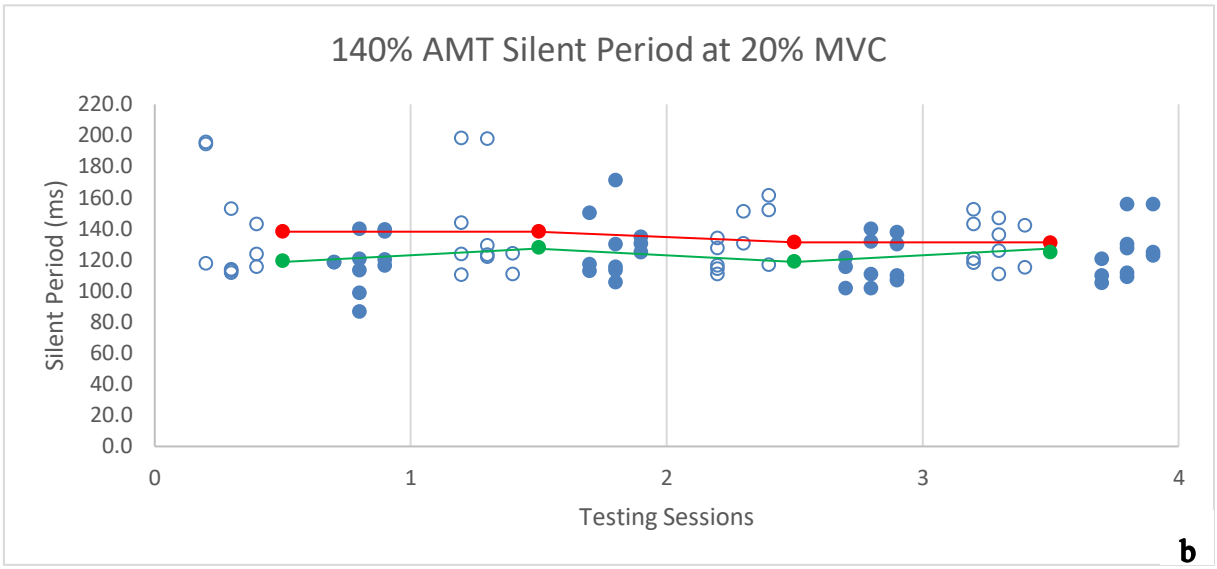
FIGURE 8. At 60% MVC, MEP response changes throughout four testing time points at 120% (a), 140% (b), and 160% (c) aMT **(open circles**: older group; filled **circles**: young group; red filled **circles**: mean for the older group; green filled **circles**: mean for the young group).
**: significant group difference at a given testing time point.*

8.2 Cortical silent period (cSP)

8.2.1 At 20% MVC

Except for the intensity at 140% aMT, all other variables were normally distributed. No baseline difference within group was detected at all intensities. Statistics showed just a main GROUP effect at 120% (p=0.004) aMT. Post-hoc analysis revealed that significant group differences occurred at all testing sessions except for the pre-training testing session (control: p=0.027; post-training: p=0.007; de-training: p=0.048). TABLE 2 and FIGURE 9 presented the response changes throughout four testing time points at all intensities.


120% AMT Silent Period at 20% MVC
Silent Period (ms)
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
Testing Sessions
*
*
*
a


140% AMT Silent Period at 20% MVC
Silent Period (ms)
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
Testing Sessions
b

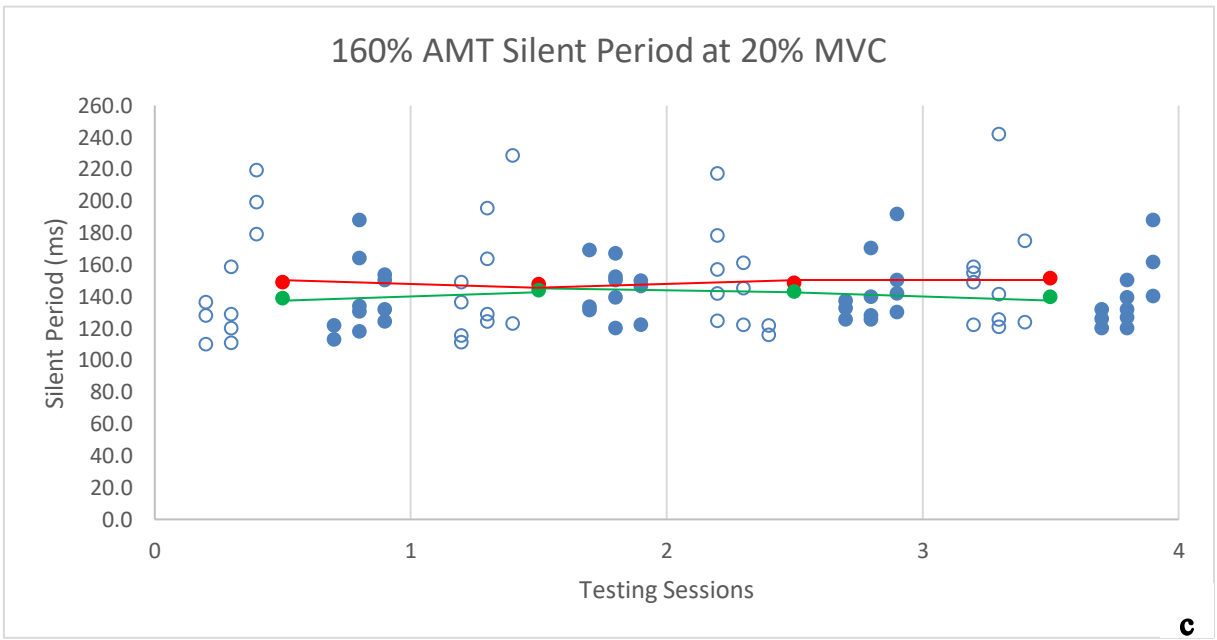
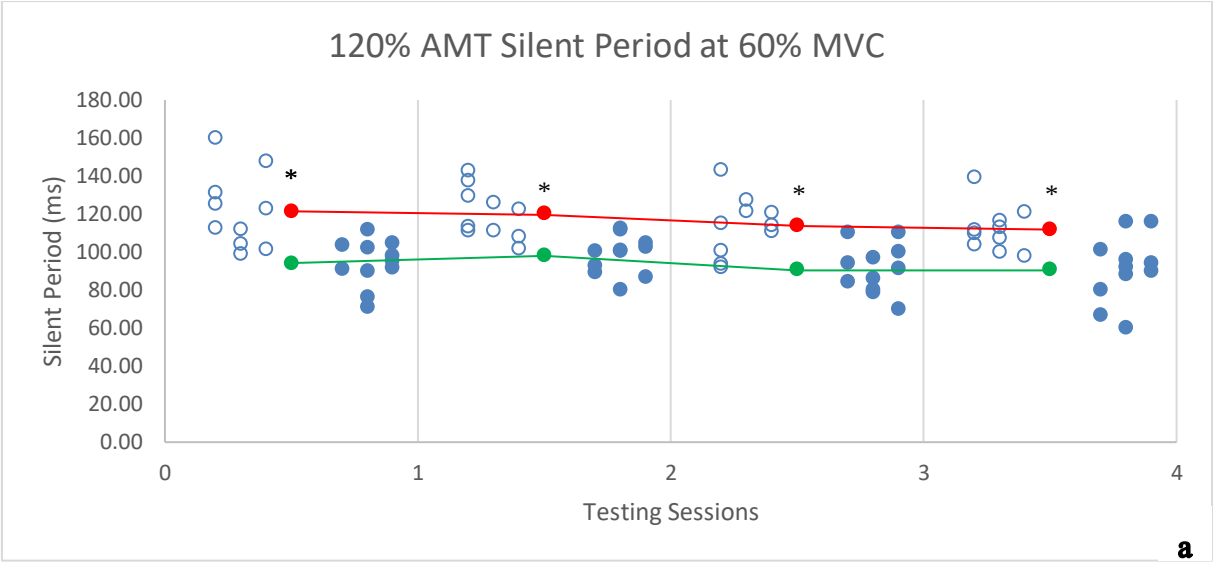
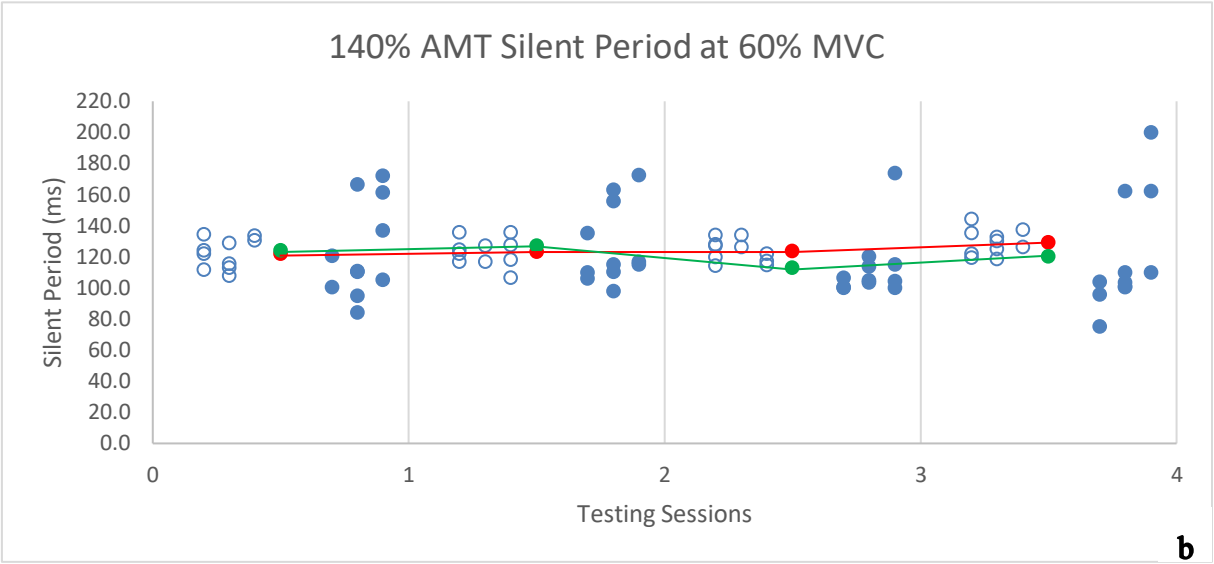

160% AMT Silent Period at 20% MVC
Silent Period (ms)
260.0
240.0
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
Testing Sessions
c

FIGURE 9. At 20% MVC, cSP changes throughout four testing time points at 120% (a), 140% (b), and 160% (c) aMT **(open circles**: older group; filled **circles**: young group; red filled **circles**: mean for the older group; green filled **circles**: mean for the young group).
**: significant group difference at a given testing time point.*

8.2.2 At 60% MVC

Except for the intensity at 160% aMT, all other variables were normally distributed. No baseline difference within group was detected at all intensities. Statistics showed just a main GROUP effect at 120% ($p<0.001$) aMT. Post-hoc analysis revealed that significant group differences occurred at all testing sessions (control: $p=0.001$; pre-training: $p<0.001$; post-training: $p=0.002$; de-training: $p=0.005$). TABLE 2 and FIGURE 10 presented the response changes throughout four testing time points at all intensities.


120% AMT Silent Period at 60% MVC
Silent Period (ms)
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
1
2
3
4
Testing Sessions
*
*
*
*
a


140% AMT Silent Period at 60% MVC
Silent Period (ms)
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
Testing Sessions
b

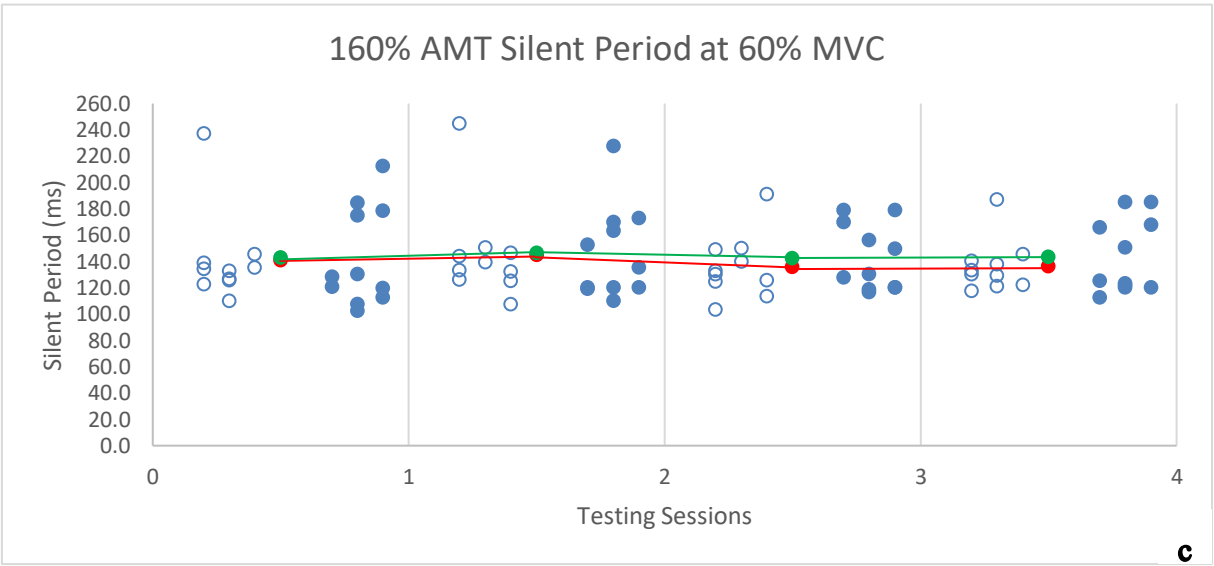

160% AMT Silent Period at 60% MVC
Silent Period (ms)
260.0
240.0
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
1
2
3
4
Testing Sessions
c

FIGURE 10. At 60% MVC, cSP changes throughout four testing time points at 120% (a), 140% (b), and 160% (c) aMT **(open circles**: older group; filled **circles**: young group; red filled **circles**: mean for the older group; green filled **circles**: mean for the young group).
**: significant group difference at a given testing time point.*

8.3 Maximal voluntary contraction (MVC): unilateral knee extension

All variables were normally distributed. No baseline difference was detected within group at all intensities. A main TIME effect ($p<0.001$) and GROUP effect ($p=0.006$) was detected. Post-hoc analysis revealed a significant MVC improvement in the older group from pre- to post-training testing session ($p=0.008$). Additionally, significant group differences were observed at all testing sessions (control: $p=0.006$; pre-training: $p=0.003$; post-training: $p=0.006$; de-training: $p=0.018$). TABLE 3 and FIGURE 11 presented the MVC change throughout four testing time points.

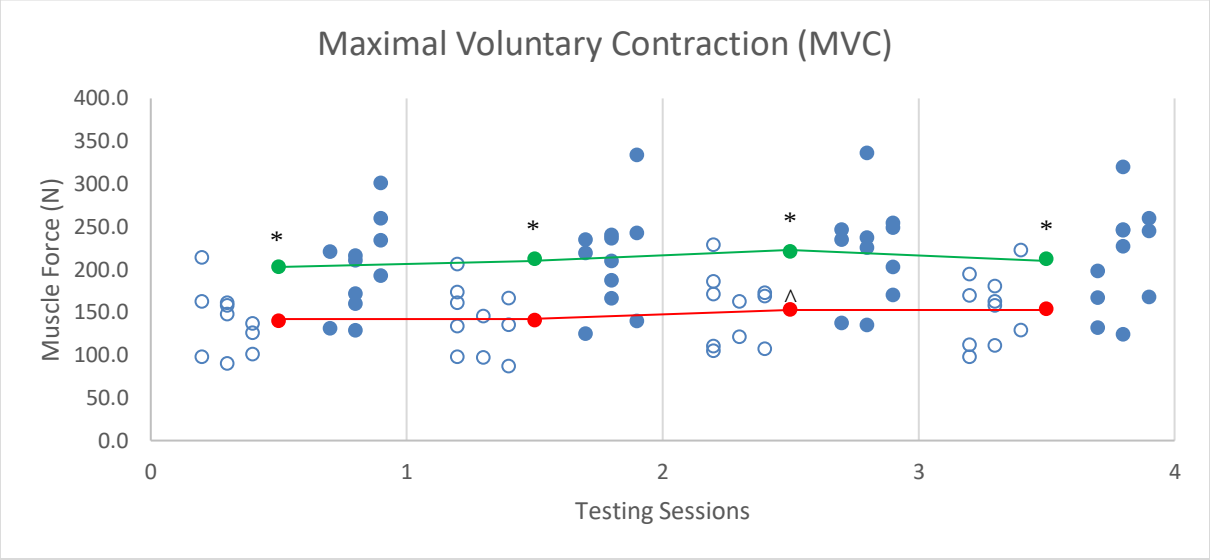


FIGURE 11. MVC changes throughout four testing time points **(open circles**: older group; filled **circles**: young group; red filled **circles**: mean for the older group; green filled **circles**: mean for the young group).
: significant **group difference at a given testing time point. ^: significant difference between pre- and post-training testing session.*

8.4 1 repetition maximum performance: bilateral knee extension

All variables were normally distributed. No baseline difference was detected within group at all intensities. Statistics showed main TIME effect ($p<0.001$), GROUP effect ($p<0.001$), and TIME*GROUP effect ($p<0.001$). Post-hoc analysis revealed significant strength improvement in both the older group ($p=0.037$) and the young group ($p<0.001$) from pre- to post-training testing session. A significant decrease in both the older ($p=0.007$) and the young ($p=0.007$) group from post- to de-training testing sessions was observed as well. Additionally, significant group differences were observed at all testing sessions (control: $p=0.002$; pre-training: $p=0.001$; post-training: $p<0.001$; de-training: $p<0.001$). TABLE 3 and FIGURE 12 presented the 1RM change throughout four testing time points.

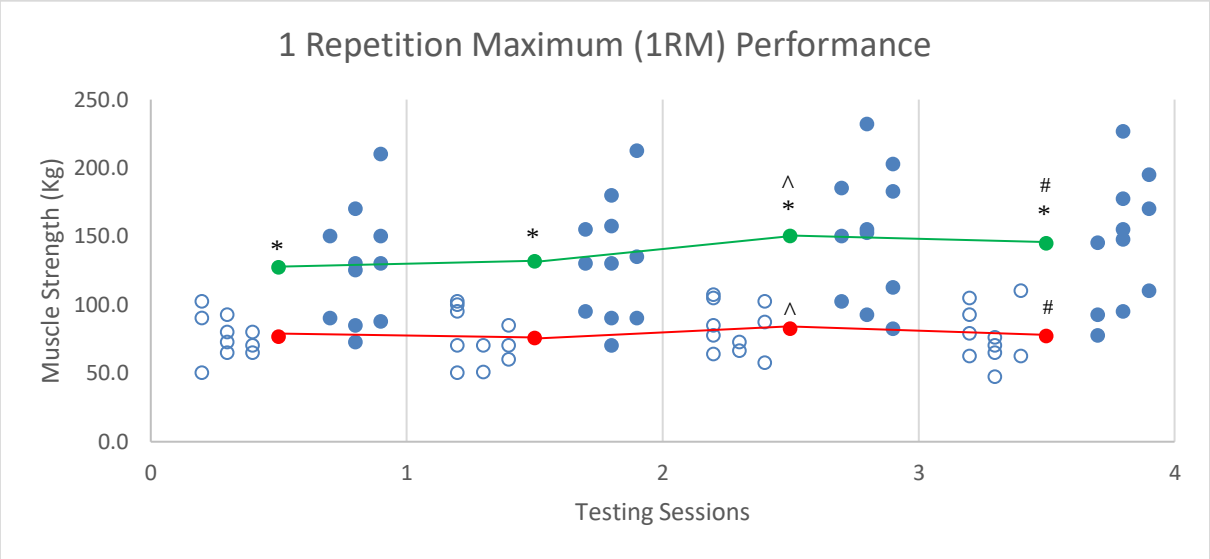


FIGURE 12. 1RM performance changes throughout four testing time points **(open circles**: older group; filled **circles**: young group; red filled **circles**: mean for the older group; green filled **circles**: mean for the young group).

: significant **group difference at a given testing time point. ^: significant difference between pre- and post-training testing session. #: significant difference between post- and de-training testing session.*

TABLE 1. Mean ± SD for M_{max} and normalized MEP throughout four testing time points.

M_{max} (v)		**Control**	**Pre-training**	**Post-training**	**De-training**
Older		1.23±0.51	1.23±0.58	1.33±0.50	1.28±0.53
Young		2.66±1.25*	2.50±0.70*	2.42±0.69*	2.47±0.61*
20% MVC MEP/M_{max} (%)		**Control**	**Pre-training**	**Post-training**	**De-training**
120% AMT	Older	41.10±21.24	40.82±30.70	33.42±23.07	34.89±19.07
	Young	36.86±28.43	39.36±19.69	41.86±28.44	41.36±25.21
140% AMT	Older	51.63±19.98	63.74±25.25	39.61±15.58	42.69±20.98
	Young	44.74±19.70	44.45±19.85	53.14±27.03	50.11±24.92
160% AMT	Older	58.39±18.55	60.20±25.11	45.58±17.69	47.84±20.12
	Young	45.14±25.24	46.72±22.02	55.10±27.91	50.25±24.26
60% MVC MEP/M_{max} (%)		**Control**	**Pre-training**	**Post-training**	**De-training**
120% AMT	Older	68.20±38.50	72.73±44.92	53.54±31.22	59.68±40.61
	Young	39.24±16.36*	42.53±17.16	54.97±26.22	43.57±23.53
140% AMT	Older	71.54±40.15	77.99±46.36	57.83±31.35	60.46±37.33
	Young	42.10±14.64*	42.71±15.00*	58.35±30.35	44.40±21.99
160% AMT	Older	76.25±45.74	79.18±46.66	55.20±29.66	59.47±38.81
	Young	44.09±19.94	44.68±17.22	48.76±17.75	44.31±21.60

: significant **group difference at a given testing time point.*

TABLE 2. Mean ± SD for SP throughout four testing time points.

20% MVC cSP (ms)		**Control**	**Pre-training**	**Post-training**	**De-training**
120% AMT	Older	116.82±18.4	119.08±15.16	112.81±14.2	115.10±11.7
	Young	99.18±15.35*	107.02±14.50	95.79±11.50*	101.70±16.6*
140% AMT	Older	137.99±21.91	138.17±32.93	131.35±17.95	130.95±14.73
	Young	119.07±16.41	127.73±19.05	118.78±14.05	124.77±17.43
160% AMT	Older	148.96±38.38	147.44±38.22	148.37±31.48	151.17±36.80
	Young	138.87±22.62	143.67±16.24	142.82±20.74	139.46±20.43
60% MVC cSP (ms)		**Control**	**Pre-training**	**Post-training**	**De-training**
120% AMT	Older	121.72±20.1	120.61±13.4	114.04±15.6	112.14±11.9
	Young	94.18±12.20*	98.37±10.10*	91.11±12.86*	90.93±17.48*
140% AMT	Older	121.96±9.69	123.02±9.09	123.59±7.38	128.96±8.42
	Young	123.86±30.63	126.96±25.48	112.87±21.26	120.32±37.49
160% AMT	Older	140.65±35.18	114.76±37.18	135.89±24.24	136.19±19.82
	Young	142.70±37.57	146.26±35.18	142.29±24.98	143.24±27.98

**: significant difference between groups within a single session.*

TABLE 3. Mean ± SD for MVC and 1RM throughout four testing time points.

MVC	**Control**	**Pre-training**	**Post-training**	**De-training**
Older	139.31±37.70	140.09±38.12	152.96±40.88^	153.40±40.50
Young	202.50±52.8*	212.24±57.7*	220.80±57.8*	212.09±59.9*
1RM performance	**Control**	**Pre-training**	**Post-training**	**De-training**
Older	76.75±15.50	75.20±19.45	82.45±17.99^	77.00±20.00#
Young	127.27±41.80*	131.36±43.26*	149.95±48.29*^	147.70±46.91*#

: significant **group difference at a given testing time point. ^: significant difference between pre- and post-training testing session. #: significant difference between post- and de-training testing session.*

9 DISCUSSION

The study compared corticospinal responses and muscle strength performance between young and older adults following resistance training and de-training. The main findings were: (1) the older group had greater corticospinal excitability at baseline when the muscle contracted at 60% MVC and the between group difference was no longer observed after training. (2) Generally, the older group had longer cSP than the young group, especially when the muscle contracted at 20% and 60% MVC at 120% aMT. (3) The young group had significantly greater muscle force performance than the older group. MVC and 1RM performance for both groups increased after training and decreased or maintained after detraining period. These findings implied an increase in muscle force performance following resistance training without being regulated by the corticospinal tract changes.

9.1 Corticospinal excitability: MEP/M_{max}

Significant group difference was detected only when the muscle contracted at 60% MVC (120% and 140% aMT) at baseline, which presented a greater response in older adults. In addition, we did not observe any corticospinal excitability alteration following training and detraining period respectively.

The baseline group differences found at 60% MVC conflicted with previous studies. According to McGinley (2010), young adults were suggested to have greater excitatory response than older adults. Additionally, it was suggested by Pitcher et al. (2003) that the stimulation-response curve for MEP in older adults shifted to the right, compared to the young, which meant a higher stimulation intensity was needed to evoke the similar MEP response in the older than the young.

For the inconsistency, several aspects can be discussed. At the motor unit level, Kamen and Knight (2004) had compared the young and older adults' motor unit firing rate following a six-week resistance training program. Dynamic knee extension exercise (3 times per week) on the nondominant knee extensors was performed. Tested with isometric knee extension at 10%, 50%, and 100% MVC, their study results suggested an increase in motor unit firing rates at 50% and 100% MVC in both young and older adults, with the young adults showing higher firing rates. Nonetheless, there's no difference in firing rates at 10% MVC for both groups. Due

to the higher excitability and greater resistance to fatigue of smaller motoneurons, based on sized principle (Enoka, 2015; Gardiner, 2011), we may infer from the finding that the older adults remained more slower motor units than faster and larger ones (Geadiner, 2011). An experiment done in mice had also suggested that there was a decline in denervated neuromuscular junctions as age advancing, especially in fast-twitch muscle fibers. However, the authors implied that a decline occurred in axon level rather than the amount of cell body per se (Chai et al., 2011). Additionally, Erim et al. (1999) mentioned in their study that motor unit recruitment pattern changes through aging. They concluded that older adults had greater motor unit firing fluctuation, a decreased common drive, and a decreased average firing rates during a slow ramp to isometric contraction. Tracy et al. (2005) also concluded that greater force fluctuation was observed in the older adults, and it was suggested to be associated with relative greater motor unit firing variability.

No change was detected in both groups with 20% and 60% MVC from pre- to post- and post- to de-training separately. It had been suggested that 2-3 times of training sessions per week for novice subjects were ideal for strength improvement (Komi, 2011). Most of previous studies presenting MEP response change had trained their subjects 3 times per week. For example, Griffin and Cafarelli (2007) reported an increased MEP response with 3 times per week over 4 weeks. Moreover, Mason et al. (2020) had also reported an increased MEP response with 3 training sessions per week over 2 weeks. In contrast to the current study, our training frequency was twice per week, which was lesser than those studies that elicited significant MEP response changes. The lower training frequency may be one of the reasons for the absence of MEP response change following training. Rather than frequency, short detraining duration may lead to the lack of MEP change after the detraining period. Data acquired from integrated EMG (IEMG) following 60 days of unilateral strength training and 40 days of detraining showed a decrease in the trained leg IEMG in Narici et al.'s (1989) study. In addition, Häkkinen et al. (2000) also concluded that short-term detraining period (3 weeks) only causes small change. These results implied enough time for detraining is required to see the effect.

The absence of group difference was in agreement with earlier research, despite that a previous study has reported a higher MEP response in young adults than the older adults (Picher et al., 2003). The target muscle was an upper limb muscle (flexor digitorum indicis) (Picher et al., 2003), which was suggested to show greater MEP response as comparing the young and the older adults (Rozand et al., 2019). Conversely, research had also measured one of the lower

limb muscles (vastus lateralis) and concluded that there's no age difference in MEP response (Rozand et al., 2019). The current study targeted at RF muscle from physically active healthy subjects, this could, at least, partially explain the lack of MEP response alteration following resistance training and detraining. Moreover, the absolute MEP response (mV) in the current study was in line with a previous study (Oliviero et al., 2006) that the young subjects have greater response than the older. The current study showed greater absolute MEP peak-to-peak response in the young adults than the older adults, but they also exhibited significantly greater M_{max}, which may be why the normalized MEP did not show group differences (Christie & Kamen, 2013; McGinley et al., 2011).

9.2 Corticospinal inhibition: cortical silent period (cSP)

The results suggested a general longer cSP in the older adults, especially with the muscle contraction level at 20% and 60% MVC at 120% aMT. No significant cSP alterations following training and detraining period were found in both groups.

Longer cSP in older adults matched McGinley et al.'s (2010) study result. They had reported that the older adults (70.9±1.8 years) had longer corticospinal inhibition and intracortical inhibition when compared to the young (21.4±0.8 years). However, some other studies suggested differently. Oliviero et al. (2006) studied cSP in a group of young (26±4 years) and a group of older subjects (71±6 years) with TMS on first dorsal interosseous muscle. cSP was measured with 50% MVC muscle activation background. The results reported that the older group had significantly shorter cSP than the young. Christie & Kamen (2014) also conducted a study aiming to investigate age-related differences in the short-term training neural adaptations. A shorter cSP was shown in the older compared to the young.

The discrepancies of cSP results were found across studies. Additionally, it was challenging to compare study results because various experimental designs were applied among studies. For example, study populations, protocols, TMS coils, and the definition and judgement of cSP. As much as I know, more studies suggested a shorter cSP in older adults than in the young adults (Christie & Kamen, 2013; Oliviero et al., 2006; Sale & Swmmler, 2005). Current study revealed a similar cSP result as McGinley et al.'s, (2011). Some methodological factors may contribute to the discrepancy. First, various study and experimental designs were applied. The current

study had a relatively small sample size. Some studies applied rMT (Sale & Semmler, 2005) while some used aMT (Christie & Kamen, 2013; McGinley et al., 2011; Oliviero et al., 2006) to measure cSP.

Second, the hardware. Choosing a proper coil is important for producing reliable results. Current study used double cone coil for the rectus femoris muscle. To be consistent on the stimulation site, we put a marker on the subject's scalp after defining the hotspot. However, since the coil was holding manually throughout the whole testing session, some slight errors caused by minor movements of the coil could influence the stimulation spot. This was also one of the limitations in the current study.

Third, cSP trials varied among studies. It was suggested in Hupfeld et al.'s (2020) review paper that identical trials as acquiring reliable MEP (at least 20 trials) was recommended. Moreover, as processing cSP data, studies defined differently regarding the onset of cSP. Some studies defined the onset of cSP from the TMS stimulation artifact (Colomer-Poveda et al., 2020; Tazoe et al., 2007), some from the onset of a MEP (McGinley et al., 2011), while others from the offset of a MEP (Oliviero et al., 2006). Additionally, some studies, including the current one, visually inspected and manually marked down the onset and offset of cSP, which may influence the results' reliability. For the purpose of reducing variability, the present study defined the onset of cSP at the TMS artifact, which the MatLab configuration could precisely locate each of it. However, there were cases showing unclear offset of sEMG, such as an EMG breakthrough (the presence of EMG signals during cSP) or a gradual restoration of the sEMG signal. It would influence the judgement. Even though it was suggested by Hupfeld et al. (2020) that including the sEMG breakthrough as a part of cSP is more recommended, data analyses in current study were done by different master's degree students, we could not be certain that all the analyses were done based on the same judgment.

With a physiological aspect, both longer spinal and intracortical inhibition were found in previous studies, as compared the older to the young adults. It had been reported that cSP had two origins: the spinal and the cortical origin (Chen et al., 1999; Inghilleri et al., 1993). The total duration of cSP was suggested to be roughly 200 ms and it had been established that the initial part (50ms) was spinal oriented, including after-hyperpolarization and activation of recurrent inhibition of activated motoneurons. The later part (>50ms) was most likely due to the intracortical inhibitory mechanisms (Cantello et al., 1992; Chen et al., 1999; Inghilleri et

al., 1993). Research had described a longer after-hyperpolarization as age advancing (Piotrkiewicz et al., 2007). Furthermore, it had been reported that older adults (70.9±1.8 years) increase in intracortical inhibition and decrease in intracortical facilitation, compared to the young adults (21.4±0.8 years) (McGinley et al., 2010). This finding described the possibility of increasing the GABA mediated intracortical inhibition through aging (McGinley et al., 2010). Based on above mentioned research results, it is possible that the older subjects have longer spinal and intracortical inhibitory effects on the corticospinal tract, leading to an overall increased cSP.

No cSP changes were detected following training and detraining period in both groups. Literatures had inferred a decrease in cSP following resistance training. Christie & Kamen (2014) recruited both young (21.9 ± 3.1 years) and older subjects (72.9 ± 4.6 years) and allocated them to trained and control groups. Following two weeks of dorsiflexor isometric training (3 times per week), they reported a decrease in cSP in both trained young and older subjects. In Kidgell & Pearce's (2010) research, they focused on the isometric strength training effect on the cSP. Sixteen right-handed college students were involved in the study and were allocated into training and control group. After 4 weeks of isometric resistance training on flexor digitorum indicis muscle (3 times per week), a significant cSP reduction was observed in the trained subjects. Conversely, Tazoe et al. (2007) had reported no cSP change following a single session of resistance training with both 25% and 75% MVC elbow flexor training. The authors implied that a single session of light load and heavier load of training were not sufficient enough to elicit corticospinal inhibition mechanisms working. Similarly, lacking cSP change in current study could also be elaborated that the training frequency was not enough to elicit neural response after the training period.

9.3 Muscle strength: MVC and 1RM performance

Current results indicated that the young adults had significant greater MVC and 1RM performance than the older adults at all testing time points. Further, significant MVC improvement was found in the older adults after the training program. Both young and older adults had an evident 1RM performance improvement after the training period and a decrease after the detraining period.

As expected, the young adults have greater MVC and 1RM performance than the older adults, which was in line with most of the studies (Christie & Kamen, 2014; Keller & Engelhardt, 2014; Kittilsen et al., 2021). With advancing age, loss of muscle mass and strength had been reported (Ikezoe et al., 2011; Keller & Engelhardt, 2014). Decreased physical activity level in older populations was reported to be one of the reasons for the loss of muscle mass and strength. With regular physical activities, age-related loss of muscle mass and strength was suggested to be preventable (Goodpaster et al., 2008). In addition, the level of sex hormone and growth factor decline may contribute to muscle mass loss as well, which was suggested to result in muscle and bone tissue catabolic (Priego et al., 2021). The decreased function of motoneurons was another factor leading to muscle mass and strength loss. Chai et al. (2011) performed an experiment in mice that had suggested a decline in denervated neuromuscular junctions, especially in fast-twitch muscle fibers.

The improvement in MVC in older subjects following resistance training matched most of the study results. Christie and Kamen (2014) reported in their study that a short-term isometric resistant training (3 times per week for 2 weeks) was beneficial for MVC improvement in both trained healthy young and older adults. Bårdstu et al. (2020) also performed a study in older adults with functional or medical disabilities receiving home care service (all subjects were above 70 years old, and the median age was 86.0). Resistance training program was offered twice per week, lasted for eight months, and was executed by trained instructors. MVC improvement was found in knee extension.

The lack of de-training effect in MVC performance could be explained by the short period of detraining, which may not have been enough to see the change. In Häkkinen et al.'s (2000) study, comparison could be made between detraining period of three weeks and twenty-four weeks. Despite the fact that the study used 1RM as the outcome measure, the result presented a greater muscle strength decrease following twenty-four weeks of detraining period. This inferred that perhaps a longer detraining time is needed to elicit detraining effects, or the effects were not measurable with the methods the study employed. In addition, lacking MVC change in young adults was consistent with Lowndes et al.'s (2009) study results, which suggested that age was not associated to the training induced MVC changes and was inversely correlated with 1RM change. Additionally, the absence of MVC change may resulted from training specific effect as well. The experiment done by Siddique et al. (2020) examined whether corticospinal and muscular performance responses were modulated in a task-specific manner. Forty-two

right-handed subjects were recruited and allocated to four groups: control, paced isotonic strength training (PST), self-paced isotonic strength training (SPST), and isometric strength training (IST) group. Following 4 weeks of elbow flexor training (three times per week), PST and SPST group had an increase in 1RM performance while the IST group showed improvement in MVC performance. The finding suggested that strength training effect is task specific.

Significant differences in 1RM performance were found in both groups from pre- to post-training and from post- to de-training testing time points, which matched most of other study results (Häkkinen et al., 2000; Kittilsen et al., 2021). In addition, our training program involved dynamic movements. In terms of task-specific principle, 1RM performance improved more evident than MVC's in both groups, which had been explained above. Due to the detraining effect, both groups had a decrease in 1RM performance. Despite that a significant 1RM decrease was detected following four weeks of detraining, Häkkinen et al. (2000) still suggested that a shorter-term of detraining may evoke only minor strength change by comparing a 3-week detraining and a 24-week detraining period.

9.4 Limitations of the study

Force generation is closely related to motor unit behaviors (Enoka, 2015; Gardiner, 2011). In theory, an increase in MEP response with a decrease in cSP may lead to greater muscle strength (Kidgell & Pearce, 2010; Mason et al., 2019 & 2020; Siddique et al., 2020). A study done by Jensen et al. (2005) had examined the correlation between MEP_{max} and muscle strength. They concluded a lack of correlation between each other, suspecting if corticospinal excitability change was functionally important to the increase in muscle strength.

Similar to the conclusion from Jensen et al.'s (2005) study, the present study results did not reflect neural adaptation to resistance training. Several limitations in our study might be partially influential to the results. First, the study had a small sample size. It could be one of the reasons for the underpower of statistical analysis. For example, the post-hoc analysis for MEP/M_{max} could not detect pairwise difference. Second, the training program was designed at a frequency of twice per week, which might be insufficient to elicit neural adaptations, or the adaptive change was not evident enough to be detected. Most of the related studies had a

resistance training program at a training frequency of three times per week (Carroll et al., 2002; Kidgell & Pearce, 2010; Griffin & Cafarelli, 2007; Jensen et al., 2005). Whether the training frequency was enough to elicit observable neural adaptation is questionable.

Further, several studies had trained heir participants isometrically, then performed the measurement with isometric contraction (Griffin & Cafarelli, 2007; Kidgell & Pearce, 2010; Nuzzo et al., 2017). In contrast, our subjects were trained with isotonic contraction and performed all the measurement except for 1RM performance test with isometric contraction. There may be some task specific effects, but we did not get it involved. Moreover, except for the neural factors, muscle hypertrophy would lead to strength gain as well. The current study did not include body composition data, which was difficult to tell if the strength gain was mainly due to neural adaptation. The methodologies used in present study had limited us to locate the potential adaptation sites. The result could only be concluded by answering if there was neural adaptation occurred or not. Plus, CST was the only neural tract we studied. Apart from CST, there are other neural structures contributing to human motor output, such as reticulospinal tract. It could also be possible the adaptation for strength improvement had happened on other neural structures rather than CST.

Last, even though the study randomized the stimulation sets, a new randomization was done prior to each testing session. In other words, each subject experienced a completely different stimulation set order in each testing session. This may cause fatigue effects to some of the subjects. Some research had mentioned that older adults were more susceptible to muscle fatigue (Baudry et al., 2007; McNeil & Rice, 2007). There are two origins for muscle fatigue: central fatigue and peripheral fatigue. Central fatigue reduces motor unit firing rates, subsequently, influence peripheral activation. Peripheral fatigue is situated in the muscle cell level, such as the decrease in contractile function and energy supply (Gardiner, 2011). Since the subjects were required to perform isometric muscle contraction at their 60% MVC, which was relatively high. Plus, some randomization orders would require the subjects to perform 60% MVC contraction in a row, peripheral muscle fatigue may occur. During the process, we did not monitor fatigue signs from sEMG data either. A higher MEP response at such muscle activation level might be a compensation from the CNS to help maintaining the force level.

10 CONCLUSION

The present study compared the neural adaptation between young and older adults following a resistance training program. The finding suggested that muscle strength improvement was not accompanied with CST adaptation. However, our results also implied that having resistance training twice per week for at least six weeks was effective in improving muscle strength. Both young and older adults were responsive to resistance training. Moreover, training specificity effect should be considered while designing a training program. Present study also suggested that detraining for four weeks was long enough to see minor strength lost. Collectively, current study did not detect neural adaptation following resistance training across time. However, for the purpose of strength maintenance or improvement, both young and older adults would be beneficial from a resistance training program that trained at least twice a week over 6-7 weeks, and the training load was roughly 70%-80% of 1RM.

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