The Effect of Attentional Focus Cues on Corticospinal Excitability and Neuromuscular Efficiency during a Sustained Task:

By

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Abstract

Attentional focus has been studied in the context of physical activity and sports as a form of feedback or instruction that aims to improve performance by directing a person's focus either externally or internally. Adopting an external focus (i.e., focus on goals and environment) has been shown to be beneficial to performance relative to an internal focus (i.e., focus on self and body movements) for a range of tasks. However, little is understood about the mechanisms underlying improved performance associated with external focus. Emerging neuroimaging studies have shown changes in brain activity relative to the direction of attention, and data from electromyography shows changes at the muscular level. To bridge the gap in knowledge between what is seen in the brain and the muscle during external and internal focus, we explored corticospinal excitability, which is the connection between brain and muscle and reflects the ability of the motor cortex to generate movement. Understanding the relationship between attentional focus and corticospinal excitability is important for advancing our understanding of basic neural mechanisms and informing the development of interventions aimed at improving motor function and physical performance in individuals.

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List of Abbreviations

EF	External Focus
IF	Internal Focus
FOA	Focus of Attention
EMG	Electromyography
iEMG	Integrated Electromyography
TMS	Transcranial Magnetic Stimulation
TMES	Transmastoid Electrical Stimulation
CMEP	Cervicomedullary-evoked motor potential
CSE	Corticospinal Excitability
CNS	Central Nervous System
MVC	Maximum Voluntary Contraction
M_{max}	Maximal Muscle Compound Potential
M1	Primary Motor Cortex
SMA	Supplementary Motor Area
fMRI	Functional Magnetic Resonance Imaging
TTF	Time to Task Failure

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Chapter 1.0 - Introduction

1.1 Overview

At any given moment, we are inundated with sensory information that demands our focus of attention (FOA). Thus, the ability to selectively attend to relevant information while filtering out irrelevant distractions is a fundamental cognitive skill (Wiley & Jaroza, 2012). Selective attention strategies also play a critical role in a variety of physical activities, and a growing body of literature suggests that the direction in which we focus our attention can promote or hinder physical performance (Grgic & Mikulic, 2022; Lorenz-Spreen et al., 2019; Wulf, 2013). Our selective and conscious attention, termed attentional focus, is directional in that we can focus 1) externally, that is, placing our attention on our environment and movement effects, or 2) internally, where our focus is directed towards ourselves or body movements (Wulf, Ho¨ß, & Prinz, 1998; Wulf, McNevin, & Shea, 2001; Wulf, 2013).

The majority of attentional-focus research evaluates the effect of direction of focus on observable task performance. Research suggests that external focus (EF) is beneficial to performance compared to internal focus (IF) (Wulf, 2013). For instance, Halperin et al. (2016) observed a 9% higher peak force production during an isometric mid-thigh pull when participants adopted EF. Marchant et al. (2009) found that EF resulted in significantly greater force production during isokinetic elbow flexions when compared with IF. Similar results of the benefits of EF are reported for tasks that involve accuracy, force and endurance (Chua et al., 2021; Wulf, 2013; Schücker et al., 2009; Schücker and Parrington, 2019)

While research demonstrates the benefits of adopting EF, little is understood about the neural and physiological mechanisms associated with this improved performance (Chua et al., 2022; Kuhn et al., 2017; Wulf, 2013; Wulf & Lewthwaite, 2016). Commonly, electromyography

(EMG) is employed in attentional-focus research to offer insight into neuromuscular activity relative to the direction of focus and changes in performance (Wulf, 2013). EF is often associated with reduced EMG, suggesting reduced overall muscle activity; and optimal co-activation of agonist and antagonist's muscles, which together might facilitate improved performance (Chua et al., 2021; Grgic, Mikulic & Mikulic, 2021; Marchant et al., 2009; Wulf, 2013). More recent neuroimaging studies have included functional magnetic resonance imaging (fMRI). Imaging studies suggest that the direction of focus might differentially activate areas of motor planning and execution areas in the brain (Zentgraf et al., 2009; Zimmerman et al., 2012). Unfortunately, fMRI is limited to cortical activity and is unable to distinguish between the excitation and inhibition of motor units and the muscle they innervate (Kuhn et al., 2017).

While offering insight for future research, the evidence from surface EMG and imaging studies alone do not address the persistent lack of detailed mechanistic evidence for attentional focus and, thus, warrants a deeper dive into the neuromuscular system. Our lab has previously investigated the neural correlates of attentional focus by measuring EMG, force, and changes along the corticospinal tract during maximal voluntary contractions (MVC) of the elbow flexors (Wiseman et al., 2020). Researchers found that co-activation of the elbow flexors, measured using EMG, was reduced, and force output was greater when EF (focus on pulling up on the handle) than IF (focus on contracting your biceps) was cued. The improved performance and evidence of more efficient use of neuromuscular resources align with the bulk of attentional focus research that utilizes similar experimental protocols (Wulf, 2013). However, the results did not demonstrate that corticospinal excitability (CSE), which reflects the ability of the motor cortex to generate movement, was differentially modulated by the direction of focus as anticipated. The authors provided methodological considerations around stimulation, suggesting that the corticospinal tract might not have been optimally stimulated. Their study determined the stimulation intensities during a 5% MVC but was given during a 100% MVC. To replicate a similar experimental protocol, the cues in the current study were adapted from those in Wiseman et al. (2020) to reflect a sustained rather than maximal task. To address their methodological considerations, stimulation intensities were set during a contraction at 10% of MVC and given during a sustained contraction at 50% of MVC. Thus, the current study aims to expand on previous work by measuring CSE throughout a sustained submaximal elbow flexor force production task to fatigue instead of during repeated maximal voluntary contractions (MVC). The present study will also consider MVC force and endurance (time to task failure) performance measures.

1.2 Purpose

The purpose of the proposed study is to investigate if the direction of focus differentially modulates corticospinal excitability (CSE) and if there are changes in physical performance. We will compare co-activation patterns of the biceps brachii and triceps brachii using electromyography (EMG) and use the length of time in which the person can sustain a submaximal contraction (i.e., time to task failure (TTF)), and maximal force output (MVC) as measures of performance. To measure CSE, we will employ stimulation techniques throughout the sustained contraction, including transcranial magnetic stimulation (TMS), transmastoid electrical stimulation (TMES), and brachial plexus stimulation at Erbs's point, which elicit a motor evoked potential (MEP), corticomedullar evoked potential (CMEP) and maximal muscle action potential (MMAX), respectively. Together these measures may provide mechanistic insight into how EF and IF cues affect task performance.

1.3 Research Hypotheses

It is hypothesized that:

1. Mean EMG and Co-activation will be higher with an IF-cued contraction (Triceps/biceps brachii EMG)
2. CSE, measured using MEP, CMEP and MMAX parameters, will be differentially modulated between EF and IF cued contractions.
3. MVC EF > MVC IF (Force, N)
4. EF endurance performance > IF endurance performance (TTF)

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Chapter 2.0 - Review of Literature

2.1 Introduction

Over the last two decades, motor performance and sport psychology researchers have extensively investigated the impact of attentional focus (AF) on human movement (See Chua et al., 2021; Wulf, 2013; Park et al., 2015 for reviews). Attentional focus (AF) is a type of instruction which directs a performer's conscious attention and can be categorized by direction as either 1) External or 2) Internal (Nideffer, 1976; Wulf, Hoss, & Prinz, 1998; Wulf, 2013). External focus (EF) means to direct our attention toward a goal or object (movement effects). For example, EF would direct your focus on the bull's eye during a game of darts. In contrast, internal focus (IF) means directing conscious attention toward our body movements. In the same dart-throwing scenario adopting IF would direct your focus on your arm position as you release the dart. In sports and exercise, the conscious effort to focus our attention externally can catalyze a positive outcome (Lauber and Keller, 2014; Park et al., 2015; Wulf, 2013).

The literature supports adopting an EF as beneficial to performance for skills requiring force (Halperin et al., 2017; Wiseman et al., 2020), power (Zachry et al., 2005), balance abilities (Becker & Hung, 2020) and, in some cases, endurance (Schücker and Parrington, 2019). Positive outcomes associated with EF are generally consistent across the lifespan of the average healthy individual and in some clinical populations (Abdollahipour & Psotta, 2017; Chiviacowsky, Wulf & Wally, 2010; Chua et al., 2021; Chiviacowsky et al., 2012; Wulf, 2013; Piccoli et al., 2018). Conversely, adopting an IF has been shown to hinder each of these performance measures (Chua et al., 2021; Wulf, 2013). For instance, Marchant et al. (2009) found that when participants were instructed to adopt an external focus (EF) rather than an internal focus (IF), force output was significantly greater during an elbow flexion task. Similarly, Halperin and colleagues (2017) found that intermediate and expert combat athletes' performance improved when an external focus was instructed, evidenced by increased punching velocity and force. Regarding endurance, or the ability to sustain a task, Lohse & Sherwood (2012) found that EF instruction increased time-to-task failure (TTF) and reduced perceived exertion during a sustained wall-sit task.

Despite the extensive descriptive documentation supporting EF for a range of tasks, more exploratory evidence is needed to best inform coaching, training, and rehabilitation practices that aim to optimize movement and, in turn, client outcomes (Chua et al., 2021; Kuhn et al., 2017; Wulf, 2013). The constrained action hypothesis proposed by Wulf and colleagues (McNevin et al., 2003; Wulf et al., 2001) is commonly accepted to explain the effects of focus on motor performance and is generally supported by surface EMG and observable changes in performance. According to this theory, IF elicits conscious control of the movement, constraining the motor system and contributing to poorer performance through inefficient and ineffective neuromuscular coordination. However, the mechanisms underpinning the theorized constraint have not been fully defined. To test this theory and expand mechanistic evidence, our lab has previously measured performance and corticospinal excitability (CSE) during a repeated maximal force task of the elbow flexors where either EF or IF was cued (Wiseman et al., 2020). While no change in CSE was observed, the protocol was associated with significantly greater MVC force when EF was cued (Wiseman et al., 2020). Others have used fMRI to identify the neural correlates of attentional foci, yet there is still no definitive mechanistic explanation (Zentgraf et al., 2009, Zimmermann et al., 2012, Kuhn et al., 2017, Wulf, 2013). Thus, our goal is to gather and offer evidence on potential mechanisms underlying how attentional focus impacts motor performance and movement. This review will first discuss evidence of altered movement efficacy and efficiency relative to the focus direction and the associated impact on performance. We will then examine the facets of force production and the pathway of voluntary movement, including the role of the corticospinal tract. Finally, the techniques used to quantify CSE will be discussed.

2.2 Attentional Focus

Movement Effectiveness

EF is commonly associated with enhanced aspects of motor performance, including more effective movements and improved task outcomes compared to IF for tasks that involve balance, accuracy, force and, in some cases, endurance (Wulf et al., 1998; Park et al., 2015; Wulf, 2013; Chua et al., 2021; Grgic & Mikulic, 2022). Early work from Wulf, Ho¨ß, & Prinz (1998, Experiment 2) found that directing participants' attention externally (focus on device) led to more effective balance learning compared to directing an internal focus (focus on feet). Balance performance and learning, typically measured by deviations from a balanced position, has since been widely observed as more effective when EF rather than IF is adopted (Chiviacowsky et al., 2010; McNevin et al., 2003; Wulf et al., 2009). The benefits of EF are also observed in target-orientated tasks (Wulf, 2013). Zachry et al. (2005) studied basketball free throws to compare the accuracy of throws when EF (basket) and IF (wrist movement) were instructed. Free throw accuracy was greater when EF was adopted, and EMG activity of the biceps and triceps brachii was simultaneously lower compared to IF-cued throws. Similarly, Loshe (2010) reports less error and decreased EMG activity in the triceps brachiii when EF was adopted during a dart-throwing task, suggesting improved movement effectiveness and efficiency. Loshe et al. (2011) paired measures of accuracy and force by instructing participants to apply 30% of their maximal force by pressing their foot against a force platform. When participants adopted EF (focus on the platform) compared to IF (focus on calf muscles), force production was more accurate. Co-

contractions between agonist (soleus) and antagonist (tibialis anterior) muscles were also reduced. Similar positive effects on maximal force production have been observed for tasks that involve the upper limbs. In our lab, Wiseman et al. (2020) found that maximal force output was greater during repeated isometric MVC of the elbow flexors with EF. They also reported decreased force output and increased co-activation of the antagonist and agonist muscles (triceps brachii/biceps brachii) during IF.

It has been suggested that improved neuromuscular efficiency could contribute to more effective movement control, thus leading to enhanced performance outcomes (Chua et al., 2021; McNevin et al., 2003; Wulf et al., 2001; Wulf, 2013). In contrast, IF is associated with inefficient movement patterns and greater neuromuscular activation, which could hinder performance for the same task. These assumptions are widely accepted for tasks that require balance, accuracy, and force, where EF is associated with acute positive effects on performance (Wulf, 2013; Chua et al., 2021; Grgic & Mikulic, 2022). However, in longer-duration tasks, such as those requiring submaximal or maximal force production over an extended period, there is not a clear consensus on the effects of foci (Grgic & Mikulic, 2022). In sustained muscle contractions, declines in the motor system can occur that might impact endurance or the ability to perform the task (Kluger et al., 2013).

Movement Efficiency

For this review, neuromuscular efficiency is defined as a decrease in measures of neurophysiological resources for the same task (Farina et al., 2004,2014). For tasks that require force, when focus is directed externally, performers typically exhibit a more efficient use of neuromuscular resources (i.e., decreased EMG) (Wulf, 2013; Chua et al., 2021. To illustrate, Vance et al. (2004) measured integrated EMG activity (iEMG) during a biceps curl task to examine muscular activity under external (focus on the bar) and internal (focus on the arm) focus instruction. For the same task, EMG activity of both the antagonist (triceps brachii) and agonist muscles (biceps brachii) was significantly less with EF than IF. Marchant et al. (2009) studied the force output of the elbow flexors using an isokinetic dynamometer while the electromyographical activity of the biceps brachii was measured. The task and instruction were similar to Vance et al. (2004), and participants were instructed to focus on the arm and muscles (internal) or toward the curl bar (external). Authors report a significant main effect of focus; when EF was instructed, mean EMG and mean iEMG decreased, and simultaneously peak net joint torque increased compared to IF.

The performance advantage of EF has been consistently observed for tasks that rely on producing maximum force for optimal performance (Wulf, 2013; Grgic & Mikulic, 2022). Among the tasks studied, endurance exercise has received comparatively less attention, and there is no clear consensus on how foci influence muscular endurance (Wulf, 2013; Chua et al., 2021). Muscular endurance can be described as the ability of muscles to contract and sustain a load for an extended period; this ability depends on many factors, including the consummation of physiological resources (Kell et al., 2001). In theory, more efficient use of physiological resources could improve endurance. Schücker and Parrington (2019) studied running economy by measuring oxygen consumption using spiroergometric, and participants were instructed to focus internally (breathing and movement) or externally (video on screen). When focused on a video (EF), participants running economy improved, evidenced by lower oxygen consumption, a marker of improved efficiency. In contrast, a less efficient running economy was observed when focused internally. In another lower body-focused study, Nolan (2011) assessed the effects of either external (imagine sitting on a chair) or internal (focus on knee angle) focus on endurance during an isometric wall sit. They found EF was associated with a longer wall sit (s). Relevant to the upper limb, Marchant et al. (2011) found that the number of repetitions performed with EF (focus on the bar) was greater than IF (focus on limbs involved) during three different exercises (smith machine bench press, free bench press, and free squat). However, to our knowledge, the effects of attentional focus on a submaximal isometric task of the upper limb have yet to be studied.

The means used to assess the use of neural and physiological resources is attentional focus research is often limited, and much of the data has been observational rather than exploratory. EMG is commonly used to identify neural activity relative to the direction of focus, and while it provides a global indication of nervous system output, there are limitations. EMG alone cannot provide information about excitations and inhibition in the nervous system, which is crucial for understanding the mechanisms behind how focus affects performance (Farina et al., 2004, 2014). A few studies have focused on the supraspinal and spinal centers to better explain the mechanisms underlying attentional focus and provide evidence for the theoretical framework examined in the following section. Researchers have begun employing functional magnetic resonance imaging (fMRI) to identify the neural centers associated with EF and IF. In a keyboard task studying movement execution, participants were asked to focus on their fingers (IF) or focus on the keys (EF) (Zentgraff et al., 2009). Using fMRI, authors observed an increase in blood oxygen level-dependent (BOLD) response under an EF (focus on keys) in areas necessary for the independent movement of the fingers and wrist, including the primary motor cortex, primary somatosensory cortex, and the insular region of the left hemisphere (Zentgraff et al., 2009; Chauoinard & Paus, 2006; Maier et al., 2002). These publications, however, present innate limitations, given that fMRI does not distinguish between inhibition and excitation (Zentgraff et al., 2009; Zimmerman et al., 2012; Kuhn et al., 2017). Thus, the larger question remains, what system(s) facilitate improved learning and performance when EF is adopted?

2.2.1 Theoretical Framework

The detriments and advantages of attentional focus instruction on performance are often explained using the constrained action hypothesis (McNevin et al., 2003; Wulf et al., 2001). According to this viewpoint, IF evokes conscious control of the system and is attentionally demanding, interfering with automatic motor control processes and hindering performance (McNevin et al., 2003; Wulf et al., 2001). Wulf and Lewthwaite (2010) contend that the constraint on the motor system associated with IF causes 'micro-choking' episodes marked by less effective movement coordination and muscular activity, which degrade performance. Conversely, EF allows automatic system control and promotes fast unconscious or reflexive motion (Wulf and Lewthwaite, 2010). Furthermore, performers are thought to free up attentional resources by focusing on movement effects (EF), allowing the motor control system to interpret environmental stimuli more effectively (Wulf, 2007; Wulf and Lewthwaite., 2010).

Research supporting the constrain action hypothesis often includes non-invasive surface electromyography (EMG) which detects the cumulative electrical activity generated in muscle fibres in response to activation (DeLuca, 1997; Farina et al., 2004,2014). For instance, Zachry and colleagues (2005) assessed the accuracy of basketball free throw shots when the performer's attention was directed internally (wrist motion) and externally (basket). The authors report that task accuracy was more significant when participants adopted EF. Simultaneous co-activation of the biceps and triceps brachii was reduced, indicating more effective coordination of agonist and antagonist muscles (Zachry et al., 2005). The findings suggest that EF (basket) may reduce "noise" in the motor system, typically making the movement less reliable. Conversely, adopting

IF (wrist motion) seems to constrain the motor system, leading to freezing the neuromuscular degrees of freedom and decreased accuracy (Zachry et al., 2005). Similar evidence has been provided by Wulf et al. (2010), where increased jump height coincided with reduced EMG when EF was adopted. Wiseman et al. (2020) reported greater force production and more efficient co-activation of antagonist and agonist muscles of the upper arm during repeated maximal voluntary contractions (MVC) during EF.

Some neuroimaging research suggests that EF instruction activates cortical regions associated with vision (i.e., occipital lobe, cuneal cortex & lingual gyrus) and ventral streaming pathways, allowing for more automatic motor control (Raisbeck et al., 2020; Zentgraf et al., 2009). In contrast, activity within the cortical regions responsible for motor control (i.e., pre-central gyrus, postcentral gyrus, and cerebellum) is increased when IF is instructed (Raisbeck et al., 2020). The increased activity within the motor planning and control centers, observed when the focus is directed internally, is thought to interfere with faster automatic motor processes, thus constraining the system and hindering performance (Raisbeck et al., 2020; Wulf et al., 2001). EF is instead believed to mediate afferent input to the motor cortex, allowing for automatic or reflexive movement and facilitating optimal motor performance (Raisbeck et al.,.2020; Wulf et al., 2001; Wulf and Lewthwaite, 2016; Suzuki & Meehan, 2020). The constrained action hypothesis offers a testable explanation about the influence of attentional focus instruction on performance (Wulf, McNevin, & Shea, 2001; Wulf & Lewthwaite, 2010).

2.3 Voluntary Movement

In attentional-focus research, surface EMG data from relevant muscles are frequently analyzed during voluntary movement, including MVCs and sustained tasks. This data is used as evidence to understand the neuromuscular events that could explain changes in performance concerning the direction of focus (Wulf, 2013). However, while EMG provides valuable insights into muscle activation patterns and overall neural activity, it alone cannot reveal excitation and inhibition changes that allow signals to propagate from the central nervous system (CNS) to the muscle (Farina et al., 2004, 2014). To a lesser degree, some neural imaging has identified areas of the cortex that are differentially activated by focus, and few have identified potential changes in the excitability and inhibition of neural drive to the muscle using stimulation techniques (Zimmermann et al., 2012, Kuhn et al., 2017, Wiseman et al., 2020, Wulf, 2013). According to the constrained action hypothesis, IF impairs voluntary movement, and potential mechanisms underlying their theory might lie within the neuromuscular system (McNevin et al., 2003; Wulf et al., 2001, Wulf, 2013). For instance, when IF is cued, force production is hindered and co-activation, whereby agonist muscle activity decreases and antagonist muscle increases, has been observed to increase, which might contribute to poorer performance outcomes (Loshe et al., 2011; Wiseman et al., 2020). Changes in EMG patterns could be attributed to altered synaptic input and the recruitment or rate of graduation of motor units. To better understand how focus can influence motor output, specifically force production, this review will examine the pathway of voluntary movement and how the neuromuscular system can adapt to act more efficiently.

2.3.1 Synaptic input

The synaptic input that drives voluntary muscle contraction originates from supraspinal, or brain centers, where multiple areas communicate and connect to initiate and control motor output or movement (Heckman et al., 2009; Schwartz, 2016). While the entirety of mechanisms underlying voluntary movement are not fully established, studies have identified networks of different brain areas, namely, the prefrontal cortex, supplementary motor area (SMA), and parietal cortex, that underlie voluntary action (Virameteekul & Bhidayasiri, 2022). In the prefrontal cortex, thoughts, actions, and emotions are regulated through connection with other brain regions, including the motor cortex, for motor planning and execution (Arnsten, 2009; Yip & Lui, 2023). The SMA is understood to be involved in the self-initiated movement (Stein, 2017). Within the parietal cortex, there is an association between visual, auditory, and proprioceptive input, lending it a role in allocating attention (Stein, 2017).

To elicit motor output, the cortical centers involved in voluntary movement send excitatory or inhibitory signals to the periphery via input to spinal motor neurons by way of spinal interneurons or direct connections (Heckman et al., 2009; Carp & Wolpaw, 2010). Motor commands are communicated along the descending pathways responsible for facilitating gross voluntary movement, including the reticulospinal tract, rubrospinal tract and corticospinal tracts. The descending pathways can be identified based on the point of origin and the primary function. The reticulospinal tracts arise from the reticular formation in the brainstem and are involved in regulating muscle tone and posture and facilitating learned and automatic movements (Carp & Wolpaw, 2010; Haines, 2012). The rubrospinal tract originates in the midbrain's red nucleus, primarily receiving input from the cerebellum and motor cortex. It then transmits signals via synapses with inter- and spinal motor neurons that contribute to the coordination of voluntary arm movement (Martinez-Lopez et al., 2014). The corticospinal tract receives input from the primary motor and sensory cortices, synapses on an interneuron in the medulla, and descends to contract muscles in the contralateral limbs and trunk (Haines, 2012). The corticospinal tract is primarily responsible for controlling gross muscle activation and is largely excitatory due to glutamate and aspartate in most of its terminals (Haines, 2012). Relevant to the current study, which includes contractions of the elbow flexors, the corticospinal fibers influence the spinal motoneurons that innervate the muscles of the trunk and limbs (Usuda et al., 2022). In brief, activating spinal motoneurons for the muscle of interest releases neurotransmitters at the neuromuscular junctions, and a depolarization of the muscle fibres follows, initiating a muscle contraction. A range of mechanisms are employed to generate and sustain muscle contraction; these are reviewed in more depth in the following section.

2.3.2 Modulating motor unit activation

Voluntary force production results from the activation of motor units, which consist of a spinal motor neuron and the muscle fibres it innervates within the neuromuscular system (Kernell, 2002; Martin, 2006). Generally, the more motor units activated and the more often these units "fire," the greater the force produced. Muscle force is modulated by varying the number of active motor units (recruitment gradation) and the rate at which these units "fire" (rate gradation) (Kernell, 2002; Enoka & Duchateau, 2017). The net result of excitatory and inhibitory synaptic input is a determining factor in whether a motor unit is recruited and fired (Carp & Wolpaw, 2010). Simultaneously, the motoneuron may adapt to these synaptic inputs, enabling the unit to be more efficiently employed by the system (Carp & Wolpaw, 2010).

Multiple influences on the motoneurons exist, and two systems are essential in motor unit activation. The first, the ionotropic system, exerts its influence by opening ion channels triggered by supraspinal input (Binder et al., 1996; Carp & Wolpaw, 2010). Action potentials are generated through the release of neurotransmitters that bind to ligand-gated ion channels allowing specific ions to enter or exit the cell and facilitating the subsequent depolarization or hyperpolarization of the motoneuron membrane (Burke, 1981, Henneman and Mendell, 1981). The second system is the neuromodulator or metabotropic system, which alters the properties of voltage-sensitive ion channels altering the resting membrane potential or voltage threshold of a designated motoneuron (Kernell, 2006; Heckman et al., 2009). In varying membrane potentials, the system may reduce the voluntary input needed to reach the voltage threshold and allow units to be recruited more efficiently.

The systems mentioned above are critical to consider in the proposed study, given force is the product of recruitment and rate modulation (firing) of motor units (Enoka & Duchateau, 2017; Heckman & Enoka, 2004). Specifically, the motor unit is recruited based on whether the synaptic input generates sufficient depolarization to meet the voltage threshold demands of the motoneuron (Heckman et al., 2009). Thus, motor units can be more efficiently recruited when their designated motor neurons undergo processes to reduce the voltage threshold, reducing the amount of synaptic input required to enable recruitment (Heckman et al., 2009).

Similar efficient practices can arise through the ionotropic and metabotropic systems, which increase the resting membrane potential where less input is required to reach an increased potential and recruit the motor unit (Heckman & Enoka, 2004). In the case of a sustained force production task, rate modulation of motoneurons occurs as there is a continuous generation of action potentials after a motor neuron reaches its threshold (Heckman et al., 2003; Kernell, 2006). Relevant to efficiency, the neuromodulatory system can reduce the amount of synaptic input required to increase the firing rate, which, in combination with recruitment processes, produces muscle twitches, leading to tension and muscle contraction (Binder et al., 1996; Heckman et al., 2003). Generally, as recruitment and firing rate increase, so do muscle twitches which manifest as a more significant contraction (Binder et al., 1996; Heckman et al., 2003; Martin, 2006). In summary, the excitatory synaptic input is a significant determinant in motor unit recruitment and firing rate, which impacts voluntary force production (Del Vecchio et al., 2019).

2.4 Corticospinal Excitability

The positive effects of EF on performance have been attributed to the effective and efficient coordination of the neuromuscular system (Wulf, 2013). However, there is limited evidence on how supraspinal and spinal centers contribute to optimal performance when focus is directed externally. Measuring the excitability of the corticospinal tract can provide insights into the functional state of the CNS and how it influences motor control.

The primary motor cortex (M1), situated in Brodmann area 4, sends most electrical impulses out of the motor cortex and fibers originating in M1 generally terminate in the spinal cord via the corticospinal tract (Yip & Lui, 2023). The nerves within the corticospinal track are critical for gross voluntary movement, including the production and maintenance of force. The excitability of the corticospinal tract reflects the responsiveness or readiness of the neural pathways within this tract to transmit motor commands from the brain to the spinal cord and, subsequently, to the muscles (Weavil & Amann, 2017). In the context of efficiency, alterations in CSE lead to adjustments in the neural drive required for initiating and sustaining muscle contractions (Martin et al., 2006). Decreased CSE, or decreased excitability, requires greater synaptic input to maintain muscle activation (Martin et al., 2006). CSE changes may be associated with various factors, including fatigue, where CSE may decrease, affecting the ability to generate force and maintain muscle contraction (Taylor et al., 2000). In our lab, Wiseman et al. (2020) expected an increase in CSE in combination with an increase in MVC force when EF was adopted, suggesting an increase in central drive facilitated, in part, improved performance. However, while an increase in MVC force was observed, there was no significant change in CSE. The current study measured CSE during a sustained submaximal contraction where an increase in CSE combined with a prolonged TTF is also expected when EF is cued.

To assess CSE, a combination of stimulation techniques is used. Transcranial magnetic stimulation (TMS), which evokes short-latency excitatory responses termed motor-evoked potentials (MEP) in the muscle of interest, is often used in conjunction with transmastoid electrical stimulation (TMES), which elicits cervicomedullary motor evoked potentials (CMEP) can be used (Taylor & Gandevia, 2004; Taylor, 2006). Brachial plexus stimulation is also used to elicit maximal compound action potentials (M_{max}). Using surface EMG, we can record the stimulus-evoked responses and measure various facets of MEP, CMEP and M_{max} to explore corticospinal excitability during sustained contractions.

2.4.1 Transcranial Magnetic Stimulation (TMS)

TMS was introduced as a technique for the non-invasive stimulation of the central nervous system (CNS) (Barker et al., 1985). The TMS technique can be used to study many cortical areas. Of interest to the current study, it has been used to elicit activation of the primary motor cortex (M1), the area responsible for providing signals to facilitate skilled movement (Sira & Mateer, 2014). A range of TMS paradigms can highlight different aspects of corticospinal and cortical excitability (Fried et al., 2017). Those include 1) a single pulse, where a single pulse TMS is delivered over the area of interest, in our case M1, which is used to investigate corticospinal excitability (Reis et al., 2008) and 2) a paired-pulse, where a stimulus is used to investigate cortical excitability, including intercortical and intracortical properties. In either case, a round or figure eight coil is used to generate a magnetic field that penetrates unimpeded through the cranium inducing an electric current in the underlying region of the cerebral cortex (Barket et al., 1985; Grunhaus et al., 2002). If the stimulus intensity is high enough to reach the supraspinal motor threshold, the electric field induces neuronal depolarization and an action potential (Grunhaus et al., 2002; Ugawa et al., 1997; Taylor & Gandevia, 2004). The activation of neural tissue results in a motor-evoked potential (MEP), measured at the muscle of interest using surface EMG.

The principal MEP parameters include motor threshold, amplitude, latency and corticospinal silent period. The motor threshold is the lowest TMS intensity or magnetic stimulation output (MSO) that can elicit a discernible MEP in the muscle of interest at rest or during a contraction (Mills, Kannan, & Nithi, 1998). The peak-to-peak amplitude of each MEP is used as an indicator of corticospinal cell excitation (Rossini et al., 2015). Latency, often defined as the time (in milliseconds) following the TMS stimulus artifact, indicates the time taken by descending impulses to reach the target muscle (Fuhr et al., 1991). When TMS stimulation is given at a high enough intensity, it is possible to stimulate the corticospinal tract directly; these responses are termed D-waves, marked by their latency of approximately 1-1.4 ms (Burke et al. 1993). The silent period is defined as the duration from the onset of the stimulus artifact to when voluntary EMG returns following the evoked response. The silent period reflects changes in the level of GABAergic inhibition imposed on cortical and spinal motoneurons (Ziemann et al., 1995).

In the context of the present study, it is important to note that changes in MEP parameters can occur during a fatiguing task (Taylor et al., 2000). These changes may arise as the CNS experiences increasing impairments during sustained submaximal contractions, consequently reducing the ability to generate force (Taylor et al., 2000; Søgaard et al., 2006). When the contraction is initiated, MEP amplitude is increased in the upper limb muscles, reflecting the increased central drive to the lower motoneurons (Gruet et al., 2013). As the CNS becomes fatigued, it becomes less efficient in recruiting and activating motoneurons, reducing the MEP amplitude post-exercise (Gruet et al., 2013). For the same fatiguing exercise, the duration of the silent period increases as neural networks involved in inhibition increase activity (Taylor et al., 2000).

While limited, emerging research suggests that it is possible to change an individual's corticomotor excitability by manipulating attentional focus. Ruge et al. (2014) demonstrated decreased MEP amplitude when attention is directed internally toward the hands relative to when attention is directed externally toward a visual task. Similarly, Bell et al. (2018) reported that visual attention had a significant effect on MEPs when participants were instructed to focus toward or away from their hands. These data suggest EF might increase cortical excitability, evidenced by increased MEP amplitude. In contrast, Wiseman et al. (2020) found no significant difference in MEPs measured during a maximal force task. Thus, further research is warranted to assess the effects of attention on MEPs, specifically during active and sustained movement.

2.4.2 Transmastoid Electrical Stimulation (TMES)

TMS stimulates the entire corticospinal tract, including the supraspinal (cortical) portion (Cantone et al., 2019). Therefore, growth or reduction of the MEP can result from changes in cortical neurones' excitability or spinal motoneurons (Taylor et al., 2002). TMES only stimulates the spinal portion, and the resulting cervicomedullary motor evoked potential (CMEP) is unaffected by altered cortical excitability (Taylor, 2006). Combining stimulation techniques allows researchers to deduce or break up supraspinal from spinal excitability (Taylor, 2006).

TMES stimulates the descending axons of the corticospinal tract at the subcortical (spinal) level by passing an electrical stimulus between the mastoid processes (Ugawa et al., 1991; Gandevia et al., 1999; Taylor, 2006). A single descending volley (50–100 μs duration, up to 750 V) activates corticospinal neurons, which then recruit motoneurons and evoke a muscle response (CMEP), which can be used as a measure of motoneuron excitability (Day et al., 1987;

Rothwell et al., 1984; Taylor, 2006). CMEPs can typically be evoked in the upper limbs' muscles (Ugawa et al., 1995).

Parameters of interest in a CMEP include latency and amplitude. CMEPs measured with surface EMG at the muscle of interest typically should have a relatively consistent latency, representing the time between electrical stimulus artifact and the response onset (Taylor, 2006). Caution should be made about CMEP latency; an extended latency (~ 2ms) can indicate that the stimulation has shifted to include axons of the cervical ventral roots (McNeil et al., 2013; Taylor, 2006). The amplitude of a CMEP is considered as the excitability of the motoneuron pool and should increase in size during voluntary contraction, indicating increased excitability (Taylor, 2006; Ugawa et al., 1995). Similar to the MEP, during a sustained submaximal contraction of the elbow flexors at 25% to 50% of MVC, CMEPs have been shown to be depressed, which reflects changes in the descending drive required to activate motoneurons (Petersen et al., 2002).

2.4.3 Brachial Plexus Stimulation

To partition the entire system into supraspinal, spinal, and peripheral components, researchers can employ peripheral nerve stimulation. For the elbow flexors, the brachial plexus is stimulated using an electrical current passed between electrodes placed at Erb's Point (fossa, 2-3 cm above the clavicle) and at the acromion process. The resulting maximal muscle response (M_{max}) is measured using EMG at the muscle of interest. The MEP and CMEP, elicited using TME and TMES, respectively, can then be normalized to M_{max}. The process of normalizing accounts for peripheral excitability and highlights changes in the cortical and spinal segments of the corticospinal pathway.

2.5 Conclusion

Research has extensively investigated the effect of attentional focus instruction on performance for a range of tasks, and of interest to the present review those that include force (Halperin et al., 2017; Wiseman et al., 2020), endurance (Schücker and Parrington, 2019), power (Wulf et al., 2009). Studies using EMG demonstrate that EF might allow for more effective and efficient coordination of the neuromuscular system, including optimized muscle coordination and co-activation, thus facilitating improved performance (Chau et al., 2021; Grgic & Mikulic, 2022; Wulf et al., 2009; Wulf, 2013). These EMG studies also support the constrained action hypothesis, which suggests EF facilitates fast, reflexive, and automatic movement, improving performance. In contrast, IF contributes to less effective movement coordination and muscular activity, which degrades performance (Chua et al., 2021; Wulf, 2007; Wulf and Lewthwaite., 2010).

Despite the substantial evidence supporting the benefits of EF for performance, the literature lacks a mechanistic explanation for the influence of attention on motor performance (Grgic & Mikulic, 2022; Kuhn et al., 2017; Wiseman et al., 2020; Wulf, 2013). To bridge the gap in understanding how voluntary movement is influenced by focus direction, we can explore the corticospinal tract, which is the primary excitatory pathway that connects the CNS to the periphery (Chouinard et al., 2006; Usada et al., 2022). Our lab has previously attempted to measure CSE and was unable to find a significant change in excitability during a repeated MVC task where either EF or IF was cued (Wiseman et al., 2020). In previous work, stimulation intensities were set during a low contraction at 5% of MVC and delivered at 100% of MVC during repeated maximal contractions of the elbow flexors, which might have negated the effects of focus on CSE. In the current study, intensities were instead set during a contraction at 10% of

MVC and delivered at 50% of MVC while participants held the contraction until failure. In all cases, there is a possibility that the stimulation might distract the participant from the cue. We have attempted to address the effect of distraction on CSE by prolonging the contraction so that the cues adapted from Wiseman et al. (2020) can be delivered multiple times during a lower intensity contraction.

Thus, our goals were to: (1) investigate potential changes in CSE to upper limb muscles following specific focus instruction during a submaximal sustained elbow contraction and (2) determine whether these potential changes are related to improved performance outcomes (i.e., greater endurance, force).

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Co-authorship Statement

My, Erika Noel, contributions to this thesis are outlined below:

- I recruited all participants and analyzed all data collected for this thesis with the assistance of my peers, Ms. Nehara Herat (master’s student), Ms. Angie Antolinez (master’s student) and Mr. Philip Edwards (master’s student).
- I prepared the manuscript and thesis with the help and guidance of my supervisor, Dr. Duane Button.
- Dr. Duane Button provided constructive feedback on the manuscript and thesis.

Chapter 3

Exploring the Neuromuscular Mechanisms Underlying Changes in Force Production During an Attentional Focus Task

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3.0 Abstract

We examined how attentional focus cues influence maximal and sustained submaximal force production while exploring the associated physiological mechanisms. Twenty volunteers (10F & 10M) participated in one experimental stimulation session where external focus (EF) and internal focus (IF) instructions were provided. In the stimulation session, maximal voluntary contractions (MVC) were measured before a sustained submaximal isometric contraction held at 50% of MVC until task failure (TTF). Corticospinal excitability (CSE) was measured during the sustained contraction using transcranial magnetic stimulation, transmastoid electrical stimulation, and brachial plexus stimulation at Erb's point to elicit motor evoked potentials (MEP), corticomedullary evoked potentials (CMEP), and maximal muscle action potentials (M_{max}), respectively in the biceps brachii. Nine participants returned to complete an additional experimental session where no stimulation was administered, and MVC was measured before and after the sustained contraction. Independent of focus, MVC was significantly reduced after task failure ($p<.001$) with no change in CSE ($p=0.982$). In the stimulation session, MVC force ($p=0.593$) and muscle co-activation ($p=0.358$) were not significantly different between focus conditions. In the no-stimulation session, force ($p=0.541$) was not different for both the pre-task MVC and post-task MVC. Muscle co-activation was not significantly different in the pre-task MVC ($p=0.883$) but was significantly different in the post-task MVC ($p<0.001$). TTF was not significantly different between EF and IF during the stimulation ($p=0.713$) or no stimulation ($p=0.821$). In conclusion, focus did not significantly affect performance or CSE. The combination of fatigue and stimulation techniques might distract participants from the instruction and confound the effects of attentional focus.

Key Words: Attentional focus, Verbal Cues, Corticospinal Excitability, Endurance, Force

3.1 Introduction

In sports performance and physical activity, verbal cues or instruction can be used strategically to enhance a person's performance by helping them direct their conscious attention to support their goals (Chua et al., 2020, 2021; Wulf, 2013). Attentional focus cues can direct a person's attention externally or internally (Wulf, Hoss, & Prinz, 1998). When verbal cues direct attention externally, termed external focus (EF), they focus the person's attention on an external object or goal, such as a target or movement outcome (Wulf, Hoss, & Prinz, 1998). For example, a running coach might direct the person to focus on the finish line (EF). In contrast, when verbal cues direct attention internally, termed internal focus (IF), they focus the person's attention on their body movements or sensations. For example, a coach might instruct the runner to focus on putting one foot in front of the other (IF). EF is understood to optimize performance for tasks that involve accuracy, strength, and endurance, and effects are consistent across the lifespan of the average healthy and active individual (See Grgic & Mikulic, 2022; Park et al., 2015; Wulf, 2013 for reviews).

The literature demonstrates more efficient neuromuscular coordination and optimal motor performance with EF (Wulf, 2013). For example, Vance et al. (2004) found a significant reduction in EMG to the biceps and triceps brachii during a biceps curl task where participants were instructed to focus on the barbell (EF) compared to when they were instructed to focus on their arm (IF). Marchant et al. (2009) replicated the instruction from Vance et a. (2004) and, using an isokinetic dynamometer to measure the peak net joint torque of the elbow flexors, found a significant increase in force and a decrease in mean EMG with EF. Concerning endurance, Marchant et al. (2011) found that participants performed more repetitions of bench press & squat exercises at 75% of their maximal output with EF. Lohse and Sherwood (2012) studied submaximal performance using a wall sit task; when focused externally, participants sustained the task longer than when focused internally. To explain the observed effects of focus on motor performance, authors proposed the constrained action hypothesis (Wulf et al., 2001; McNevin et al., 2003). According to the theory, when individuals adopt an EF, they prioritize the result of their movement, which promotes flexibility in the motor system. The greater degree of flexibility allows the system to coordinate muscles automatically and efficiently, enhancing performance. In contrast, IF directs attention towards the movement, which emphasizes conscious control, constraining the motor system, which results in less efficient coordination and hinders performance.

Despite the substantial evidence supporting the benefits of instructing EF on force and, to some extent, endurance performance, the literature lacks a definitive mechanistic explanation for the influence of attention on motor performance (Grgic & Mikulic, 2022; Wulf, 2013, Kuhn et al., 2017. The measurement of corticospinal excitability (CSE), which reflects the ability of the motor cortex to generate movement, could help to bridge the gap in determining mechanisms underlying performance enhancement due to verbal cues (Haines, 2012; Wiseman et al., 2020). CSE is a measure of the responsiveness of the corticospinal tract, a neural pathway that originates in the brain's motor cortex and extends down to the spinal cord (Natali, Reddy & Bordoni, 2022). The corticospinal path is responsible for controlling voluntary movements in the body (Haines, 2012). Transcranial magnetic stimulation (TMS) and transmastoid electrical stimulation (TMES) are both non-invasive brain stimulation techniques used to quantify CSE (Ugawa et al., 1995, 1991; Taylor & Gandevia, 2004; Taylor, 2006; Petersen et al., 2002). TMS elicits a motor-evoked potential (MEP) in a muscle of interest (Taylor, 2006; Taylor & Gandevia, 2004). TMES elicits a cervicomedullary MEP, and the combination of measures is used to determine whether modulation of CSE is predominantly supraspinal or spinal (Petersen et al., 2002; Taylor, 2006). An increase in MEP and CMEP amplitude indicates greater excitability in the corticospinal tract, associated with stronger and more precise muscle contractions (Ridding et al., 1995). To date and to the best of our knowledge, only one study has measured CSE during cued maximum voluntary contractions (MVC). In our lab, Wiseman et al. (2020) found increased MVC force and reduced muscle co-activation during repeated MVC of the elbow flexors when EF was cued compared to IF. However, they observed no change in CSE and suggested their stimulation intensity might not have been sufficient to activate the corticospinal tract consistently. Specifically, Wiseman et al. (2020) set stimulator intensities during a contraction at 5% of MVC force and delivered them during 100% of MVC in the experimental protocol. The current study is the next step in expanding earlier work and addressing the methodological considerations posed by stimulating the corticospinal tract while trying to direct someone's attention. To date, no studies have measured the effects of attentional focus on a prolonged submaximal isometric task of the upper limb.

The purpose of the current study was to determine the effect of EF and IF on 1) a prolonged fatiguing submaximal elbow flexor contraction and 2) CSE of the biceps brachii during the prolonged contraction. More specifically, we compared EF and IF: 1) the co-activation of the biceps brachii and triceps brachii during sustained and maximal contractions, 2) performance measures time to task failure (TTF) and MVC and (3) CSE throughout the sustained task. We hypothesize that; 1) the co-activation ratio will be greater for all IF-cued tasks, 2) TTF and MVC will be greater for EF, and 3) the cued direction of focus will differentially modulate CSE.

3.2 Materials and Methods

3.2.1 Ethical Approval

The study was approved by The Memorial University of Newfoundland Interdisciplinary Committee on Ethics in Human Research (ICEHR No. 20220524-HK) and was in accordance with the Tri-Council guidelines in Canada. Prior to commencing data collection, all participants were informed of all potential risks and benefits of the study via verbal and written explanation and were given an opportunity to ask questions. All participants then gave written informed consent.

3.2.2 Participants

Twenty healthy university-aged students (ten females and ten males, 24.3±3.4 years of age; 18 right-hand dominant, two left-hand dominant) volunteered to participate in the study. We chose to recruit recreationally active individuals, and their status was determined as meeting Canadian Society of Exercise Physiology guidelines of 150 minutes of moderate to vigorous physical activity per week (CSEP, 2020). Participants completed a Physical Activity Readiness Questionnaire (PAR-Q+) to confirm their ability to partake in physical activity. Participants also completed a magnetic stimulation safety checklist before participation to screen for potential contraindications with magnetic stimulation procedures (Rossi et al., 2009; 2011). Finally, Hand dominance was determined using the Edinburgh Handedness Inventory (Veale, 2014).

3.2.3 Experimental setup

Elbow Flexor Force

In all trials, participants were seated in an upright position in a custom-built chair (Technical Services, Memorial University of Newfoundland). With the shoulders at 0 ° and the dominant elbow flexed to 90 °, the forearm was held horizontal, in supination, and the wrist was secured in a custom-made orthosis (see Figure 1). A load cell connected to the orthosis detected force output, which was amplified (x1000) (CED 1902, Cambridge Electronic Design Ltd., Cambridge, UK) and the data was displayed on a computer screen in direct view of the participant. Data was sampled at 5000 Hz. Participants completed test trials during their familiarization session to ensure they understood the task.

Electromyography

Electromyography (EMG) activity from dominant arms biceps brachii and triceps brachii was recorded by using surface EMG recording electrodes (MediTraceTm 130 Foam Electrodes with conductive adhesive hydrogel, Covidien IIC, Massachusetts, USA). Electrodes were placed in a bipolar configuration 2 cm apart (center to center) over the midpoint of the muscle belly of the participant's biceps brachii and triceps brachii lateral head. A ground electrode was placed over the lateral epicondyle of the opposite arm. Skin preparation for all recording electrodes included shaving and cleaning the area with an isopropyl alcohol swab. An inter-electrode impedance of <5 kΩ was obtained prior to recording to ensure an adequate signal-to-noise ratio. EMG signals were amplified (×1000) (CED 1902) and filtered using a 3-pole Butterworth filter with cut-off frequencies of 10–1000 Hz and converted at a sampling rate of 5 kHz using a CED 1401 (Cambridge Electronic Design Ltd., Cambridge, UK) interface.

3.2.5 Stimulation Conditions

Motor Responses from the bicep brachii were elicited via 1) transcranial magnetic stimulation (TMS), 2) transmastoid electrical stimulation (TMES) and 3) brachial plexus electrical stimulation at Erb's point above the clavicle of the dominant arm. Stimulation intensities used for TMS and TMES were adjusted so that the evoked potentials produced by each MEP and CMEP were of similar amplitude and normalized to a maximal M-wave (M_{max}).

Stimulation intensities were set during three-second isometric elbow flexion contractions equal to 10 % of MVC.

Transcranial Magnetic Stimulation (TMS)

TMS-evoked motor-evoked potentials (MEPs) were used to measure corticospinal excitability. A TMS (Magstim 200, maximal output 2.0 T) circular coil (13 cm outside diameter) was placed directly over the vertex of the head to induce MEPs in the active (10% maximal voluntary contraction (MVC) dominant biceps brachii muscle. The vertex was located by marking the measured halfway points between the nasion and inion and tragus to the tragus. Stimulation intensity was set to elicit a MEP of 10-20% of M_{max} taken as an average of eight trials in the biceps brachii during a 10% MVC.

Transmastoid electrical stimulation (TMES)

Stimulation was applied via surface electrodes placed over the mastoid processes, and current was passed between them (100µs duration, 80-200 mA); model DS7AH, Digitimer Ltd, Welwyn Garden City, UK). Stimulation intensity was adjusted to elicit a response that matched the size of MEP amplitude (±5%), taken as an average of eight trials in the biceps brachii during a 10% MVC.

Brachial plexus stimulation

The brachial plexus was stimulated to measure maximal compound muscle action potential (M_{max}). Erb's point was marked as the supraclavicular fossa (2-3 cm above the clavicle)—a cathode in the fossa and an anode placed on the acromion process. Electrical current pulses were delivered as a singlet (100 µs duration, 90-300 mA). The current was gradually increased until M_{max} of the biceps brachii at a 10% MVC was observed. A supramaximal stimulation current of 120% was then used to ensure maximal stimulation throughout the experiment (Collins et al., 2017).

3.2.6 Experimental Protocol

The study initially included one familiarization session and one randomized experimental session with stimulation separated by at least 48 hours. The experimental session took 1.5 hours and included parts A) the external focus cued task and B) the internal focus cued task, during which stimulation techniques were used. The order of focus cues was randomized, and a 30-minute break separated each focus condition. An additional experimental session was added midway through the data collection to test for the effects of stimulation. In the additional no-stimulation session, participants completed parts A) the external focus-cued task and B) the internal focus-cued task, but no stimulation techniques were used.

Familiarization session

After participants were screened with our TMS safety protocol, deemed healthy to partake in physical activity with the PARQ+ questionnaire and provided informed consent, they were seated in our custom chair and fitted with the orthosis. Participants then performed three 3-second MVCs with one minute of rest between contractions. No focus cues were given during the MVCs. Participants then completed a sustained isometric contraction at 50% of their maximal force output until task failure, the time at which they cannot maintain ±5% of the required force.

Experimental session 1

Once fitted with EMG and marked for TMS as per the specifics in section 3.2.5, stimulation conditions, participants were seated, and the orthosis was adjusted so that the elbow was flexed to 90°. Participants then performed two-three MVCs where no focus cues were provided. Next, the stimulation intensities were set in the order of M_{max}, CMEP, and MEP during a 10% MVC. Participants were instructed to perform a focus-cued protocol, where the order of instruction type (condition) was randomized. In one condition, participants were verbally instructed to “focus on pulling up on the brace as hard and fast as you can" (MVC external cue). In the other condition, participants were verbally instructed to “focus on contracting your biceps as hard and fast as you can" (MVC internal cue). In both conditions, the tasks were the same; the only change was the verbal cue given. Participants were then instructed to complete two-three MVCs where verbal cues were given. After a 5-minute break, participants were instructed to hold 50% of their maximal force output as shown on a screen in their direct view. In the EF condition, participants were instructed to “focus on pulling up on the brace to maintain the required force.” In the IF condition, participants were instructed to “focus on contracting your biceps to maintain the required force.” The respective focus cues were repeated during the sustained contraction every 10-15 seconds. Stimulations were given throughout the sustained contraction until failure and randomized so that TMS, TMES and an M-wave were given individually or in combinations.

Additional Experimental Session 2

After recruiting and analyzing the data from the initial 11 participants who participated in both the familiarization session and the experimental session with stimulation, we recognized the need for an additional experimental session in which no stimulations were administered. Nine participants were recruited to participate in the familiarization session, the experiment session with stimulation and the experimental session without stimulation. The order of stimulation and no stimulation sessions were randomized, and experiments were conducted on separate days at least 48 hours apart. The experimental protocols, including focus cues, were the same in both experimental sessions. However, in the no-stimulation session, following the sustained contraction, participants completed three focus-cued MVCs with no breaks to measure fatigue. A 30-minute break was allotted, then the experimental protocol was repeated with the alternate focus cue.

3.2.7 Data analysis

Force, EMG, and CSE data were measured offline using Signal 4.0 software (Cambridge Electronic Design Ltd., Cambridge, UK). All offline computations were conducted using Microsoft Office Excel (Microsoft Corporation, Redmond, WA, USA).

Maximum voluntary isometric contractions (MVCs).

Peak Elbow Flexor Force

Peak force is a term used to describe the maximum amount of force that can be produced during a muscular contraction. Participants completed two to three MVC of their dominant arm before and three maximal contractions after the sustained contraction. The average peak force of pre-sustained and post-sustained MVC were measured and reported in Newtons (N).

Electromyography (EMG)

EMG was collected from the dominant biceps and receipts brachii during each MVC and throughout the sustained contraction at 50% of MVC (external cues and internal cued conditions), as well as the stimulation and no stimulation sessions. The root mean square EMG (rmsEMG) was calculated as the 100 ms window about the midway point of each 5-second MVC. During the sustained contractions, rmsEMG was calculated from a 100 ms window at 30%, 60% and 90% of the participant's total contraction time. Muscle co-activation was quantified as the percentage of triceps rmsEMG / Biceps brachii rmsEMG. Muscle co-activation was calculated from all focus-cued MVC and throughout the sustained contractions at 30%

intervals for all conditions (External, internal cued trials and stimulation vs no-stimulation sessions).

Corticospinal Excitability (CSE)

Initially, we intended to normalize MEP and CMEP peak-to-peak amplitudes to M_{max} peak-to-peak amplitudes as a measure of supraspinal and spinal excitation, respectively. MEP, CMEP, and M_{max} peak-peak values (mV) were extracted during the sustained contraction under each condition (external-cued contraction and internal-cued contraction). Upon inspection of the initial data, we decided that TMES-elicited CMEPs were to be removed from the study as the stimulation distracted participants. As such, only MEP peak-to-peak amplitudes were normalized to M_{max} amplitudes (%M_{max}).

3.2.8 Statistical Analysis

Prior to statistical analyses, all data underwent quality control checks in Microsoft Office Excel (Microsoft Corporation, Redmond, WA, USA) for missing data points and outliers. Twenty participants completed the familiarization and stimulation sessions, including the external and internal focus protocols, separated by a 30-minute break. Nine participants (P11-P20) returned to complete the additional no-stimulation session. No force, MEP or M_{max} data points were missed for P1-P20. One-way ANOVAs were completed for measures of force (MVC), time (TTF), and muscle co-activation (EMG). Effect size from AVOVAs were determined by eta^2 are based on Cohen's (1988) benchmarks for small ($\eta 2$ = 0.01), medium ($\eta 2$ = 0.06), and large ($\eta 2$ = 0.14) effects. Paired sample T-tests were also used to compare stimulation and no-stimulation sessions. Effect size, measured with Cohen’s d, was interpreted using the following thresholds: trivial (<0.20), small (0.20–0.49), medium (0.50–0.79), and large (≥0.80) (Cohen, 1992). Data are presented and shown in tables as mean ±SD.

3.3 Results

3.3.1 Force (N)

Force was measured to determine how instruction (external vs. internal) impacted maximal force output (MVC). Following the experimental protocol outlined in our methods, MVC, where either external or internal focus was cued, was repeated prior to the fatiguing task for the stimulation group (n=20) and the no-stimulation group (n=9). There was no significant difference between force output during external and internal trials for the simulation (p=0.593, $\eta2$=0.018) or no-stimulation sessions (p=0.541, $\eta2$=0.02), respectively. The no-stimulation group also completed an additional set of three MVC post-sustained task. MVC did not significantly (p=0.49, $\eta2$=0.03) differ between EF and IF post-fatigue (Table 1). $\eta2$ effect sizes were trivial or trended toward small ($\eta2$ = 0.01). A paired sample t-test was used to compare the overall pre-task to post-task MVC force in the no-stimulation session. Irrespective of focus, the pre-task force (234.3 ±102.6 N) was significantly greater than the post-task force (201.5 ±95.2 N) (p<0.001, d=1.69). The large effect size suggests the onset of fatigue (d ≥0.80).

3.3.2 Time to task failure (TTF)

Muscular endurance and performance were measured as the time participants could no longer sustain the forceful task. There were no significant differences between EF and IF for time to task failure (TTF) in stimulation (p=0.713, η2=0.004) and the no stimulation (p =0.821, η2=0.003) sessions (Table 2). η2 effect sizes were trivial. Irrespective of focus condition, TTF was longer (p=0.068, *d=0.35)* in the no-stimulation session (110.23 ±62.2 s) compared to the stimulation session (92.86 ±42.25 s). The difference in time, while not significant, demonstrated a large effect size.

3.3.3 EMG

All EMG data are reported in Table 3 (MVC) and Table 4 (TTF).

MVC

In the stimulation session, no significant differences were found between rmsEMG for the biceps brachii (p=0.551, η2=0.009), triceps brachii (p=0.922, η2=0.00) or muscle co-activation (p=0.854, η2=0.001) during the pre-fatigue MVCs.

In the no-stimulation session, no significant differences were found between EF and IF for the pre-task contractions in the biceps brachii (p=0.787, η2=0.005), triceps brachii (p=0.771, η2=0.005) or muscle co-activation (p=0.883, η2=0.001). All η2 effect sizes were trivial. The post-fatigue contraction results also show no significant difference between EF and IF for the triceps brachii (p=0.769, η2=0.006). However, there was a significant difference between EF and IF for the biceps brachii (p=0.003, η2=0.44) and muscle co-activation significantly increased with IF ($p < 0.001$, η2=0.6); both effect sizes are trend toward large.

Time to Task Failure (TTF)

In the simulation session, no significant difference was found for the biceps brachii rmsEMG between EF or IF at 30% (p=0.219, η2=0.04), 60% (p=0.241, η2=0.03), or 90% (p=0.409, η2=0.018) of TTF. The same was true for the triceps brachii, where no significant difference was found between EF and IF at 30% (p=0.401, η2=0.019), 60% (p=0.669, η2=0.005), or 90% (p=0.704, η2=0.004) of TTF. No significant difference in the triceps brachii/biceps brachii co-activation was observed at 30% (p=0.768, η2=0.002),60% (p=0.712, η2=0.004), or 90 % (p=0.789, η2=0.002) of TTF. All effect sizes trended toward small (*η2* = 0.01).

In the no-stimulation session, no significant difference between EF and IF for the biceps brachii rmsEMG were reported for 30% (p=0.340, η2=0.057), 60% (p=0.153, η2=0.069), or

90% (p=0.527, η2=0.025) of TTF. The same was true for triceps brachii rmsEMG in the no-stimulation session, where no significant difference between EF and IF was observed at 30% (p=0.439, η2=0.025), 60% (p=0.293, η2=0.069) or 90% (p=0.841, η2=0.003) of TTF. No significant difference in muscle co-activation at 30% (p=0.929, η2=0.001), 60% (p=0.86, η2=0.002), or 90% (p=0.465, η2=0.034) of TTF were found. All condition effect sizes trended toward small (*η2* = 0.01), with the exception of 60% of TTF EMG during the no-stimulation session, which trended toward medium (*η2* = 0.06).

3.3.3 CSE

There was no significant difference in M_{max} amplitude (p=0.982, η2=0.00) or latency (p = 0.151, η2=0.053) between EF and IF. For MEPs, there was no significant difference in amplitude (p=0.922, η2=0.00), latency (p=0.29, η2=0.029) or silent period (p=0.95, η2=0.00) between EF and IF.

3.4 Discussion

The primary purpose of this study was to determine if: (1) the direction of focus led to changes in performance, including MVC force production and time to task failure (TTF) during a sustained submaximal elbow flexor contraction and (2) the direction of focus differentially modulated CSE. A significant body of evidence supporting the positive effects of an external focus of attention on motor performance for a range of tasks, including those requiring strength, force and, to some extent, muscular endurance (Grgic & Mukulic, 2022; Neumann, 2019; Wulf, 2013). However, the current study showed that the focus direction did not influence MVC force and TTF, mean rmsEMG measured during MVC and at 30%, 60% and 90% during the sustained contractions, muscle co-activation, nor were there any differences in CSE.

3.4.1 Performance was not significantly improved when external focus was cued.

Force

In studies examining the influence of focus on maximal force production, authors typically report greater maximal force production when EF is cued (Chua et al., 2020,2021; Wulf, 2013; Neumann, 2019). For instance, Marchant, Greig & Scott (2009) studied a repeated MVC of the elbow flexors and found participants produced a greater peak net joint torque (force) with EF rather than IF. Similarly, in our lab, Wiseman et al. (2020) report significantly greater MVC force when EF rather than IF is cued during a repeated MVC task of the elbow flexors. In line with previous work and specifically that from our lab (Wulf, 2013; Wiseman et al., 2020), it was hypothesized that force production would be greater during all EF contractions.

We did not find our hypothesis to be true, and EF was not associated with improved MVC performance compared to IF in both the stimulation (p=0.539) and no-stimulation sessions (pre p=0.541, post p=0.49). The results contradict those previously found in our lab and much of the available literature that supports EF as beneficial to acute force production (Wiseman et al., 202; Wulf, 2013; Grgic et al., 2021). Unlike the aforementioned studies, the current study did not employ a repeated MVC task; instead, participants only completed two to three MVCs. Perhaps a repeated MVC protocol is required to see the effects of EF vs IF on maximal force production. However, the results of the current study do align with research from lower body studies that did not find significant effects of focus on MVC force. Marchant & Greig (2017) studied the impact of focus on a maximal isokinetic concentric leg extension exercise where participants were instructed to focus internally (specific muscle) or externally (movement outcome) and found no change in force output. Despite no changes in muscular force, authors do report lower muscular activity. In the upper body, and to our knowledge, no studies have reported reduced MVC in the elbow flexors when EF is cued compared to IF.

EMG & Muscle co-activation

Studies examining maximum force production often include surface EMG, which is a global measure of nervous system activation, as a mechanistic explanation for the effect of focus on performance and evidence for the constrained action hypothesis (Wulf, 2013; Farina et al., 2004,2014; Lohse, Wulf, & Lewthwaite, 2012; Wulf et al., 2001a). Much of the data shows reduced mean EMG amplitude when EF is adopted and simultaneous instances of improved performance. Research suggests that a more efficient use of neuromuscular resources could optimize performance when EF is adopted compared to IF (Wulf, 2013). In a jump-and-reach task, Wulf et al. (2010) demonstrate increased jump height when participants are focused externally (on the rungs) than internally (on the fingers) and when focused externally, EMG is significantly decreased. Relevant to the current study, when peak joint torque was greater for an EF-cued repeated elbow flexion task, Marchant, Greig & Scott (2009) also report coinciding lower peak EMG of the biceps and triceps brachii compared to when IF was cued. The instance of lower muscular activity where the same or greater output (force) is generated reflects increased neuromuscular efficiency.

EMG data is also used to support the constrained action hypothesis. The hypothesis proposed by Wulf et al. (2001a) suggests that IF constrains the motor system through increased attentional demands and encouraging conscious control of movement. In contrast, EF promotes automatic control processes which facilitate the motor system's effective and efficient coordination, improving performance (Wulf, 2007b; Wulf and Lewthwaite, 2016). The results of the current study do not support the idea that EF facilitates efficient activation of muscles and improves performance for a task that requires maximal voluntary force. There was no change in mean EMG measured from the biceps or triceps brachii during any pre-task MVC and no significant change in force output relative to the direction of focus. While limited, some research does present similar EMG results to what was found in the current study. In a similar task, Halperin et al. (2016) studied isometric MVC and EMG activity of the elbow flexors during four attention conditions. They found no significant changes in EMG measured from the biceps and triceps brachii across all conditions. However, in contrast to the current study, they report that participants produced significantly greater force and no significant changes in EMG from biceps and triceps brachii muscles across all conditions.

Achieving maximal force requires both the efficient activation of the neuromuscular system and the optimal coordination of agonist and antagonist, where unnecessary co-contractions would result in less-than-maximal force output. For example, Vance et al. (2004) instructed participants to focus on the weight (external) or on their arm (internal) during a bicep curl task. When focused, externally integrated EMG (iEMG) was lower in both the biceps brachii (agonist) and triceps brachii (antagonist), suggesting more effective coordination between the muscles. Similarly, Wiseman et al. (2020) found that forces were significantly lower and muscle co-activation of the biceps and triceps brachii was greater under internal compared to external focus during an elbow flexion task. In line with the available literature, muscle co-activation was anticipated to be greater with IF, while force would be lower compared to EF. Instead, the current study found the mean EMG of the biceps brachii to be significantly greater with EF in the post-task contractions (p=0.003). The increase in EMG could be related to fatigue, given that force was significantly less in the post-task MVC compared to pre-task MVC, irrespective of focus (p<0.001). In the same post-task MVC where IF is cued, co-contraction of the triceps and biceps brachii was significantly greater than when EF was cued ($p<0.001$), but there was no observable effect on MVC force.

Time to Task Failure (TTF)

As an additional performance measure, we explored how attentional focus would impact muscular endurance during a sustained contraction. Kell et al. (2001) defined muscular endurance as “the ability of a muscle or muscle group to perform repeated contractions against a load for an extended period.” And this definition of muscular endurance has been applied in attentional-focus research (Grgic & Mikulic, 2022). For example, Marchant et al. (2011) report that when EF was adopted, participants performed more repetitions of forceful tasks (Smith machine, a free bench press, and a free squat lift) before fatigue. Relevant to sustained tasks, Loshe and Sherwood (2011) found that participants could sustain a wall sit longer when EF compared to IF was adopted. In the upper limb, Kuhn et al. (2017) studied the neuromuscular correlates of fine motor tasks involving the fingers. Participants held a sustained submaximal contraction of the first dorsal interosseous and were able to prolong the contraction. EF was adopted compared to IF.

In the current study, muscular endurance was considered as the ability of the muscle group to sustain a desired force for as long as possible until fatigue and task failure (TTF). Based on previous research that suggests that EF improves motor system efficiency, which improves performance, it was hypothesized that TTF would be prolonged with EF. However, no significant difference in TTF was observed across focus conditions in the stimulation and no-stimulation sessions. EMG measured from the biceps and triceps brachii at 30%, 60%, and 90% of TTF (s) was also not significantly different relative to the direction of focus in both sessions.

Our hypothesis that EF would facilitate improved muscular endurance rested on the literature that supports EF as beneficial to tasks requiring repeated maximal force and, in limited cases, sustained submaximal force (Wulf, 2013, Marchant et al., 2011, Kuhn et al., 2017). In contrast, our results align with those in Loshe and Sherwood (2012, experiment 2), where participants held forceful contractions of the elbow flexors at 30, 60 and 100% of MVC. They reported that attentional focus had no significant impact on time-to-task failure or rating of perceived exertion. While not the same task, Collum et al. (2021) found no statistical difference between repetitions performed until failure and attentional focus strategies for a bench press task at 85% of maximal output. Our results contradict most of the literature that reports EF as superior to IF. However, a study has recently found significant reporting bias in attention focus research (McKay et al., Preprint). When bias was accounted for, the estimated mean effects of EF on performance and EMG were negligible, which aligns with the results of the current study.

3.4.2 The direction of focus does not differentially modulate CSE.

Limited research has attempted to assess the neuromuscular mechanism underlying the advantage of EF on performance. In the current study, it was hypothesized that the direction of focus would differentially modulate CSE. The hypothesis was based on information from previous studies that identified focus as a means to modulate cortical activity. In a fMRI study, Binkofski et al. (2002) investigated how the brain responds to various attentional conditions. Their findings indicated that attention influences brain activity, particularly in the posterior part of M1 (Brodmann's area 4). Zentgraf et al. (2009) also used fMRI to measure blood-oxygen-level-dependent (BOLD) while participants performed a keyed task and found an increase in BOLD response in the contralateral sensorimotor area when EF was adopted compared to IF.

fMRI is useful for identifying areas of interest in the cortex; however, it cannot distinguish between the coordination of neural inhibition and excitation that facilities complex movement.

Kuhn et al. (2017) suggest that inhibitory mechanisms within the cortex might be involved, given that when EF is adopted, enhanced motor performance is observed, often a coinciding decrease in muscle activity. Using two different TMS protocols, researchers measured cortical inhibition within M1. Different attention strategies were adopted during a sustained submaximal contraction of the fingers until failure, and EF was associated with prolonged TTF. Results also showed a significant effect of attention on short-interval intracortical inhibition (SICI), suggesting that increased inhibition with EF might contribute to improved motor performance. In another TMS study, Kuhn et al. (2018) demonstrate that motor performance improves and surround inhibition increases with EF. The combination suggests that the brain's ability to detect and process somatosensory information increases, which might contribute to more efficient motor system coordination.

The effects of attention on intracortical circuits have been briefly explored using imaging and stimulation techniques. Using similar stimulation paradigms, our lab has looked at motor cortical output and the effect of attention on the excitability of the corticospinal tract. Wiseman et al. (2020) recruited resistance-trained participants to examine the impact of attentional focus instruction on performance during a series of 5-second maximal isometric contractions of the elbow flexors. In one experimental session, single-pulse TMS, TMES and electrical stimulation at Erb's point were delivered to participants throughout a series of repeated maximal voluntary isometric contractions of the elbow flexors. At least 48 hours later, participants returned for a second experiment session where the task was the same, but no stimulus paradigms were used. In both sessions, surface EMG was measured from the biceps and triceps brachii and reported as mean peak EMG and muscle co-activation. The participant's arm was secured in a brace similar to the one in the current study. The instruction to focus either externally ("focus on pulling up on the handle as hard and as quickly as you possibly can") or internally ("focus on contracting your biceps as hard and as quickly as you possibly can") were given prior to each MVC. Their results showed a significant increase in MVC force when EF compared to IF was cued in both the stimulation and no-stimulation session. Similar to the current study, which found an increase in co-activation when IF was cued during the no-stimulation session, Wiseman et al. (2020 also report increased co-activation when IF was cued. There was no significant difference in CSE, including Mmax, MEP, or CMEP amplitudes or MEP/CMEP ratios, relative to the direction of focus cued, and the authors suggest that the stimulation might have compounded the effects of focus. To address the methodological considerations, the current study measured CSE during a sustained-submaximal contraction using a similar experimental set-up with the goal of ensuring focus was maintained in the target direction. Despite the change in task, once again, no significant difference in CSE was observed, and given our results that contradict much of the available literature, there is reason to explore factors that might have confounded our results.

3.5 Methodological considerations

Distance

Research originally differentiated attentional focus by direction, as either external or internal (Nideffer, 1976; Wulf, Hoss, & Prinz, 1998; Wulf, 2013). Focus has been divided into proximal and distal (McNevin et al., 2003). McNevin et al. (2003) suggest that distal focus allows for the movement effect to be distinguishable from the body movements—the observation of improved importance with distal EF aligned with the constrained action hypothesis. According to the hypothesis, IF elicits conscious control of the motor system and results in less efficient and effective coordination of the motor system, which hinders performance. The greater the distance, the more distinguishable EF from IF becomes. In the current study, there was a short distance between the EF-cue which directed attention toward the brace around the forearm, and IF, where focus was directed at the biceps. However, given that Wiseman et al. (2020) used a similar setup and still found significant effects of focus on MVC force, we must consider other confounding factors.

Cue

The cue used differed from that in the Wiseman et al. (2020) study in that participants were asked to do two things during the sustained contraction, 1) focus on pulling up on the brace as hard and as fast as you can (EF), or focus on contracting your biceps as hard and as fast as you can (IF); and 2) “to maintain the required force” in either focus condition. Sweller (1994) proposed that a dual-task paradigm might negatively affect performance because attentional resources are split between two tasks. The detriments of dividing attention between multiple tasks are explained by the Cognitive Load Theory, which suggests that the cognitive system has a limited processing capacity. When stimuli overload the system, there can be detriments in performance (Sweller, 1994). To avoid overloading the system, participants might focus on only one component of the cue to complete the task. In our case, that could mean participants focused on the first part of the cue, which differentiated between an internal or external direction of focus, or they could have directed their focus on the screen in front of them, which showed the force they were trying to maintain. Using a similar cue dual-task cue, Marchant et al. (2017) asked participants to “contract the vastus medialis oblique whilst generating maximal effort” (IF); or “Try to exert maximal effort during the movement whilst focusing on pushing against the pad” (EF). The authors report no influence of attention on force production during isokinetic knee extensions. In addition to the duality of the cue, the frequency in which we chose to repeat the cues throughout each sustained contraction (10-15 s) likely would have overloaded participants' ability to process the stimuli and, thus, distracted them from the intended goal.

Fatigue

Muscle endurance was measured as time, where participants could no longer maintain the required force, at which point fatigue is understood to limit their ability to sustain the force. This “fatigue” can be due to both peripheral and central components, where impaired muscle function is associated with peripheral fatigue, and a reduced capacity of the CNS to activate muscles is related to central fatigue. Carroll, Taylor & Gandevia (2017) suggest that muscle fatigue typically subsides within 2-5 minutes during short bouts of maximal force; thus, between MVCs, we allotted 5 minutes of rest. However, post-MVC, the participants in the current study completed a sustained submaximal contraction until failure and fatigue. After a 30-minute break, the protocol was repeated with the alternative focus cue. The results show a significant reduction in MVC force between the pre-task MVC and post-task MVC in the no-stimulation session, suggesting that the task resulted in some fatigue. Research indicates that the complete recovery of muscle function after a sustained contraction until fatigue might take hours, and thus, we believe the 30-minute break might not have been sufficient to allow for the muscle to recover, which in turn would negatively impact our results (Enoka et al., 2011; Carol, Taylor & Gandevia., 2017).

Stimulus

Similar to the methodological considerations in Wiseman et al. (2020), we note that stimulating the corticospinal pathway may confound attentional focus. The stimulations may distract participants from the cues and/or disrupt areas of the cortex responsible for attention and focus. The physical experience of the stimulators might also distract participants. We found this to be a particular issue with transmastoid electrical stimulation (TMES) and, thus, removed the stimulus from the study. Participants also noted that the noise made by the TMS machine was distracting. Given the restricted processing capacity for environmental input, the repetition of the cue during the sustained contraction every 10-15 seconds might have also adversely influenced our findings. Together these sensory inputs would occupy the participant's attentional resources and limit their ability to focus on the direction-cued task. While the result is insignificant, there was a small effect of stimulus on TTF, where participants held the contraction longer when no-stimulation was used, irrespective of the focus direction (p=0.068, d=0.35).

In addition to receiving verbal instruction, participants were seated in direct view of a computer monitor that gave a visual presentation of their timed contraction. A trace on the screen indicated how much force they should be holding, and the visual might have impacted our results. In a study by Ruge et al. (2014), MEPs were recorded from the dominant hand as participants were instructed to shift their visual attention towards (internal) and away from their hand (external); the result indicated that MEP amplitudes were significantly affected by the direction of visual attention. Attentional focus studies have often made an effort to minimize distraction to limit confounding factors. Marchant, Greig & Scott (2009) controlled for the presence of audience effects and encouragement by only allowing the participant and researcher in the laboratory during the study. The authors also ensured the monitor on the dynamometer was positioned out of view from the participants. The effect of an audience and the screen should be considered when using simulation techniques; in our experimental setup, a lab member helped the magnetic coil about the head to ensure the correct area was consistently stimulated, which could distract participants.

3.6 Conclusion

This is the second study from our lab to examine neuromuscular mechanisms and their relation to performance when EF and IF are instructed. Wiseman et al. (2020) measured performance and CSE using a repeated maximal voluntary contraction of the elbow flexors where the direction of focus was manipulated. In the current study, we expanded on the initial investigation to include a sustained task during which we attempted to measure CSE throughout and until task failure (TTF). Our results showed that CSE was not differentially modulated by the direction of focus (external vs internal). In contrast to much of the available literature, there was no significant improvement in performance when the external focus was cued in the stimulation and no-stimulation session.

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Table 1: Mean peak Maximal Voluntary Contraction (MVC) force in Newtons (N), reported for external versus internal focus for the stimulation group (n=20) and the no-stimulation group (n=9). Note: the no-stimulation group completed 2-3 pre-task MVC and two post-task MVC, whereas the stimulation group completed only pre-task MVC. No significant differences were found between focus conditions for all sessions, and effect sizes are trivial. A large effect size and significant difference (p<0.001, d=1.69) were found for pre-task versus post-task MVC in the no-stimulation session, irrespective of focus.

MVC Force (Newtons, N)			
	Stimulation Pre-Task	**No-Stimulation PRE-Task**	**No-Stimulation POST-Task**
External Contraction	228.9 ±100.2 N	249.7 ±108.2 N	217.5 ±96.3 N
Internal Contraction	233.5 ±96.2 N	218.9 ±100.6 N	185.35 ±95.2 N

Table 2: Time to Task Failure (TTF) measured in seconds (s) throughout the sustained contraction at 50% MVC.

Time to task failure (TTF, s)		
	Stimulation	**No-Stimulation**
External Contraction	90.4 ±36.4 s	106.8 ±61.0 s
Internal Contraction	95.4 ±46.3 s	113.7 ±66.9 s

Table 3: Mean RMS electromyography (EMG) activity of the biceps and triceps brachii measured during MVC. Peak-to-peak amplitude is reported as mean and standard deviation.

Maximal Voluntary Contraction (MVC) EMG												
Session	**Stimulation**				**No-Stimulation**							
Condition	**External Contraction**		**Internal Contraction**		**External Contraction (PRE)**		**Internal Contraction (PRE)**		**External Contraction (POST)**		**Internal Contraction (POST)**	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Biceps Brachii rmsEMG (mV•s)	0.365	0.214	0.33	0.146	0.33	0.143	0.352	0.19	0.361	0.19	0.132	0.052

Triceps Brachii rmsEMG (mV•s)	0.133	0.097	0.131	0.064	0.11	0.046	0.122	0.044	0.114	0.047	0.108	0.043
Co-activation (% Triceps/Biceps)	40.8	21.7	41.9	16.8	41.5	24.7	39.9	18.3	38.9	21.4	82.7	15.85

Table 4: Root mean squared peak-peak amplitudes for the biceps and triceps and muscle co-activation are reported at 30%, 60% and 90% of TTF (s).

Time to Task Failure (TTF) EMG								
Session	**Stimulation**				**No-Stimulation**			
Condition	**External Contraction**		**Internal Contraction**		**External Contraction**		**Internal Contraction**	
	M	SD	M	SD	M	SD	M	SD
Biceps Brachii rmsEMG (30%)	0.248	0.15	0.196	0.111	0.262	0.373	0.137	0.073
Triceps Brachii rmsEMG (30%)	0.100	0.095	0.256	0.162	0.078	0.064	0.058	0.039
30% Co-activation (% Triceps/Biceps rmsEMG)	41.7	25.8	39.2	15.7	41.1	25.1	42.1	12.4
Biceps Brachii rmsEMG (60%)	0.277	0.25	0.205	0.093	0.264	0.217	0.147	0.084
Triceps Brachii rmsEMG (60%)	0.097	0.078	0.087	0.067	0.085	0.063	0.584	0.039
60% Co-activation (% Triceps/Biceps rmsEMG)	39.6	22.9	37.9	17.4	39.5	26.4	41.7	26.3
Biceps Brachii rmsEMG (90%)	0.322	0.31	0.26	0.16	0.287	0.202	0.224	0.211
Triceps Brachii rmsEMG (90%)	0.098	0.059	0.090	0.0654	0.083	0.055	0.089	0.076
90% Co-activation (% Triceps/Biceps rmsEMG)	39.6	22.9	37.8	17.4	35.5	24.4	44.6	27.2

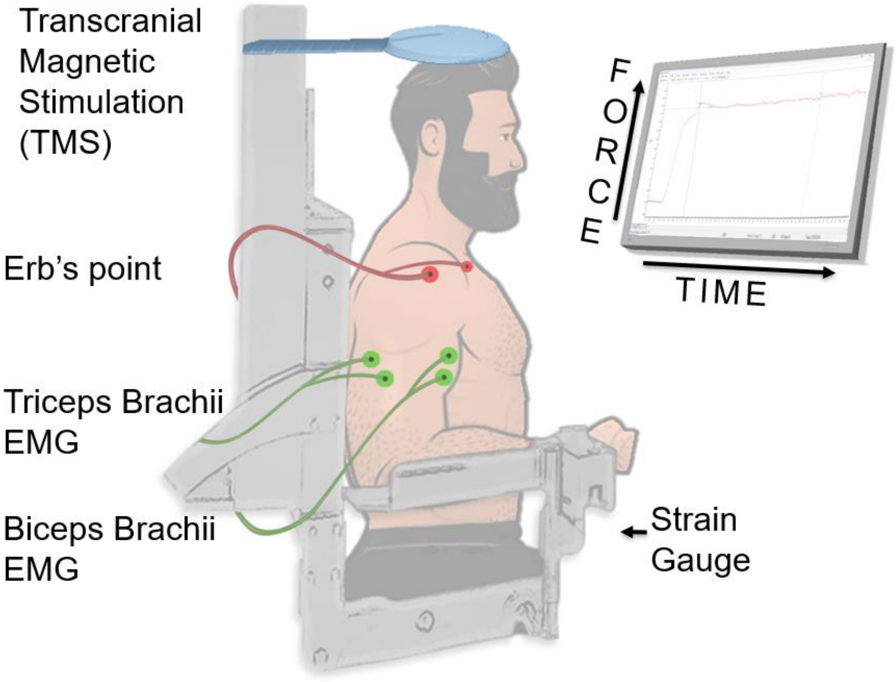
Table 5: MEP and Mmax peak-peak amplitude, latency (ms) and silent period (ms).

Condition	**External Cued Contraction**		**Internal Cued Contraction**	
	M	SD	M	SD
M_{max} amplitude (mV)	5.30	3.67	5.27	3.08
M_{max} Latency (ms)	6.5	11.0	6.3	13.0
MEP Amplitude (% of Mmax)	82.2	34.6	84.2	29.7
MEP Latency (ms)	14.0	5.1	13.0	3.0
MEP silent period (ms)	8.6	3.1	8.5	3.4

Figure Legend

Figure 1: Experimental Setup. Participants were seated in a custom chair with their dominant arm secured in a brace around the distal forearm which was connected to a strain gauge to measure force. A magnetic coil was used to elicit MEP, M-waves were elicited using electrical stimulation at Erb's Point and EMG was collected from the biceps and triceps brachii. In direct view of participants, a screen was placed to showing a force trace.

Figure 1



Appendix A: Magnetic Stimulation Safety Checklist

Please read the checklist below. If the answer to any of the questions is yes please indicate that you are ineligible to participate in the study.

You are NOT required to circle a response nor are you required to provide any further information. This checklist is for safety screening only.

1. Do you suffer from epilepsy, or have you ever had an epileptic seizure?

YES/NO 2. Does anyone in your family suffer from epilepsy? **YES/NO**

3. Do you have any metal implant(s) in any part of your body or head? (Excluding tooth fillings) **YES/NO**

4. Do you have an implanted medication pump? **YES/NO**

5. Do you wear a pacemaker? **YES/NO**

6. Do you suffer any form of heart disease? **YES/NO**

7. Do you suffer from reoccurring headaches? **YES/NO**

8. Have you ever had a skull fracture or serious head injury? **YES/NO**

9. Have you ever had any head surgery? **YES/NO**

10. Are you pregnant? **YES/NO**

11. Do you take any medication? **YES/NO**
    a. Note if taking medication, check list for contraindicated medication on next

page. 12. Do you suffer from any known neurological or medical conditions? **YES/NO**

If you are using any of the medications listed in the table below you are ineligible to participate in this study.

Name	**Brand name**
amitriptyline (& butriptyline)	Elavil, Endep, Tryptanol, Trepiline
desipramine	Norpramin, Pertofrane
dothiepin hydrochloride	Prothiaden, Thaden

imipramine (& dibenzepin)	Tofranil
iprindole	-
nortriptyline	Pamelor
opipramol	Opipramol-neuraxpharm, Insidon
protriptyline	Vivactil
trimipramine	Surmontil
amoxapine	Asendin, Asendis, Defanyl, Demolox, Moxadil
1) Tricyclic Antidepressants doxepin	Adapin, Sinequan

2) Neuroleptic or Antipsychotic drugs

a) Typical antipsychotics

- Phenothiazines
- Thioxanthenes
  - Chlorpromazine (Thorazine)
  - Chlorprothixene
  - Fluphenazine (Prolixin)
  - Flupenthixol (Depixol and Fluanxol)
  - Perphenazine (Trilafon)
  - Thiothixene (Navane)
  - Prochlorperazine (Compazine)
  - Zuclopenthixol (Clopixol and Acuphase)
  - Thioridazine (Mellaril)
  - Butyrophenones
  - Trifluoperazine (Stelazine)
  - Haloperidol (Haldol)
  - Mesoridazine
  - Droperidol
  - Promazine
  - Pimozide (Orap)
  - Triflupromazine (Vesprin)

- Melperone
- Levomepromazine (Nozinan)

b) Atypical antipsychotics

- Clozapine (Clozaril)
- Olanzapine (Zyprexa)
- Risperidone (Risperdal)
- Quetiapine (Seroquel)
- Ziprasidone (Geodon)
- Amisulpride (Solian)
- Paliperidone (Invega)

c) Dopamine partial agonists:

- Aripiprazole (Abilify)

d) Others

- Symbyax: A combination of olanzapine and fluoxetine used in the treatment of bipolar depression.
- Tetrabenazine (Nitoman in Canada and Xenazine in New Zealand and some parts of Europe)
- Cannabidiol: One of the main psychoactive components of cannabis.

Appendix B: Free and Informed Consent Form

Informed Consent Form

Title:	The influence of attentional focus on corticospinal excitability and neuromuscular efficiency of the biceps brachii during sustained elbow flexion
Researcher(s):	Erika Noel, Principal Investigator Memorial University of Newfoundland, elnoel@mun.ca Shahab Alizadeh, Post-Doctoral fellow Memorial University of Newfoundland, shahab.a91@gmail.com Philip Edwards Memorial University of Newfoundland, pfedwards@mun.ca Nehara Herat Memorial University of Newfoundland, nsherat@mun.ca Evan Lockyer School of Human Kinetics and Recreation, ejl006@mun.ca Christopher Compton School of Human Kinetics and Recreation, cc5727@mun.ca Angie Katherin Antolinez Romero, akantolinez@mun.ca School of Human Kinetics and Recreation
Supervisor(s):	Dr. Duane Button, PhD Human Kinetics and Recreation, Memorial University of Newfoundland dbutton@mun.ca, (709) 864-4886

You are invited to take part in a research project entitled:
"The influence of attentional focus on corticospinal excitability and neuromuscular efficiency of the biceps brachii during a fatiguing sustained isometric elbow flexion task."

This form is part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. It also describes your right to withdraw from the study. In order to decide whether you wish to participate in this research study, you should understand enough about its risks and benefits to be able to make an informed decision. This is the informed consent process. Take time to read this carefully and to understand the information given to you. Please contact the researcher, Erika Noel or Dr. Duane Button, if you have any questions about the study or would like more information before you consent.

It is entirely up to you to decide whether to take part in this research. If you choose not to take part in this research or if you decide to withdraw from the research once it has started, there will be no negative consequences for you, now or in the future.

Introduction:

This research is being conducted by Ms. Erika Noel, a Master's student of the School of Human Kinetics and Recreation at Memorial University of Newfoundland. The research team will consist of Shahab Alizadeh, a post-doctoral fellow, Evan Lockyer, a PhD candidate, Chris Compton, a PhD candidate, and masters' candidates, Nehara Herat, Angie Romero and Philip Edwards. As part of my (Erika Noel) Master's Thesis, we are conducting research under the supervision of Dr. Duane Button, PhD.

The influence of attentional focus instructions has been well documented however, there exists a gap in the literature pertaining to the neural and physiological mechanism which underlie these outcomes. Simply, attentional focus refers to where one is directing their attention. In exercise settings coaches and trainer will often direct the performer to focus on a specific direction with the goal of enhancing performance outcomes.

Purpose of Study:

The purpose of the study is to compare between unique focus instruction with subsequent force production and maintenance capabilities during an elbow flexion exercise targeting the biceps brachii. The details of this study explore if a greater ability to maintain force output is achieved after a specific form of attentional focus instruction is employed.

What We Will Do in this Study:

You will be expected to come to PE 1011-B0020 three times from November 2022 – March 2023 for approximately 0.5, 1.5 & 1.5 hours (3.5 hr total). The first visit corresponds to a familiarization session that will give you a short experience with the stimulations involved in the experiment. The following two sessions are distinguishable by the use and lack of stimulation techniques used during the session. In session A) The experimental groups will be given an attentional focus instruction and asked to perform an elbow flexion until muscle fatigue (tiredness) and activity disengagement. Following the first exercise trial, participants will be allowed a 30-minute break to allow for the effects of fatigue to dissipate. Following the break, participants will perform the same elbow flexion task with a different attentional focus instruction. During the exercise protocol, participants will have their corticospinal excitability measured using two stimulation techniques. The stimulation technique that will be used is described in further detail below. In session B) the same protocol will be followed. The experimental groups will be given an attentional focus instruction and asked to perform an elbow flexion until muscle fatigue (tiredness) and activity disengagement. Following the first exercise trial, participants will be allowed a 30-minute break to allow for the effects of fatigue to dissipate. Following the break, participants will perform the same elbow flexion task with a different attentional focus instruction. No stimulation techniques will be used in session B.

During the testing session, we will be recording the electrical activity from two of your muscles (biceps and triceps brachii of the dominant arm) using surface electromyography (EMG) electrodes. Once you have been prepped (the skin surface will be shaved, gently abraded, and wiped with an isopropyl alcohol swab) and the electrodes have been placed on your muscles, you will be asked to sit in a chair with a screen front of you which will display your force output in real time. The stimulation intensity will be determined with you comfortably seated and have performed 2-3 practice maximal voluntary contractions. Once the intensities have been set, you will be asked to perform several bicep contractions. During each exercise trial, you will receive approximately 20 magnetic stimulations over the cortex, 8 stimuli of the brachial plexus. In total, during the testing session, you will perform about 6 maximal voluntary contractions under one type of focus instruction, followed by a 30-minute break and then about 6 maximal voluntary contractions with the alternate focus instruction. The stimulation in this study is safe and have been used extensively by Dr. Button for 10+ years.

During transcranial magnetic simulation, a copper coil of wire encased in plastic will be placed over the top of your head. High electrical current will be passed through the copper coil, which will induce a magnetic field to be discharged through the coil. You will hear a ‘clicking’ noise once this occurs. This magnetic field will pass through the scalp and skull and activate underlaying neural tissue in the brain. This technique is painless and has shown no short- or long-term effects on any neurological function. You may feel a slight involuntary contraction of various muscles during transcranial magnetic stimulation. The brachial plexus at Erb’s point will be electrically stimulated via electrodes placed upon the skin in the supraclavicular fossa and on the acromion process. Again, electrical singlet stimulations with a pulse duration of 100 microseconds will be used.

Length of Time:
The study will include a familiarization session (approx. 30-minutes) followed by a testing session at least 72 hours later. During the testing session the fatigue protocol will take approximately 60 minutes and include a 30-minute break for a total duration of 2.0 hours.

Withdrawal from the Study:
You will be free to withdraw from this study at any time, without explanation. To do so you simply need to inform the researchers and you will be free to leave the lab. You may request for the removal of your data up to one year later by contacting the primary investigatory at elnoel@mun.ca and starting your desire to have your data removed. If you are a student, withdrawal from this study will not in any way, now or ever, positively or negatively impact

either your grade in a course, performance in a lab, reference letter recommendations and/or thesis evaluation.

Possible Benefits:
Benefits to the participants may include education of how to properly perform a bicep flexion exercise using unique attentional focus instructions. The current research may also benefit physicians, athletes, and the general population by increasing the pool of research related to the neurophysiological control of movement.

Possible Risks:
There are a number of minor risks associated with participating in this study which include:
1) strain or soreness of the biceps muscle. For some individuals who do not regularly participate in upper body strength training, there could be some residual muscle discomfort which would recede after continued exercise.
2) High intensity voluntary contractions could also lead to some residual discomfort for 2-3 days after the testing however with those who partake in upper body strength training, this response is highly unlikely.
3) You will have electrodes placed on the front and back of your arms. These electrodes have an adhesive that tends to cause redness and minor irritation of the skin. This mark is temporary (usually fades within 1-2 days) and is not generally associated with any discomfort or itching.
4) Transcranial magnetic stimulation is used to assess motor cortex excitability and is applied at the top of the skull. You will feel the stimulation, however it is a painless sensation. Each stimulation will be less than one second in duration.
5) While the brachial plexus stimulation are not painful, some participants may experience discomfort and/or minor anxiety during the stimulations.

In order to minimize risk, all testing will be supervised by an investigator all of whom are trained in first aid and CPR. Additionally, numbers for emergency services will be on hand in case medical attention is necessary. Team members will also take the necessary COVID-19 precautions to ensure your safety. We have provided you with the contact information of necessary facilities, should you experience any significant physical, cognitive, social, or emotional harm as a result of participation in this study.

University Counselling Centre
5th Floor University Centre, UC-5000
Memorial University of Newfoundland
St. John's NL A1C 5S7
Tel: (709) 864-8874
Fax: (709) 864-3011

Confidentiality:
Confidentiality is ensuring that identities of participants are accessible only to those authorized to have access. The ethical duty of confidentiality includes safeguarding participants' identities, personal information, and data from unauthorized access, use, or disclosure. Participant's data will be kept anonymous and confidential by way of a numeric code assigned to the data files in place of any identifiable information such as the name. The code will be assigned and known only by the primary investigator (Erika Noel). Coded data will be stored in physical form and digitally in Dr. Button's locked office.

Anonymity:

Anonymity refers to protecting participants' identifying characteristics, such as name or description of physical appearance. Participation is this study is not anonymous, given the location of the laboratory (PE – 1011A) where various people who may be near the lab will likely see participants entering / exiting the lab. However, every reasonable effort will be made to ensure your anonymity. Your participation will not be made known to anyone except researchers who are directly involved in this study. Your identity will not be identified in any reports, conferences or publications without your explicit consent. A coded identification number will be used in place of your name on any documents or files that may be linked to your participation in this study, so that any data is not identifiable. All data will be collected independently and kept confidential by way of codes assigned to participants.

Recording of Data:
There will be no video or audio recordings made during testing.

Use, Access, Ownership, and Storage of Data:

A) All data will be stored in hardcopy and password-protected digital copy in Dr. Duane Button's office at Memorial University of Newfoundland. Consent forms will be stored separately from participant data in a locked cabinet in Dr. Duane Button's office. Data access will be limited to Dr. Duane Button and investigators. Data will be kept for a minimum of five years, as required by Memorial University's policy on Integrity in Scholarly Research.
B) The data collected as a result of your participation can be withdrawn from the study at your request up until the point at which the results of the study have been accepted for publication (~1-year post study). Requests for removal of data can be emailed to the primary investigator at elnoel@mun.ca.

Reporting of Results:
Data potentially may be published in a thesis and online journal articles. Published data will contain no personally identifying information. Results of this study will be reported in written and spoken form (local and national conferences and lectures). Written forms will include Erika Noel's Master's thesis, which will be made accessible to the public following its completion via

the QEII Library at Memorial University via http://collections.mun.ca/cdm/search/collection/theses.

Sharing of Results with Participants:
Upon completion of the study, please ask any specific questions you may have about the activities you were just asked to partake in. If you wish to receive a brief summary of the results then please indicate this when asked at the end of the form.

As a COVID-19 safety measure:
The research team will complete the COVID-19 Daily Self-Assessment Tool before coming to campus.

Memorial University requires that we keep a record of all participant's names, contact information and the data and time of their session, which will be provided to health authorities for the purposes of contact tracing if participants may be exposed to COVID-19. This information will be stored separately from your consent form and research data.

Questions:
You are welcome to ask questions before, during, or after your participation in this research. If you would like more information about this study, please contact:
Erika Noel, elnoel@mun.ca or Dr. Duane Button, dbutton@mun.ca.

The proposal for this research has been reviewed by the Interdisciplinary Committee on Ethics in Human Research and found to be in compliance with Memorial University's ethics policy. If you have ethical concerns about the research, such as the way you have been treated or your rights as a participant, you may contact the Chairperson of the ICEHR at icehr@mun.ca or by telephone at 709-864-2861.

Consent:
Your signature on this form means that:

- You have read the information about the research.
- You have been able to ask questions about this study.
- You are satisfied with the answers to all your questions.
- You understand what the study is about and what you will be doing.
- You understand that you are free to withdraw participation in the study without having to give a reason and that doing so will not affect you now or in the future.
- You understand that if you choose to end participation **during** data collection, any data collected from you up to that **point will be destroyed**.

By signing this form, you do not give up your legal rights and do not release the researchers from their professional responsibilities.

Your Signature Confirms:

☐ I have read what this study is about and understood the risks and benefits. I have had adequate time to think about this and had the opportunity to ask questions and my questions have been answered.

☐ I agree to participate in the research project understanding the risks and contributions of my participation, that my participation is voluntary, and that I may end my participation.

☐ A copy of this Informed Consent Form has been given to me for my records.

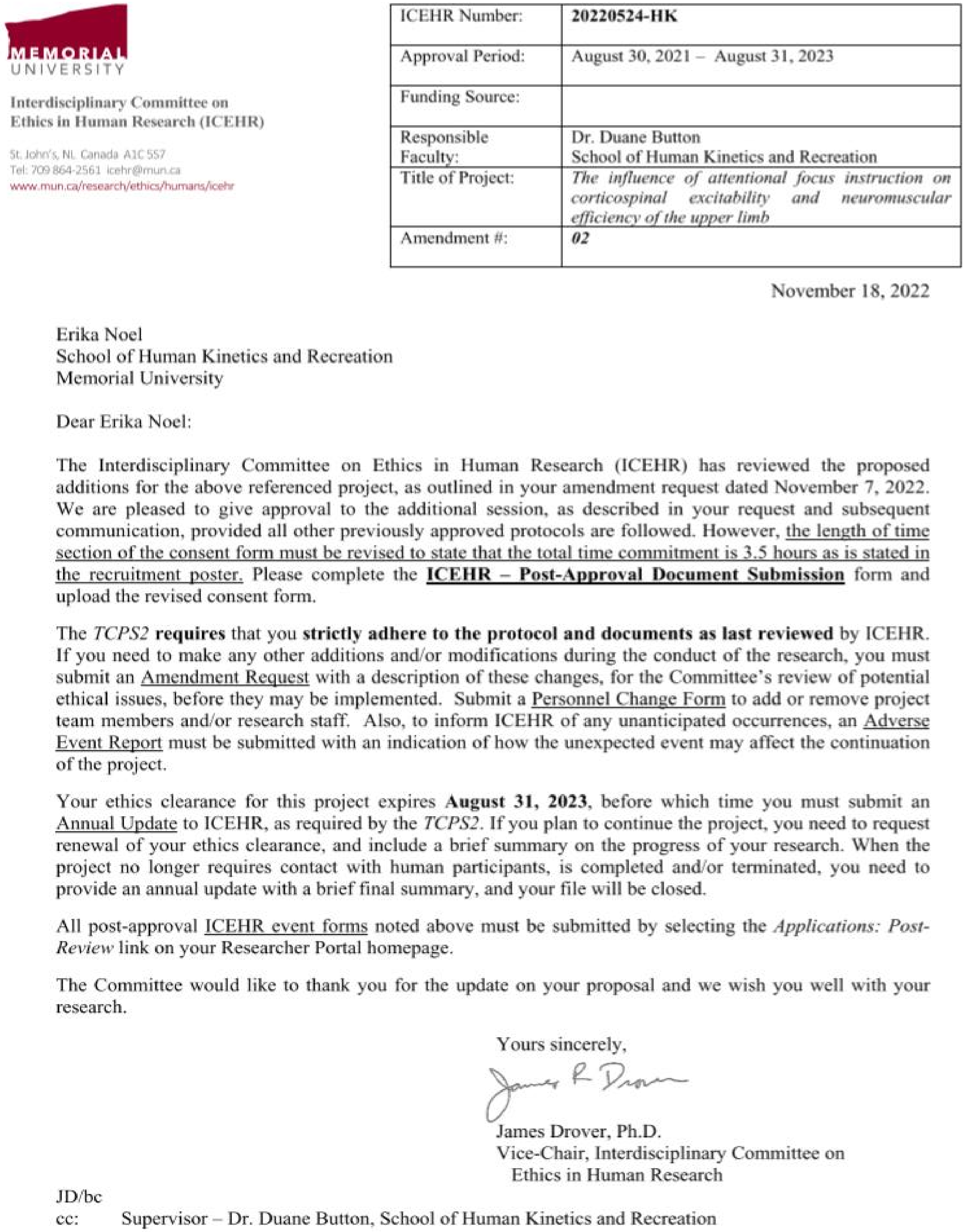
Signature of Participant ____________________ Date ____________________

Researcher's Signature:
I have explained this study to the best of my ability. I invited questions and gave answers. I believe that the participant fully understands what is involved in being in the study, any potential risks of the study and that he or she has freely chosen to be in the study.

Signature of Principal Investigator ____________________ Date ____________________

Upon the completion of this study, would you like a brief summary of its results? (Circle Answer)
Yes No

Appendix C: Ethical Approval



MEMORIAL
UNIVERSITY

**Interdisciplinary Committee on
Ethics in Human Research (ICEHR)**

St. John's, NL Canada A1C 5S7
Tel: 709 864-2561 icehr@mun.ca
www.mun.ca/research/ethics/humans/icehr

ICEHR Number:	**20220524-HK**
Approval Period:	August 30, 2021 – August 31, 2023
Funding Source:	
Responsible Faculty:	Dr. Duane Button School of Human Kinetics and Recreation
Title of Project:	*The influence of attentional focus instruction on corticospinal excitability and neuromuscular efficiency of the upper limb*
Amendment #:	***02***

November 18, 2022

Erika Noel
School of Human Kinetics and Recreation
Memorial University

Dear Erika Noel:

The Interdisciplinary Committee on Ethics in Human Research (ICEHR) has reviewed the proposed additions for the above referenced project, as outlined in your amendment request dated November 7, 2022. We are pleased to give approval to the additional session, as described in your request and subsequent communication, provided all other previously approved protocols are followed. However, the length of time section of the consent form must be revised to state that the total time commitment is 3.5 hours as is stated in the recruitment poster. Please complete the **ICEHR – Post-Approval Document Submission** form and upload the revised consent form.

The *TCPS2* **requires** that you **strictly adhere to the protocol and documents as last reviewed** by ICEHR. If you need to make any other additions and/or modifications during the conduct of the research, you must submit an Amendment Request with a description of these changes, for the Committee's review of potential ethical issues, before they may be implemented. Submit a Personnel Change Form to add or remove project team members and/or research staff. Also, to inform ICEHR of any unanticipated occurrences, an Adverse Event Report must be submitted with an indication of how the unexpected event may affect the continuation of the project.

Your ethics clearance for this project expires **August 31, 2023**, before which time you must submit an Annual Update to ICEHR, as required by the *TCPS2*. If you plan to continue the project, you need to request renewal of your ethics clearance, and include a brief summary on the progress of your research. When the project no longer requires contact with human participants, is completed and/or terminated, you need to provide an annual update with a brief final summary, and your file will be closed.

All post-approval ICEHR event forms noted above must be submitted by selecting the *Applications: Post-Review* link on your Researcher Portal homepage.

The Committee would like to thank you for the update on your proposal and we wish you well with your research.

Yours sincerely,

James R Drover

James Drover, Ph.D.
Vice-Chair, Interdisciplinary Committee on
Ethics in Human Research

JD/bc
cc: Supervisor – Dr. Duane Button, School of Human Kinetics and Recreation