THE EFFECTS OF NOISE AND CONTRACTION INTENSITY ON VIGILANCE PERFORMANCE

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ISBN: 0-612-93015-7
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ISBN: 0-612-93015-7

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The Effects of Noise and Contraction Intensity on Vigilance Performance

By

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A thesis submitted to
The School of Graduate Studies
in partial fulfillment of the
requirements for the degree of
Master of Physical Education

School of Human Kinetics and Recreation
Memorial University of Newfoundland

October, 2003

St. John's Newfoundland

ABSTRACT

There were two major objectives for this thesis: 1) to integrate the existing literature based on vigilance, noise, and neuromuscular fatigue and 2) to determine the effects of muscle contraction intensity, neuromuscular fatigue, and noise on the performance of complex and simple vigilance tasks. Vigilance or an individual's state of physiological or psychological readiness to mediate performance when reacting to a stimulus can be affected simultaneously by noise and neuromuscular stimuli. Noise exposure and muscle contraction have been shown to both negatively and positively affect vigilance performance. However, this contradiction may be a result of differences in muscle contraction and noise intensities, durations, and type as well as the complexity of the vigilance task. It was determined in the present experiment that continuous noise at an intensity of 95 dB (A) impairs both simple and to a greater extent complex vigilance task performance. Isometric muscle contractions at 5% and 20% of a maximum voluntary contraction also impaired simple and complex vigilance task performance. There did not seem to be an interaction effect between noise and contraction intensity.

ACKNOWLEDGEMENTS

Due to the kindness of several individuals my educational experience at Memorial University of Newfoundland was extra special and was one in which I hope future graduates will embark upon while achieving their own dreams and aspirations. The journey to my ultimate goal (PhD) would never have taken place without Dr. David Behm. He has been my guidance and mentor throughout my tenure at Memorial University. I would like to thank my parents Calvin and Elizabeth Button for providing unconditional support, an opportunity for a post-secondary education, and believing in me when I did not. My family, Danielle and Baily, has shown and continues to show me tireless patience and love day in and day out. William, Nadine, Edward-Roy, and Dorothy Vardy are my second parents and provided an environment that was free of stress and with different educational experiences. I would also like to thank my sister and brother in-law Lori and Jason Savory for all of their advice when I was faced with tough and personal decisions. Lastly, I would like to thank Kevin Power and Mike Powell for a friendship that may only transpire once in a lifetime and the faculty/staff especially Dr. Colin Higgs, Dr. Scott MacKinnon and Dr. Basil Kavanagh for all their support. All of these people have affected my educational experience in a very positive manner and may never fully understand the gratitude I owe them.

> *The difference between a successful person and others is not a lack of strength, not a lack of knowledge, but rather in a lack of will.*
> *--Vince Lombardi*

This research was supported by the Newfoundland and Labrador Center for Applied Health Research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

5-HT	Serotonin
BP	Blood Pressure
BPM	Beats Per Minute
cm	Centimeter
CNS	Central Nervous System
CVT	Complex Vigilance Task
dB (A)	Decibels
EEG	Electroencephalogram
EMG	Electromyography
ERP	Event Related Brain Potential
HN	High Intensity Noise
HR	Heart Rate
H-reflex	Hoffman Reflex
Hz	Hertz
IEMG	Integrated Electromyography
IMMG	Integrated Mechanomyogram
IT	Interpolated Twitch
ITT	Interpolated Twitch Technique
LN	Low Intensity Noise
MEP	Motor Evoked Potential
ms	Millisecond
MT	Movement Time
mV	Millivolts
MVC	Maximal Voluntary Contraction
N	Newton's
NIOSH	National Institute for Occupational Safety and Health
NWHSCC	Newfoundland Workplace Health Safety and Compensation Committee
OHSA	Ontario Safety and Health Association
PSNS	Parasympathetic Nervous System
PTS	Permanent Threshold Shift
RT	Reaction Time
s	Seconds
SD	Standard Deviation
SNS	Sympathetic Nervous System
SR	Sarcoplasmic Reticulum
SVT	Simple Vigilance Task
TES	Transcranial Electrical Stimulation
TMS	Transcranial Magnetic Stimulation
TRP	Tryptophan
TTS	Temporary Threshold Shift
VC	Voluntary Contraction

LIST OF APPNEDICIES

Appendix A:

Appendix B:

1 INTRODUCTION

1.1 BACKGROUND OF STUDY

For approximately three-quarters of a century the term "vigilance" has been studied by an array of scientists with psychology, physiology, motor learning, biomechanical and medical backgrounds. The earliest known studies centered around industrial settings (28), lookout and radar operators (19), and the military (20). Research on vigilance and other contributing factors to vigilance have been well documented. This research has included: vigilance signal characteristics and theories (8), classification of vigilance tasks, criterion and sensitivity shifts, effects of the environment and general state on vigilance, individual and group differences, and vigilance and the brain (7). More recently, researchers have attempted to describe vigilance through psychophysiological responses and human behavior which include, the nervous system (central and peripheral), electroencephalography (EEG), electromyography (EMG), papillary response, the brain, and the cardiovascular system (2).

Understanding this literature is important for today's society. Many individuals have to multi-task during daily operations whether at work, home or during leisure activities. In an ideal world vigilance task performance should be at an optimal level to help ensure success during daily tasks. Unfortunately, human vigilance task performance is usually not at optimal levels. These levels are inhibited or facilitated by external (environmental factors) and internal (human behavior) factors. External factors can include different levels of noise, temperature, lighting, and ventilation. Internal factors can include fatigue, sleep apnea, influence of drugs, motor control tasks, speech, and the nervous system.

Interestingly, there is very little research pertaining to vigilance based on internal influences of factors such as neuromuscular fatigue and muscular force or a combination of both on vigilance. Furthermore, there is little research explaining the underlying effects of integrating noise, neuromuscular fatigue, contraction intensity and vigilance performance by an individual. Since many work environments entail noise and require that individuals perform muscle contractions, their effect on vigilance task performance is of importance.

1.2 PURPOSE OF STUDY

The concept of vigilance is encountered frequently in activities (e.g. hockey, fighter pilots, police pursuit) demanding varying intensities of muscular contractions or neuromuscular fatigue, while being exposed to noisy and quiet environments of varying levels of noise. According to Davies and Tune (1970) the term "vigilance" describes a state of the nervous system which is thought to mediate performance at certain kinds of tasks. Muscle contractions and subsequently fatigue are also controlled or mediated through the central nervous system (10). A plausible postulate, therefore, is during these types of activities, the nervous system may be placed under excessive stress causing detrimental effects on vigilance task performance.

Noise is another factor which may affect vigilance performance. Muscle contractions, fatigue and noise are all factors that stress the CNS which in turn influence vigilance task performance (21). However, research illustrating the effects of noise on vigilance task performance is conflicting (13,15,16), probably due to the levels and types of different noise exposures (13,15,16). Thus, the purpose of this thesis is to assess the independent and integrative effects of noise, neuromuscular fatigue, and the extent of muscular contractile force on human vigilance task performance.

1.3 SIGNIFICANCE OF STUDY

Vigilance-induced fatigue has been described as mental fatigue in healthy (1,14) and unhealthy (12) individuals, sleep-deprived fatigue (9,17), chronic fatigue (24), and monotony (23). Furthermore, the vigilance and fatigue research have recruited subjects employed as machine operators, nurses, and doctors, many of whom perform shift work (17). However, there is a lack of information pertaining to the integration of vigilance, neuromuscular fatigue, and the intensity of muscular contractions.

Many jobs induce an individual to develop muscular fatigue while performing tasks. For example, a police officer in foot pursuit of a criminal would likely fatigue quickly while having to maintain his or her attention at all times. A hockey player has to skate, pass, shoot, and check, all of which includes muscle contractions, fatigue and vigilance. If an individual becomes physically exhausted while on the job, vigilance may be affected in such a way that problems may be encountered. For instance, a hockey player fatigued due to a long shift may shift his attention from the immediate environment to the sensations of fatigue. This loss of attention or vigilance could result in an unanticipated check from an opponent resulting in injury or missed tactical opportunities. Likewise, an industrial labourer who constructs scaffolds has to climb while carrying bulky and heavy pieces of steel. As muscle fatigue develops, the labourer may focus on the fatigue sensation and become less attentive to the precision of the climbing task, resulting in injury. Therefore, it would be very important to gain knowledge about muscle fatigue and its effect on vigilance. This current research may give insight on the effects and mechanisms regarding how neuromuscular fatigue and the intensity of muscle contractions affect vigilance.

Noise has also been a popular research factor with respect to vigilance (22,25). Noise is certainly a constant irritant to workers in many occupations. Kilburn et al. (18) found that occupational noise exposure caused iron-workers to become prematurely deaf and impaired their balance. A loss in balance or muscular function resulting in serious falls or injury may be due to a combination of noise and vigilance tasks which industrial employees are exposed to daily. Acute (26) and intermittent (6) noise exposures on vigilance tasks have been reported to decrease accuracy on vigilance tests. Individuals who work in industrial settings or professional sports are exposed to noise daily. This noise may impede both physical and mental performance.

1.4 DEFINITIONS

Vigilance. Vigilance is the ability to maintain a state of readiness for a long time, in order to detect and respond to certain specified infrequently occurring events in a stream of events which have to be neglected (2). For example, hockey players have to pay attention to all of the events taking place in their surrounding environment and most of those events do not need a response. For a hockey player to have good vigilance, he/she will have a high probability of detecting a signal, a low error rate, and a high speed of response .

Task. A task involves the detection of a signal and the ability to execute the required performance due to that signal. A simple task usually includes sensory stimulation such as a change in color or tone whereas a complex signal includes a more intricate thought process or multiple decisions (7).

Fatigue. Fatigue is used to describe any reduction in physical or mental performance. The rate of fatigue depends on the muscles employed and whether or not the contractions are continuous or intermittent. Fatigue may affect either central or peripheral elements in the motor system (11). Central fatigue encompasses emotions and physiological factors responsible for the sense of effort as well as descending motor pathways and the inter-neurons and motor units in the brain stem and spinal cord (3).

Peripheral fatigue can occur anywhere from by a disruption in neural transmission from the motor axon to deep inside the muscle where the contractile process takes place (5).

Noise. Noise can be considered as a sound at a particular amplitude and frequency, where it causes annoyance to the listener, or interferes with communication (27).

Reaction Time (RT). The time it takes for an individual to sense a stimulus, think about the stimulus, and move the proper muscle in response to the stimulus (7). For example, the most common RT test includes one stimulus and one response such as a person waiting to see a light. Once the light appears they have to press a button. The time it takes from seeing the light to pressing the button is the person's RT.

Movement Time (MT). The time it takes for an individual to move the proper muscle in response to a stimulus to a specified target.

Interpolated Twitch Technique (ITT). ITT is a method of estimating muscle inactivation. It is calculated by dividing the force produced by a superimposed electrical stimulus during a muscular contraction by the evoked force produced immediately following the voluntary contraction. It measures the percentage of muscle fibers that were not recruited during the contraction (4).

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2 REVIEW OF LITERATURE

2.1 INTRODUCTION

As early as 1890, the concept of vigilance has been documented in published scientific discourse. William James (90) observed that:

> Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization and concentration of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state which in French is called *distraction*, and *Zerstreutheit* in German.... It is difficult not to suppose something like this scattered condition of mind to be the usual state of brutes when not actively engaged in some pursuit. Fatigue, monotonous mechanical occupations that end by being automatically carried on, tend to reproduce it in men....The abolition of this condition is what we call the awakening of the attention. One principal object comes then into the focus of consciousness, others are temporarily suppressed. The awakening may come about either by reason of a stimulus from without, or in consequence of some unknown inner alteration; and the change it brings with it amounts to a concentration upon one single object with exclusion of aught besides, or to a condition anywhere between this and the completely dispersed state.... As concentrated attention accelerates perception, so, conversely, perception of a

> stimulus is *retarded by anything which either baffles or distracts the attention* with which we await it. If, for example, we make reactions on a sound in such a way that weak and strong stimuli irregularly alternate so that the observer can never expect a determinate strength with any certainty, the reaction-time for *all* for various signals is increased, - and so is the average error.

In this passage, William James identifies several key terms which indicate that attention is centrally oriented at its inception and it may be "retarded" by external distractions.

Attention is synonymous with "long term attention" or "sustained attention" which, are otherwise known as vigilance. Vigilance, like a variety of other human-related tasks is dependent on the brain, spinal cord and an array of other things. During times of vigilance or "long-term attention" the human brain usually attends to other pending internal and external cues. Two such cues of great interest and significance are muscular contractions, which can lead to central and/or peripheral fatigue (neuromuscular fatigue), and noise. William James observed that these cues may impede the vigilance process thus allowing an increase in human error. One hundred and ten years later, research on vigilance, neuromuscular fatigue, and noise has been examined in many aspects. For example, vigilance task performance has been investigated during noise (21,25,29,31,32), cardiovascular functions (32), arousal (45), physical and perceptual workloads (66), monotony (101), operational performance (110), driving (56), and sleep deprivation (130). Neuromuscular fatigue has been investigated in a context of work performance under various parameters including; isometric and dynamic muscle contractions (12,15,17,18,69) with many different muscle groups (69), aging (3,34), disease and injury

(1,2,30,43,46), training (55,89,93,97) and cold (129,143). Furthermore, the central and peripheral mechanisms of neuromuscular fatigue have been examined (23,49,68,98,109). The effects of noise on vigilance (11,20,21,82,85), cardiovascular function (83), blood pressure (108), work (91), anxiety (154), and auditory impairment (141) have also been investigated. Indeed there are still some questions pertaining to vigilance unanswered.

Information regarding these individual cues is in relative abundance, the research pertaining to the effects of integrating neuromuscular fatigue, noise and vigilance is scarce. Understanding their interaction would be important because many occupations (such as a police officer, industrial worker, pro-athlete) involve all three factors. Since vigilance and neuromuscular fatigue are controlled by the central nervous system, it would be important to identify how interactions between the two can facilitate or inhibit human performance. In addition, noise, an external sensory stimulus, which is sensed via the central nervous system (CNS), could further influence one's mental model during the vigilance and neuromuscular fatigue reaction. The purpose of this review is to identify existing literature surrounding vigilance, neuromuscular fatigue, contraction intensity, and noise and postulate how their co-existence may affect an individual's ability to perform a task.

2.2 VIGILANCE

2.2.1 DEFINITIONS OF VIGILANCE

The idea of vigilance was first described in a technical sense by a British neurologist, Henry Head. He stated "the extent to which the activities of a particular portion of the central nervous system exhibit at any moment signs of integration and purposive adaptation indicate its vigilance. When vigilance is high, the body is more prepared to respond to an effective stimulus with a more or less appropriate reaction" (86). Decades later, vigilance was defined as "a state of readiness to detect and respond to certain specified small changes occurring at random time intervals in the environment" (114). Thus, vigilance can be considered as an individual's state of physiological and psychological readiness (within the nervous system) to mediate performance when reacting to an environmental stimulus or stimuli.

Human vigilance task performance relies on sensory information, cognitive processing and movement. Of course, there are many other factors which come into play (i.e. endocrine system, arousal and motivation). Thus, attention is not localized in one section of the brain. Instead, it is a by-product of a network of neural systems from supraspinal to peripheral origins (40). For instance, the limbic system and basal ganglia which modulate impulses from the lower and higher cortical sites have excitatory and inhibitory capabilities and can tune in or out less modulated subcortical impulses (40). This would indicate that during a vigilance task, a human has the ability to choose appropriate stimuli (depending on its importance) even when the stimuli may be of a weak intensity. According to Cohen (40) "these systems seem to be highly flexible in their behavioral repertoire, as they respond to and integrate multimodal sources of information and facilitate the encoding of this information in a distributed cortical system". Communication between the brain centers enables integration between the biological pressures and associative processes that create attentional control (40). Lastly, attentional control is established by a combination of inhibitory and excitatory processes, evident at many different levels in the nervous system (NS).

As stated before "vigilance task involves the detection of a signal" (114). The stimuli used as signals in a task situation can take many forms and help categorize vigilance tasks into sensory and cognitive processes. In a sensory vigilance task, the signal is a change in sensory stimulation (48), for example, a change in light color or noise intensity. In a cognitive vigilance task, the observer is required to detect a specified stimulus sequence (48), for example, the sequencing of letters and numbers. Thus, cognitive tasks are considered more complex than sensory tasks because they require individuals to make multiple decisions rather than one.

2.2.2 MEASURES OF STATE OF VIGILANCE

The most commonly used measure of vigilance task performance in experimental studies is correct detection or the number of times an individual can correctly identify a stimulus. If an individual fails to detect the stimulus then they have made an omission error. If an individual reports a signal falsely then they have made a commission error.

One type of simple vigilance task which includes correct detection, omission and commission errors is simple reaction time (RT). Reaction time is described as the time it takes for an individual to sense a stimulus, think about the stimulus, and initiate the proper locomotor muscles in response to the stimulus (47). For example, the most common RT test includes one stimulus and one response such as a person taking a hearing test. Once the sound commences they have to press a button. The time it takes from hearing the sound to pressing the button is the person's RT (also known as detection latency).

Detection signals involve two processes; discrimination and decision. During the discrimination process the individual distinguishes between signal and non-signal events. The decision process requires the individual to choose the correct signal (48). For example, in a RT task an individual may decide to hit the RT button for the wrong stimulus in hopes of correctly detecting the right stimulus. However, during signal detection, an individual must observe a display unit in anticipation for the signal called observing responses. This is evident in complex vigilance tasks like playing video games or performing mental computations. Individuals have to observe in order to detect, discriminate, and decide before reacting to a stimulus.

2.2.3 PHYSIOLOGICAL RESPONSES TO VIGILANCE

A series of experiments by Surwillo (155-158), indicated a relationship between RT and period of the electroencephalogram (EEG). The bursts of EEG activity decrease in duration as the frequency of stimulus increases. As we age, RT becomes slower and more variable due to a longer EEG period. Sersen et al. (142) indicated that fast RTs were accompanied by relatively low EEG power before and after stimulation and by higher EEG frequency after the stimulus. Sersen et al. (142) suggested faster RT may occur under relaxed conditions and high arousal, and concentrated attentiveness may be an attempt to compensate for boredom or distraction.

Event-related potentials (ERP) are EEG changes that are time-related to sensory, motor, or cognitive events. ERPs measure cortical and subcortical activity in the brain including the cerebral cortex, cerebellum, and brainstem. With regards to attention, ERPs have been used to a greater extent than raw EEG in the literature. ERP amplitudes are greater with an attended stimulus compared to an unattended stimulus (79). However, Andreassi (5) states "research by Naatanen (124) would argue increased ERP amplitude does not reflect attention or cognitive activity per se, but rather the non-specific arousal effects produced in response to expected, task relevant stimuli. Because stimuli were presented in a regular manner, subjects could not anticipate, and be prepared for the critical stimulus, and therefore, ERP amplitude increases could be due to general cortical activation, not selective attention." In other words, task-related activities arouse an individual, thereby increasing brain activity as a whole.

In a classical study by Davis (51), electromyography (EMG) was recorded from the forearm extensor muscles during a RT task. Muscle tension began at 200 – 400 milliseconds (ms) after the ready signal and continued to increase until the reaction took place. Davis (51) also observed that higher muscle tension pre-RT decreased RT and that higher muscle tension and decreased RT were greater during standardized versus unstandardized foreperiods (time leading up to the stimulus response). It is also noteworthy that with practice, EMG will decrease and increase in non-working muscles and working muscles respectively, during vigilance tasks (16). Thus, increased neural drive to stimulus responding muscle(s) enhance stimulus response.

All three physiological measures are interconnected. With regards to laboratory RT tests (which requires attention) an individual is usually in a relaxed state prior to the RT task-related activity, becomes aroused, increasing brain activity as a whole, which sends increased neural drive to the muscles, all of which work together for increased RT performance. However, most vigilant tasks are not performed under the ideal circumstances such as above. During vigilance, humans often have to multi-task during conditions of physiological stress. These conditions may increase or decrease an individual's state of arousal and motivation, ability to filter and inhibit information, and expectancy of stimulus.

2.2.4 THEORIES OF VIGILANCE

Researchers have developed many theories to describe the underlying mechanisms, which determine vigilance performance.

2.2.4.1 Inhibition and Expectancy

The Inhibition Theory was described by Mackworth (113) as "a decrement in vigilance or in his particular experiment, an extinction of the conditioned response when that response is no longer reinforced." Mackworth (113) noted that experimental extinction appeared to parallel the decline in detection rate. In other words, as the experiment progressed in time, the individual became less motivated when detecting a stimulus. This inhibition is easily seen in an array of Mackworth's experiments (111-114). Subject's clock test, radar task, and listening task performances over two hours decreased by 12%, 6%, and 16% respectively. However, knowledge of results and rest periods abolished this inhibition. Thus, Davies and Parasuraman (47) define inhibition as "a fatigue-like construct which is considered to build up with each non-reinforced occurrence of a conditioned response and when the accumulation has become sufficiently great, the response no longer appears." Vigilance decrements may not rely solely on inhibition, but rather on expectancy.

The Expectancy Theory is described as the course of events experienced by the observer during a vigilance task, establishing a level of expectancy, which in turn influences subsequent detection performance. If an average frequency of a signal remains low so will expectancy and vice versa (54). For example, McFacland and Halcomb (118) studied expectancy and stimulus generalization in vigilance. They found that when subjects performed an auditory pre-test in which white noise was terminated at a high probability ($p = 0.18$), followed by a visual monitoring task at a high probability ($p = .18$) of expecting the stimulus, subjects were able to perform reliably ($p < 0.01$) greater than subjects who performed the same tasks at low probabilities ($p = 0.02$) of expecting the stimulus. Their results suggest that pre-test activity plays a crucial role in vigilance performance and that subjects need not respond or even know that a signal is occurring to develop an expectancy set.

2.2.4.2 Filtering

Broadbent (28) developed a filter theory which suggested that incoming information passes through a filter before being processed for meaning by higher centers in the brain. The filter operates on the physical characteristics of the incoming message and filters out information that doesn't have the correct characteristics. Thus in a dichotic listening experiment, when a person is asked to listen only to messages in their left ear, they filter out any messages in their right ear and hence report not having heard anything in the unattended ear. However, Moray (123) demonstrated that approximately 33% of the time, people would detect their own name when it was presented to the unattended ear. Gray and Wedderburn (76) elicited mixed stimuli to each ear. When the individuals reported what they had heard (e.g. in the right ear - saw, one, Duane and in the left ear – two, three, I) it was usually reported in a meaningful group ("I saw Duane" or "one, two, three"). Subconsciously they must have been attending to all the information concurrently, without a filter as Broadbent had suggested.

In 1964, Triesman (161) suggested that information were filtered twice (Attenuation Theory). Physical characteristics of unwanted information were weakened by filter one and the attenuated information would pass through a second filter for meaning extraction. If the meaning were strong enough, it would become conscious. Of course, an individual's response to stimulus depends on the significance of that particular stimulus. Norman's Pertinence Theory (127) argued that the two stage model in Triesman's attenuation theory was unnecessarily complex and in fact all information could be filtered semantically regardless of its physical characteristics. This semantic filtering would determine if the information was pertinent or not, and this would determine whether the information would be attended to or ignored. Corteen and Wood (44) supported this theory by measuring galvanic skin response to particular words. Electrical stimulus was elicited from individuals during particular words. When these previously electrically stimulated related words in the attended ear were presented to the unattended ear there was an increase in subjects' galvanic skin response, indicating that the word was detected unconsciously. The filter theory may have been replaced by a more appropriate theory, a "Limited Capacity (128)."

Limited capacity suggests that if we can only attend to one thing at a time, there must be a limit to how much information we process. Norman and Bobrow (128) suggest that our attentional system has a limited capacity. Variables that place limits on this capacity include; performance required on more than one task, an increase in task complexity, an increase in memory demand, either an excessively high or low rate of occurrence of target events, and excessive task duration (40). However, with practice individuals may be able to divide or extend attention (4,152) or attention becomes automatic and therefore largely unconscious (144).

The aforementioned theories illustrate how an individual's attention may possibly be influenced. Two other powerful factors, which determine the versatility of human task performance, are arousal and motivation.

2.2.4.3 Arousal and Drive

Arousal and drive work together by impinging on the general state of the individual during task performance. Arousal refers to the mobilization or activation of energy that occurs in preparing an individual for a particular action (53). Arousal includes excitatory and inhibitory responses of the sympathetic nervous system (SNS) and parasympathetic nervous system (PSNS). Arousal can be measured by levels of EEG or brain arousal, psychological arousal or how subjectively aroused an individual feels, energetic arousal including a range from feeling tired to vigor, and tense arousal including a range from feeling calm to feeling very anxious (53). Individual arousal activation may be impinged upon by motivation or drive. Drive states are characterized by tension and discomfort due to a physiological need followed by relief when the need is satisfied. It can be categorized into two types. The first type includes both elementary states (servomechanisms and set-points) and more complex physiological regulatory forces (blood flow responses, shivering, nutrient intake) brought into play by alterations in internal physical conditions such as hunger, thirst, and temperature. The second type is personal or social aspirations acquired by experience (92). Brehm and Self (27) suggested that the degree of arousal or drive during task preparation is based on three factors 1) the severity of the person's need, 2) the value of the incentive being pursued, and 3) the likelihood that successfully completing the behaviour will actually result in the incentive. With respect to their suggestion, laboratory methodologies in the context of a typical muscular contraction and fatigue protocol (which includes monotony, discomfort and possibly an electrical stimulus) may push arousal outside its optimal area, causing a decrease in performance. This phenomenon of decreased force or performance with electrical stimulus interpolated upon a maximum contraction has been documented (13). Levels of arousal and their effect on performance can be explained by the Inverted U Hypothesis.

The inverted U-shaped relationship between arousal and performance predicts that performance will be optimal at medium levels of arousal and will fall off at either high or low levels of arousal (40). Sjoberg (148) illustrated this U-shaped curve through heart rate and reaction speed (reactions/second). In his experiment, subjects pedaled a stationary bicycle at steady state workloads of 150, 300, 450, 600, and 750 kilopond meters per minute while being subjected to a choice RT test. Heart rate was an indicator for the individual's state of arousal and number of times the subject pressed the proper RT task button measured performance. Correct RT detections/per minute increase linearly from 100 – 120 beats per minute (BPM) followed by an identical linear decline from 120-150 BPM. Hence, low arousal (approximately 95 BPM) paralleled with poor performance (3.2 reactions/second), optimal arousal (approximately 120 BPM) paralleled optimal performance (3.5 reactions/second), and high arousal (approximately 150 BPM) paralleled poor performance (3.2 reactions/second). Pribram and McGuinness (133) suggested that there are three inter-related neural systems controlling arousal; "one regulates arousal resulting from input, a second controls the preparatory activation of response mechanisms, and a third operates to coordinate arousal and activation." Thus, in relation to the muscle contraction and fatigue-related set-up, input from external factors (e.g. noise and fatigue) may increase anxiety and in turn decrease human performance.

Furthermore, when evaluating the inverted-U arousal hypothesis many other input factors (i.e. noise, music, anxiety, and fatigue) may negatively or positively impact task performance. In opposition, Neiss (125) states "the inverted-U hypothesis is psychologically trivial and the hypothesis is a potential impediment to the understanding of individual differences in response to incentive and threat." Two inputs (noise and fatigue) which may be interpreted as an incentive or threatening to vigilance task performance will be discussed later.

2.2.5 CONCLUSION

Vigilance is a very important aspect of daily activity. It relies on the nervous system and other behavioural characteristics developed genetically and environmentally. A vigilance task takes place within many external contexts (e.g. noise and fatigue), while internal (e.g. auditory centers, neuromuscular centers, visual centers) stimuli collide and either impede or improve the task performance. Theories such as filtering, inhibition, expectancy, arousal, and motivation can give insight into why vigilance task performance is enhanced or inhibited. Arousal, from a cardiovascular endurance exercise, is a common factor for improved simple task performance. However, information on the effect of muscular fatigue on vigilance performance is somewhat deficient in the literature. Fatigue can limit performance and can produce general feelings of discomfort and frustration and interferes with well-being (145). Thus, fatigue involves mental activity and may affect mental acuity. Neuromuscular fatigue-related brain activity may radiate to other brain centers affecting vigilance task performance.

2.3 NEUROMUSCULAR FATIGUE

A compilation of fatigue definitions have been developed to describe fatigue. These include; "diminishing and disappearing ability of a muscle group in the course of a series of repeated maximal or near maximal voluntary contractions (VC)" (7) "a transient decrease of working capacity" (6), "failure to maintain the required or expected force" (62), and "any exercised-induced reduction in the ability of a muscle to generate force or power" (69). However, the true nature of these fatigue definitions is usually characterized by decrements in maximal force, which are not applicable to most activities of daily living and vigilance activities.

Fatigue can also develop during prolonged submaximal VCs. Bigland-Ritchie (22) defined this type of fatigue as "the sensations of increasing effort experienced during the execution of a task or any physiological change resulting from prolonged activity" or "any exercise-induced reduction in the ability to exert muscle force or power, regardless of whether or not the task can be sustained" (24). Whereas maximal force induced-fatigue is atypical during daily activities and vigilance, submaximal force induced-fatigue is common. However, research has indicated that during prolonged activity, vigilance tasks used as a diverting activity away from fatigue can increase the time to fatigue.

2.3.1 DIVERTING ACTIVITIES

Asmussen and Mazin (7) defined diverting activity as "any physical or mental activity performed between or simultaneously with bouts of exhaustive, local muscular work." They provided two important pieces of research describing fatigue events during diverting activity. In the first experiment, (7) subjects performed 8 bouts of 2-3 minutes dynamic contractions in both the elbow flexors and the middle finger flexors. Weight was adjusted so 2-3 minutes of exercise induced fatigue. Upon the first bout of the fatiguing task or subject's inability to maintain required contraction, a two-minute passive rest took place. Bout two then began followed by a subsequent two-minute active (dynamic and static contractions in the unfatigued arm) recovery. Bout three started followed by passive rest. In both elbow flexors and middle finger flexors diverting activity (dynamic and static) had a positive effect on work that can be performed after active pauses compared to passive pauses. When diverting activity was simultaneous to test work, fatigue decreased compared to non-simultaneous diverting activities during work. Furthermore, mental activity during active pauses also improved performance. Since, blood flow to the muscles was stopped during all diverting activities; they suggested that the effect of diverting activity was of CNS origin.

In the second experiment, (7) there was a similar set-up except the subjects were seated on a table with the ankle connected to a strain gauge and EMG electrodes were placed on the rectus femoris. This set-up was used to measure the mechanical response to an intrapatellar tendon tap (patellar reflex). They compared fatigue when subjects closed their eyes as compared to having opened eyes during all activities. The results demonstrated that the amount of work before exhaustion is greater when subjects had their eyes open. When complete exhaustion was attained with eyes closed, opening the eyes resulted in an immediate return of a working capacity amounting to 15-30% of that already performed. Furthermore, patellar reflexes were faster when the eyes were open and diverting activity once again improved performance. They suggested that during work, changes to the muscles take place. The transmission of afferent information to the brain (reticular formation) can result in inhibitory signals to motor neurons, declining mechanical output. Whereas a rest pause will restore homoeostasis in the muscles, diverting activity will influence other facilitory signals from the periphery and the brain to be sent to the motor system and increase performance. Rotstein and co-workers' (137) study supported the findings of previously mentioned studies. Muscle fatigue during isokinetic contractions of the quadriceps was 25% less during diverting activities compared to passive activities. However, in subjects with hemiparesis, diverting activities did not have any apparent effect on fatigue performance recovery (33). Stroke patients have brain damage, which can affect the facilitory responses during fatigue. Furthermore, the evidence suggests that it is of central origin. Diverting activity in the form of noise or music may also enhance CNS activity and augment endurance.

In the context of work performance, the ability to exert maximal force is highly dependent upon the neural output of the brain and its ability to fully activate the multitude of motor neurons innervating muscle fibres (15). Since fatigue can increase muscle inactivation, the distracting effect of noise on concentration might be expected to further decrease muscle activation and force output of an individual. Conversely, when bursts of noise (approximately 80 – 100 decibels (dB (A)) are used in a form of cheers and motivation (lasting for periods of 3s) during a typical maximal voluntary contraction (MVC) protocol, subjects tend to achieve greater force production. Perhaps music is another source of motivation and can help improve an individual's force production or susceptibility of fatigue.

The effect of noise and music on fatigue has been studied. Becker et al. (11) examined the influence of music, judged mellow and frenetic, played before measuring stationary bicycle mileage assessed exercise. Sixty volunteers from three age groups (child, adult, and senior) and with two levels of prior activity (high and low) participated. Mileage in both music conditions was significantly higher than that during the white-noise control trial except among the senior subjects. No significant differences between frenetic and mellow music were noted. Furthermore, Szabo et al. (159) demonstrated that fast music and slow to fast music during progressive exercise results in the accomplishment of more work without proportional changes in heart rate. Perhaps the noise disturbance may have an inhibitory or diverting effect on the sensation of discomfort associated with prolonged muscular exertion. Ferguson et al. (64) also supported the use of music to enhance karate skills. They found an enhancement of performance for both types of music over white noise. In opposition, Harrison and Pauly (84) measured 50 male subjects' (ages ranging from 17 – 22) right hand grip strength and index finger tapping rate, while the subjects were exposed to white noise levels of 63 and 82 dB (A). The white noise did not increase inhibitory sensory input to the cerebral hemispheres, as indicated by no changes in grip strength or rate of fatigue. Pujol and Langenfeld (135) investigated the effects of music on supramaximal (Wingate anaerobic test) exercise bouts. On each test day, subjects performed a series of three Wingate anaerobic tests with 30s rests. In one of the tests, 3 subjects were asked to continue pedaling until fatigued. Time to fatigue on trial 3 gave no significant differences between conditions for any measures. Thus, the literature indicates that music and noise either positively affects fatigue resistance or does not affect it at all.

2.3.2 THE EFFECTS OF FATIGUE ON VIGILANCE

Vigilance tasks used as a method of diverting an individual's attention away from the sensation of fatigue increases fatigue resistance. However, will similar effects occur if the factors are reversed (fatigue effects on vigilance)? Assuming a physical task can result in muscle fatigue; will its effect on vigilance be negative or positive? Collardeau et al. (42) found that running for 90 minutes leads to significant improvement in RT performance. Chmura and co-workers (39) illustrated that during a 20 minute (at 10% above the lactate threshold) and a 60 minute (at 30% below the lactate threshold) bicycle ergometer test, subjects' RT improved before and after the onset of lactate threshold. The results of improved RT after the onset of the lactate threshold were not previously reported in their literature. Hogervorst et al. (87) also demonstrated better RT performance after a bicycle ergometer test compared to pre-test. Subjects performed the cycle test at 75% of their maximal workload until 60 revolutions/second could no longer be maintained. The authors attributed increased RT to subjects' arousal (due to the exercise) being optimal. However, each of these experiments was performed by elite endurance trained subjects and as Neiss (125) suggested, individuals respond differently to incentive and threats. Thus, the results for this group of highly motivated subjects who trained daily for endurance may not apply to sedentary or average physically fit individuals. For example, Fery et al. (65) found that decision tasks of physically fit men decreased during a progressive workload bicycle ergometer test. It is difficult to compare their results to the previous due to different physical characteristics of the subjects and the type of cognitive tasks.

Moderate muscular exercise can improve cognitive performance while low to high muscular exercise may neither improve nor impair it (160). Devienne et al. (57) studied the effect of 50% MVCs of the triceps brachii on cognitive performance. Although EMG measurements of the triceps did not illustrate fatigue, RT decreased from pre- to post-fatigue test. Thus, Devinne and workers illustrated improved performance with moderate intensity contractions. However, their protocol was not sufficient to induce fatigue in the muscle. If fatigue occurred, RT responses may not have improved. Maybe MVCs would induce a decrease in vigilance task performance. Yeung et al. (166) compared RT before and after 30 intermittent MVCs (5s on, 5s off) of the quadriceps. Fatigue was demonstrated by a 15% decrease in MVC force. Electromechanical delay increased, while the pre-motor time increased resulting in no change to total RT. Thus, the CNS may provide compensation during fatigue for the individual to maintain their ability to perform a vigilance task. Even fatigue, induced by an hour of strength training had no effect on motor performance functions of the hands, speed of movement, tapping speed and coordination of healthy subjects (97). The previous studies have demonstrated no effect of prior fatigue on vigilance when vigilance tasks were performed after fatiguing tasks. On the other hand, vigilance task performance may decrease when performed concurrently with fatiguing contractions.

Assessing the differences between the aforementioned studies in the previous two sections is difficult. There are many different types, intensities, durations of noise, music, and muscle contractions. Another reason why there may be discrepancies in the literature related to fatigue and vigilance task performance is the supraspinal and peripheral responses to fatigue that take place during sustained muscle contraction.

2.3.3 FACILITATING AND INHIBITING FORCE MAINTENANCE

As the muscle fatigues, there are several supraspinal and peripheral neuromuscular mechanisms that work in concert or independently to maintain the required force. For detailed readings of these mechanisms refer to (49,50,62,69,77,102,109).

Supraspinal (or the brain's processing power) output can be inhibited during fatigue. Gandevia (69) defined supraspinal fatigue as "fatigue produced by failure to generate output from the motor cortex; a subset of central fatigue." Cortical output from the motor cortex to its distal sites are not optimal during fatigue (70), as indicated by increased muscle activation and inactivation (13,14,19) (measured by the EMG and the Interpolated twitch Technique (ITT) respectively – for further information on the ITT and EMG see methodologies in Appendix A and B). Increased activation has been assumed to be due to failure in the muscle contractility, so that with maintained contraction the individual active fibers exert progressively less force. In compensation of this effect, recruitment of additional motor units and increased firing frequencies of already active motor units will maintain the level of contraction (61). However, the increases in fatigue-induced motor unit firing frequency and recruitment may necessitate greater neural drive perhaps detracting from supraspinal resources available for vigilance tasks.

The prime mover may share its work with other neighbouring motor units in the same muscle or other muscles in order to maintain force. This is known as a substitution phenomenon whereby low-threshold motor units showed periods of inactivity (104,163). Whereas the supraspinal processing involved with muscle substitution could detract from vigilance processing, the delayed onset of fatigue may facilitate vigilance tasks.

Another suppressor of the supraspinal centers is the passage of blood-borne substances across the blood-brain barrier. Serotonin (5-HT) is known to affect arousal, lethargy, sleepiness and mood (50). The Central Fatigue Hypothesis suggests that increased concentration of brain 5-HT can impair CNS functioning, thus, decreasing athletic performance (126). Exercise bouts of 1- 3 hour(s) duration can increase 5-HT (35-38) and elevate blood ammonia (115,136), which is also known to cause CNS dysfunction. Hence, these fatigue-related substances are another factor that may help to inhibit human vigilance task performance.

Fatigue at the spinal level and periphery may also cause a neuromuscular deficit resulting from afferent inhibition. Garland et al. (72) demonstrated that there may be a reflex inhibition of motoneurons by afferents from the fatigued muscle. Afferent Ia reflex inhibition has been shown via the Hoffman reflex (H-reflex) (afferent excitability of the motor neuron elicited by electrical stimulation) to decrease during fatigue (73,162). However, reflex inhibition may be mediated by the smaller diameter afferents originating from the fatigued muscle (71). Group III and IV afferents exert an inhibitory influence on motor neurons during contraction (164). Prolonged muscle contractions to fatigue are susceptible to and induce the release of high quantities of metabolites into the extracellular portions of the muscle. With an increase of metabolites, there is a greater depolarization of the type III and IV afferents (94-96,119-122,138,139), which can result in widespread inhibition of the motor neurons. Group III and IV afferent can also pre-synaptically inhibit type Ia and Ib afferents (8,52,134,140,153,165). Thus, the decrease in Ia and Ib afferent reflexes and the inhibiting effects of the groups III and IV afferents, may lead to impaired movement during vigilance tasks.

During muscle contractions, not only do afferents reflexively travel to the spinal center via spinal pathways, but to the supra-spinal centers via transcortical (long-loop latency reflexes) pathways (81,116). Latency time can be influenced by fatigue. According to Duchateau and Hainaut (59) "fatigue induces an enhanced descending supraspinal drive which compensates for a loss of excitation from the peripheral afferents on motorneurones." Balestra et al. (10) illustrated that short-latency reflexes increased during fatigue but long-latency stretch reflexes were enhanced. Although long-latency stretch reflexes facilitate muscle contraction during fatigue to compensate for the failure of the shorter latencies (spinal), this activity may become problematic during vigilance tasks. Enhanced latency requires increased brain processing. Again, an enhancement in fatigue-induced long-loop latency periods may necessitate greater neural drive perhaps detracting from supraspinal resources available for vigilance tasks.

2.3.4 CONCLUSION

Muscle contraction, supraspinal and peripheral mechanisms work together to maintain required forces. The brain sends impulses to the motor neuron and in turn sends impulses to the muscle. During fatigue, force is facilitated by increases in EMG indicating stronger impulses from spinal and supraspinal centers. Diverting activity (active, mental and music activities) may also increase overall neural drive from both centers. However, neuromuscular inhibition increases with the duration of contraction and eventually becomes pervasive enough whereby an individual can no longer sustain a submaximal force. Supraspinal centers may decrease its facilitory signals due to blood-borne substances and inhibition from the motor neuron. Peripheral mechanisms (Ia, Ib, II, III, IV afferents) may influence reflex inhibition, thus decreasing excitability of the motor neuron and ultimately decreasing force or by enhancing long-latency reflexes to maintain force and possibly decreasing vigilance. The effects of fatigue on vigilance remain inconclusive.

2.4 NOISE

Another irritant which impinges on the supraspinal level and may affect vigilance performance is noise. Sound is a physical phenomenon consisting of an expanding and compressing of air that travels in all directions from its source. As sound intensifies it may become an unwanted stimulus to the human ear, known as noise. Noise is endemic to our society and permeates the workplace, educational institutes, recreational settings and the home. While the tolerance of noise may be somewhat subjective (music versus ambient), there are physiological tolerance levels, which if exceeded may lead to impaired performance and injury. According to the Ontario Safety and Health Association, Canada (OSHA) the maximum daily dose exposure (8 hours) should not exceed 90 dB (A), while the Newfoundland Workplace Health Safety and Compensation Committee, Canada (NWHSCC) recommends not more than 85 db (A) over an 8 hour exposure. Brief exposures (several mintues) according to the OSHA should not exceed 115 decibels. These parameters are based on findings pertaining to the increased incidence of injury or damage to individuals. The terms "damage to individuals" can include hearing impairment, increased cardiovascular functioning, and decreased vigilance task performance and ultimately encumber our well-being.

2.4.1 EFFECTS OF NOISE ON HUMANS

Daily activities for most individuals include noise exposures of the same intensity and greater, per eight hours, as suggested by OSHA and NWHSCC. The stress of this daily noise exposure can lead to auditory fatigue or manifest itself as a temporary loss of hearing sensitivity, called temporary-threshold shift (TTS). TTS is noise-induced morphological and functional modifications of the sensory cells in the inner ear causing frequency, temporal and spatial impairments. These impairments can decrease an individual's ability to detect a signal and speech communication. However, TTS is reversible after a few hours of non-noisy conditions. Whereas, after several days of continuous exposure or TTS, an individual may develop a permanent-threshold shift (PTS) which is irreversible. Research demonstrates that construction workers are regularly overexposed to noise. Sinclair and Haflidson (146) illustrated that average noise levels during construction work ranged from 93.1 dB (A) to 107.7 dB (A). Tools were the major source of noise and often led to over-exposure. Furthermore, Greenspan et al. (78) found a wide-spread overexposure to noise and lack of hearing protection use during road construction. Hence, the workers may develop severe cases of TTS or PTS. In addition, TTS and PTS can impede cognitive abilities (hearing and communication) and cardiovascular functions (blood pressure (BP), heart rate (HR)) (150) and lead to pain, nausea, fainting, fits, psychosis and death (135). Even short-duration noise exposure can affect human functioning.

2.4.1.1 Effect of Noise on Cardiovascular System

The effect of noise on resting cardiovascular responses has been investigated. An assortment of studies have reported increases in HR and BP with sudden onset, intermittent and prolonged noise. Holand et al. (88) elicited a 110 dB (A) stimulus every five minutes for 25 minutes. The acute loud noise produced increases in BP and HR within 10s of stimulation. Gautier and Cook (74) illustrated that an initial intense noise burst at 110 dB (A) elicited a phasic cardiac acceleration. Intermittent noise exposure of 92 dB (A) for 55 minutes significantly increased BP, HR, and HR variability. They further significantly increased during unpredictable noise bursts (32). Prolonged noise exposure similar to those of industrial settings, caused the blood pressure of monkeys to increase by more than 20% and these increases were permanent (132). Furthermore, studies on noise-affected areas (airports and high traffic) suggests that humans may have higher diastolic and systolic BP, local and general vascular changes, higher pulse rate, and cardiovascular abnormalities (41,105,131) Thus, requiring greater medical attention for cardiovascular functions. An increase in total peripheral resistance due to an increased sympathetic response to the noise could probably account for both the increased heart rate and blood pressure. The results from Holand et el. (88) indicated increased peripheral resistance and that the cardiovascular response was probably due to neural rather than humeral mechanisms.

"Startle stimuli" occur daily throughout normal and industrial settings. A rapid onset of short duration in BP and HR could be detrimental for sedentary or obese employees that already have overload stress placed on their cardiovascular system. In addition, increased BP and HR under resting conditions should result in a higher energy output and physiological stress during any given work period. Thus, a person will require more energy during a given workload, inducing a quicker rate of fatigue.

Noise-induced changes in coronary care patients have also been examined. Although HR was significantly higher during conversation sounds compared to low ambient sounds, BP did not change during any of the sound conditions (9). No change in BP may be a direct result of lower ambient noise 70 dB (A) compared to the aforementioned studies (32,88) of 92 and 110 dB (A) respectively. Furthermore, Harrison and Kelly (83) compared age differences (19 versus 77) in cardiovascular performance under noise conditions. Both HR and BP were elevated in the old age group on the noise (80 dB (A)) day. Their results also suggested a potential for increased cardiovascular risk as a function of sensory stimulation. Suffice it to say, the literature describing the effects of noise (whether suddenly, intermittently or prolonged) on cardiovascular function shows a trend for increased BP and HR. But, scientific literature regarding the impact of noise on cardiovascular function during prolonged work or exercise activities involving the aerobic system is sparse (58,107). Since noise affects negatively cardiovascular functions in a non-arousing matter, it would only be fitting to suggest the same for vigilance tasks.

2.4.1.2 Effect of Noise on Vigilance

Researchers investigating the impact of noise on vigilance task performance are far more abundant compared to cardiovascular functions. Most researchers identify noise to have a negative impact on vigilance. When exposed to recorded profiles of jet engine noise and traffic noise and in a natural setting of aircraft noise, human vigilance task performance decreases. Becker et al. (11) examined the effects of exposure to intermittent jet aircraft noise (70 or 95 dB(A) maximum intensity) and knowledge of results concerning signal detections on performance efficiency. Overall, 40 minutes of noise had a degrading effect on signal detection, indicating that noise affects information processing. Furthermore, Gomes et al. (75) reported that the noise associated with occupational exposure to jet engines accelerated cognitive deterioration. They suspected that this impairment could be an explanation for the increased rate of job accidents around airports. Chronic aircraft noise exposure (16 hours) of greater than 66 dB (A) around elementary schools caused higher levels of noise annoyance and poorer reading comprehension in children aged 8 – 11 compared to their non-noisy elementary school counter parts (80). Fortunately, their results also suggested that there were no signs of mental health problems within the noise-exposed children. Belojevic et al. (20) studied the effects of moderate levels of recorded traffic noise (55 and 75 dB (A)) on mental performance. Short-term memory and mental arithmetic performance decreased with noise and decreased even further in noise-sensitive subjects compared to subjects in quiet conditions (30 dB (A)). Vigilance task performance also decreases when exposed to ambient noise. Smith (149) investigated the effects of acute (30 minutes) ambient noise of 85 dB (A) on two different task parameters (detection of specific targets and general categorization of events). Detection processing was impaired in both tasks regardless of task difficulty, with no apparent differences between tasks. Even an 80 dB (A) intermittent ambient noise exposure can lead to a deficit in numeric monitoring performance (21). Furthermore, McCann (117) identified that intermittent noise is more detrimental to a numerical checking ability test than continuous noise. However, his results were based on omission errors and not total errors. Maybe decreased vigilance task performance was not only due to noise, but noise-induced anxiety.

Anxiety is defined as an unpleasant emotional state in which a present and continuing strong desire or drive seems likely to miss its goal (63). Hence, increased anxiety could decrease vigilance. Edsell (60) placed students under three levels of noise (51, 61, and 75 dB (A)) while playing a social interaction game. The students showed greater anxiety under the noise conditions (61 and 75 dB (A)) compared to low noise (50 dB (A)). Standing and Stace (154) measured state-trait anxiety (state-external stimulus, train-internal stimulus) via the State-Trait Anxiety Inventory and found that state anxiety increased when subjects were exposed to 75 dB (A) noise for only 30 minutes. Both experiments did not adversely affect vigilance (as measured by subject's eye blink rate over thirty seconds). However, increased anxiety from another source in addition to increased anxiety from noise may work together to decrease vigilance task performance. Singh and Singh (147) studied the effect of job anxiety and noise (90 dB (A)) on vigilance task performance with locomotive drivers. They characterized job anxiety as job security, recognition, self-esteem and capacity to work. Both noise and job security anxiety impaired stimulus detection. They suggested that high anxiety about job security might exert low phasic arousal under stress, inhibiting vigilance. On the other hand, Key and Payne (99) found no combination effect of noise and anxiety on vigilance task performance. Their noise levels were similar to those previously mentioned.

Conflicting evidence regarding the effects of noise on vigilance is not a recent finding. Harcum and Monti (82) found no effects of 100 dB (A) ambient noise on a subject's visual and card sorting tasks. However, their finding may be due to a lack of subject sensitivity in performance. Blackwell and Belt (25) found that vigilance task performance did not change regardless of noise intensity (50, 75, 90 dB (A)) during a visual display vigilance task. Likewise, Koelega et al. (103) demonstrated no effect of noise on vigilance performance and no effect of temporal pattern of noise (frequency of interruption and regularity). What is more interesting is their finding that frequent noise improved the RT response. Harrison and Kelly (83) demonstrated that ambient white noise (80 db (A)), compared with quiet (52 db (A)) testing environments improved the performance of elderly and younger subjects on simple addition. One possible explanation for contradicting evidence in performance is the arousal theory. Kryter (106) states "noise conveys meaningful, emotion arousing information to the person." This must be under the assumption that noise is wanted instead of unwanted.

Another explanation for increased performance or at least no change in performance due to noise is hearing habituation. The presence of any continuous stimulus commonly results in a process called habituation, whereby an individual responds less and less to the stimulus as long as it does not have any special meaning. Eventually the signal will no longer be detected and cortical neurons will become non-compliant. Sokolov (151) explains habituation through two types of reflex responses. Sokolov calls the orienting response, wherein the autonomic system responds to any sound stimulus in order to alert and make ready the organism for the purposes of receiving and responding as appropriate to this response. This orienting response is postulated to get stronger as the noise stimuli become weaker, because the organism would require more effort to the weaker than more readily observed stimuli. The second reflex is a defense response (fight or flight). This defense becomes stronger as the noise stimuli become stronger. These responses work together during meaningless noise, but as the noise becomes established through repetition (the noise does not warrant either response) the response becomes inhibited or habituated. According to Borg (26) "habituation takes place rapidly when the sound is continuous, but under intermittent stimulus conditions, acute reactions may be elicited during several days." The aforementioned methodologies illustrating no effect or a positive effect of noise on vigilance entailed a noise exposure regime that was continuous. Thus, subjects may have gone through the process of habituation and tuned out unwanted noise stress.

Does habituation change during vigilance? Frith and Allen (67) examined skin conduction and habituation of noise during RT, arithmetic and non-concomitant tasks through two different experiments. In the first experiment, skin conductance magnitude was significantly greater to noise during RT and arithmetic compared to noise during no RT and arithmetic. This indicates that attention was greater during the vigilance tasks. However, this experiment did not reflect direction of attention. The second experiment was developed to approach the direction of attention problem. Subjects performed a forewarned RT task or a non-concomitant task during noise. Their findings indicated that habituation reflected direction of attention. During a RT task, subjects seemed to habituate noise at a faster rate by directing more attention to the task at hand. Thus, their hypothesis that both RT and habituation will fight for central processing was not confirmed.

2.4.2 CONCLUSION

The literature stating the effects of noise on cardiovascular function and cognitive performance may somewhat conflict, the vast majority of research indicates detrimental problems (cardiovascular and cognitive) associated with noise. If noise negatively impacts cognitive performance, then psychomotor skills involving co-ordination and physical effort might be negatively impacted. Kilburn et al. (100) found that occupational noise exposure caused iron-workers to become prematurely deaf and impaired their balance. A loss in balance or muscular function resulting in serious falls or injury may be due to a combination of noise, vigilance tasks and submaximal fatigue in which industrial employees are exposed to daily. On the other hand, noise exposure in small doses may arouse an individual and increase performance or the process of habituation may take place whereby an individual tunes out the stimulus and focuses on the task at hand. However, there are a paucity of studies investigating the relationship between noise and submaximal neuromuscular fatigue.

2.5 SUMMARY

Everyday humans are required to perform vigilance tasks during activities that involve muscular contraction, fatigue, and noise. Independently, vigilance performance can be a derivative of inhibition, expectancy, filtering, drive, and arousal. We measure these derivatives by correct detection, omission, and commission errors. In order to make one of these errors, an individual must discriminate, observe, and decide among the stimuli. Fatigue and noise may impact upon individuals' detection and decision making abilities and subsequent movements during a vigilance task. Fatigue, or the sensations of increasing effort, experienced during the execution of a task resulting from prolonged activity has been shown to facilitate, maintain, and inhibit vigilance performance. Of course, one must consider the psychological attributes of fatigue. Individuals perceive fatigue differently and one group of subjects may be well motivated and aroused by the physical task while others may not. On the other hand, the neuromuscular and cardiovascular physiological characteristics of the human body are equipped to fight and compensate the sensations that occur at different levels of fatigue. However, once fatigue extends beyond this physiological compensation, muscle performance decreases. Thus, required movements for a vigilance task may also decrease with a parallel affect on vigilance task performance. Furthermore, the supraspinal centers may direct its resources to force maintenance due to the peripheral and spinal failure and provide less neural outputs to vigilance tasks. Similar to fatigue, noise has been shown to facilitate, maintain, and inhibit vigilance task performances. Depending on the duration, intensity, and type of noise it may also motivate and arouse subjects and increase vigilance task performance. Physiologically it may suppress the supraspinal centers by annoying or distracting the subjects and place a diminishing effect on human vigilance task performance. The literature has independently reported the effects of noise and fatigue (rhythmic movements) on vigilance. However, the interaction of continuous high level noise for duration of one hour and isometric muscle contraction induced fatigue has not..

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3 CO-AUTHORSHIP STATEMENT

I will address my contributions to this thesis in four statements:

i) This thesis research idea was a modification of a United States Armed Forces grant proposal developed and written by Dr. David Behm. Dr. Behm and I discussed his original idea and developed the current research. Together we designed an experimental methodology. D. Behm and I put together a reaction and movement time apparatus on paper and then contracted the Memorial University Technical Services - Electronics, to develop it. I developed the reaction time and movement time desk and made modifications to the leg extension table to better suit the participants. All other equipment was obtained by Dr. Behm or myself through a Newfoundland and Labrador Center of Applied Health Research Developmental Grant.

ii) Beltone Audiology (St. John's, Newfoundland) provided hearing assessments on all participants before the practical portion of the research started. Michael Homes and I recruited all participants and performed all research testing on each participant. The experimental methodology required two researchers at all times.

iii) Raw data was collected by Michael Homes and myself. With the guidance of Dr. Behm, I performed all data analysis procedures.

iv) With the guidance of Dr. Behm, I prepared the manuscript.

4 Contractile Activity and Noise Impair Simple and Complex Vigilance Tasks

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4.1 ABSTRACT

The objective of this study was to determine the effects of muscle contraction intensity, neuromuscular fatigue, and noise on vigilance performance. Dependent variables included simple (reaction time and movement time) and complex (video game: Tetris) vigilance tasks (SVT and CVT respectively) and maximum voluntary contraction (MVC) force and activation. Vigilance tasks and MVC were randomly allocated to 5 minute blocks during a pre-test. Following the pre-test, the tests were again randomly allocated within three, 15 minute testing sessions over 65 minutes, while 1) being exposed to high (95 dB (A)) or low (53 dB (A)) levels of noise, and 2) performing muscle contractions at 20% and 5% of MVC, or no contractions. Ninety-five (95) dB (A) noise increased ($p \leq 0.01$) SVT (reaction time and movement time combined) by 11.2% and decreased ($p \leq 0.01$) CVT by 20%. Both 20% and 5% MVC impaired SVT and CVT to a similar extent, while no changes were seen with no contractions. Furthermore, neuromuscular fatigue had no apparent effect on vigilance task performance. These findings suggest that the distraction of noise and divided attention between muscle contraction and a vigilance task decreases performance.

Keywords: Reaction Time, Movement Time, Electromyography

4.2 INTRODUCTION

Vigilance is defined as "the extent to which the activities of a particular portion of the central nervous system exhibit at any moment, signs of integration and purposive adaptation" (31,38) or "a state of readiness to detect and respond to certain specified small changes occurring at random time intervals in the environment" (38). James (33) indicated that attention is centrally oriented at its inception and it may be "retarded" by external distractions. This suggests that a central nervous system (CNS) stimulus such as fatigue or muscle contraction or an environmental stimulus such as noise could affect or degrade vigilance task performance.

Since muscle fatigue has been documented to affect the CNS as evidenced by an increasing inability to activate muscle fibers (2,3) and suggestions of decreased supraspinal output (25), there may be related impairments with the performance of vigilance tasks. Fery et al. (22) found that decision tasks of physically fit men decreased during a progressive workload bicycle ergometer test. However, a simple vigilance task like reaction time (RT) has been shown to improve; after running for 90 minutes (15), before and after a 20 minute (at 10% above the lactate threshold) and a 60 minute (at 30% below the lactate threshold) bicycle ergometer test (12,32). Whereas, these studies are related more to cardiovascular fatigue; prolonged isometric contractions may provide different effects. Devienne et al. (18) studied the effect of 50% maximum voluntary contractions (MVCs) of the triceps brachii on cognitive performance. Although electromyography (EMG) of the triceps did not demonstrate fatigue, RT decreased from pre- to post-fatigue testing. According to Tomporowski and Ellis (52) "moderate muscular exercise can improve cognitive performance while low or high muscular exercise neither improves nor impairs it." To our knowledge there is little literature reporting the effects of sustained intermittent muscle contractions on simple and complex vigilance tasks.

Another stimulus which can affect vigilance task performance is noise. Noise has been shown to negatively impact both simple and complex vigilance tasks. Gomes et al. (27) reported that noise accelerates cognitive deterioration. Moderate levels of acute, intermittent, and continuous noise (55 dB (A) - 85 dB (A)) impairs short-term memory and mental arithmetic performance (5), detection processing (50), and numeric monitoring performance (6). In addition, the effects of noise are greatest when a task requires continuous vigilance; a person may show intermittent blanking of attention (11). Cohen et al. (14) illustrated that puzzle solving time decreased in elementary school children when exposed to 79 dB (A) compared to 57 dB (A) of noise. However, there is evidence that noise does not negatively affect vigilance task performance and in some cases improves performance. Harcum and Monti (29) found no effects of 100 dB (A) ambient noise on visual and card sorting tasks. Harrison and Kelly (30) demonstrated that ambient white noise (80 dB (A)), compared with quiet (52 dB (A)) testing environments improved the performance of subjects simple addition. Since, the duration of noise in the aforementioned experiments only range from 15 – 45 minutes with low noise intensities, it may not represent typical industrial work. Continuous noise for longer durations and at higher intensities which are characteristic of industrial work, military, sports and other situations may negatively affect vigilance task performance.

There are many situations where people are required to make decisions under conditions involving muscular contractions and noise exposure. For example, plant mechanics have to work vigilantly and safely around heavy machinery, electricity, and co-workers. During work, they perform continual muscular contractions (wrench tourques, lifting and climbing in stable and unstable conditions) while exposed to high levels of continuous noise. If muscle contractions and noise impede their thought processes, the implications of that may be serious. Thus, it is important to understand how muscle contractions and noise affect vigilance task performance.

The purpose of this study was to investigate the effects of intermittent submaximal muscle contractions (5% and 20% of MVC), neuromuscular fatigue, and two different continuous noise at intensity of 53 and 95 dB (A) on simple and complex vigilance tasks (SVT and CVT respectively). There were three hypotheses. 1) Twenty percent (moderate level of muscular exercise) but not 5% MVC (low level of muscular exercise) would negatively affect SVT and CVT performance. 2) Continuous noise would not affect performance of either vigilance task. 3) Neuromuscular fatigue will negatively affect SVT and CVT.

4.3 MATERIALS AND METHODS

4.3.1 Operational Definition of vigilance

Vigilance can be considered as an individual's state of physiological and psychological readiness (within the nervous system) to mediate performance when reacting to an environmental stimulus or stimuli.

4.3.2 Subjects

Five healthy physically active male (height 176.3 ± 4.7 cm, weight 77.9 ± 9.4 kg, age 24.2 ± 3.3) and five female (height 162.6 ± 8.6 cm, weight 64.2 ± 8.6 kg, age 23.4 ± 2.2) subjects from the university population volunteered for the experiment. Subjects were verbally informed of the procedures, and if willing to participate, read and signed a consent form prior to participation. The study was approved by the Memorial University of Newfoundland Human Investigation Committee.

4.3.3 Testing Protocol

Exercise Protocol. Subjects performed the experiment over six days with a minimum of 24 hours rest between each testing period. During each testing period subjects were exposed to a combination of contraction intensity and noise (no contraction, 5% and 20% of MVC; 53 and 95 dB (A)).

A single 65 minute experimental session included a pre-test and three 15 minute testing blocks commencing at 10, 30, and 50 minutes. Dependent variables were randomly interspersed at five minute intervals within the testing block. Thus all measures were repeated four times over the experimental session (Table 4.1). Since diurnal rhythms have been shown to affect force output (39), experiments were performed at approximately the same time each day for each subject.

4.3.4 Dependent Variables

Dependent variables included leg extensor 100% MVC, activation ((integrated electromyography (IEMG) and interpolated twitch technique (ITT)) and performance in vigilance tasks. Vigilance tasks included simple (SVT) (upper limb reaction and movement time) and complex (CVT) (computer game: Tetris) tasks. All vigilance tasks were performed during the conditions of noise and/or leg extension contractions.

Leg Extension Force. Subjects sat on a table with the knee flexed at 90° with their upper leg, hips, and upper body supported by three different straps and a backrest (Figure 4.1.a). The ankle was inserted into a padded strap attached by a high-tension wire that measured force using a Wheatstone bridge configuration strain gauge (Omega Engineering Inc. LCCA 250, Don Mills, Ontario). All forces were detected by the strain gauge, amplified (Biopac Systems Inc. DA 100 and analog to digital (A/D) converter MP100WSW; Hilliston, MA) and monitored on computer (Sona Phoenix, St. John's, Newfoundland). Data were sampled at 2000 Hertz (Hz) – A/D converted and stored on a computer for further analysis on a commercially designed software program (AcqKnowledge III, Biopac Systems Inc., Holliston, MA).

Muscle Activation. Prior to attempting maximal contractions, subjects would perform approximately 3-5 sub-maximal knee extension isometric contractions. During the pre-test, subjects were requested to perform at least two maximum MVCs to determine their maximum isometric force output. During the pre-test, in order to ensure a consistent maximal effort, the subjects proceeded with the ITT if there was less than 5%

difference between the two MVCs (3). An ITT was utilized as a measure of the CNS ability to fully activate the target muscle. The ITT was performed, with two evoked doublets superimposed at 1.5 second (s) intervals on a series of 4s duration maximal voluntary contractions to estimate an average superimposed signal (3) (Figure 4.2). A potentiated doublet was recorded 1.5s after the voluntary contractions (3,4). An interpolated twitch (IT) ratio was calculated comparing the amplitude of the superimposed stimulation with the post-contraction stimulation to estimate the extent of inactivation during a voluntary contraction (interpolated doublet force / potentiated doublet force x 100 = % of muscle inactivation (3)).

Superimposed stimulation was accomplished with bipolar surface stimulating electrodes, 4-5 centimeters (cm) in width. They were secured over the proximal and distal portion of the quadriceps. Stimulating electrodes were constructed from aluminum foil, coated with conduction gel (Eco-Gel 200, Eco-Med Pharmaceutical Inc., Mississauga, Ontario), and immersed in an aqueous solution. The electrode length was sufficient to cover the width of the muscle belly. Subjects received peak twitch torques that were evoked with electrodes connected to a high-voltage stimulator (Stimulator Model DS7H+; Digitimer, Welwyn Garden City, Hertfordshire, UK). The amperage (10 milliamps (mA) – 1amp (A)) and duration (50 micro-seconds (μs)) of a 100 - 200 volt square-wave pulse was progressively increased until a maximum twitch torque was achieved.

EMG activity was used as a measure of peripheral muscle activation. Surface EMG recording electrodes (Ag/AgCl, disc shape, and 10 mm in diameter) were placed approximately 3 cm apart over the middle segment of the vastus lateralis. A ground electrode was secured on the fibular head. Thorough skin preparation for all electrodes included removal of dead epithelial cells with an abrasive (sand) paper over the designated areas followed by cleansing with an isopropyl alcohol swab. EMG activity was sampled at 2000 Hz, with a Blackman -61 dB band-pass filter between 10-500 Hz, amplified (bi-polar differential amplifier, input impedance = 2MΩ, common mode rejection ratio ≥ 110 dB min (50/60 Hz), gain x 1000, noise ≥ 5 μV), and analog-to-digitally converted (12 bit) and stored on personal computer for further analysis. EMG was full-wave rectified and integrated. EMG was measured; 1) over a one second period between the first two superimposed doublets, in order to allow generation of peak forces and 2) over a one second period during 20% MVC and 5% MVC.

Simple Vigilance Task. RT and movement time (MT) were measured by an apparatus developed by the Memorial University Technical Services (Electronics, Newfoundland, Canada). The testing apparatus (Figure 4.1.b) consisted of a stop clock (58007, Lafayette Instrument Company, Lafayette, IN), an analog timer (L15-365/099, Triton Electronics, Great Britain), a stop clock latch (58027, Lafayette Instrument Company, Lafayette, IN) which connected the stop clock and the analog timer, a custom designed box (62 cm (length) x 15.5 cm (width) x 9 cm (height)) with the distance of 50 cm from center of start button to the center of the stop button, and a trigger plate for the start of the task. The task entailed movement of the dominant arm in response to the illumination of an incandescent light bulb. The subject would start with the index finger placed on the start button. Upon illumination of the light signal the subject would release the start button and move their arm and index finger to touch the stop button. RT was measured as the time between the illumination of light stimulus and release of the start button. MT was measured as the time between the illumination of light stimulus and the touching the stop button. Five trials of RT and MT were randomly performed during a five-minute time period.

Complex Vigilance Task. Performance using a Nintendo Gameboy (Figure 4.1.c) (DMG-01, Nintendo 1989, Japan) with the software game "Tetris" (DMG-TR-CAN-1, Japan) was tested three times over the 65 minute testing period (once/15 minute testing block). CVT was performed over a five minute period. Vigilance was assessed by the number of points for each trial scored by the subject. A 60 minute re-familiarization period was permitted prior to the start of testing. All subjects had previous experience with the game.

4.3.5 Independent Variables

In order to mimic typical occupational environmental factors, the following noise and fatigue variables were imposed upon the subjects separately and in combination.

Noise Exposure. Participants were subjected to digitally recorded (www.sounddogs.com) high noise (HN) intensity (similar to industrial and construction work) at 95 dB (A) (49) or low noise (LN) intensity (similar to a very quiet office environment) at 53 dB (A) (46) for 65 minutes.

Subjects were exposed to the construction noise stimulus through stereo headphones (HR-80, Toshiba, Japan) that were connected to an am/fm stereo receiver (VRX-2700, Vector Research, USA) (Figure 4.1.d). Noise levels were at the highest allowable intensity (95 dB (A)) per one-hour test duration during the HN exposure. According to the National Institute for Occupational Safety and Health (NIOSH) an average individual can be safely exposed to noise for approximately one hour at 95 dB (A). Noise levels were averaged by placing a digital sound level meter (Sound Level Meter 33-2055, Radioshack, Canada) between the stereo headphones over a five-minute duration pre-test. This ensured that the noise levels remained within the NIOSH limits.

All subjects were tested (Beltone Audiology, St. John's), and recorded, for normal range of hearing. All subjects had to score in the normal hearing range and were required to follow noise exposure guidelines (recommended by Beltone Audiology) for 24 hours prior to testing.

Contractions. Subjects were asked to perform no contractions or maintain either 5% or 20% of an MVC during the 65 minute period. Individual contractions were held for 20s with rest periods of 10s each.

Subjects were seated in a straight-backed chair with hips and knees at 90°. Contractions were performed or elicited with their ankle secured in a padded strap. The subject would increase voluntary force as quickly as possible and hold at 20 % or 5% MVC for 20s and then decreased the voluntary force immediately. This duration was based on results of a pilot study which determined that subjects could maintain 20% MVC for a minimum of 65 minutes. Knee extension force at 20% MVC decreased maximum force up to 40% during the pilot study. Gridlines were provided on the software interface output on the computer monitor at 20 % and 5 % MVC to guide the force output of the subjects. See Figure 4.1.e for complete set-up.

4.3.6 Statistical Analysis

Data were analysed with a three way ANOVA (2x3x4) (noise, contraction intensity, and time) with repeated measures (SPSS 11.0.1 for windows) to determine whether there were significant main effects or interactions for noise, contraction intensity and time (testing blocks). F ratios were considered significant at $p<0.05$. If significant main effects or interactions were present, a Bonferroni (Dunn's) procedure was conducted. Descriptive statistics include means +/- standard deviation (SD) for both the text and figures.

4.4 RESULTS

Overall, continuous HN and the two contraction intensities (5% and 20% MVC) impaired subjects' ability to perform both tasks. Four different measures of fatigue (max force, max force activation and inactivation, and submaximal activation) indicated that 20% MVC for 65 minutes induced fatigue while 5% MVC did not.

The effect of noise on vigilance. HN exposure significantly ($p \leq 0.01$) increased the durations of RT and MT by 11.5% and 7.5% respectively (Figures 4.3a,b), while CVT scores significantly ($p \leq 0.01$) decreased 20% (Figure 4.3c) compared to LN. HN exposure significantly ($p \leq 0.01$) decreased CVT by 15% compared to SVT. All data were collapsed over contraction intensity and testing blocks to see the overall affect of noise intensities on vigilance task performance.

The effect of contraction intensity on vigilance. RT significantly ($p \leq 0.003$) increased by 18.3% and 24.1% during the 5% and 20% MVCs respectively compared to no contractions. There were no significant differences between 5% and 20% MVC (Figure 4.4a). MT significantly ($p \leq 0.001$) increased by 15.9% and 21.6% during the 5% and 20% MVCs respectively compared to no contractions (Figure 4.4b). CVT scores significantly ($p \leq 0.05$) decreased by 10.1% and 21.9% during the 5% and 20% MVCs respectively compared to no contraction (Figure 4.4c). All data were collapsed over noise condition and testing blocks to see the overall effect of contraction intensities on vigilance task performance.

Irrespective of which vigilance task was performed or which noise condition was administered, vigilance performance significantly ($p = 0.025$) decreased 8% from 5% to 20% MVC. There were no significant differences in the percentage of performance decrements between SVT and CVT during 5% and 20% MVCs. Furthermore, the interaction of contraction intensity and noise did not result in a significantly greater decrement in the SVT and CVT scores.

Fatigue. MVC force with the 20% MVC intervention significantly ($p \leq 0.001$) decreased by 14.2%, 23.3%, and 28.5% during testing blocks 1, 2, and 3 respectively compared to pre-test MVC force. All 20% MVC forces in the testing blocks were significantly different (Figure 4.5a). MVC force during 5% MVC significantly ($p \leq 0.001$) decreased by 8.8%, 11.8%, and 12.2% during testing blocks 1, 2, and 3 respectively compared to pre-test MVC force (Figure 4.5b). There were no significant MVC force differences between testing blocks during no contractions. MVC force at the end of the 65 minute experimental session was significantly ($p < 0.01$) less during the 20% MVC compared to no contraction and 5% MVC by 15.4% and 8.4% respectively. There were no significant differences for MVC force between no contractions and 5% MVC. All data were collapsed over noise condition to see the overaal effect of contraction intensity on fatigue.

Irrespective of noise condition, MVC inactivation during 20% MVC significantly ($p \leq 0.001$) increased by 5.2%, 5.4%, and 9.4% during testing blocks 1, 2, and 3 respectively compared to pre-test MVC force (Figure 4.6a). There were no significant differences for MVC inactivation between testing blocks during no contraction and 5% MVC.

MVC activation (measured by EMG) following 20% MVC intervention significantly ($p \leq 0.007$) decreased 14.8%, 21.2%, and 26.4% during testing blocks 1, 2, and 3 respectively compared to pre-test MVC activation (Figure 4.7a). Submaximal contraction activation during the 20% MVC intervention significantly ($p \leq 0.005$) increased 25.6%, 41.8%, and 50.2% during testing blocks 1, 2, and 3 respectively compared to pre-test submaximal contraction activation. All testing blocks were significantly different (Figure 4.7b). There were no significant differences for submaximal MVC activation between testing blocks during no contraction and 5% MVC. All data were collapsed over noise condition.

The effects of fatigue on vigilance. During 20% MVC testing blocks 1, 2, and 3, RT and MT significantly ($p \leq 0.01$) increased by 19.6%, 23.7% and 21.7% (Figure 4.8a) and 17.7%, 19.4% and 17.1% (Figure 4.8b) respectively compared to pre-test values.

CVT significantly ($p \leq 0.03$) decreased by 24%, 26.9% and 17.5% during testing blocks 1, 2, and 3 respectively compared to pre-test values (Figure 4.8c). There were no significant differences in any vigilance tasks between pre-test values and testing blocks 1, 2 and 3 during no contraction. All 20% MVC data were collapsed over noise condition and testing blocks to see the general effect of fatigue on vigilance task performance.

Reliability of tests. The intraclass correlation coefficient for MVC force, RT, MT and CVT reliability was 0.99, 0.87, 0.95 and 0.67 respectively. These reliabilities indicate to a high degree that the variables measured prior to the start of the six testing sessions were indeed similar and that no learning curve occurred. The reliability score of the CVT may have been lower compared to the reliability scores of other variables because of the nature of the CVT itself. The CVT or computer game Tetris was randomly different each time the game started. Thus, due to this randomization some games may have set-up for an individual to score more points.

4.5 DISCUSSION

The most important findings in the study were that muscular contractions (5% and 20% MVC) and continuous HN impaired the ability to perform the SVT and CVT. There were no interaction effects of noise and contraction intensity on vigilance task performance.

To our knowledge, the finding that isometric contractions (5% and 20% of MVC) impaired SVT and CVT performance, have not been previously reported. In fact, other experiments investigating the effects of exercise on vigilance task performance have shown that moderate muscular exercise (similar to the isometric muscle contraction employed in the current study) improves vigilance task performance while low or high muscular exercise had no effect (52). Fleury et al. (23) demonstrated that subjects improved their performance in constant error and temporal variability while simultaneously performing perceptual tasks and pedaling on a cycle ergometer at 4.1 and 8.1 km/h respectively. Collardeau et al. (15) found after 40 minutes of running that there was a significant improvement in RT during exercise. However, both studies included rhythmic muscle contractions of the lower limbs while performing RT with the upper limbs, whereas the current study used isometric contractions instead. Prolonged isometric contractions can impair blood flow contributing to a hypoxic environment (9) resulting in greater reliance on anaerobic metabolism. The associated release of metabolites can activate type III and IV afferents (34-36,41-44,47,48), inhibiting motor neuron depolarization (55) resulting in impaired muscle performance and possibly supraspinal processing to the fatigued muscle and other muscles. Thus, isometric contraction-induced fatigue may decrease subsequent movements during vigilance tasks.

As contraction intensity increased, the overall ability to perform the vigilance tasks decreased. As muscle contraction intensity increases, neural drive (recruitment, rate coding, agonist and antagonist-synergist coordination) to the muscle also increases (7,8,26,54). This increased taxing of the supraspinal motor resources may negatively impact the processing and output associated with vigilance task performance.

Intermittent 20% MVCs for 65 minutes resulted in fatigue. However, the lack of significantly greater impairments in SVT and CVT after the first testing block indicated that the intensity of the contraction and not fatigue impeded vigilance task performance in the present study. Other studies have also reported no effects of fatigue on vigilance performance. Devienne et al. (18) studied the effects of 50% MVC triceps brachii extension to fatigue on a 3-choice RT task which consisted of reaching a target with a sword when a light-emitting diode was illuminated. However, 50% MVC was continuous and subjects only performed the contractions between testing blocks. More recent studies have shown the same effect. One hour of dynamic strength training (37) and 30 intermittent (5s on and 5s off) MVCs (56) did not affect subsequent RT tests. One possible explanation for the lack of impairment in vigilance task performance with fatigue is that the supraspinal processing centers compensate for fatigue by modulating neural drive to the muscle to maintain homeostasis (1,19,25). This was evident in the present study as there was an observed increase in IEMG during the 20% MVC session (figure 4.7b). If homeostasis is maintained during sustained muscle contractions then vigilance task performance should not suffer.

In addition to contraction intensity, HN also impeded performance. The finding that noise impairs vigilance task performance has been reported previously. Short-term memory (5), mental arithmetic (6), categorization of events (50), numerical checking (40), and reading comprehension (28) have all been impaired by noise exposure. However, these simple and complex vigilance tasks relied solely on thought processes and did not require a subsequent movement in a limb. The results from our study showed that vigilance tasks requiring simple and complex thought processes with subsequent movement in the upper extremities were also impaired during HN compared to LN exposure. On the other hand, Van Gemmert and Van Galen (53) found that subjects' RT and MT were not impaired when exposed to the same HN (95 dB (A)) compared to LN (approximately 55 dB (A)) intensity. However, the duration of their noise exposure (53) was not clearly reported. Furthermore, subjects who participated in the current study all had normal hearing (as tested by audiologists), while subjects who participated in their study were not tested for normal range of hearing. Thus, some subjects may not have been as sensitive to the 95 dB (A) of noise.

The HN significantly impaired CVT to a greater extent compared to SVT. A complex cognitive vigilance task requires the detection of a specified stimulus sequence as opposed to a simple sensory vigilance task which involves detecting a change in sensory stimulation (16). Thus, the distraction of HN might be expected to have a greater effect on a task involving greater processing. Contradictory to the present findings, Smith (50) observed that noise (85 dB (A)) reduced the hit-rate on a task involving detection of repeated numbers, but the noise effects were not altered by changes in the priority, difficulty or probability of the two tasks. The greater noise intensity and duration could partially explain why CVT performance decreased in the present study. The type of CVT employed must also be considered. The video game Tetris involves anywhere from 10 – 15 decisions and subsequent fine motor movements at any given time, whereas, other complex tasks like such as Smith's study may only require 4 - 5 decisions and fine motor movements at any given time.

Another reason why noise may have decreased vigilance task performance is because of anxiety. Anxiety is an unpleasant emotional state in which a present and continuing strong desire or drive seems likely to miss its goal (21). Edsell (20) showed that during a social interaction game, students revealed a greater anxiety under the noise conditions (61 and 75 dB (A)) compared to low noise (50 dB (A)). Furthermore, state anxiety increases when subjects are exposed to 75 dB (A) noise for only 30 minutes (51). In addition, increasing anxiety could potentially over arouse the CNS, thereby decreasing vigilance task performance. Delay and Mathey (17) illustrated this effect. Subjects' time estimation of 5, 10, 15, and 30s intervals became increasingly more accurate as intensity of noise increased from (50 – 80 dB (A)). However, once noise intensity reached 90 dB (A) the subjects ability to estimate time decreased, especially during the longer time intervals. In the current study, the HN intensity may have resulted in higher levels of arousal.

Another interesting finding was that the negative effects of noise on SVT and CVT were almost immediate (within first 10 minutes of exposure) and remained unchanged thereafter. A continuous stimulus commonly results in a process called habituation, whereby an individual responds less and less to the stimulus as long as it does not have any special meaning. According to Borg (10) habituation takes place rapidly when the sound is continuous. Eventually the signal will no longer be detected and cortical neurons will become non-compliant. In Frith's and Allen's (24) experiment, subjects performed a forewarned RT task or a non-concomitant task during noise. During a RT task, subjects seemed to habituate noise at a faster rate by directing more attention to the task at hand. Thus, since subjects in the current study performed vigilance tasks throughout the duration of the session, the process of habituation may have occurred to maintain performance.

Although noise and contraction intensity impaired vigilance task performance, their interaction did not result in a greater performance decrement. A non-compounding effect of noise and contraction intensity may be due a limited capacity, which suggests that there is a limit to how much information our brain can process at a given time (45). This capacity may be limited by variables including: multi-tasking, and increases in task complexity, memory demand, occurrence of target events, and task duration (13). The lack of further SVT and CVT decrements with changes in contraction intensity and noise suggests a dose response relationship in the present study. Whereas the additional processing of another task (force maintenance) or distraction (noise) results in vigilance impairment, a greater dose which involves both variables does not significantly increase the impediment. The present finding however does not suggest that tasks or distractions of greater intensity or complexity (tasks, greater % of MVC or maintenance of modulating forces, distractions, higher volume of noise or meaningful versus white noise) might not overwhelm supraspinal processing and output resulting in significantly greater impairments.

4.6 CONCLUSION

Vigilance task performance decreased in response to noise and muscle contractions, whereas there was no greater response to neuromuscular fatigue or an interaction of noise, muscle contractions and fatigue. Ear protection may be one way to combat the noise-induced vigilance task decrement. Unfortunately, different physical tasks requiring different contraction intensities vary from job to job and unless all industries become automated, physical tasks will rely on muscle contractions. Thus, it would be important to determine how other contraction intensities and rest periods would affect vigilance task performance. Moreover, how would the addition of another job irritant such as unstable conditions (balancing, climbing, and reaching which are required by many industrial jobs) factor in vigilance task performance?

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4.8 FIGURE LEGEND

Figures 4.1: Illustrations of the a) isometric knee extension apparatus, b) simple vigilance task (RT,MT) apparatus, c) complex vigilance task, d) headphones and receiver for noise amplification, and e) whole apparatus.

Figure 4.2: The top channel illustrates the ITT which was used with a MVC to estimate the extent of inactivation during a voluntary contraction by comparing the amplitudes of the evoked doublet superimposed upon a MVC, with the post-contraction potentiated doublet (interpolated doublet amplitude / potentiated doublet amplitude x 100 = percentage of muscle inactivation). EMG tracings were derived from the vastus lateralis (second channel). The spikes in the EMG tracings represent the stimulus artifact.

Figures 4.3: A comparison of the main effect of the noise condition on a) RT, b) MT, and c) CVT performance. In all graphs, values are means ± standard error and significant ($p \leq 0.01$) differences are identified by an asterisk (*). In all graphs, noise data were collapsed over contraction intensity and testing blocks.

Figures 4.4: A comparison of the main effect of contraction intensity on a) RT, b) MT. and c) CVT performance. In all graphs, values are means ± standard error and significant ($p \leq 0.05$) differences are identified by an asterisk (*). In all graphs, contraction intensity were collapsed over noise level and testing block.

Figures 4.5: A comparison of the effect of testing block and a) 20% and b) 5% MVC on MVC force. Asterisks (*) represent significant differences ($p \leq 0.001$) from all other testing blocks. In all graphs, values are means ± standard error. MVC force was collapsed over the noise condition.

Figure 4.6: A comparison of the effect of testing block and 20% MVC on MVC inactivation. 20% MVC and testing blocks are collapsed over noise. In the graph, values are means ± standard error and significant ($p \leq 0.01$) differences are identified by an asterisk (*).

Figures 4.7: **a)** A comparison of the effect of time and 20% MVC on MVC activation. 20% MVC and testing blocks are collapsed over noise. **b)** A comparison of the effect of time and 20% MVC on submaximal MVC activation. In the graph, the noise condition is collapsed. In all graphs, values are means ± standard error. Asterisks (*) represents significant differences ($p \leq 0.01$) from all other testing blocks.

Figures 4.8: A comparison of the effect of time and contraction type subject's **a)** RT, **b)** MT, and **c)** CVT. In the graphs contraction intensity, testing blocks and noise are collapsed. In all graphs, values are means ± standard error. Asterisks (*) represent significant differences ($p \leq 0.01$) from all other testing blocks.

Table 4.1. Experimental Protocol

Experimental Sessions (Randomized)	Pre-Test Block	10 – 25 Minute Block	30 – 45 Minute Block	50 – 65 Minute Block
1) Low Noise (LN) + No Contraction	**Simple Vigilance Task (SVT)**	**Simple Vigilance Task (SVT)**	**Simple Vigilance Task (SVT)**	**Simple Vigilance Task (SVT)**
2) High Noise (HN) + No Contraction	**Complex Vigilance Task (CVT)**	**Complex Vigilance Task (CVT)**	**Complex Vigilance Task (CVT)**	**Complex Vigilance Task (CVT)**
3) LN + 5% MVC	**MVC**	**MVC**	**MVC**	**MVC**
4) LN + 20% MVC	**Randomized Testing in 5 minute Blocks**	**Randomized Testing Commencing at 10 Minutes**	**Randomized Testing Commencing at 30 Minutes**	**Randomized Testing Commencing at 50 Minutes**
5) HN + 5% MVC				
6) HN + 20% MVC				

Figure 4.1.a

Figure 4.1.b

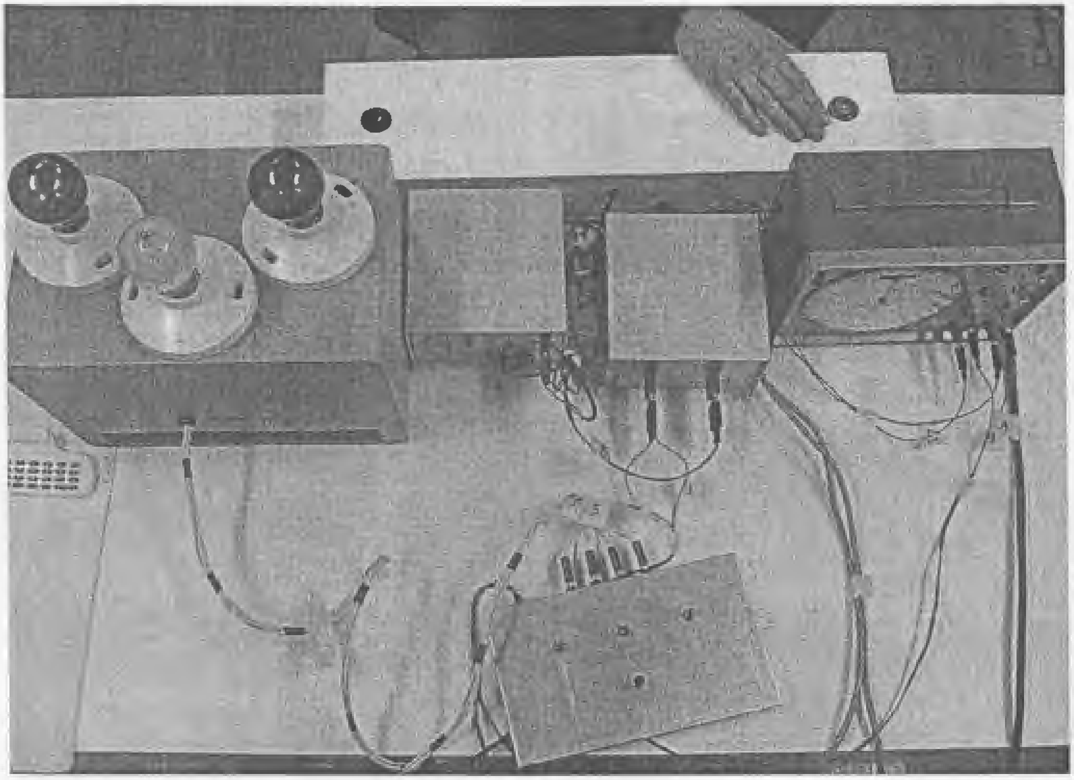


Figure 4.1.c

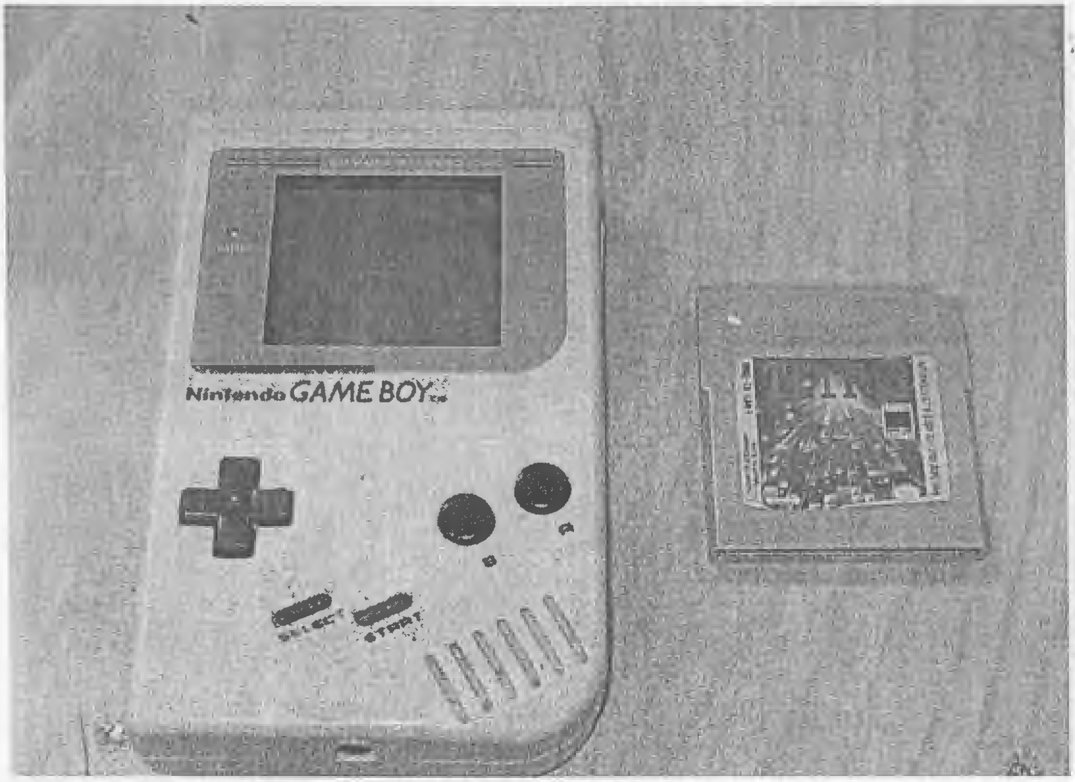
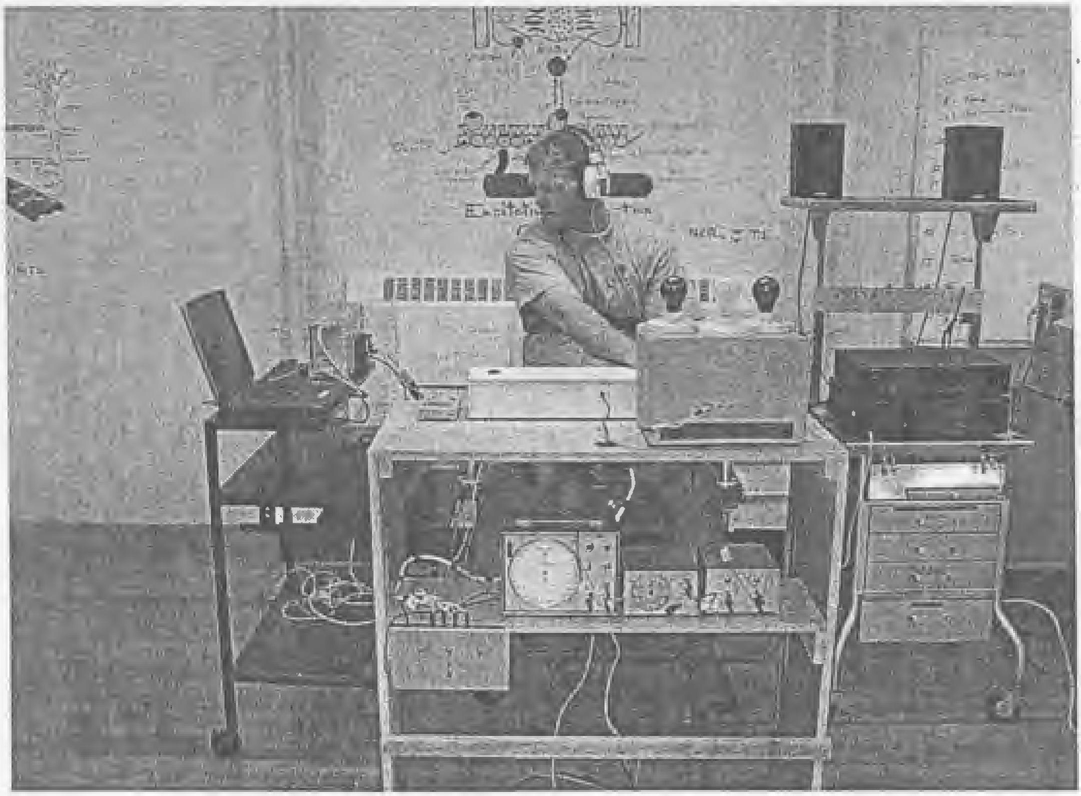


Figure 4.1.d

Figure 4.1.e



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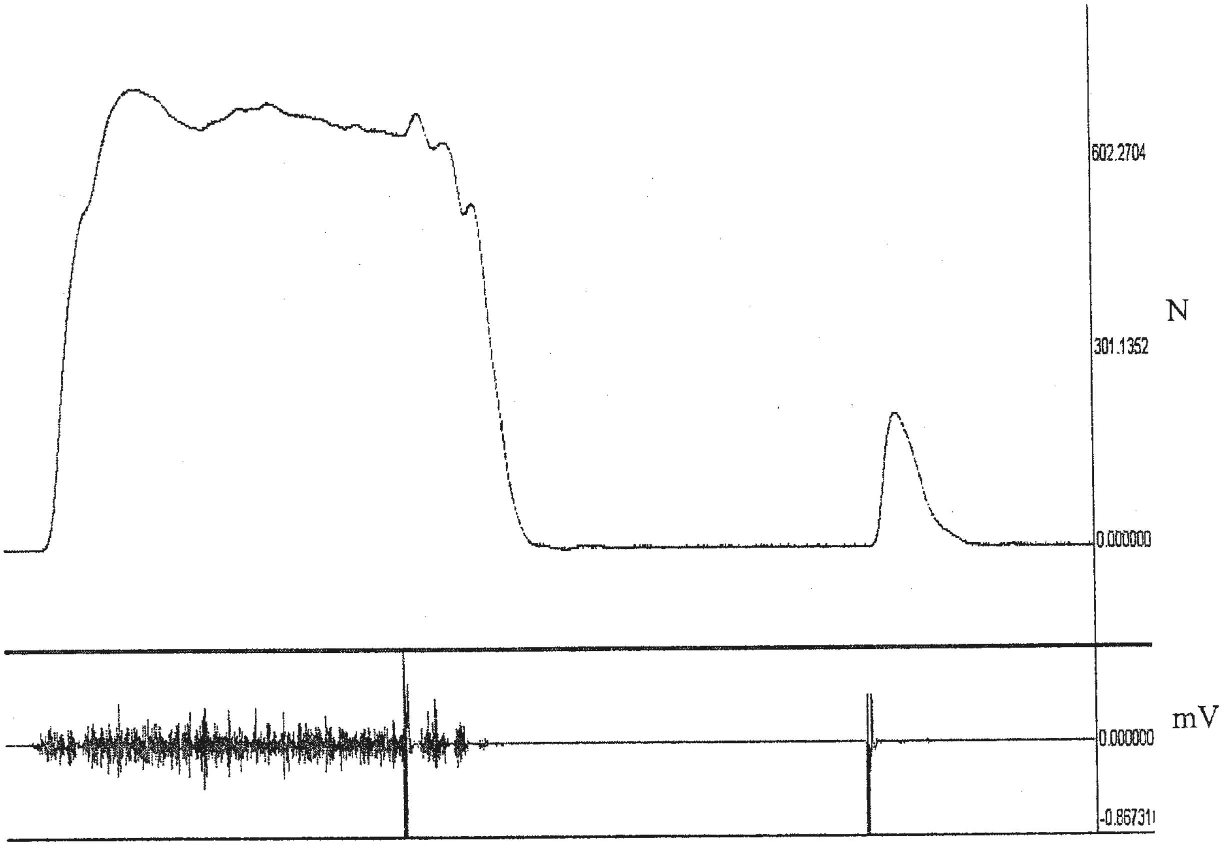

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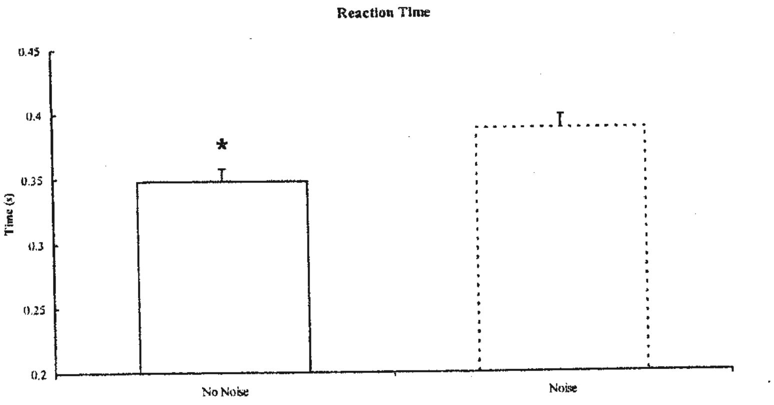

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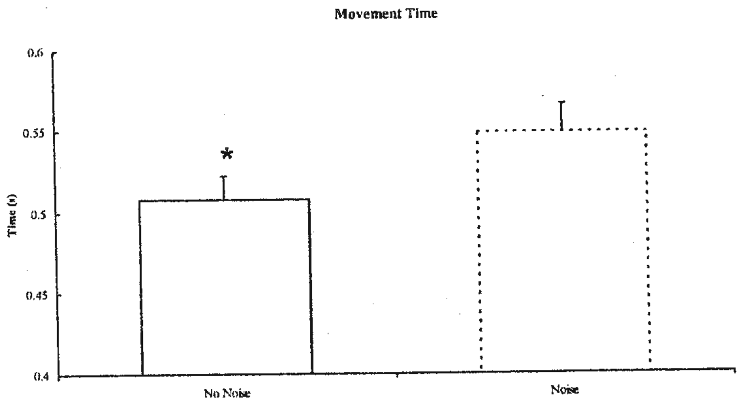

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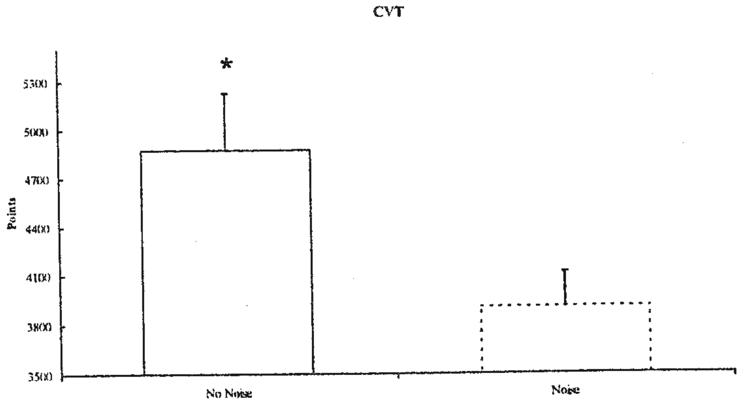

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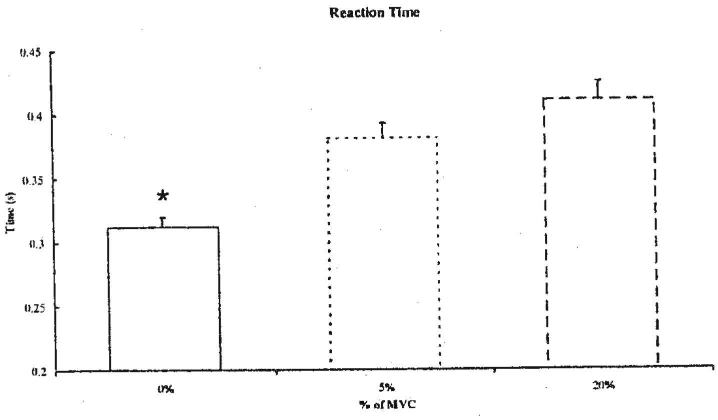

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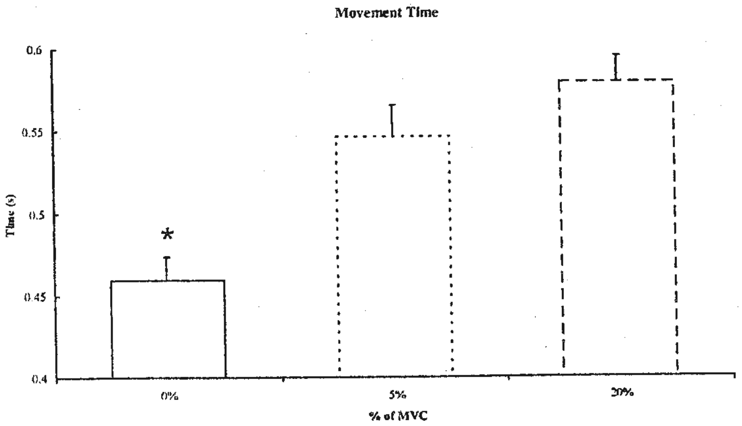

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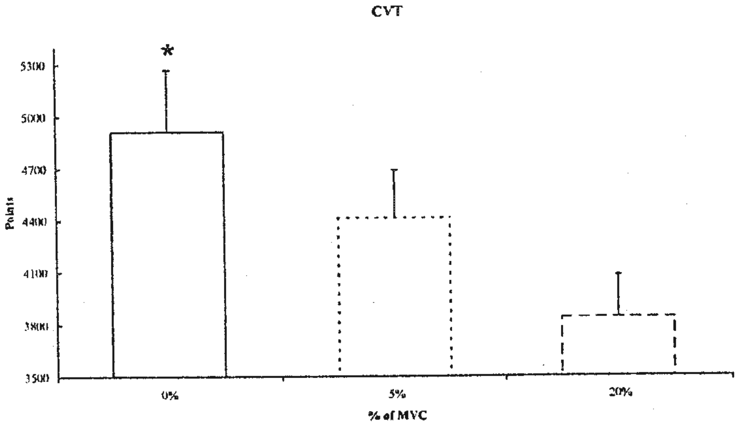

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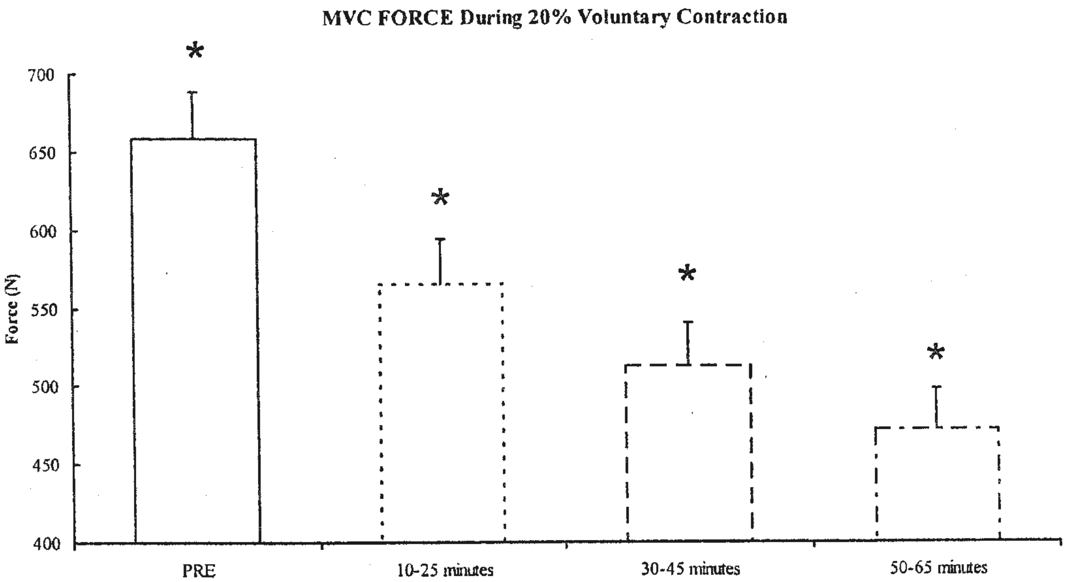

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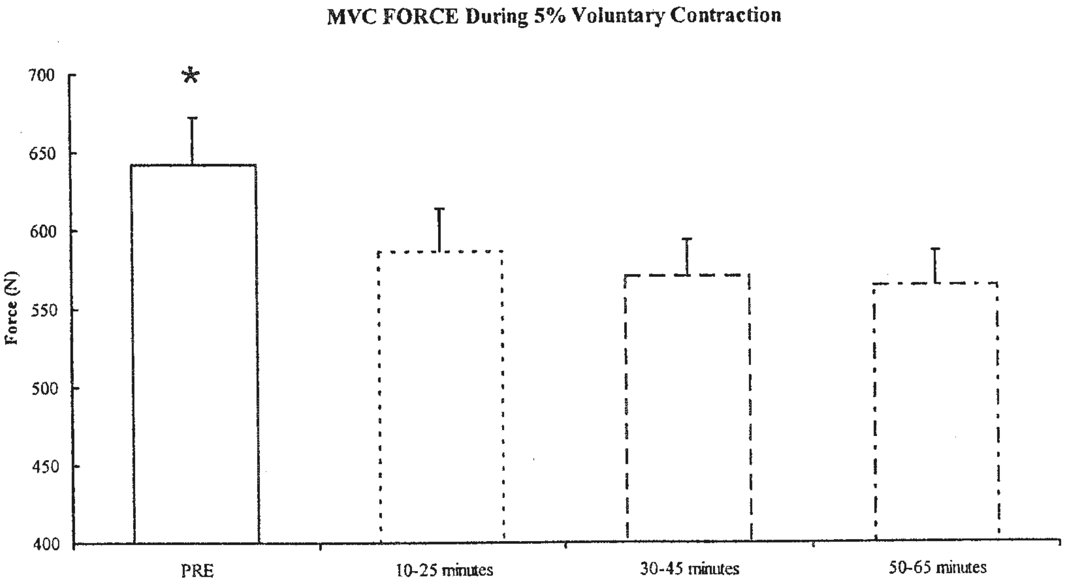


Figure 4.6

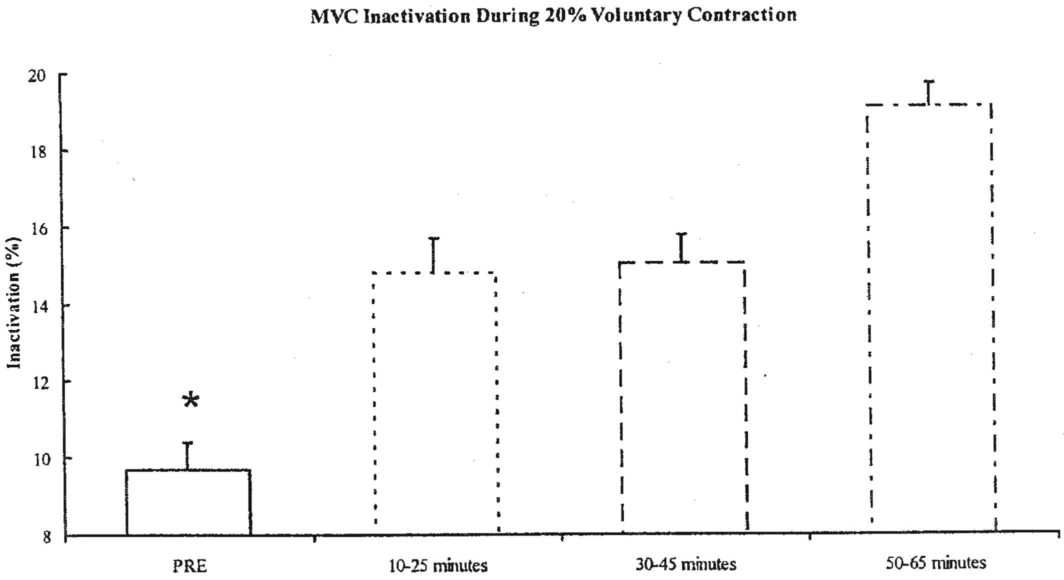

MVC Inactivation During 20% Voluntary Contraction
Inactivation (%)
20
18
16
14
12
10
8
*
PRE
10-25 minutes
30-45 minutes
50-65 minutes

Figure 4.7a

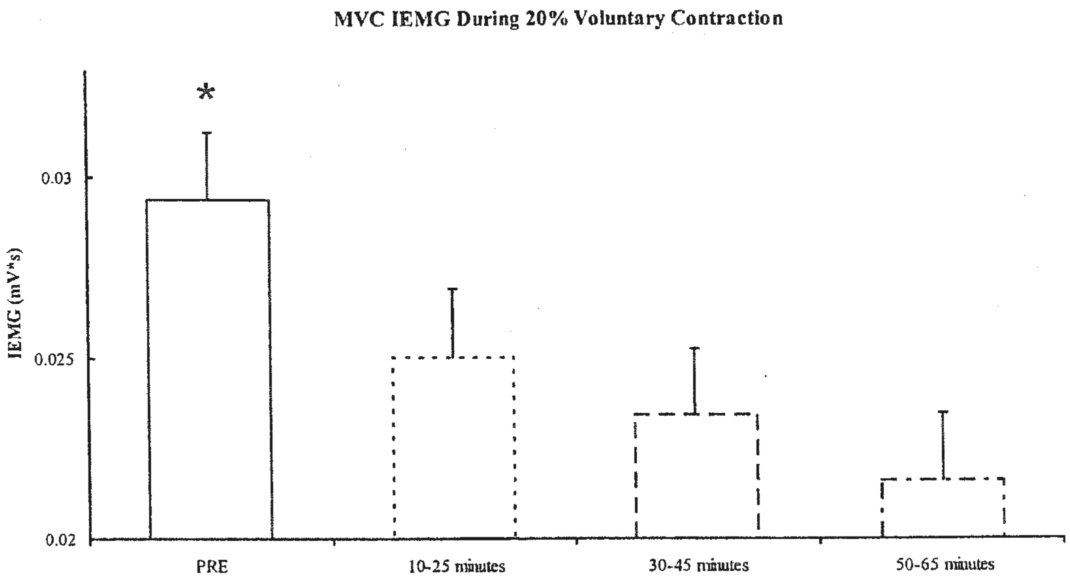


Figure 4.7b

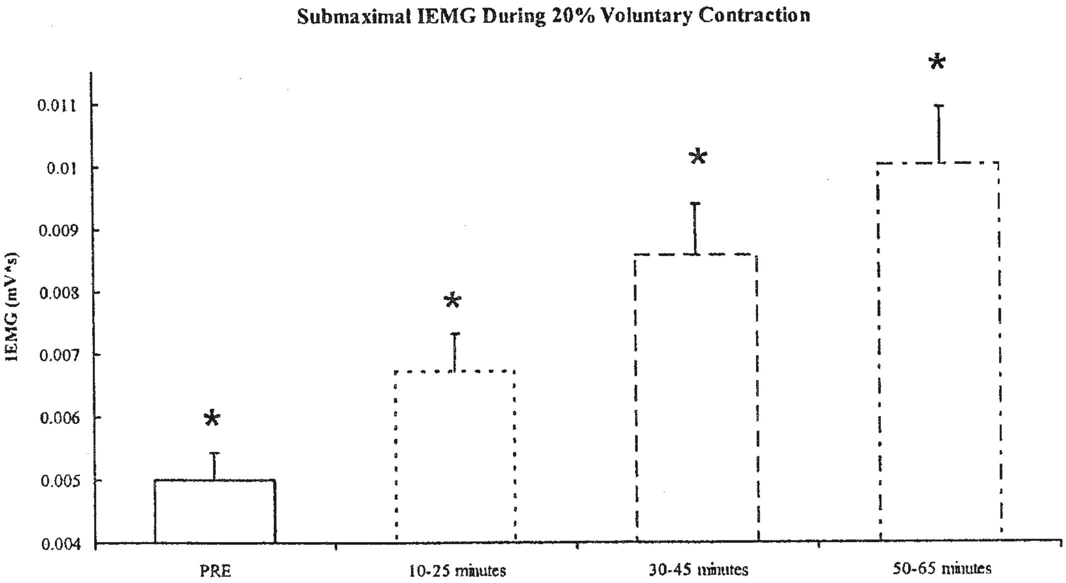


Figure 4.8a

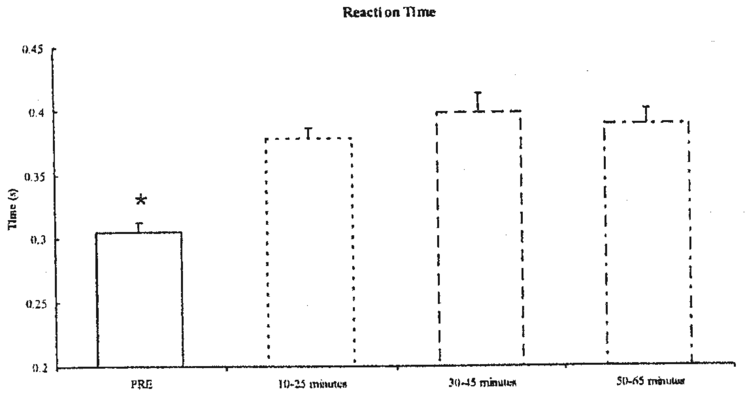


Figure 4.8b

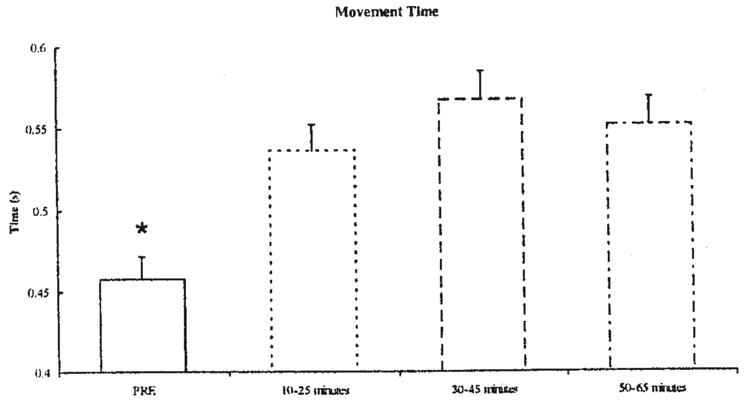
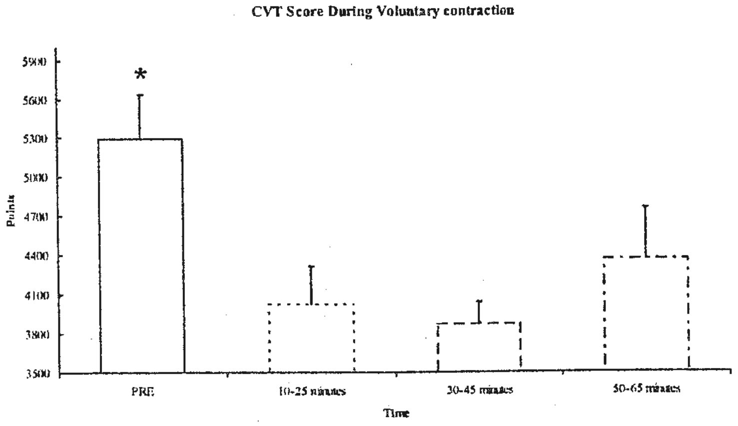


Figure 4.8c



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APPENDIX A:

Behm DG, Button DC and Butt JC. Factors affecting force loss with prolonged stretching. *Canadian Journal of Applied Physiology* 26: 261-272, 2001

Factors Affecting Force Loss With Prolonged Stretching

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Catalog Data
Behm, D.G., Button, D.C., and Butt, J.C. (2001). Factors affecting force loss with prolonged stretching. **Can. J. Appl. Physiol.** 26(3): 262-272. ©2001 Canadian Society for Exercise Physiology.

Key Words: antagonist, electromyography, maximum voluntary contraction, muscle activation, twitch, tetanus
Mots clés : antagoniste, électromyographi.e., contraction maximale volontaire, activation musculaire, secousse, tétanos

Abstract/Résumé

*The purpose of this study was to investigate factors underlying the force loss occurring after prolonged, static, passive stretching. Subjects were tested before and 5–10 min following 20 min of static, passive stretching of the quadriceps (*N = 12*) or a similar period of no stretch (control,* N = 6*). Measurements included isometric maximal voluntary contraction (MVC) force, surface integrated electromyographic (iEMG) activity of the quadriceps and hamstrings, evoked contractile properties (twitch and tetanic force), and quadriceps inactivation as measured by the interpolated twitch technique (ITT). Following stretching, there was a significant 12% decrement in MVC with no significant changes in the control group. Muscle inactivation as measured by the ITT and iEMG increased by 2.8% and 20.2%, respectively. While twitch forces significantly decreased 11.7%, there was no change in tetanic force post-stretch. Although possible increases in muscle compliance affected twitch force, a lack of tetanic force change would suggest that post-stretch force decrements are more affected by muscle inactivation than changes in muscle elasticity.*

Le but de cette étude est d'analyser les facteurs relatifs à la réduction de la force musculaire après une longue période d'étirement statique et passif. Les sujets sont évalués avant et 5-10 min après un étirement statique et passif du quadriceps (n = 12) d'une durée de 20 min;

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la même évaluation est faite 5-10 min après une période d'égale durée sans étirement (contrôle, n = 6). Les variables analysées sont les suivantes : la force de contraction isométrique maximale volontaire (MVC), l'intégration de l'activité myoélectrique de surface (iEMG) du quadriceps et des ischiojambiers, les propriétés contractiles évoquées (tension de secousse et tétanique) et l'inactivation du quadriceps indiquée par la technique de la secousse interpolée (ITT). Après l'étirement, on observe une réduction de 12% de MVC mais pas chez le groupe de contrôle. L'inactivation du muscle indiquée par ITT et par iEMG augmente de 2,8% et 20,2% respectivement. Malgré la diminution significative (11,7%) de la tension de secousse, la tension tétanique après la période d'étirement n'est pas affectée. Même si l'augmentation possible de la compliance musculaire s'est répercutée sur la tension de secousse, l'absence de variation de tension tétanique indique que la réduction de la force consécutive à un étirement est plus affectée par l'inactivation du muscle que par des modifications de l'élasticité du muscle.

Introduction

Stretching is pervasive throughout sport and therapy. It has been reported to increase range of motion (ROM; Safran et al., 1989), prevent injuries (Worrel et al., 1995), and increase performance (Worrel et al., 1995). Recently, there have been reports (Fowles et al., 2000; Kokkonen et al., 1998; Nelson et al., 1998) of decreases in force output after extensive stretching. It would be difficult to imagine that overall athletic performance would be consistently enhanced if, following acute bouts of prolonged stretching, force output was diminished. While the duration of stretching for one muscle group in this study exceeds typical sport applications (Alter, 1996), the body of scientific literature investigating the effects of pre-exercise stretching on force output is still limited in its scope.

Investigations examining the effects of pre-exercise stretching on subsequent performance have reported decreases in 1 repetition maximum (RM) for both knee flexion and extension following stretching of the quadriceps and hamstrings (Kokkonen et al., 1998). Nelson et al. (1998) examined the effects of acute stretching on vertical jump performance and found that after three different stretches of the knee and hip extensors, counter movement jump heights were significantly decreased. Fowles et al. (2000) monitored the time course of plantar flexor strength deficit following 30 min of maximum, passive stretching, finding voluntary strength decreased for up to an hour. While flexibility exercises can improve ROM and may prevent injuries, the causes and scope of force loss associated with extensive stretching should be thoroughly documented.

Some authors have suggested that a portion of the stretch-induced force loss can be attributed to changes in muscle compliance (Kokkonen et al., 1998), based on decreases in twitch force output (Fowles et al., 2000) and tendon tap reflex activity (Rosenbaum and Hennig, 1995). However, there have not been any studies to investigate the effects of prolonged stretching on the evoked force output of a high frequency tetanic contraction. Furthermore, all myoelectric and evoked muscle testing post-stretch has been performed on the triceps surae muscle group (Fowles et al., 2000; Guissard et al., 1988; Rosenbaum and Hennig, 1995). The greater size and differing fibre composition (Johnson et al., 1973) of the quadriceps may result in a muscle specific response.

Therefore, the purpose of this study was to determine the extent and causes of the acute force deficit following a single 20-min bout of prolonged, static, passive stretching of the quadriceps.

Materials and Methods

SUBJECTS

Sixteen subjects originally volunteered for the experiment. Four of the subjects were disqualified since they were unable to activate more than 80% of their quadriceps as measured by the interpolated twitch technique (ITT). The remaining 12 healthy, active, male subjects from the university population (20–43 years, 181.6 cm ± 14.8, 87.3 kg ± 15.2) volunteered for the experiment. A control group of 6 subjects from the experimental group repeated the testing procedure over a 20-min period without the stretching intervention approximately a week following the experiment. Subjects were verbally informed of the procedures and read and signed a consent form prior to participation. The study was sanctioned by the Ethics Committee of the School of Physical Education, Recreation, and Athletics at Memorial University of Newfoundland.

EXERCISE PROTOCOL

Subjects performed a 5-min sub-maximal warm-up on a cycle ergometer to increase muscle temperature. Five sets of stretches were then performed for a total duration of 20 min. Each stretch was held for 45 s and followed by a 15-s relaxation period.

The first stretch performed was the standing quadriceps stretch. The subject stood upright with knee flexed, heel raised to buttocks, and pulled the heel toward the buttocks attempting to not over-compress the knee, while extending the hip. The second stretch was the hurdler quadriceps stretch. This stretch was performed while seated on the floor, hips flexed, with one leg extended in front of the body, while the leg to be stretched was abducted, internally rotated, and knee flexed. The quadriceps were stretched when the subject leaned back toward the floor. The third stretch was kneeling hip extensions. This stretch was performed by kneeling on a mat with knees flexed at an angle greater than 90° and then attempting to extend the hips. The position was supported by extended arms behind the body. The final stretch was the assisted quadriceps stretch. The subject would lie on the mat, face down with one hip extended and knee flexed. A partner would place one hand under the subject's knee and the other hand rested above the buttocks, and the partner would passively extend the hip and leg with the knee flexed. All stretches attempted to reach and stress the subjects' range of motion limits.

TESTING

All testing was conducted prior to and 5–10 min following the stretching regime. Twitch contractile properties were tested at the 5-min recovery mark, followed by a random selection of two tetanic and three voluntary contractions from 6–10 min of recovery. One minute rest was allocated between each contraction. For all voluntary and evoked testing, subjects sat on a bench with hips and knees flexed at 90°, their upper leg and hips restrained by two straps. The ankle was inserted into a padded strap attached by a high-tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc. LCCA 250). Subjects performed three isometric maximum voluntary contractions (MVC) of the quadriceps during a single leg extension movement (before stretching protocol and 6–10 min after stretching protocol). Force, EMG, and inactivation as measured by the ITT were recorded from the MVC with the greatest force output. All voluntary and evoked torques were detected by the strain gauge, amplified (Biopac Systems Inc. DA 100 and analog to digital converter MP100WSW), and monitored on computer (Sona Phoenix PC). All data were stored on a computer at a sampling rate of 2000 Hz. Data were recorded and analyzed with a commercially designed software program (AcqKnowledge III, Biopac Systems Inc.).

Surface electromyographic (EMG) recording electrodes were placed approximately 3 cm apart over the mid-portion of the rectus femoris and biceps femoris. A ground electrode was secured on the fibular head and tibial shaft. Thorough skin preparation for all electrodes included removal of dead epithelial cells with an abrasive (sand) paper around the designated areas followed by cleansing with an isopropyl alcohol swab. EMG activity was amplified (X 1000), filtered (10-1000 Hz), rectified, monitored and stored on computer. The integrated EMG (iEMG) activity was measured over a 1-s period, 1.5 s after the beginning of the MVC, in order to allow peak forces to be generated.

Bipolar surface stimulating electrodes were secured to the superior and distal portion of the quadriceps. Stimulating electrodes, 4–5 cm in width, were constructed in the laboratory from aluminum foil, paper coated with conduction gel (Aquasonic), and immersed in water. The electrode length was sufficient to wrap the width of the muscle belly. The electrodes were placed in approximately the same position for each subject. Peak twitch torques were evoked with electrodes connected to a high-voltage stimulator (Digitimer Stimulator, Model DS7H+). The amperage (10 mA-1A) and pulse duration (50 μs) of a 100 volt square wave pulse were progressively increased until a maximum twitch torque was achieved. The average of 3 trials was used to measure twitch amplitude, time to peak twitch torque (TPT), and peak twitch half relaxation time (1/2 RT).

In order to investigate the summated and fused evoked force of the quadriceps, two trains of tetanic stimulations (100 Hz) were administered at the same stimulus intensity as the twitch for a 300 ms duration. Measures were generated from the tetanus with the greatest torque. Greater stimulation durations (> 300 ms) could not be used due to the pain tolerance of the subjects. All stimulation parameters were identical for pre- and post-stretch testing.

The interpolated twitch technique (ITT) was administered as a measure of the extent of muscle inactivation (Behm et al., 1996; Belanger and McComas, 1981). The ITT involved superimposing 2 electrically stimulated doublets with an interpulse interval of 10 ms upon a voluntary contraction. Torque signals were sent through a high gain amplifier with the superimposed force isolated and further amplified by the software computer program (AcqKnowledge III). An interpolation ratio was calculated comparing the amplitudes of the superimposed stimulation with the post-contraction stimulation to estimate the extent of inactivation during a voluntary contraction (interpolated doublet torque / potentiated doublet torque x 100 = % of muscle inactivation). Three-minute rest periods were provided between all pre-stretch contractions.

STATISTICAL ANALYSIS

Data were analyzed using both a 1-way (12 experimental subjects pre- and post-stretch) and 2-way ANOVA (2 x 2) with repeated measures. The 2-way ANOVA factors included groups (6 control versus 6 experimental) and testing (pre- and post-stretch). Control and experimental subjects were the same individuals. F ratios were considered significant at $p < .05$. A Bonferroni (Dunn's) procedure test was conducted if significant main effects were present. Descriptive statistics include means +/- standard deviation (SD).

Results

There were no significant changes in any voluntary or evoked measures in the control group, pre- and post-testing.

VOLUNTARY MEASURES

MVC was significantly ($p < .05$) decreased 12.2% (Figure 1) between 6–10 min post-stretching. Muscle inactivation as measured by the ITT significantly ($p < .05$) increased in the experimental group by 2.8% (pre: 5.7% +/- 2.2, post: 8.5% +/- 6.0) following the stretching protocol (Figure 2). There were significant ($p = .02$) and non-significant ($p = .11$) decreases in quadriceps and hamstring iEMG activity, respectively (Figure 3). Post-stretch quadriceps iEMG activity decreased 20.2% while hamstrings iEMG decreased 16.8% from pre-stretch measures.

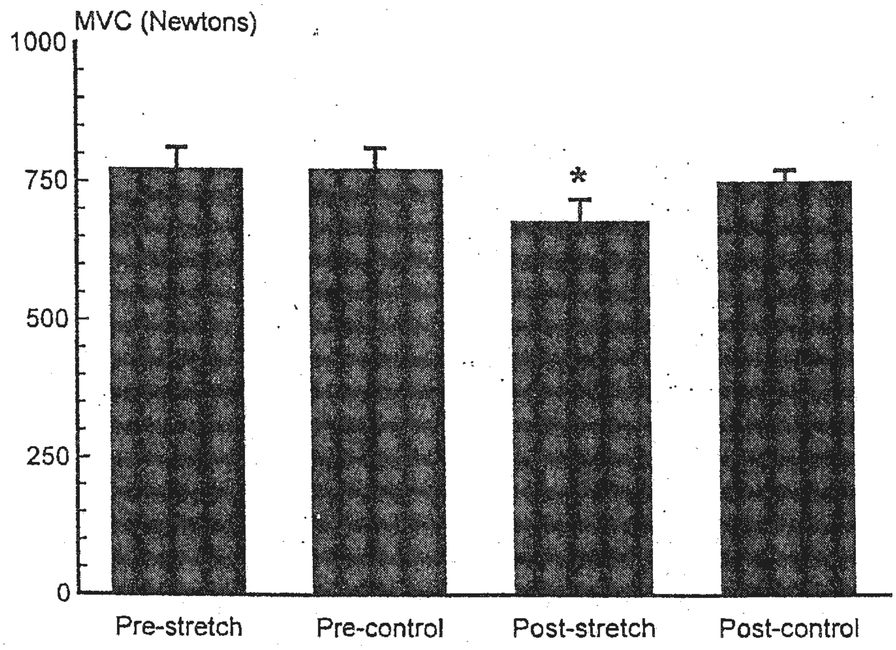

Figure 1. Changes in control and experimental MVC leg extension force (Newtons) prior to and 6–10 min after a 20-min, static, passive stretching protocol. Vertical bars indicate standard error of the means. A single asterisk (*) represent significant differences at the $p < .05$ level.

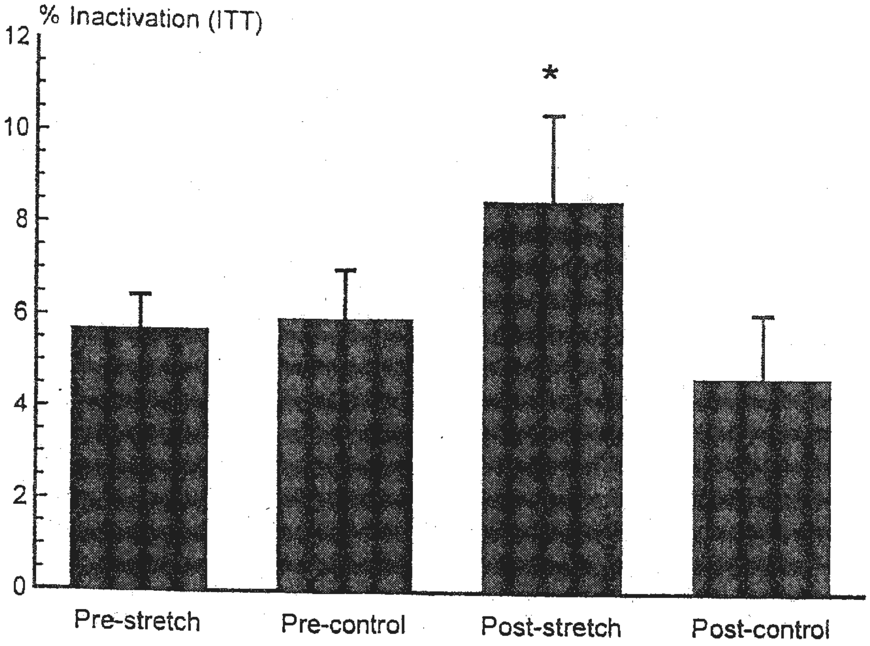

Figure 2. Changes in control and experimental muscle inactivation as measured with the interpolated twitch (IT) ratio prior to and 6–10 min after a 20-min, static, passive, stretching protocol. Vertical bars indicate standard error of the means. A single asterisk (*) represent significant differences at the $p < .05$ level.

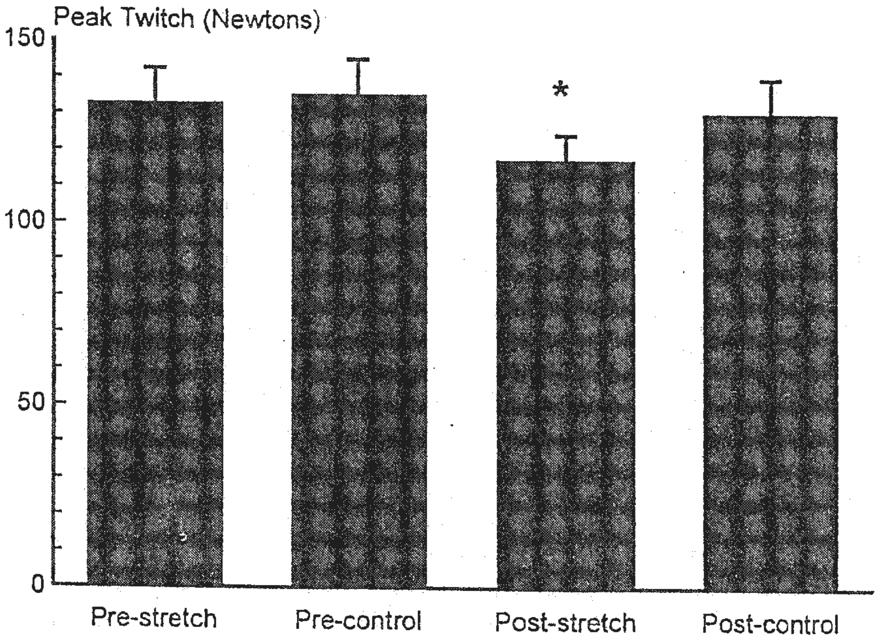

Figure 3. Changes in control and experimental peak twitch force (Newtons) prior to and 5 min after a 20-min, static, passive stretching protocol. Vertical bars indicate standard error of the means. A single asterisk (*) represent significant differences at the $p < .05$ level.

EVOKED MEASURES

Although post-stretch peak twitch force significantly ($p < .05$) decreased 11.7% (Figure 4), prolonged, static, passive stretching did not significantly affect tetanic force (pre: 311.3 N +/- 126.1, post: 309.4 +/- 125.8), TPT (146.0 ms +/- 16.5, post: 144.3 ms +/- 16.4), or 1/2 RT (pre: 49.9 ms +/- 15.2, post: 45.4 +/- 14.5).

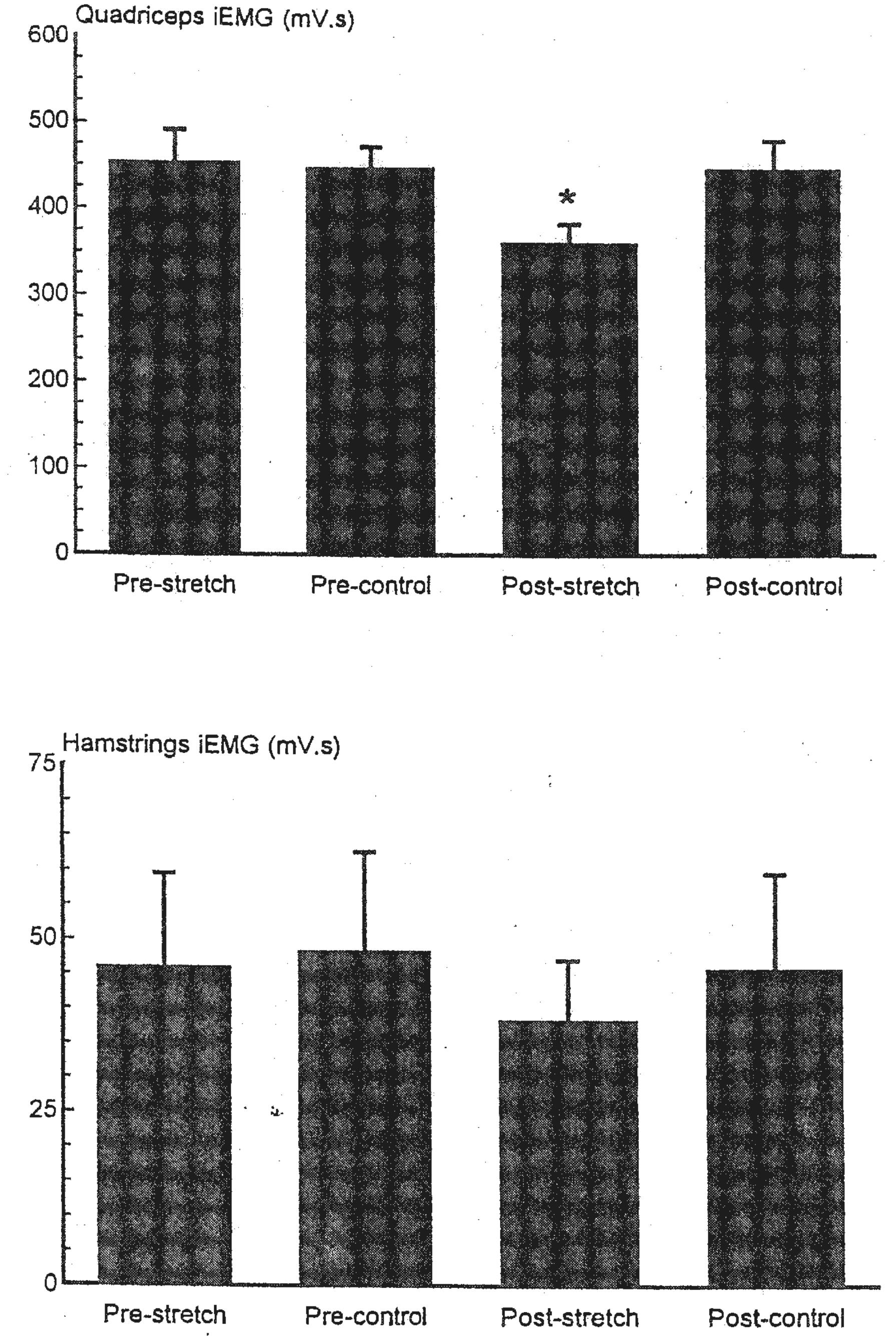

Figure 4. Changes in control and experimental integrated electromyographic (iEMG) activity of the agonist quadriceps (upper graph) and antagonist hamstrings prior to and 6–10 min after a 20-min, static, passive stretching protocol. Vertical bars indicate standard error of the means. A single asterisk (*) represent significant differences at the $p < .05$ level.

Discussion

This study's most important contribution was that the stretch-induced decrease in MVC could be partially attributed to decreases in muscle activation. Both measures of muscle activation (ITT and iEMG) were decreased following the stretching protocol. While muscle inactivation as measured by the ITT increased (or activation decreased) 2.8%, iEMG activity decreased by 20.2%. This disparity in the level of activation may be attributed to the non-linearity of both the interpolated twitch (IT) ratio—force and EMG—force relationships. It has been reported that the superimposed or interpolated force to voluntary force relationship is not linear, but actually curvilinear (Behm et al., 1996; Belanger et al., 1981; Dowling et al., 1994; LLoyd et al., 1991; Norregard et al., 1994; Rutherford et al., 1986; Siemionow et al., 2000). Similarly, the EMG-force relationship has been reported to be non-linear in a number of muscle groups (quadriceps femoris; Alkner et al., 2000), dorsiflexors, plantar flexors (Genadry et al., 1988), tibialis anterior (Bigland and Lippold, 1954), and a variety of other muscles (Perry and Bekey, 1981). A non-linear relation would not permit an accurate extrapolation of muscle activation from either a single IT ratio or a change in iEMG. Thus, the use of iEMG or single IT ratios may not provide a precise estimate of muscle activation, although they can still be useful as a gross indication of increases or decreases in muscle activation.

Yue et al. (2000) suggest that the conventional ITT overestimates the activation level. This hypothesis is supported by estimates of muscle activation with magnetic resonance techniques that are routinely lower than ITT (Adams et al., 1993). The problem with the prediction may partially arise from the amplitude of the superimposed or interpolated force. Upton et al. (1971) suggested that the evoked force cannot be fully developed due to collisions from the anti-dromic volley of electrical stimulation. Herbert and Gandevia (2000) using a computerized model also found that antidromic collisions as well as spinal reflexes could reduce the amplitude of the interpolated twitch. This reduction was most significant with contractions between 40–80% of MVC but also occurred to a lesser degree with MVC. The decrement in force would artificially lower the amplitude of the superimposed force, falsely indicating that less muscle fibres had been activated by the stimulation. In summary, disparities in the percentage change of muscle activation after stretching may be ascribed to the non-linearity of both measures and the tendency for the ITT to underestimate the extent of muscle inactivation. However, the main message was consistent; extensive static passive stretching results in decreased muscle activation affecting force output.

Decreased activation following prolonged stretching is consistent with other research as well. Fowles et al. (2000) reported a 20% decrease in force 5 min after stretching, which was accompanied by a significant 13% decrease in activation as measured by the ITT and a non-significant 15% decrease in EMG activity. In their discussion, they reviewed a number of factors that could have contributed to the post-stretch inactivation. The extent of autogenic inhibition provided by the Golgi tendon reflex is related to tension development, and thus this inhibitory reflex could contribute to the inexcitability of the motoneurons. However, as pointed out by Fowles et al. (2000), Golgi tendon organ discharge rarely persists during maintained stretch and the inhibitory effects are transitory (Alter, 1996).

Type III (mechanoreceptor) and IV (nociceptor) afferents could contribute as well. Rutherford et al. (1990) reported extensive quadriceps inactivation with muscle pain. However, both deAndrade et al. (1965) and Wood et al. (1988) reported that swelling-induced reflex inhibition of the quadriceps was independent of pain. Behm and St. Pierre (1997a) reported only a 0.1 correlation between pain and inactivation in previously immobilized ankle fracture patients. Stokes and Young (1984) infiltrated human knee joints with bupivacaine to block the pain of post-surgery meniscectomies and reported no change in the severity of inhibition. Again, Fowles et al. (2000) commented that the discomfort and pressure would be present only during the stretch, with these inhibitory components absent 5–10 min following the stretching protocol, making it unlikely that inhibition induced by mechanoreceptors or nociceptors provided substantial inhibition during the testing period.

Similarly, fatigue-induced inhibition (Behm and St. Pierre, 1997b, 1998) would be an unlikely candidate, since muscle activation was absent during the stretch as evidenced by the lack of increase in iEMG over resting conditions (Figure 5).

In three of the four stretches used in the protocol, the knee was flexed to the limit of the individual's ROM. Knee flexion during a quadriceps stretch would increase intra-articular knee pressure (Eyring and Murray, 1964; Jayson and Dixon, 1970) as well as compress the patella upon the joint. In addition, dislocating torques would be placed upon the tibial portion of the knee joint, by forces pulling or pushing the distal portion of the tibia toward the pelvis. Prolonged stress on the joint receptors could possibly lead to inhibitory effects upon the motoneuron. McComas et al. (1983) demonstrated greater inactivation in patients with joint pathologies. However, Sabbahi et al. (1990) desensitized healthy ankle joint receptors with xylocaine and then observed motoneuron excitability by monitoring H-reflex activity. They found no significant changes in H-reflex activity suggesting

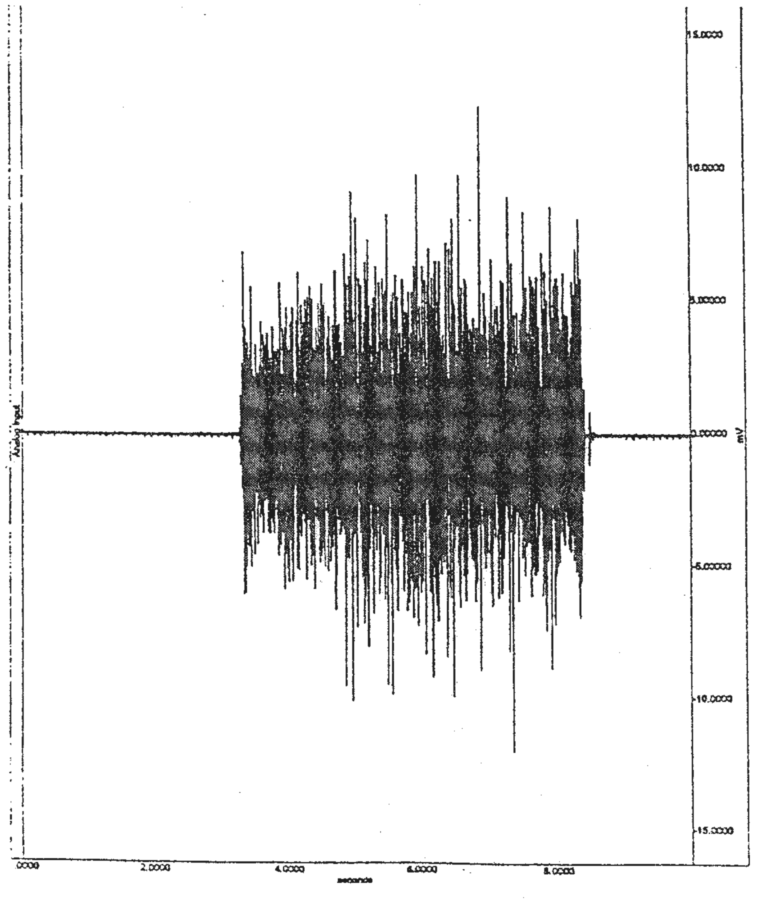

Figure 5. The graph depicts the rectified electromyographic (EMG) activity of the quadriceps for a single subject; while stretching (approximately first 2.5 s), performing a maximal voluntary contraction (MVC; approximately 2.5–8 s) and then at rest (8–10 s).

the joint receptors have minimal inhibitory effects on the excitability of the motoneurons. Similar to other reflex actions, any inhibitory actions would exert their greatest effects during the stretch period with minimal continuance 5–10 min into recovery.

Finally, Fowles et al. (2000) indicated that a transient increase in muscle length due to stretching might negatively impact the excitatory stretch reflex originating from the muscle spindles. However, this excitation is more prevalent during the stretch and recovers immediately after the stretch (Guissard et al., 1988). Thus the origin of the post-stretch inactivation has yet to be established and should provide impetus for further research.

Changes to the visco-elastic properties of the muscle after stretching have been suggested to affect force output. A recent study by Kokkonen et al. (1998) reported a decrease in 1 RM for the knee extensors and flexors after an acute bout of passive stretching of both muscle groups for 20 min. They suggested that the stretching treatment might have influenced maximal strength through a reduction in either the passive or active stiffness of the musculotendinous unit. Rosenbaum and Hennig (1995) investigated the acute effects of prior exercise (warm-up and stretching) on Achilles tendon reflex activity. They found a decrease in the reflexive peak force and myoelectrical activity of the triceps surae. Additionally, they also found the passive peak force caused by a tendon tap to be significantly reduced following the stretching treatment. This increased compliance may relate to the significant 11.7% decrease in peak twitch force as seen in this study. A similar 10–19% decrease in peak twitch torque (post stretch, 15-min recovery) following prolonged stretching was implicated as evidence of impaired muscle contractile force by Fowles et al. (2000). However, an evoked twitch involves an incomplete saturation of the myofilaments with Ca^{++} (Binder-Macleod et al., 1996), resulting in significantly less force than an MVC or a tetanus. The dramatically smaller force of a twitch would be more sensitive to changes in muscle stiffness. Indeed, if increased compliance was a dominant factor in MVC force reduction, then tetanic force should also have been reduced. A non-significant reduction of 1.9 N indicated that the summated contractions of the 300 ms high frequency tetanic stimulation were sufficient to overcome the increased laxity of the musculotendinous unit and provide an efficient transfer of force from muscle to bone. The greater force and duration of the MVC would also be expected to be sufficiently efficient in overcoming the tendon laxity.

However, unlike the Fowles et al. (2000) study, the present study did not measure force output at a variety of angles. Fowles et al. (2000) indicated that the optimal force that was achieved at 10° dorsiflexion pre-stretch was shifted to 20° dorsiflexion post-stretch. Perhaps alterations in tetanic force in the present study could have been discovered at other angles.

Conclusion

The data indicated that a given regimen of prolonged, static, passive stretching can inhibit MVC force and activation of the knee extensors. A loss of maximal force due to the inefficient transfer of force with a more compliant musculotendinous unit was not substantiated at the angle measured, since tetanic force was not diminished.

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Acknowledgments

This research was supported by the Special Initiatives Opportunity Fund as well as a Research Infrastructure Grant through the Memorial University of Newfoundland. The authors appreciate the diligence and co-operation of all the subjects in the study.

APPENDIX B:

Behm DG, Whittle J, Button D and Power K. Intermuscle differences in activation. *Muscle and Nerve* 25: 236-243, 2002

ABSTRACT: The objective of this study was to investigate differences within individual subjects in the ability to activate the quadriceps, plantar flexors (PF), dorsiflexors (DF), and elbow flexors (EF) during isometric contractions. Twelve male subjects performed submaximal and maximal voluntary isometric contractions, and maximal tetanic contractions were also induced by electrical stimulation. The interpolated twitch technique was used to gauge the extent of muscle inactivation or inability to produce maximum force. Measurements included torque output, absolute and relative rate of force development (RFD), and percentage of muscle inactivation. The quadriceps exceeded all other muscle groups in voluntary and tetanic torque output, voluntary absolute RFD, and absolute and relative tetanic RFD. The quadriceps also exceeded the PF and DF in voluntary relative RFD and had greater muscle inactivation (15.5%) than the EF (5.0%), PF (5.0%), and DF (1.3%). Although the higher RFD may suggest a higher percentage of type II fibers in the quadriceps, their higher threshold of recruitment leads to greater difficulty in fully activating the quadriceps.

© 2002 John Wiley & Sons, Inc. *Muscle Nerve* **25:** 236–243, 2002
DOI 10.1002/mus.10008

INTERMUSCLE DIFFERENCES IN ACTIVATION

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Accepted 8 August 2001

Whether humans possess the ability to fully activate human skeletal muscle in order to produce maximum force is a contentious issue in the literature. Anecdotal accounts of individuals performing "superhuman" feats of strength during periods of duress were attributed to a vast untapped reserve of muscle fibers that were previously inaccessible. A number of studies purport to show that humans can fully activate their quadriceps,[13,36,37,40] elbow flexors (EF),[14,28,32] dorsiflexors (DF),[10,30] and plantar flexors (PF),[4,5] but other researchers have reported a lack of full activation of the quadriceps,[9,25,42,44] EF,[2,15,46] and PF.[6,7] Whereas some studies purport full activation of a single muscle within individuals, it is unknown whether a number of muscles of differing function can be fully activated by the same individual.

None of the aforementioned studies investigated more than two muscle groups in a single individual or study. Some studies have compared PF and DF,[30] PF and quadriceps[5,8] as well as diaphragm and EF,[32] but none has comprehensively investigated differences in muscle activation of four muscle groups within individuals. The PF and DF are an antagonistic pair of weight-bearing, postural muscles known to possess high proportions of slow-twitch muscle fibers.[24] Conversely, the weight-bearing quadriceps possesses a much higher percentage of fast-twitch fibers than PF and DF.[24] Whereas the lower limb muscles receive consistent stimulation with standing and locomotion, upper limb muscles such as the EF receive less consistent use. We therefore sought to compare a variety of muscles with differing functions (flexion and extension), fiber compositions, and patterns of stimulation (consistent and inconsistent weight-bearing).

To determine the extent of activation, some investigators have interpolated an evoked twitch upon a single voluntary contraction.[4–6,9,11,13,31–33] Many recent studies have documented that the curvilinearity of the interpolation ratio–force relationship[8,9,14,15,39] necessitates a prediction of muscle activation that is best determined by a second-order polynomial[8,14] or exponential equation.[15] Perhaps part of the problem in resolving the ability of humans to fully activate muscle is related to method-

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Abbreviations: DF, dorsiflexors; EF, elbow flexors; EMG, electromyography; ITT, interpolated twitch technique; MVC, maximum voluntary contraction; PF, plantar flexors; RFD, rate of force development
Key words: dorsi flexors; elbow flexors; interpolated twitch technique; muscle inactivation; plantar flexors; quadriceps; rate of force development

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ological inadequacies. Thus further investigations using the most valid methods for the interpolated twitch technique (ITT) are necessary.

We hypothesized that although some individuals may be able to fully activate specific muscles, there will be significant activation differences between muscles within an individual. Therefore, the objectives of this study were to investigate under isometric conditions: (1) whether individuals can fully activate limb muscles of differing function, and (2) whether significant differences exist in the activation levels of specific muscles within individuals.

METHODS

Subjects. Twelve physically active, male subjects from the university population (175.9 ± 7.7 cm, 78.3 ± 11.2 kg., 22.9 ± 1.4 years) volunteered for the study. Four of the subjects were involved in a resistance training program, three other subjects participated in competitive sport (tennis, hockey, martial arts), and the remaining subjects were not involved in a regular training program. Subjects were verbally informed of the procedures and provided written consent prior to participation. The study was approved by the institutional Ethics Committee.

Subjects performed a series of maximal and submaximal voluntary contractions as well as tetanic contractions involving their knee extensors, PF, DF, and EF. All subjects were requested to perform their voluntary contractions with the highest rate of force-production possible, and they received substantial verbal encouragement during the contractions.

Knee Extensor. Subjects were seated on a bench with their hips and knees flexed at 90°. The lower limb was inserted into a padded strap at the ankle and attached by a high-tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc., LCCA 250, Don Mills, Ontario). Bipolar surface stimulating electrodes were secured over the inguinal space, superficial to the femoral nerve as well as the distal portion of the quadriceps.

Plantar Flexors (PF). Subjects were seated in a straight-backed chair with hips and knees at 90°. Contractions were performed or elicited with their leg secured in a modified boot apparatus[9] with their ankles flexed at 90°. Bipolar surface stimulating electrodes were secured over the popliteal space and gastrocnemius–soleus intersection.

Dorsiflexors (DF). Subjects were seated in a straight-backed chair with hips and knees at 90°. They performed voluntary contractions with their leg secured in a modified boot apparatus[9] with their ankles plantar flexed at 120°. Bipolar surface stimulating electrodes were secured over the anterior segment of the peroneal nerve anterior to the fibular head and at the mid-belly of the tibialis anterior.

Elbow Flexors (EF). Subjects sat in a modified elbow-flexion apparatus with their shoulder extended and elbow flexed at 90°. The arm was supported with pads under the upper arm and forearm, and secured in place by Velcro straps. The wrist was inserted into a padded strap attached by a high-tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc., LCCA 250). Bipolar surface stimulating electrodes were secured to the proximal, anterior portion of the forearm flexors and deltoid–biceps brachii intersection.

Electrode Preparation. Thorough skin preparation for all electrodes included removal of dead epithelial cells with an abrasive (sand) paper around the designated areas followed by cleansing with an isopropyl alcohol swab.

Stimulating electrodes, 4–5 cm in width, were constructed from aluminum foil, coated with conduction gel (Signa Creme, Parker Laboratories, Fairfield, New Jersey), and immersed in a saline solution. The electrode length was sufficient to wrap the width of the muscle belly. The electrodes were placed over the motor point of each muscle in approximately the same position for every subject.

Torque Measurement. All voluntary and evoked torques were detected by strain gauges, amplified (Biopac Systems Inc., DA 100: analog-digital converter MP100WSW; Holliston, Massachusetts) and monitored on computer (Sona Phoenix, St. John's, Newfoundland). Data were stored on a computer at a sampling rate of 2,000 Hz. Data were recorded and analyzed with a commercially designed software program (AcqKnowledge III, Biopac Systems Inc.).

Evoked Contractile Properties. Peak twitch torques were evoked with electrodes connected to a high-voltage stimulator (Stimulator Model DS7H+; Digitimer, Welwyn Garden City, Hertfordshire, UK). The amperage (10 mA–1A) and duration (50 μs) of a 100–200 volt square-wave pulse was progressively increased until a maximum twitch torque was achieved. Tetanic stimulation (100 Hz) was administered at the same stimulus intensity as the twitch for a 300 ms duration. Greater stimulation durations (> 300 ms) and voltages were not used due to the pain tolerance of the subjects. The average of two trials were used to measure peak tetanic torque and rate of force development.

Interpolated Twitch Technique (ITT). The ITT was performed, with two evoked doublets superimposed at 1.5-s intervals on a series of 4-s duration, submaximal [25, 50, and 75% of maximum voluntary contraction (MVC)] and maximal (three trials) voluntary contractions to estimate an average superimposed signal. Furthermore, a potentiated doublet was recorded 1.5 s after the voluntary contractions. Superimposed doublets rather than twitches were utilized to increase the signal–noise ratio. An IT-doublet ratio was calculated, comparing the amplitudes of the superimposed stimulation with the postcontraction stimulation (Fig. 1) to estimate the extent of inactivation during a voluntary contraction (interpolated doublet amplitude/potentiated doublet amplitude × 100 = percentage of muscle inactivation).[8] A ratio estimating muscle inactivation rather than activation was calculated because the superimposed or interpolated force evoked upon the voluntary contraction activates those muscle fibers "not activated" or left "inactivated" by the voluntary command. Because the interpolated force/voluntary force relationship has been reported to be curvilinear,[8,9,15,28,35,39,39,41] equations were applied to the series of contractions. All maximal and submaximal (100, 75, 50, and 25% of MVC) forces were correlated with their respective ratios and subjected to a second-order polynomial equation to estimate the extent of muscle inactivation. Rest periods of 3 min were provided between all contractions. MVC force and voluntary rate of force development (RFD) were also measured.

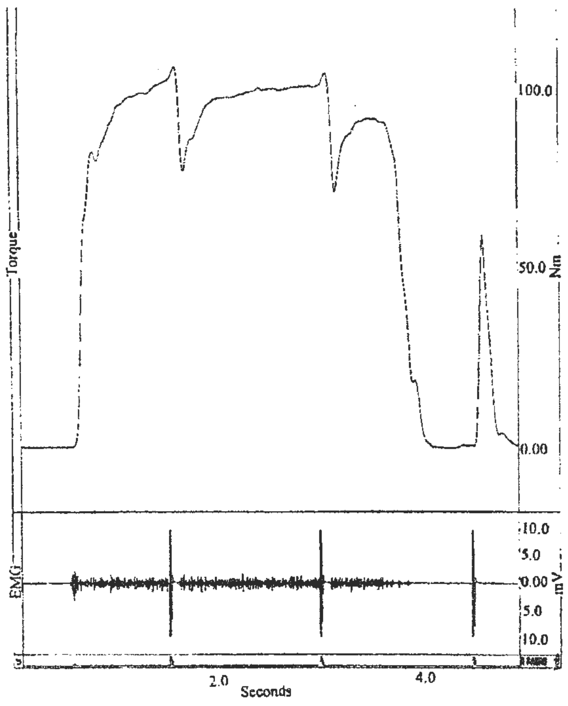

FIGURE 1. An interpolated doublet ratio to estimate the extent of inactivation during a voluntary contraction was calculated by comparing the amplitudes of evoked doublets superimposed upon voluntary contractions, with the postcontraction potentiated doublet (interpolated doublet amplitude/potentiated doublet amplitude × 100 = percentage of muscle inactivation).[8] The lower panel depicts the evoked stimulation (large vertical spikes) and EMG activity.

Absolute RFD was calculated by measuring the duration of the initial rapid rise in force and dividing that time into the maximum force prior to the plateau (Fig. 2). The duration of the rapid rise in force slope was taken from the initial deviation from baseline until the initial indication of a plateau in the force slope. Relative RFD was calculated by ascribing a value of 1 to the maximum force at the plateau of the force slope and dividing by duration.

Statistical Analysis. Data were analyzed with both one- and two-way ANOVAs with repeated measures. A one-way ANOVA was used to determine whether significant differences in muscle inactivation existed between muscle groups. The two-way ANOVA was used when comparing contractile property responses between muscle type (quadriceps, PF, DF, EF) and type of contraction induced (tetanus, voluntary contraction). F ratios were considered significant at $P < 0.05$. If significant interactions were present, a Bonferroni (Dunn's) procedure was conducted. Means ± standard deviations are reported in the text, whereas means ± standard errors are illustrated in the figures. Statistical power equations to determine minimum population samples to achieve significance at the $P < 0.05$ level with a power of 0.9 revealed that a range of 5–10 subjects was necessary depending upon the muscle tested and measure utilized.

RESULTS

The force and muscle activation measures for the muscles tested demonstrated intraclass correlation coefficients ranging from 0.91 to 0.99.

With data collapsed over type of stimulation (tetanus, voluntary), the quadriceps exerted significantly ($P < 0.0001$) greater torque than the PF, EF, and DF (30.2, 52.1, and 81.3% less than the quadriceps, respectively). In addition, the DF had significantly ($P < 0.0001$) less torque than either the PF or EF (Fig. 3). With both voluntary and tetanic contrac-

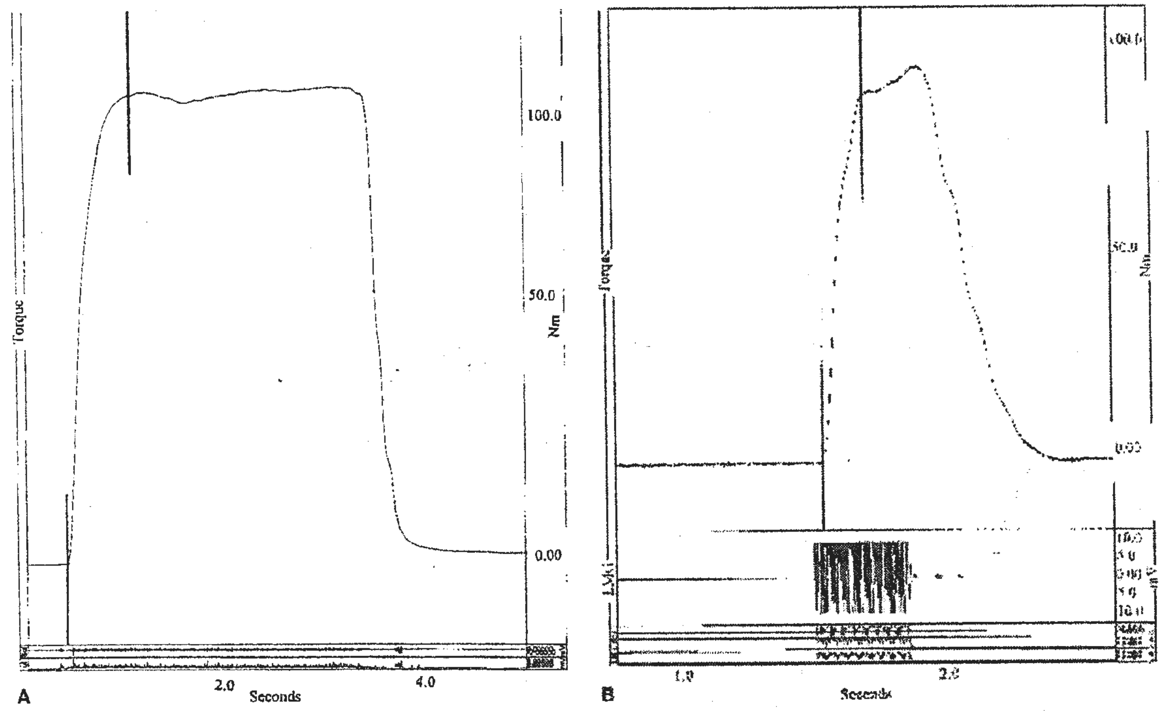

FIGURE 2. Absolute rate of force development was calculated by dividing the duration of time for the rapid rise in force (between the initial baseline deviation [first vertical line] and the first plateau in force [second vertical line]) into the force at the plateau. Relative RFD was calculated by ascribing a value of 1 to the maximum force at the plateau of the force slope and dividing by duration. **(A)** depicts a maximum voluntary contraction, whereas **(B)** depicts a tetanic contraction (150 volts at 1 amp with a 50-μs pulse duration for 300 ms at 100 Hz).

tions considered as separate factors, in each case, the quadriceps torque was significantly ($P < 0.0001$) greater than all other muscles while PF exceeded DF ($P < 0.0001$). EF exerted greater torque than DF with tetanic stimulation and MVC ($P < 0.0001$). Although there were no significant differences between PF and EF with a MVC, PF produced significantly more torque than EF during a tetanus.

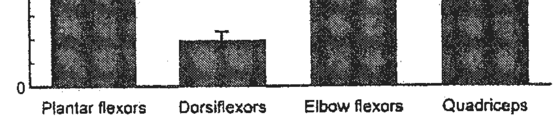

FIGURE 3. Bars represent differences in torque between muscle groups with data collapsed over types of stimulation (tetanic and voluntary). Asterisk (*) indicates significant differences at the $P < 0.0001$ level between the quadriceps and all other muscle groups. An inverted V (∧) indicates that the plantar flexors and elbow flexors are significantly different at the $P < 0.0001$ level than the dorsiflexors. Vertical bars represent standard errors.

During voluntary contractions, quadriceps inactivation was 10.5% greater than both the PF and EF, and 14.2% higher than the DF ($P = 0.0007$) (Fig. 4).

With data collapsed over type of stimulation, the quadriceps absolute RFD was 58.3, 63.4, and 87.1% ($P < 0.0001$) faster than the PF, EF, and DF, respectively (Fig. 5). The DF were 68.9 and 64.5% ($P < 0.0001$) slower than the PF and EF, respectively. Similar results were found when calculating absolute RFD for the specific types of contractions. Whether voluntary or tetanic contractions were elicited, quadriceps exceeded all other muscle groups whereas PF and EF had higher RFD than DF.

With data collapsed over types of stimulation, the quadriceps exhibited 24.5, 32.1, ($P < 0.0001$), and 11.3% (not significant) higher relative RFD than the DF, PF, and EF, respectively (Fig. 6). Quadriceps significantly ($P < 0.0001$) exceeded all other muscle groups when subjected to tetanic contractions (Fig.

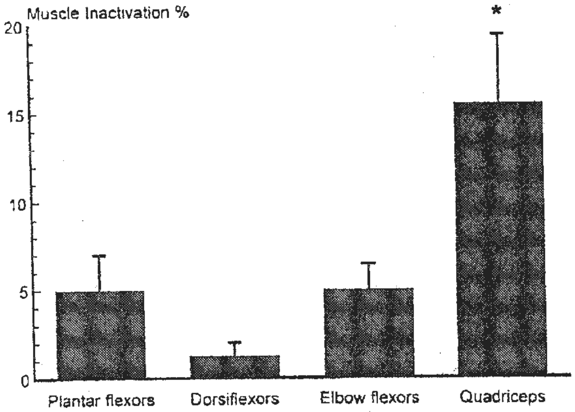

FIGURE 4. Bars represent differences in the percentage of muscle inactivation as measured by the interpolated twitch technique. Asterisk (*) indicates significant differences at the $P <$ 0.0001 level between the quadriceps and all other muscle groups. Vertical bars represent standard errors.

6). The quadriceps also had significantly ($P = 0.003$) higher relative RFD than PF and DF with MVCs. There were no significant relative RFD differences between the PF, DF, and EF with MVCs or tetanic contractions.

DISCUSSION

Are There Significant Differences in the Activation Levels of Specific Muscles? The most important finding in this article was the significantly greater quadriceps inactivation (or lower activation) in comparison to the PF, DF, and EF with isometric contractions. Quadriceps inactivation averaged 15.5% whereas PF, EF, and DF obtained average inactivation values of 5.0, 5.0, and 1.3%, respectively. The substantial quadriceps inactivation that we found conflicts with studies reporting full activation,[10,30] but accords with a number of other studies reporting 10.4 to 23.4% quadriceps inactivation.[12,23,35,42,44]

The greater inactivation of the quadriceps could not be attributed to the number of motor units that must be activated. Although the quadriceps are typically larger than the PF, DF, or EF,[45] the estimated number of motor units allocated to the quadriceps muscles (i.e., vastus lateralis: 300,[38] vastus medialis: 230[38]) does not significantly exceed the number of motor units innervating the PF (soleus: 801,[27] me-

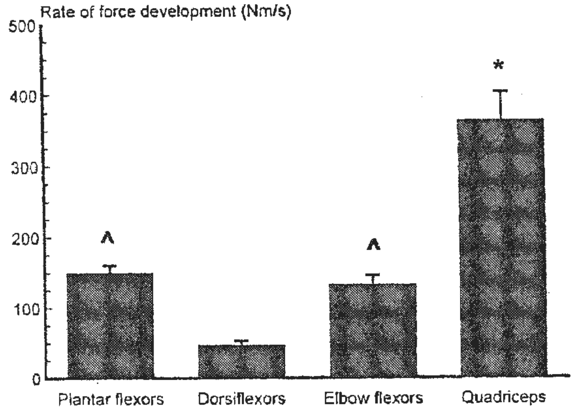

FIGURE 5. Bars represent differences in absolute rate of force development between muscle groups with data collapsed over types of stimulation (tetanic and voluntary). Asterisk (*) indicates significant differences at the $P < 0.0001$ level between the quadriceps and all other muscle groups. An inverted V (^) indicates that the plantar flexors and elbow flexors are significantly different at the $P < 0.0001$ level than the dorsiflexors. Vertical bars represent standard errors.

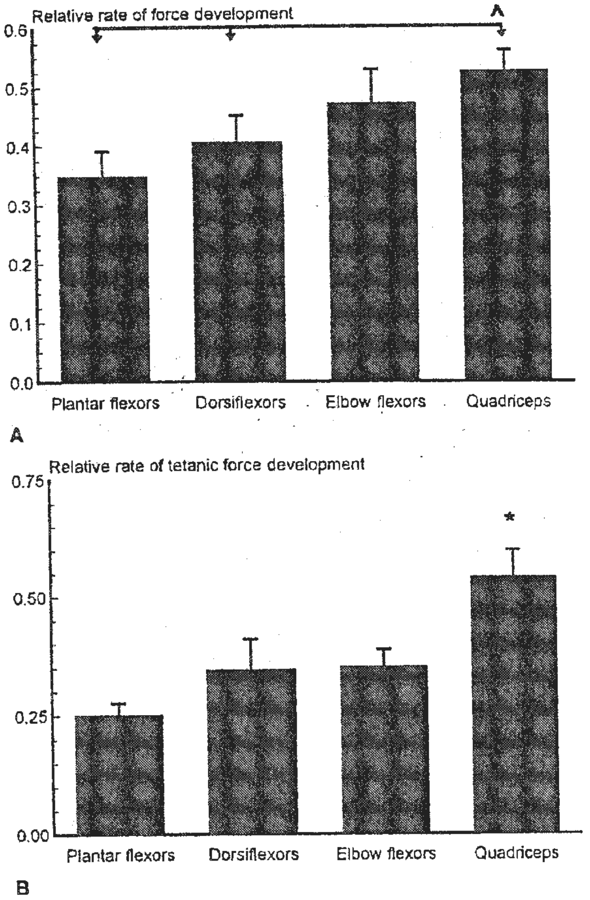

FIGURE 6. Bars represent differences in relative rate of force development (ratio of maximum force/second) with data collapsed over type of stimulation **(A)** and tetanic stimulation **(B)**. An inverted V (^) indicates the quadriceps were significantly different at the $P < 0.0001$ level than the plantar flexors and dorsiflexors **(A)**. Asterisk (*) indicates significant differences at the $P < 0.0001$ level between the quadriceps and all other muscle groups **(B)**. Vertical bars represent standard errors.

dial gastrocnemius: 579[27]). Furthermore, it is unlikely that architecture would play a major role in muscle inhibition as both the quadriceps and the lateral gastrocnemius (PF), which exhibited differing activation levels, are bipennate muscles.[45]

A plausible explanation for the greater quadriceps inactivation may be related to the differing fiber compositions of the muscle groups. Johnson et al.[24] reported that the mean percentage of type II fibers in the vastus lateralis (surface: 67.3%, deep: 53.1%) was higher than in the tibialis anterior (surface: 26.6%, deep: 27.3%), soleus (13.6% surface, deep: 11.0%), lateral gastrocnemius (surface: 56.5%, deep 49.7%), medial gastrocnemius (49.2%), and biceps brachii (surface: 57.7%, deep: 49.5%). Similarly, others have reported higher mean type II fiber percentages ranging from 58–68% in the vastus lateralis,[16,17,21] as compared to the soleus (30%),[16] gastrocnemius (50%),[16] and biceps brachii (42–47%).[18] The higher percentage of slow-twitch fibers in the PF and DF would be a consequence of their role as postural muscles. Due to the screw-lock mechanism in the knee,[45] the quadriceps are not necessarily activated during standing; the need for endurance is therefore not as great as the PF and DF. However, there are similarities in the fiber composition of the non–weight-bearing EF and the weight-bearing lateral and medial gastrocnemius.[24] The size and fiber composition of the gastrocnemius provides additional power during locomotion that would not be available from the smaller, slow-twitch predominant soleus. Correspondingly, the EF must provide high forces while also accommodating loads for sustained periods. As the evoked stimulation of the ITT would activate all PF, similar degrees of muscle inactivation would correspond with the comparable fiber compositions of EF and gastrocnemius. According to the size principle of motor unit recruitment,[19] the fast-twitch motor neurons would have the highest recruitment thresholds; thus it might be expected that fast-twitch predominant knee extensors would be more difficult to fully activate.

Rate of Force Development. If the quadriceps had a greater percentage of fast-twitch fibers, it would be expected to possess a greater RFD than the other muscles tested. This was indeed the case, with the quadriceps absolute and relative RFD exceeding all other muscles tested with tetanic stimulation. In addition, the quadriceps absolute voluntary RFD exceeded all other muscles, and the quadriceps relative voluntary RFD exceeded the PF and DF. The absolute RFD may not be truly indicative of a faster contracting muscle as the RFD would be greater in the larger or more powerful of two muscles with the same speed of contraction. However, relative tetanic RFD is irrespective of the size of the muscle or neural input and thus should indicate whether a muscle has an intrinsically higher RFD. The greater difficulty in fully activating the quadriceps may be related to its reportedly higher percentage of high-threshold type II motor units.

It is interesting to note that although the present study reported a significant difference in muscle inactivation between the quadriceps and PF, a previous study by the same principal investigator reported no significant difference.[8] In both studies, similar acquisition techniques, equipment, and polynomial calculations were used. Although the mean difference in type II fiber percentage may exceed 10% between quadriceps and PF,[16,17,21,24] the range of individual type II fiber compositions can be considerable. If the subjects used in the first study conducted at another laboratory[8] had a lower mean type II percentage in their quadriceps or a higher type II percentage in the PF, there may have been no significant difference in the percentage of higher threshold motor units between the muscle groups. Since many of the studies cited have sample populations of only 8–16 subjects, it would not take many individuals to alter the mean fiber composition of the group and thus affect the inactivation values reported.

Can Individuals Fully Activate Muscles of Differing Fiber Composition and Function? Most other studies investigating muscle inactivation within individuals have examined only one or two muscles. McComas et al.[30] found that only half their subjects could fully activate the PF, whereas their subjects achieved full activation of the DF. McKenzie et al.[31] investigated the EF and diaphragm muscle groups reporting higher, yet not full activation of the EF. Thus disparities in activation levels between muscles seem to exist both within individuals and between studies.

Whereas, in the present study, mean estimates of activation calculated from polynomials indicated less than full activation for all muscles, there were individuals whose regression equation estimates indicated full activation (two each for PF, DF, EF, and one subject for quadriceps). However, if full muscle activation had been determined by the absence of interpolated force upon a single MVC, then full activation would have been achieved in the PF of two subjects, DF of three subjects, and EF of nine subjects. Although, according to the regression equation, one subject's quadriceps was fully activated, all subjects had extra evoked force elicited in the quadriceps.

Yue et al.[47] suggested that the conventional ITT overestimates the activation level. This hypothesis is supported by estimates of muscle activation with magnetic resonance techniques, which are routinely lower than ITT.[1] It has been suggested that the superimposed evoked force cannot be fully developed due to collisions from the antidromic volley of electrical stimulation[43] and spinal reflexes.[20] The decrement in force would artificially lower the amplitude of the superimposed force, falsely indicating that less muscle fibers had been activated by the stimulation. The use of regression equation estimates should decrease the error associated with the ITT due to the curvilinearity of the ITT-force relationship.[8] However the use of a regression equation estimate is still not exact, as evidenced in the present study, in which one subject, determined to be fully activated by a polynomial estimate, registered extra evoked force upon a quadriceps MVC. Whereas one subject could fully activate two of the four muscle groups tested (PF and DF), there were no subjects that could fully activate all muscle groups.

Why Is Full Activation Reported in Some Studies and Not Others? There have been many studies investigating the effectiveness of the ITT.[6,8,15,26,29,30,34,39,41] The inability to detect superimposed forces upon voluntary contractions may be related to a lack of sensitivity in the acquisition and evaluation of data,[8] or the type of calculation used to estimate inactivation (single contraction,[8] linear,[8] exponential,[15] or polynomial equation[8]). Furthermore, the experimental procedure may inhibit full muscle activation. Hortobagyi et al.[22] reported that evoked stimulation may interfere with the ability to produce a MVC due to the pain associated with the noxious evoked stimuli. Mechanical considerations such as stability[3] may also affect an individual's ability to exert maximal force.

Considering the inadequacies of the ITT, should the technique be used in research or clinical settings? The use of electromyography (EMG) as an indication of muscle activation is widespread in research and clinical settings, yet the determination of full activation cannot be estimated from the EMG activity of an MVC. The extra force on a voluntary contraction with the ITT is indicative of inactive muscle fibers, even if the amplitude of the interpolated force may be diminished due to the antidromic volley.[43] Whereas the use of regression equation estimates attempts to rectify some of the inadequacies, the prediction will contain some degree of error. Since the ITT has been shown to be reliable,[8] but its precision is questionable, it can be used to detect muscle inactivation as well as quantify relative changes in muscle activation over time.

This research was supported by the Special Initiatives Opportunity Fund as well as a Research Infrastructure Grant through the Memorial University of Newfoundland.

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