A COMPARATIVE ASSESSMENT OF COGNITIVE LOADING ON GAIT PATTERNS OF LOWER LIMB DERMOSKELETON USERS

by

Alexa MacDonald

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Supervisors:	Chris A McGibbon, PhD, Faculty of Kinesiology Jeremy Noble, PhD, Faculty of Kinesiology
Examining Board:	Wayne Albert, PhD, Faculty of Kinesiology Emily Read, PhD, Faculty of Nursing Jonathon Edwards, PhD, Faculty of Kinesiology, Chair

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ABSTRACT

The objective of this thesis was to assess the impact of a verbal fluency cognitive loading task and obstacle crossing on gait biomechanics of dermoskeleton users. Twelve participants with equal sex distribution were recruited and underwent a timed-up-and-go (TUG), cognitively loaded TUG (CL-TUG), an obstacle-cross TUG (OC-TUG) and a cognitively loaded obstacle cross TUG (CLxOC-TUG) in three different EXO conditions: KControl (no exoskeleton), KPassive (unpowered exoskeleton) KActive (powered exoskeleton). Motion analysis was performed for TUG time, turn radius, turn time, sit time, rise time, stride length, step width, and toe clearance. CL and OC conditions were found to impact results in KActive and KPassive mode similarly. Small, statistically significant increases were found in TUG time, turn time, turn radius, stride length and a decrease in toe clearance. The results demonstrated that overall, cognitive loading from dual-task and obstacle crossing while wearing the Keeogo™ minimally impacts gait biomechanics of the user.

DEDICATION

To my parents Ross and Virginia, thank you for your unwavering support and encouragement; I owe every success to you.

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List of Symbols, Nomenclature or Abbreviations

ASIA/ISCS: American Spinal Injury Association/International Spinal Cord Society

Ach: Acetylcholine

Acetyl CoA: Acetyl Coenzyme A

AP: Action potential

ANOVA: Analysis of Variance

CK: Creatine Kinase

CL: cognitive load

BP: blood pressure

Ca^{2+} - Calcium

CNS: Central Nervous System; brain and spinal cord

CDR: Centre for Dermoskeletics Research

CDC: Centre for Disease Control

CI: confidence interval

DSK: Dermoskeleton

EMG: electromyogram

EEG: electroencephalogram

EXO: exoskeleton (condition)

KControl: control condition (no exoskeleton)

KPassive: passive exoskeleton; powered off, clutches disengaged

KActive: active exoskeleton; powered on, clutch engaged

FLength: femoral length; greater trochanter to lateral condyle (Table 3.3.1)

HR: heart rate

Hz: Hertz

Keeogo ™: lower limb assistive exoskeleton

MoCA: Montreal Cognitive Assessment Tool

MU: Motor Unit

NMJ: neuromuscular junction

OA: osteoarthritis

OC: obstacle crossing

PAR-Q: Physical Activity Readiness Questionnaire

PNS: Peripheral Nervous System; nerves

PCr: Phosphocreatine

RER: respiratory exchange ratio

ROM: range of motion

SCI: spinal cord injury

TBI: traumatic brain injuries

TLength: tibial length; medial malleolus to medial condyle (Table 3.3.1)

TG: thigh girth; measured at lateral 1/3 of femoral length (Table 3.3.1)

TUG: timed up-and-go test (control)

Type I Muscle Fibers: slow twitch muscle fibers, predominantly aerobic

Type IIA Muscle Fibers: fast twitch muscle fibers, predominantly oxidative

Type IIB Muscle Fibers: fast twitch muscle fibers, predominantly glycolytic

CL-TUG: cognitively loaded timed-up-and-go test (experimental)

TBI: traumatic brain injury

Verbal Fluency: tasks that require word production spontaneously and under pre-specified search conditions which have recently been used to examine executive functions (Strauss, Sherman, & Spreen, 2006)

VO2: Voluntary oxygen consumption

VO2max: maximal voluntary oxygen consumption

WC: Waist Circumference: narrowest point between the inferior ribs and iliac crest; approx. 2.5cm superior to umbilicus (Table 3.3.1)

Chapter 1 Introduction

1.1 Exoskeletons

Over the last fifty years, researchers have been developing motorized assistive devices in the form of wearable exoskeleton technology to improve the quality of life of individuals affected by gait abnormality and neurological impairment (De Rossi et al., 2011). Exoskeleton technology is currently classified in a specialized category of powered orthoses which include both single-joint and multi-segment exoskeletons. These devices can also be further classified into non-mobile robots and over-ground rehabilitation robots either of which may or may not be fully automated.

Many of the currently available robotic gait rehabilitation devices are stationary and allow for highly controlled gait training in a fixed setting (generally treadmill based) with increased stability and decreased risk to the patient especially in earlier stages of rehabilitation (Alcobendas-Maestro et al., 2012; G. Chen, Chan, Guo, & Yu, 2013; B. Dobkin et al., 2007; B. H. Dobkin et al., 2003). One of the purported benefits to stationary robotic exoskeletons is the ability to use the technology in clinics to rehabilitate patients more efficiently, while reducing the physical strain on the clinician (Hornby et al., 2008). An example is the Lokomat, which is indicated in Table 1.1.1.

Over-ground (non-stationary) rehabilitation robotic devices have in recent years been cleared by the U.S. Food and Drug Administration (Food and Drug Administration HHS, 2015) and allow for more ecologically realistic gait training in the clinical setting, and may have potential for community ambulation. Mobility in over-ground rehabilitation systems is much greater as the patient is not confined to stationary sagittal plane movements on a treadmill. Mobile over-ground assisted ambulation devices can be further classified into two categories: automatic and assistive trainers.

Automatic devices tend to include body weight supportive extensions and are targeted towards patients with higher vertebral spinal cord injury (SCI) (motor complete) where motor control is limited or absent in the torso and the patient is unable to initiate stabilizing musculature to support their own body weight (B. Dobkin et al., 2007). Devices listed in Table 1.1.1 include the ReWalk, Indego, HAL, HULC, eLegs, Honda Legs, MIT Biomechatronics group legs, WALL-X, and Ekso (G. Chen et al., 2013).

Assistive exoskeleton devices are less common because they require a much more sophisticated level of control. Currently there is only one commercial product available in this class, the Keeogo™ developed by B-Temia Inc (Figure 1.1.1). This class of device provides lower limb gait assistance but requires the user to stabilize and initiate gait. Keeogo™ utilizes sensors and artificial intelligence to identify the phase of the gait cycle to provide the appropriate assistance through the use of motors at the knee.

Exoskeletal technology is still a relatively new field of research. The first orthoses loosely classified as an exoskeleton was an assistive apparatus developed in 1890 by Nicholas Yagn which relied upon stored potential energy created by gas compression (Yagn, 1890). The first suit developed that would fit the current definition of an exoskeleton was the Hardiman in 1961 (Vukobratovic, 2007) This contraption was highly impractical as it weighed 680kg and used "master-slave" control dynamic that was highly volatile producing intense, uncontrollable motion (Vukobratovic, 2007). A large contributor to the development of these human-augmentation technologies was initially created by the military; however, upon reaching a conceivable impasse in the early 2000s between mass reduction and increased battery power, the drive for development switched to a primarily rehabilitation source (Vukobratovic, 2007). The impact of human-augmentation technology and human-robotic interface has just begun, and the increasing demand of rehabilitation, in the presence of a healthcare worker deficit for the aging population in Canada, has intensified pressure for technological advances that can improve mobility.

Figure 1.1.1 Keeogo ™ Exoskeleton

Table 1.1.1 Lower-Limb Exoskeletons

Exoskeleton	Institution	Stationary or Over-Ground	Active or Passive	Joint Segments Crossed
BLEEX	Berkeley	Over-Ground	Active	Hip, Knee, Ankle
ExoHiker	Berkeley	Over-Ground	Active	Hip, Knee, Ankle
ExoClimber	Berkeley	Over-Ground	Active	Hip, Knee, Ankle
HULC	Berkeley/Lockheed Martin	Over-Ground	Active	Hip, Knee, Ankle
eLegs	Berkeley	Over-Ground	Active	Hip, Knee, Ankle
Austin	Berkeley	Over-Ground	Active	Hip, Knee, Ankle
INDEGO	Vanderbilt	Over-Ground	Active	Hip, Knee, Ankle
AXO-SUIT	U of Limerick	Fixed/Free	Active	Full Body
WALL-X	U of Gent	Over-Ground	Active	Ankle/Foot
MIT-EXO	MIT	Over-Ground	Active	Hip, Knee, Ankle
Lokomat	Hocoma	Stationary	Active	Hip, Knee
Hardiman	USA	Stationary	Active	Full body
SMA	Honda	Over-Ground	Active	Hip
Ekso	Eksobionics	Over-Ground	Active	Hip, Knee, Ankle
Rewalk	ReWalk Robotics, Israel	Over-Ground	Active	Hip, Knee, Ankle
Rex	Rex Bionics, NZ	Over-Ground	Active	Hip, Knee, Ankle
NASA X1	NASA	Over-Ground	Active	Hip, Knee, Ankle
HAL	Cyberdyne Inc, Japan	Over-Ground	Active	Hip, Knee, Ankle
Gams et al	prototype	Stationary	Active	Knee
Gregorczyk et al	prototype	Free	Passive (Spring)	Hip, Knee
Elliot et al	Prototype	Over-Ground	Passive (Elastic)	Knee
Exo Softsuit	Walsh et al	Over-Ground	Active	Hip, Knee, Ankle
Keeogo	BTemia	Over-Ground	Active	Knee

** upper limb exoskeletons excluded, as well as isolated dorsiflexion exoskeletons

1.2 Mobility Impairment in Canadian Society

The World Health Organization (WHO) has identified stroke as the leading cause of long-term disability in developed nations resulting in potential loss or interruption of regular motor, sensory or cognitive abilities; it is estimated that 15 million people experience a stroke each year (Mackay, Mensah, Mendis, & Greenlund, 2004). Mobility impairment is an issue with growing prevalence in Canadian society as an aging population creates an urgency for increased rehabilitation and treatment methodologies, as well as the development of new technology. Common causes of mobility impairment and gait abnormality include spinal cord injury (SCI), stroke, traumatic brain injury, knee osteoarthritis and underlying neurological conditions such as multiple sclerosis or Parkinson's. Advancement in therapy from the time of occurrence in conjunction with continual treatment and rigorous rehabilitation will help to improve quality of life and overall health in individuals with mobility impairment.

The aging population is creating increased prevalence of mobility inhibiting conditions, thus contributing to the growing stress on both the Canadian healthcare system and economy. Stroke is currently the leading cause of adult impairment in Canada as well as the leading cause of mobility impairment and neurological disability in Canadian adults. Almost 400, 000 Canadians are currently living with a long-term stroke related disability and an estimated 46,500 new stroke hospitalizations per year (Thériault, Stonebridge, & Browarski, 2010).

Multiple Sclerosis is a debilitating autoimmune disease that attacks the neurological system and affects Canadians at disproportionately high rates (1 in 340) than any other country in the world (Poppe, Wolfson, & Zhu, 2008) (Statistics Canada, 2012). The systematic review Poppe, Wolfson & Zhu (2008) also suggest that there are regions in Canada which experience even higher prevalence of MS meaning individuals living in the Prairies or Atlantic Canada experienced significantly higher rates of MS than other MS regions of British Columbia, Ontario, and Quebec (Beck, Metz, Svenson, & Patten, 2005; Poppe et al., 2008). More than half of MS patients develop the condition between 15 and 40 years of age, with females developing MS at three times the rate as men (Statistics Canada, 2012). The cause of MS remains unsolved however, it is theorized to be a combination of genetic, biological and environmental factors.

Multiple sclerosis is an incurable autoimmune disease that attacks the central nervous system by way of the myelin sheath; the membranous protection of central nervous system nerves. The disease causes inflammation and damage of the myelin sheath leading to scar tissue, disruption of nerve impulses, and nerve damage. As such, MS has a broad, unpredictable, range of effects on vision, hearing, memory, balance, and mobility (Kingwell et al., 2015). Exoskeleton technology may be beneficial to patients suffering from mobility issues as a result of MS, especially exoskeletons that are not confined to laboratory or clinic settings that will allow for personal use or consistent training.

Another significant condition that is impacting Canadian quality of life is knee osteoarthritis with 10% of Canadians suffering from some form of osteoarthritis (OA) and that prevalence is growing with the aging population. For adults over 20 years old 37.1% of provincial residents are afflicted with some form of OA and 29.4% with knee OA (Statistics Canada, 2015). The average age of symptom onset is 47.6 years while diagnosis is only at 50.4 years of age (Litwic, Edwards, Dennison, & Cooper, 2013). Osteoarthritis is a slow progressing degenerative joint disease that attacks the cartilage and surrounding tissues particularly the knees and hips. The disease causes degenerative damage/loss of articular cartilage, bone remodeling, osteophyte formation, ligamentous laxity, weakening of periarticular muscles, and tends to produce significant disability requiring surgical intervention. OA may also produce synovial inflammation. Knee OA also tends to be more prevalent in women (Litwic et al., 2013). A recent study in 2013 analyzed the feasibility of using a wearable robotic system (HAL) for rehabilitative gait training on a variety of patients with limited mobility over 16 sessions in 8 weeks. This study only included three knee OA patients independent ambulatory ability and found that 2/3 experienced increased gait speed, decreased number of steps, and increased cadence following the training program (Kubota et al., 2013). Due to the small representation of knee OA patients, more research is necessary to fully analyze exoskeleton use in knee OA patients.

Motor incomplete paraplegia and motor complete paraplegia are conditions that affect an increasing proportion of the population. As of 2010, an estimated 85,556 Canadians are living with a spinal cord injury; traumatic spinal cord injury (TSCI 49%) or a non-traumatic SCI (51%) resulting in tetraplegia or paraplegia (Noonan et al., 2012). With this aging population, researchers are predicting that the trend toward older adults being the fastest growing population of SCI and TBI due to low height falls (Thompson, McCormick, & Kagan, 2006). This finding is further exacerbated by the increased mortality and decreased functional outcome elderly TBI patients present with than their non-elderly counterparts (Susman et al., 2002).

The International Spinal Cord Society has developed the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI), a protocol for classifying the broad range of SCI symptoms in order to provide improved patient care and rehabilitation.

Spinal cord injuries are highly diverse, and symptoms manifest uniquely depending on the location and extent of neurological damage; see Table 1.2.1 (Ditunno, Young, Donovan, & Creasey, 1994). Variability between patients requires patient care to be based upon a rigorous standard of specificity. ACSM indicates that specific rehabilitation and training methodologies allow for specific adaptation (ACSM). The American Spinal Injury Association (ASIA) impairment scale defines five separate levels of impairment dependent upon motor and sensory function (Table 1.2.1).

Table 1.2.1 ASIA Impairment Scale (Ditunno et al., 1994)

ASIA Level	Sensory	Motor
A (complete SCI)	None	None below S4-S5
B (sensory incomplete SCI)	Preserved	None
C (motor incomplete SCI)	Yes/No	preserved below neurological and > half of the key muscle functions are below the neurological level of injury with a muscle grade less than 3[1],
D (motor incomplete SCI)	Yes	preserved below the neurological level, key muscle functions below neurological level of injury has a muscle grade ≥3
E (Normal)	Normal	Normal

[1] Muscle Function Grading as per the international spinal cord society indicate muscle grading as follows: 0=total paralysis, 1=palpable/visible contraction, 2=active movement, full range of motion (ROM) gravity eliminated, 3=active movement full ROM against gravity, 4=active movement, full ROM and moderate resistance in a muscle specific position, 5=active movement, full ROM against gravity and full resistance in a functional muscle position to the same expectation of an otherwise unimpaired person, 5*=active movement, full ROM against gravity with sufficient resistance to be considered to be normal if other symptoms (ie pain, disuse) were not present, NT=not testable due to immobility, amputation or >50% contracture of normal range of motion (International Spinal Cord Society, 2013)

Traumatic brain injury (TBI) is another primary cause of gait disturbance and mobility impairment especially in younger adults (15-25years) and is considered to be the leading cause of disability in adults under the age of 40 (Kraus & McArthur, 2006). TBI due to falls in seniors is also problematic with the aging population. TBI can also cause gait abnormalities due to muscle weakness, impaired neurological control, and locomotion pattern disturbance. Abnormalities tend to manifest in the spatiotemporal aspects of gait such as decreased velocity and bilateral asymmetry of gait (Kraus & McArthur, 2006).

The occurrence of neurological issues involving hemiparesis (unilateral paralysis) and paraplegia (bilateral paralysis) can also have further serious complications for patients. Patients with high thoracic or cervical injuries have disrupted input to the sympathetic preganglionic neurons which can cause neurogenic shock and long-term cardiac dysfunction. Absence of supraspinal inhibitory input may lead to the sympathetic activation remaining unopposed and thus producing vasoconstriction and hypertensive episodes increasing the patient's risk for myocardial infarction, intracranial hemorrhage, and death (West, Bellantoni, & Krassioukov, 2013). Alterations in autonomic cardiovascular control additionally increases the risk and prevalence of cardiovascular disease. The systematic review by West, Bellantoni & Krassioukov (2013) also determined that the extent of cardiovascular function that is affected by the neurological complication is highly specific and presents in different severity depending on the extent of neurological damage (Furlan & Fehlings, 2008; West et al., 2013). Common complications include bradycardia, ECG abnormalities, hypotension, hemodynamic complication, lower mean arterial pressure (increased demand for vasopressors), increased systolic blood pressure, increased heart rate, neurogenic shock, and an increased chance of orthostatic hypotension (West et al., 2013).

Advances in motor assistive device development have rapidly increased, producing wearable apparatus designed to improve the quality of life of individuals affected by gait abnormality and neurological impairment. Motor-assistive robotic exoskeleton technology is a new and under-researched field of study that has the potential to impact many Canadians' quality of life. More research is imperative in determining the full capabilities of this technology.

1.3 Military and Defense

Exoskeletal technology also presents unique militaristic benefits. One of the greatest current concerns with domestic military injury is overuse and overtraining injuries. In 2006 alone there were almost 750,000 injuries among non-deployed forces members in the United States military (Hauret, Jones, Bullock, Canham-Chervak, & Canada, 2010). The primary incidence being the result of musculoskeletal microtrauma with 83% classified as overuse and inflammation, 15% stress fractures, 22% knee/lower leg pain, 20% lumbar spine pain and 13% ankle/foot pain (Jones et al, 2009). The epidemiological study by Jones et al (2009) also found that department of defense rate for injury visits was 1600 visits per 1000 service members per year (Jones, Canham-Chervak, Canada, Mitchener, & Moore, 2010). Various disorders that presented symptoms and are classified broadly as knee pain in the studies, include but are not limited to: patellofemoral pain syndrome, patellar tendinitis, bursitis, and ligamentous strain (Knapik, Reynolds, & Harman, 2015). Exoskeletal assistance provides the opportunity to attempt to alleviate some of the loading at the knee and allow for real-time biomechanical guidance throughout kneel to stand and stand to kneel movements.

1.4 Dual-Task Paradigm

Attention will be defined from here on as:

"[…] the information processing capacity of an individual. An assumption regarding this information processing capacity is that it is limited for any individual and that performing any task requires a given portion of capacity. Thus, if two tasks are performed together and they require more than the total capacity, the performance on either or both deteriorates"

-Woolacott & Shumway-Cook, 2002, p 2

Dual-tasking is a paradigm created through the diversion of attentional resources to two unrelated simultaneous tasks. Dual-tasking gait scenarios were designed to test the premise that gait is automatic and non-attention demanding. However, numerous studies have argued that if gait is automatic then the addition of a secondary task should not negatively impact the performance of the secondary task and thus proposed several different theories as to why performance on one or both tasks decreases when engaging in a dual-task scenario (Springer et al., 2006). The main theories proposed are capacity-sharing, multiple resource theory, and bottleneck theory and will be further explored in Chapter 2.3. The theories all conclude that when an individual is presented with two stimuli or tasks one or both tasks will experience detriments in performance (Galit Yogev-Seligmann, Hausdorff, & Giladi, 2008). Dual-tasking has been researched thoroughly in many populations and with increasing complexity with neuroimaging and brain mapping in recent years to better understand the underlying neurophysiology (Galit Yogev-Seligmann et al., 2008).

Understanding the link between cognitive functioning and gait is essential in providing progressive, evolving care for patients afflicted with mobility issues combined with neurological conditions. At the point of this study, there has been no published research on the impact of dual-tasking on users of exoskeletons; an emergent popular technology for clinical populations. This thesis aims to address this issue by examining a dual-task paradigm in young, healthy adult Keeogo™ users.

1.5 Obstacle-Crossing

Obstacle-crossing is a relatively common activity in daily life, and is often completed with minimal difficulty especially in young, healthy populations. However, certain musculoskeletal or neurological conditions and aging can cause this simple task to become a fall-risk or an unmanageable activity (L. S. Chou, Kaufman, Hahn, & Brey, 2003). In a comparative systematic review by Galna et al., (2009) young, healthy adults were compared to healthy older adults and it was found that when emphasis was not placed on time both groups were able to successfully navigate the obstacle with no differences however; when emphasis was placed on time, older adults tended to perform significantly worse primarily due to less time to adapt foot placement and swing trajectories (Galna, Peters, Murphy, & Morris, 2009). Another study found that in order to navigate an obstacle, stroke patients had to significantly increase step time and toe clearance, and decrease distance post-obstacle thus demonstrating a difference in leading limb trajectory that allowed them to cross but may leave them vulnerable to other fall risks (Said, Goldie, Patla, & Sparrow, 2001). Chou et al., (2004) found that individuals with TBI experience difficulties with dynamic stability in the frontal plane and stopping momentum in the sagittal plane compared to matched healthy participants indicating that those with TBI may experience difficulty with obstacle avoidance due to functional instability impairments (L.-S. Chou, Kaufman, Walker-Rabatin, Brey, & Basford, 2004). Obstacle crossing will be discussed further in Chapter 2.4.3. Due to the importance of obstacle avoidance in daily life in populations that may benefit from the Keeogo™ exoskeleton, this thesis aims to examine the impact of a wearable exoskeleton during obstacle crossing in young, healthy adults.

1.6 Problem Statement and Objectives

Thus far the research has been focused primarily upon biomechanical analysis, physiological cost/benefit, and engineering modifications, however there has been a substantial lack of investigation into how attentional demand affects performance when using the device and how the interaction between device and participant changes with increased distraction or cognitive demand. Research investigating the impact of cognitive loading and obstacle crossing on healthy participants could help to predict the function of an exoskeleton under yet to be studied circumstances.

The objective of this thesis was to assess the impact of a verbal fluency cognitive load task and obstacle crossing on gait biomechanics of lower-extremity exoskeleton users. This study integrated simple (straight) gait with complex multi-component tasks (sit-to-stand, stand-to-sit, turning) to represent and apply the findings to activities of daily living and allow for realistic analysis of the outlined biomechanical variables during a functional mobility task. The primary outcome measure will be total time to complete the timed-up-and-go task in each condition. Secondary outcome variables will include stride length, stride width, cadence, single support time, double support time, toe clearance, turning radius, and mediolateral shift.

1.6.1 Hypotheses

1) TUG time H_{01}: $\mu_C = \mu_{CL}$, H_{A1}: $\mu_C \neq \mu_{CL}$

   The primary null hypothesis for cognitive loading was that there would not be a significant effect of cognitive load condition on TUG task times between KControl, KPassive, and KActive times. The primary CL alternative hypothesis was that there would be a main effect of cognitive load condition on TUG task times between KControl, KPassive and KActive.

2) Gait Biomechanics H_{02}: $\mu_C = \mu_{CL}$, H_{A2}: $\mu_C \neq \mu_{CL}$

   The secondary null hypothesis was that there would not be a significant effect of cognitive load condition on associated gait biomechanics during a TUG task between KControl, KPassive, and KActive times. The secondary alternative hypothesis was that there would be a main effect of cognitive load on associated gait biomechanics between KControl, KPassive and KActive.

3) Obstacle Crossing Time H_{03}: $\mu_C = \mu_{OC}$, H_{A3}: $\mu_C \neq \mu_{OC}$

   The primary obstacle crossing null hypothesis was that there would not be a significant effect of obstacle crossing on TUG task times between KControl, KPassive, and KActive times. The primary obstacle crossing alternative hypothesis was that there would be a main effect of obstacle crossing on TUG task times and an interaction effect of CL and OC.

4) Obstacle Crossing Biomechanics H_{04}: $\mu_C = \mu_{OC}$, H_{A4}: $\mu_C \neq \mu_{OC}$

   The secondary obstacle crossing null hypothesis was that there would not be a significant effect of obstacle crossing on gait biomechanics between KControl, KPassive, and KActive times. The secondary obstacle crossing alternative hypothesis was that there would be a main effect of obstacle crossing on gait biomechanics and an interaction effect of CL and OC

This introduction has highlighted a gap in the field of exoskeletal research; specifically identifying the area of cognitive loading as a significantly under-researched in gait of users of exoskeletal technology. The next chapter will present a literature review of concepts relevant to this investigation.

Chapter 2 Literature Review

2.1 Clinical Implications

The primary area targeted by exoskeleton research is the clinical healthcare field. Patients with mobility impairments of many differing causes are the primary beneficiaries from the advances made in exoskeletal technology. The exoskeleton aims to improve the quality of life of people with paralysis from neurological disease and injury from strokes or traumatic brain injury (G. Chen et al., 2013).

A pilot study by Yoshimoto et al (2015) examined the achievability of gait training with HAL using high speed gait training over a training period of 8 weeks. They found that when chronic stroke patients (n=18) underwent 20 minute sessions of high speed gait training there were significant differences between pre and post measures that were not found in the control (traditional physical therapy for gait disturbance). The HAL group found a 55.9% increase in walking speed $p<0.011$, 17.6% decreased number of steps, $p<0.01$ and 32.8% increase in cadence, $p<0.011$ during the 10m walk test. There were also significant improvements in the timed up and go (TUG) test and Berg Balance Scale $p<0.01$ that were not found in the control after the conventional intervention (Yoshimoto et al., 2015).

These results are further reinforced in studies by Aache et al., (2014), Buesing et al., (2015), Fineberg et al., (2013), and Kressler et al., (2014) which all tested different exoskeletons. These findings suggest widespread gait improvements over a multitude of populations, regardless of the specific type of exoskeleton (Aach et al., 2014; Buesing et al., 2015; Fineberg et al., 2013; Kressler et al., 2014). While these studies differed slightly in methodology, there remained an underlying success of the exoskeletal technology to improve gait biomechanics of the patients ambulating with EXO assistance.

The use of exoskeleton assistive devices in gait rehabilitation is still relatively new; there is much that is still unknown. The cortical and spinal excitability changes were examined in a study by Blicher and Nielsen (2009) using transcranial magnetic stimulation (TMS) in order to investigate changes in corticospinal excitability after undergoing treadmill based robotic gait training. They found that after a twenty-minute session in robotic gait training using a computer controlled device there is an induced excitability change in both the motor cortex and spinal cord in healthy participants (Blicher & Nielsen, 2009). There was a decrease noted in short interval intracortical inhibition after passive training. Interval intracortical inhibition is indicative of decreased activity in $GABA_A$ inhibitory cortical interneurons (Werhahn, Kunesch, Noachtar, Benecke, & Classen, 1999). The unconditioned motor evoked potentials (uMEP) were also found to decline in amplitude and the F-wave frequency also declined after the active training (Blicher & Nielsen, 2009)

Other studies have reinforced the idea of short-term plasticity increase in untrained motor-evoked potentials however, these changes are dependent upon the complexity of the task (Jensen, Marstrand, Nielsen, Lundbye, & Jens, 2005). In healthy participants, the gait training may not have been as complex of a stimulus as required in order to lead to substantial motor evoked potential decline (MEP) to the cerebrum and/or spinal cord. Furthermore, in patients recovering from stroke or spinal cord injury (SCI) gait training may present complex enough a stimulus to induce a positive response in cortical and spinal excitability (Blicher & Nielsen, 2009). Studies examining exoskeletal technology tend to focus primarily on fully automated devices, training protocols, and physiological demand.

Currently, much of exoskeletal research is directed towards patients who have experienced neurological motor deficits as a result of a stroke, or spinal cord injury and, slightly less commonly; a traumatic brain injury. Exoskeletal technology thus has been found to complement traditional physiotherapy however, it is unclear as to whether there exists substantiated evidence in exoskeletal training being superior to physiotherapist based training (Chang & Kim, 2013; Mehrholz, Werner, Kugler, & Pohl, 2007; Werner, Von Frankenberg, Treig, Konrad, & Hesse, 2002). For example, early studies of the Lokomat gait trainer found that those who received conventional training after sub-acute stroke experienced greater recovery after three months of training in terms of walking speed and distance than those who used the Lokomat (Hidler et al., 2009; Westlake & Patten, 2009) while Huseman and colleagues found that hemiparetic patients who underwent four weeks of Lokomat therapy compared to traditional physiotherapy were able to increase muscle mass, lose fat mass, and increase single stance phase while functional scores were statistically the same (Husemann, Müller, Krewer, Heller, & Koenig, 2007). Another study of the Lokomat training compared to physiotherapy in patients with cerebral ischemic or hemorrhagic stroke found that there was significantly greater improvements in the group training with the Lokomat for each 3 week interval of training (9 weeks total), however the study was limited to only 16 patients (Mayr et al., 2007).

Morone et al. (2011) performed a study in which patients were randomized into two groups, both of which underwent the same traditional therapy for the first period (one week) and then one group continued traditional therapy for the next four weeks while the experimental group underwent robotic therapy for the four weeks. The results which showed improvements in both groups suggest that there may be an advantage to using exoskeleton technology in conjunction with conventional therapy as the robotic trained patients had greater voluntary motor function in the effected limb while all other differences were non-significant (Morone et al., 2011). The research by Morone and colleagues highlights key differences study compared to the aforementioned studies by Hidler et al (2009) and Hornby et al (2008) which creates variability of recovery outcomes depending on the type, location, and severity of initial stroke. This concept of combined therapy is further demonstrated by Pohl and colleagues (2007) which combined 20min robotic training with 25min physiotherapy compared to 45min traditional physiotherapy and found that the experimental group experienced superior benefits and independence, where independence was assessed through assignation of Functional Ambulation Category and the Barthel Index for activities of daily living by a nurse (blind to the patient randomization) (Pohl et al., 2007). Schwartz et. al (2009) also found that combined therapy offered greater independence post-intervention and functional ambulatory capacity ($p<0.01$) compared to traditional physiotherapy (Schwartz et al., 2009).

In a study performed by Peurala and colleagues (2009) they suggest that the intensity of training achieved through the use of the robotic assisted trainer may be the reason for the perceived advantages over traditional therapy (Peurala et al., 2009). An earlier study by Peurala and colleagues (2005) found no difference in 10 meter walk tests, 6 meter walk tests, lower limb spasticity and muscle force, postural sway, and modified motor assessment scales when comparing conventional and robotic therapies, however, both groups saw highly significant improvements in the outcome measures and recovery (Peurala, Tarkka, Pitkänen, & Sivenius, 2005).

Traditionally, physical activity was not recommended in MS patients due to the belief that an increased core temperature may intensify the symptoms but recent research has found exercise to create no significant alterations to disease pathogenesis and in fact has become an integral element of an MS management program. Multiple studies have illustrated increases in capacity across functional abilities including cardiorespiratory fitness, strength, and overall functional performance (Mostert & Kesselring, 2002; Petajan et al., 1996; Romberg, Virtanen, & Ruutiainen, 2005).

A study performed by Gutierrez and colleagues found that resistance training improved gait kinematics in patients with MS. After an 8 week progressive resistance training program patients experienced significant increases in swing phase, step length, and stride length, and significant decreases in percentage stride time in stance phase, double-support phase, duration of double-support, and toe clearance. There was an additional increase in isometric leg strength in 2 of 4 muscle groups with a decrease in perceived fatigue (Gutierrez et al., 2005). van den Berg et al., (2006) performed a study which used treadmill training over a period of four weeks and found that patients experienced significant decreases (4-17%) in 10m walk time and increases (6%-15%) in distance walked in 2min (van den Berg et al., 2006).

Recently, studies have examined the feasibility of using robotic assistive gait trainers for MS patients. This study compared control walking training to robot assisted gait training over three weeks for a total of 15 sessions. The group training with the robot assistance experienced increased walking velocity, walking distance, and knee extensor strength compared to an increase in walking velocity in the control group. However, both groups returned to baseline ability when tested six months post-training (Beer et al., 2008). Another study examined weight supported gait training with and without the presence of the Lokomat over a period of three weeks for a total of six sessions. No significant differences were reported between treatment groups however both groups benefited similarly from the gait training regardless of robotic assistance (Motl & Gosney, 2008).

Another mobility impairing condition that affects a larger portion of the population is osteoarthritis; specifically, of the knee and hip. Osteoarthritis is a common condition that afflicts 37.1% of adults over 20 years and 29.4% of adults over 20 years with knee OA (Statistics Canada, 2015). Symptom management can be complex as complete arthroplasty (knee replacement) is a highly invasive surgical intervention. Individuals who are obese, have experienced previous knee trauma, or are female are at an increased risk for knee OA (Blagojevic, Jinks, Jeffery, & Jordan, 2010). Globally, hip and knee OA was ranked the 11th highest contributor to global disability making management for Canada's aging population a priority for reducing the societal economic burden and increasing quality of life (Cross et al., 2014).

Pharmacological therapy including treatment with oral non-steroidal anti-inflammatory drugs, diacerhein, opiods, intra-articular corticosteroid and acetaminophen can lead to further serious complications including associated risks of hospitalization due to gastric perforation, peptic ulceration and bleeding, dependence, significant GI or renal events, myocardial infarction, and lesser gastrointestinal symptoms (Zhang et al., 2010). The lowest risk therapeutic treatments recommended for patients with knee OA include non-pharmacological therapies including self-management, exercise (aerobic and resistance), weight reduction, acupuncture, and electromagnetic therapy. Studies have found that physical activity and weight loss provide substantial benefits with reduction in pain and increased functionality (Zhang et al., 2010)

Exoskeleton use may allow users to partake in increased movement comfortably by decreasing the loading on the inflamed joint and could help to reduce dependence on pharmacological therapy and increase self-management of the condition through increased ability to exercise.

A recent study performed by McGibbon, Brandon, Brookshaw & Sexton (2017) examined the effects of the Keeogo™ on external knee moments during stance phase of gait in healthy adults to assess the impact of the exoskeleton on knee moments (McGibbon, Brandon, Brookshaw, & Sexton, 2017). This study sought to examine the effect of the exoskeleton on knee biomechanics of healthy participants so potential benefits to knee OA patients may be evaluated in the future. Overall results included decreased step length, increase step width, and reduced knee adduction moment during late stance phase which identify the Keeogo™ lessening the knee adduction moment (McGibbon et al., 2017).

While research is promising and patients are seeing benefits in robot assisted gait training while reducing the ergonomic strain on the physiotherapist there is a need for greater consistency in methods and increased research to better substantiate clear benefits to robotic gait training. This thesis proposes unique research in examining the cognitive demands exoskeletal technology places upon healthy users and the resulting biomechanical impact.

2.2 Military

Bullock, Jones, Gilchrist & Marshall (2010) created a systematic review of prevention studies targeting military populations which determined that the top injury prevention practice to implement, was the evaluated to be inhibiting overtraining (Bullock, Jones, Gilchrist, & Marshall, 2010). Dr. Hebert of Laval University examined musculoskeletal injuries and the resulting medical costs. Musculoskeletal conditions were the highest contributing medical cause of restricted duty, days off, and the number one reason for not being able to deploy. His review determined that knee pain presented with equal incidence between deployed and non-deployed armed forces (17.2%) (Hébert, 2016). The Canadian Armed Forces Surgeon' General's statistics also indicated that medical release (3B) due to musculoskeletal injury was 43%-66% of all medical releases, making musculoskeletal injury the greatest cause of medical releases classified under 3B medical release (Bernier, 2014; Jung, Pucci, Crawford, & Currier, 2010) Currently, many methodologies involving exoskeletal technology use training methodologies to analyze physiological and/or biomechanical change (Lajeunesse, Vincent, Routhier, Careau, & Michaud, 2015).

Load carriage is an aspect of the military that impacts each soldier and is highly significant when examining non-deployed injuries in the Armed Forces. Knapkik and colleagues found that for each kilogram of mass added to a soldier's pack (loading the center of mass as closely as possible to the soldier center of mass) the energy expenditure is increased by 7-10% at the foot and 4% at the hip (Knapik et al., 2015). Knapkik also found the most common injuries associated with the prolonged bouts of excessive load carriage to be: blisters of the foot, stress fractures, back strain, metatarsalgia, rucksack palsy, and knee injury (Knapik et al., 2015). Orr, Pope, Johnston & Coyle (2013) additionally identify in their review a prevalence of load carriage injuries to the lower limbs including musculoskeletal knee complications and neuropathies due to the increased physiological and biomechanical cost to the soldier (Orr, Pope, Johnston, & Coyle, 2013). As Polcyn identifies in 2000, there is compensation during increased load carriage during walking, with a primary posture adjustment that increases the range of knee flexion. With this increased loading, there is additional force moving through the knee joint and thus increased risk of injury to the soldier especially in kneel to stand repetitive motions which involve increased displacement of the center of mass relative to the knee joint, thus creating a longer moment arm (Holt, Wagenaar, Kubo, LaFiandra, & Obusek, 2005). In fact, Jennings identified that in non-combat injuries, the greatest frequency being musculoskeletal injuries to the knees and back (18%) with 47% being military (non-deployed) work related (Jennings, Yoder, Heiner, Loan, & Bingham, 2008).

When examining sex differences in normal gait, women tend to walk with a greater stride frequency and shorter stride length, however when the load carriage is increased women tend to experience greater difficulty than their male counterparts. This is hypothesized as a result of military materials being designed to suit male anthropometry. This may also present increased risk of injury to female soldiers bearing the same weight as the males with ill-fitting packs (Knapik et al., 2015). However, one of the consistent gait alterations associated with increased load carriage is the double support time (Ghori & Luckwill, 1985; Harman, Han, Frykman, & Pandorf, 2000; Polcyn et al., 2002). As such, double support time will be a key outcome measure when biomechanically assessing lower-limb exoskeleton trials. Birrell and Haslam (2009) examined the impact of military loading and lower limb kinematics for up to 32kg load. While the load is conservative comparatively speaking to other military loads, they found significantly decreased range of motion in the knee as well as pelvic rotation (adduction/abduction changes, rotation of the hip and pelvic tilt) they too found double support time was increased significantly from regular gait (Birrell & Haslam, 2009). They also noted significantly decreased stride length and significantly increased stance time and a linear trend in decreases from pelvic tilt range of motion from the maximum range of motion with increased carriage(Birrell & Haslam, 2009).

With more research and development exoskeletons have the potential to positively impact soldiers with respect to prevention of musculoskeletal injury to the knee, provide rehabilitation, and to ideally allow for quicker return to duty. More research is needed to determine if load carriage itself is the cause for the prevalence of acute knee injury or if there is a yield point at which the load becomes significant or if it is simply microtrauma. Exoskeletons present an opportunity to potentially reduce the loading impact at the knee in a military population. Research by Gregorczyk and colleagues has found that metabolic cost was increased across various loads with significant gait biomechanical alterations which is certainly unfavorable as the advancement of technology must continue to improve mechanical efficiency and retain neutral metabolic cost to best serve the user (Gregorczyk et al., 2010).

2.3 Cognitive Loading

Cognitive loading principle is the basis for skill and schema acquisition that is essential to everyday learning and to higher-order processing. A widely accepted theory of cognitive load is the Multifactorial Cognitive Load Theory. It builds on the model developed by Sweller which identifies information storage and information processing as separate independent mechanisms where information is processed using working memory and stored in schemata by the long-term theory (Paas, Renkl, & Sweller, 2003). This assumes that working memory is the resource with limited capacity thus processing requires a substantial amount of CL resources whereas information stored in schema may require less resources to be recalled to the working memory. Therefore, multifactorial cognitive load theory theorizes CL to include multiple sources of cognitive load generating specific loads (Debue & van de Leemput, 2014).

Cognitive loading principle has also been manipulated by researchers in order to produce methodologies and strategies to better understand the scope of information processing and overload. Paas, Renkl & Sweller published an article in 2003 that examined the different categories of cognitive loading and the demands placed upon each. This paper identified three main forms of cognitive loading; intrinsic cognitive load, extraneous cognitive load, and germane cognitive load. Intrinsic cognitive load is imposed directly by element interactivity and is intrinsic to the material being learned, for example the inherent difficulty of tying a simple vs complex surgical knot (Haji, Rojas, Childs, de Ribaupierre, & Dubrowski, 2015; Paas et al., 2003). Extraneous cognitive load is extensive loading that uses working memory for processing irrelevant to schema acquisition[2] and automation thus inhibiting learning by overloading the finite working memory[3] capacity (Paas et al., 2003).

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[2] Schema acquisition and automation is related to long term memory which allows expansion of processing beyond working memory and represent the amalgamation of multiple bits of information into a single element with a specified function through the use of cognitive constructs

[3] Working memory is defined by Paas, Renkl & Sweller 2003, as conscious cognitive processing that can only process a limited (2-3) of elements that are both interactive and novel

Extraneous loading is a distraction that is unrelated to a task but results in cognitive resources being diverted to the distraction instead of the task being completed (increased element interactivity without altering what is learned). For example, comprehending the concepts in a textbook passage with scientific jargon where the removal of the jargon does not alter what is learned but the presence of jargon increases element interactivity. If the removal of element interactivity alters learning, then the load is intrinsic and if it remains the same then it is extraneous.

Germane cognitive loading enhances learning through the stimulation of resource dedication to schema acquisition and automation. Motivation also increases the amount of working memory resources relegated to the task and, in terms of schema acquisition and automation, there is a subsequent increase in germane cognitive loading (Paas et al., 2003). Germane loading is essentially the product of working memory resources that are assigned to addressing the interacting elements that determine intrinsic load. When working memory resources are allocated to dealing with extraneous load, less is allocated to intrinsic load and thus germane load is low and learning is restricted. If working memory resources are primarily allocated to intrinsic load and extraneous load is reduced, then germane load is high and learning is high.

Intrinsic, extraneous, and germane cognitive loading have a cumulative factor in which their respective loads are additive and must not exceed the base absolute capacity of working memory to produce learning. Intrinsic loading establishes an irreducible baseline to which additional schemas and automation of previously acquired schemas must be constructed to reduce. Once the demand of the intrinsic cognitive load has been satisfied the remaining resources of the working memory can then be distributed between extraneous and germane loads which operate in concurrence. Thus, a decrease in extraneous loading allows for an increase in capacity for increased germane loading (Paas et al., 2003).

Cognitive loading targeting learning is improved by a design that reduces extraneous cognitive loading which allows for increased working memory capacity allocated to germane cognitive loading. For this thesis, manipulation of the extraneous cognitive demand will be essential in preventing the confounding of learning effect (Woollacott & Shumway-Cook, 2002) .

Studies often employ secondary task techniques in order to increase cognitive load. One of the first studies performed to examine the relationship between attention and gait and posture was performed by Kerr, Condon & McDonald (1985). This study was the first to identify a relationship between cognitive spatial processing and posture regulation (Kerr, Condon, & McDonald, 1985). Dual task methodologies are often employed by researchers to stimulate cognitive loading (Al-Yahya et al., 2011; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008). These tasks involve a primary task such as walking and a secondary task such as mental mathematics, carrying a glass of water, or vocal probing.

Secondary tasks are divided into two different categories of stimuli; discrete and continuous. Continuous tasks involve a constant secondary task requiring attention ex: carrying a glass of water. Discrete tasks stimulate only during specific times of the task and involves a quick response eg: Stroop probing or questioning. Woolacott & Shumway-Cook (2002) examined balance and gait control in both healthy and balance-impaired subjects finding that with the application of a dual-task paradigm, the secondary task contributes to instability in both populations to a varying extent depending on the complexity of the task and type of secondary task. With respect to gait, dual task methodology was found to impact results of the TUG test (Woollacott & Shumway-Cook, 2002). The TUG test is considered to be a gold standard measurement of functional mobility in clinical populations as it takes into account both static and dynamic mobility. The recurring trend of TUG test in the literature is significant and thus justified for inclusion in the proposed protocol.

A meta-analysis performed by Al-Yahya et al. (2011) examined cognitive motor interference while walking. The analysis included studies of both healthy participants and individuals with neurological disorders but separated the populations to analyze separately. In total 66 studies were included, studies on healthy individuals examined speed (48) and cadence (14), with the neurological group examining 26 studies that included speed analysis and 10 including cadence. Their results indicate that the factors with the most impact on gait are cognitive tasks that involve internal interfering factors as opposed to external interfering factors. They also found that healthy individuals tend to exhibit the increased cognitive load through decreased gait speed (Al-Yahya et al., 2011). This result mirrored results in patients with neurological disorders whom also demonstrated diminished gait speed with increased cognitive load. Healthy participants also demonstrated a decrease in gait cadence and stride length, while stride time subsequently increased. These results are also similar to those exhibited in neurological disorder patients (Al-Yahya et al., 2011).

Dual-task paradigm methodology is a commonly used approach used to analyze attentional demands through concurrent cognitive and motor tasks and reviewing the performance relative to single task performance as a reference to performance capacity. Dual task interference occurs exclusively during supramaximal demand on the available central resource capacity (Laessoe, Hoeck, Simonsen, & Voigt, 2008).

Brauer, Shumway-Cook & Woollacott (2001) investigated the attentional demands of postural control; which they defined as the control of the body's position in space to maintain balance and orientation. They found that there is a significant amount of attentional capacity required for postural control depending on the task, age and ability of the participant (Brauer, Woollacott, & Shumway-Cook, 2001). They built upon the motor learning principles explained by Fitts & Posner to relate the three stages of motor learning to the organization of movement and postural control (Woollacott & Shumway-Cook, 2002). They established that motor tasks that are highly ingrained and minimally demanding are performed using minimal central attention capacity allowing for the allocation of the residual central processing capacity for other activities. However, when there was a sensory or motor deficit or change there was regression to the earlier stages of motor learning principles (Woollacott & Shumway-Cook, 2002).

2.3.1 Cognitive Loading Protocols

Cognitive loading methodologies can be broadly characterized into four different classifications: reaction time tasks, verbal fluency, mental tracking tasks, working memory tasks, and determination/discrimination tasks (Table 2.3.1). Each methodology used to cognitively load the brain in a slightly different manner. The strategy of using reaction time cognitive loading tasks are traditionally used to measure processing speeds (Lezak, 2004). Reaction time tasks measure the interval of time between the sensory stimulus and the evoked behavioral response (Strauss et al., 2006). Verbal fluency tasks require spontaneous word production under specific conditions and is used to examine executive functions (Strauss et al., 2006). Mental tracking tasks examine retention of specific information while simultaneously processing extraneous information and are able to assess both sustained attention and information processing speed (Williams & Rasmussen, 1996). Working memory tasks are comparable to mental tracking tasks but are more simple; involving only holding information while mental tracking involves information retention and its manipulation (Barde & Thompson-Schill, 2002; D'Esposito, Postle, Ballard, & Lease, 1999). Discrimination and decision-making measures the subject's response to a specific stimulus and respond in a specific manner, it has been used to measure selective attention, and response inhibition (ie Stroop paradigm) (MacLeod, 1991).

Verbal fluency activates the areas of the brain that are responsible for executive functions; the prefrontal cortex (PFC). Neuroimaging studies have demonstrated activation of the prefrontal cortex in response to higher order or executive function. In a study performed by Meester et al (2014) association was found between prefrontal cortex activation and H-reflex[4] modulation during a dual task gait experiment. This experiment analyzed young, healthy adults walking on a treadmill with and without cognitive load, while monitoring functional Near-Infrared Spectroscopy on the PFC, and spinal cord reflex activity measured by the soleus Hoffman's-reflex (H-reflex) amplitude and gait changes (Meester, Al-Yahya, Dawes, Martin-Fagg, & Piñon, 2014).

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[4] H-Reflex (Hoffmann's Reflex) represents an electrically induced reflex analogous to the mechanically induced spinal stretch reflex that bypasses the muscle spindle and is used to assess the modulation of monosynaptic reflex activity in the spinal cord. It is an estimate of alpha motorneuron excitability when presynaptic inhibition and intrinsic excitability of the alpha motorneuron remain constant. The H-reflex is often used to measure neural function post-injury, primarily in the gastrocnemius-soleus complex. (Palmieri, Ingersoll, & Hoffman, 2004)

Table 2.3.1 Cognitive Loading Methodologies

CL Methodology	Mechanism	Example
Reaction Time Task	Processing speeds	Respond to a cue
Verbal Fluency	Executive function	Perform mental math
Working Memory Tasks	Short Term Memory	Ask to remember a list of items before and after task
Determination & Discrimination Tasks	Recognize-respond	Stroop Task

2.3.2 Sustained Attention

Sustained attention, such as that required to potentially operate exoskeletal technology is largely dependent upon stimulus recognition and signal transmission through the neural systems (Sarter, Givens, & Bruno, 2001). The neurology of sustained attention is complex and involves simultaneous top-down and bottom-up processing. Studies (Gevins, Smith, McEvoy, & Yu, 1997; N. S. Lawrence, Ross, Hoffmann, Garavan, & Stein, 2003; Sarter et al., 2001) have illustrated parietal and frontal cortex activation, specifically within the right hemisphere, as a response to sustained attention. The top down processing component is theorized to arise from stimulation requiring sustained attention performance association activation of the basal forebrain corticoceptal cholinergic system. The anterior attention system is believed to initiate the activation and mediate stimuli detection and selection of target stimuli (Sarter et al., 2001). Cholinergic inputs originating in the basal forebrain are believed to be a critical component of the neural network that is responsible for sustained attentional performance. This neural circuit is part of the cortical afferent system. Human and animal imaging studies illustrate neuronal circuits mediating sustained attention as a dissociated component from the circuits responsible for mediating the arousal component of attention (Sarter et al., 2001).

2.4 Gait

Gait is a unique semi-automated human function that requires little cognitive awareness but requires extremely complex neurological control (Takakusaki, 2013). Human gait control consists of a dual-faceted system of both autonomous and automatic mechanisms. Gait is initiated through either the cerebral cortex (autonomous) or limbic system (emotional). The proprioceptive system is critical in relaying rapid, detailed spatial awareness of the body and limb in space. The brain also receives information to determine the length, rate of contraction and tension that each muscle is applying at its insertion point, these main sensory inputs are the muscle spindles, Golgi tendon organs as well as sensory receptors in joints, subcutaneous tissue, and epidermal cells. Muscle tone is monitored primarily through the Golgi tendon organ and muscle spindles (Takakusaki, 2013).

2.4.1 Timed-Up-and-Go Test

One of the most consistent inclusions across research articles is the use of a timed up-and-go test (TUG Test), pictured below in Figure 2.4.1, which is a gold standard measurement of functional mobility, especially in older adults and individuals with gait impairment (Bohannon, 2006). The Timed Up and Go (herein referred to as the 'TUG' test) protocol was established and validated through the Center for Disease Control and Prevention (CDC) as part of an initiative to stop elderly accidents, deaths and injuries (STEADI) (Bohannon, 2006).

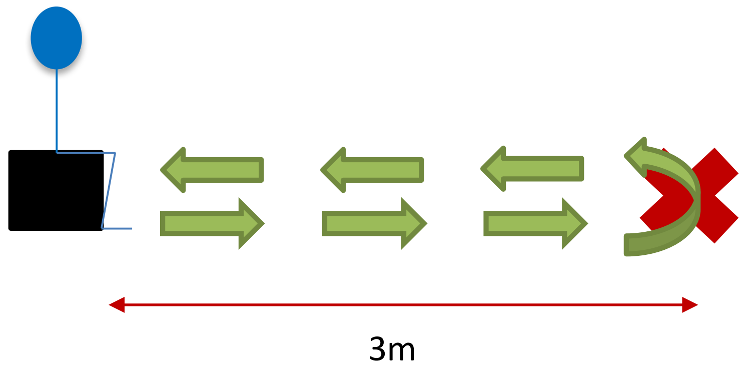

Figure 2.4.1 Timed-Up-and-Go Test (3m)

Exoskeletal technology is being targeted toward elderly and mobility impaired individuals thus, the TUG is aptly suited as a performance measure for the mobility of this population. Due to widespread use of the TUG test for functional mobility there is a substantial amount of pre-existing data on the targeted population a vital asset for research going forward and contributing to systematic reviews and meta-analyses. Similarly, cognitive load studies performed on mobility impaired or elderly populations often utilize a TUG/CL-TUG condition where the TUG is performed with and without the inclusion of cognitive loading variable (Mulder, Zijlstra, & Geurts, 2002; Vreede, 2006). Such studies often employ the use of a dual-task paradigm during which the participants are asked to walk while simultaneously cognitively processing information using one of the methodologies outlined in Section 2.3 Cognitive Loading. The experimental design manipulates the TUG methodology to create conditions for cognitive load variable (CL) and obstacle crossing (OC). Serial subtraction by factors of 7 (S7) is commonly used in (verbal fluency) cognitive loading research and has been shown to successfully overload young, healthy adults (Srygley, Mirelman, Herman, Giladi, & Hausdorff, 2009).

The TUG is composed of several phases: chair rise (sit-to-stand), walking, turning, and chair sit (stand-to-sit), which are all basic mobility activities in daily life. Sit-to-stand movements are simple in healthy adult populations but may prove to be a significant challenge in older adults or clinical populations that experience balance deficits, weakness or neurological impairments. Such populations may also experience similar challenges with the stand-to-sit movements due to the same restrictions on balance, weakness, or control impairment. The 5-repetition STS test uses sit-to-stand and stand-to-sit repetitions to analyze limitations due to knee flexor strength in clinical populations with an ICC of 0.970-0.976, interrater reliability of 0.99, and test-retest reliability of 0.989-0.999 (Mong, Teo, & Ng, 2010). The chair rise and chair sit times are therefore highly important in this thesis and these phases will be analyzed specifically.

The walking phase of the TUG is defined by the cyclic rhythm of alternating limb progression that moves the body along a determined path in addition to preserving stability. Gait is composed of both a stance and swing phase. The heel strike is the onset of stance phase when the heel makes contact with the ground upon which foot flat (loading response) occurs when the sole of the foot reaches the floor. The loading portion is the first double support period of the stance phase until the contralateral limb is no longer in contact with the ground. Midstance occurs when the body passes over the reference extremity. Heel-off is defined when the heel leaves the floor and weight passes to the contralateral foot and ends when the toe leaves the floor (toe-off). Gait then enters the swing phase which ends with the next heel strike (Pappas, Popovic, Keller, Dietz, & Morari, 2001). During the TUG, the walking phase occurs between chair rise and turning, and turning and chair sit.

The timed up and go has been found to have a moderate test-retest reliability (n=844, ICC=0.56) in healthy older adults without cognitive impairments. Construct validity is supported with (Pearson's r=0.75, n=40) for gait speed, (r=-0.48, n=40) for postural sway, and step length (r=-0.59, n=0.40) (Steffen, Hacker, & Mollinger, 2002). In a meta-analysis by Bohannon (2006) the mean TUG time of individuals over 60 years old was 9.4s where individuals in their sixties had a mean of 8.1s, those in their seventies had a mean of 9.2s and those in their eighties to nineties had a mean TUG time of 11.3s (Bohannon, 2006). The prevalence of TUG testing in populations that may benefit from exoskeletal technology indicate that it may be beneficial as a protocol to assess functional mobility in a comparison design; with and without the presence of the Keeogo™.

2.4.2 Obstacle Crossing

Falling and fall-risk are two highly researched areas in clinical studies. The potential impact of falls on elderly individuals or clinical populations can be catastrophic. Obstacle crossing is one area associated with increased fall risk. The task of crossing an obstacle requires both motor-planning and motor skills of the subject. Many clinical conditions impact the ability of patients to perform this processing or alters their neural feedback or feed-forward control, leaving them at an increased risk for falling. Newstead, Walden & Gitter (2007) identified gait variables that may differentiate fallers from non-fallers. They compared two groups of elderly adults through baseline walking, slow walking, fast walking, and obstacle-crossing This study compared step length, stride length, cadence, single support time, and double support time. Fallers were identified by having a distinct strategy for obstacle management; they reduced both stride length and velocity significantly more than non-fallers (Newstead, Walden, & Gitter, 2007). Their results are further demonstrated in a study by Toulotte and colleagues. (2006) who analyzed a dual task condition (carrying a cup of water) comparing fallers and non-fallers, determining that fallers spent significantly more time in double support than non-fallers and had significantly different cadence, speed, stride and step time (Toulotte, Thevenon, Watelain, & Fabre, 2006).

A study performed by Chou, Kaufman, Hahn & Brey (2003) examined mediolateral motion of center of mass in obstacle crossing for an elderly population. Their study showed that mediolateral motion of the center of motion during obstacle crossing had a significant positive correlation with the mediolateral range of motion of the swing foot trajectory theorized as a compensatory motion to counter the medio-lateral instability and re-establish balance (L. S. Chou et al., 2003) .

Obstacle-crossing research must therefore strive to take into account these associated aspects of gait biomechanics in healthy adults including: medio-lateral motion of the center of mass in the sagittal plane, stride length, cadence, foot clearance, crossing speed, and obstacle-heel strike difference (H. C. Chen, Ashton-Miller, Alexander, & Schultz, 1991).

One of the key features identified by Patla & Vickers (1997) was the amount of time spent looking at obstacle prior to crossing it. They found that when using an eye-tracker that participants asked to cross an obstacle spent significantly more time staring at the obstacle in the planning phase of obstacle crossing (Patla & Vickers, 1997). They also found the frequency of object fixation to be a function of the obstacle height. Higher obstacle fixation was associated with low contrast obstacles as well as higher obstacles indicating that the participants were planning and identifying stable landing (Patla & Vickers, 1997). They surmised that gaze fixation on the obstacle was essential in supplying visual information to control the swing limb trajectory. They used this conclusion to conclude that a feedforward mechanism can be utilized to control locomotion in the presence of an obstacle (Patla & Vickers, 1997).

Patla & Prentice in 1995 identified the hip as the dominating factor in limb elevation, as well as the primary source of energy absorption during the landing phase (Patla & Prentice, 1995). They found that obstacle crossing required both active and passive control to lift the limb and that there was an increase in biceps femoris activity during double support and the early swing phase, while the rectus femoris activity increased in the late swing phase (Patla & Prentice, 1995). Increased muscle activity was required for initiation and termination of the swing phase while passive inertial torque provides the leg motion in order to minimize the energy associated with task and to simplify the motor pattern (Patla & Prentice, 1995).

Thus far obstacle crossing has not been analyzed in users of lower-limb exoskeletons, however it will be essential to determine how the user will avoid the obstacle; obstacle avoidance is a key component in the work place and in daily life (ie. sidewalks or stepping over a doorframe). This project will examine biomechanical difference during the obstacle approach and planning phase prior to crossing the obstacle as well as landing and exiting the crossing phase. Further research will be needed after preliminary studies on healthy populations to determine if the Keeogo™ will be successful in assisting users that may be at higher risk of falling during obstacle crossing tasks.

2.5 Motion Capture

The previous sections have outlined different aspects of gait and biomechanics. This section will describe the use of motion analysis systems/visual tracking systems to analyze these variables. Motion analysis is a rapidly growing assessment tool that is being both advanced for greater precision and simplified for general population use. Motion capture is primarily divided into two subsets of passive and active tracking systems. Passive systems simply reflect light to indicate their orientation in space while the active systems transmit their position to the tracking system. The proposed research will use the Vicon™ with a passive marker tracking system. The marker set that will be used is outlined in Figure 3.3.1.

Visual tracking systems assume a figure with a predetermined number of joints and degrees of freedom and then track the movement of markers and 'limbs' together with each individual joint considered an independent entity with independent movement relative to the other segments (Moeslund, Hilton, & Kruger, 2006). Marker motion can be described using the Proscustes analysis, per a study performed by Grimpampi et al. (2014). The Proscustes analysis essentially states that the effect of soft tissue artefact motion on a cluster or marker on a cluster is the combination of four independent transformations; translation and rotation (rigid body motion), and change in size and shape of the cluster (non-rigid body motion) (Grimpampi, Camomilla, Cereatti, De Leva, & Cappozzo, 2014).

McGinley et al. 2009 found in a systematic review of 3D Kinematic Motion Capture that in the sagittal plane the highest reliability was found in hip and knee joints as well as the lowest error in the pelvic rotation and obliquity and hip abduction. McGinley's systematic review of 15 papers and 8 abstracts found that in healthy adults the reliability was great in intersessional (within-assessor) sagittal plane capture with reliability indices of CMC or ICC >0.8 and errors typically <4 degrees (McGinley, Baker, Wolfe, & Morris, 2009) An analysis of inter-laboratory variability of motion capture found that intersession variability is limited to an effect of less than 5 degrees excluding hip and knee joint rotations (McGinley et al., 2009). Thus, the intersessional variability was deemed acceptable among comparable protocols and gait variables with acceptable correlations (Benedetti, Merlo, & Leardini, 2013). The McGinley review also found that acceptable error was established between 2 and 5 degrees apart from both hip rotation and knee valgus/varus (McGinley et al., 2009).

2.5.1 Vicon Motion Capture System

Motion capture for movement analysis is primarily divided into two subsets of passive and active tracking systems. The Vicon system uses a passive tracking system of retroreflective markers. The specifications of the Bonita B3 Vicon cameras are further detailed in Table 2.5.1.

Table 2.5.1 Vicon Bonita B3 Specifications (Vicon Motion Systems Ltd, 2009)

VICON BONITA B3 SPECIFICATIONS	
FRAME RATE	240 Hz
MAX SHUTTER TIME	0.5ms
RESOLUTION	0.3 megapixel
CAMERA OUTPUT MODE	Grayscale
INTERFACE	Gigabit Ethernet, RJ45 connection
MOUNTING	Tripod
SYSTEM LATENCY	2ms
ACCURACY	Sub mm
OPERATING RANGE	12m (narrow lens), 8m (wide lens)
STROBE	NIR @ 780nm 68 high powered surface mount LEDs, 56 degree FOV, adjustable brightness
LENS	4-12mm field of view
POWER	15W PoE conforming to IEEE 802.3af
FOCAL LENGTH	4-12mm
IRIS RANGE	F1.4-CLOSE
MOUNT	Std C Mount
ANGLE OF VIEW	Wide 93.7 to 68.9deg Narrow 31.2 x 23.4deg
FOCUSING RANGE	0.3m-inf

2.5.2 Sources of Variability

The study by Benedetti, Merolo & Leardini (2013) found greater variability and error >5 degrees in studies in which the PI was not experienced with marker placement or did not have specific anatomical knowledge as a frame of reference. They found that level of experience with marker placement to be the most important significant contributor to error barring inter-assessor variability (Benedetti et al., 2013).

One of the greatest sources of error in motion analysis using a passive system is the incidence of slippage in marker clusters (Grimpampi et al., 2014). Determining a method which estimates the instantaneous position and orientation of a bone relative to a global frame throughout movement using non-invasive experimental design is still inadequately assessed problem in motional analysis. One of the greatest factors in creating slippage in markers is soft tissue artefact; which essentially causes the skin markers to behave as deformable bodies in motion relative to the underlying bone. The issue then becomes assuming the marker is moving synchronously with the underlying bony segment which is a rigid body and non-deformable. In exercises or motions where there is highly accelerated movement, for example rapid jumping or sprinting, the inertial effects of tissue deformation from the soft tissue may have impact on movement kinetics (Grimpampi et al., 2014).

The study by Grimpampi (2014) found that during a motor task, marker clusters undergo simultaneous translation and rotation with respect to the bone in addition to a size and shape variation. This study also found that as mass of the limb increased there was an increase in marker cluster displacement at the thigh which suggests a positive proportional relationship between quantity of soft tissue and the impact of soft tissue artefact however, this study was limited in its use of ex vivo subjects and the presence of active muscle tone may impact this relationship (Grimpampi et al., 2014). Thus, the proposed research will use a thigh girth measurement and BMI to try and account for soft tissue artefact error within the data.

This study will only involve collecting kinematic data. Kinematics do not consider the forces that produce movement unlike kinetics which study the forces and moments causing the movement. Variables calculated will consider spatial and temporal components.

This literature review has identified specific gaps in the literature with respect to research on overground exoskeleton testing; specifically in the area of cognitive loading and obstacle crossing; both of which are key components of activities of daily living. The next chapter will outline the procedures based upon the aforementioned literature that will help to explore cognitive loading and obstacle crossing in exoskeleton users.

Chapter 3 Methods

The objective of this study was to assess the impact of a verbal fluency cognitive loading task and obstacle crossing on gait biomechanics in healthy adults using a lower-extremity exoskeleton. Participants used the Keeogo™ in three different exoskeleton (EXO) conditions active (KActive), passive (KPassive), control (KControl) where KControl represented the absence of the Keeogo™. Within the EXO conditions participants underwent four randomized conditions: control (C), cognitive loading (CL), obstacle crossing (OC), and obstacle-crossing while cognitively loaded (CLxOC). The condition order table of both EXO and C, CL, OC, CLxOC conditions can be found in Table 3.3.2. The primary outcome measure was total TUG time and secondary measures were turn time, turn radius, rise time, sit time, stride length, step width, toe clearance, and S7 responses.

3.1 Ethics

This study is on file with the Research Ethics Board at UNB (REB#2017-039). Detailed REB documents may be found in Appendix I.

3.2 Participants

Participant recruitment and qualifications are based on preliminary pilot testing and are described in detail below.

3.2.1 Recruitment

Healthy, adult participants were recruited using flyers and word of mouth. Flyers were distributed through the Faculty of Kinesiology at UNB, and UREC. The population studied were young, healthy adults who were students at University of New Brunswick. Interested individuals were instructed to email or call the primary investigator to set up the testing session and be willing to self-identify height and contraindicating health factors in order to determine their testing eligibility. Participants were asked to bring their own shorts or leggings and comfortable athletic shoes. Potential participants were afforded an opportunity to inquire about the protocol and testing details prior to and during the test session. The study took place at the University of New Brunswick Lady Beaverbrook Gym and incorporated both fitting/tuning of the exoskeleton and the actual testing into a single session.

3.2.2 Sample Size

Preliminary data collected during a pilot study using a cohort of six participants performing a TUG and CL-TUG which was used to estimate the required number of participants. The pilot study performed found the TUG time to be 6.31s ± 1.09s while the CL-TUG was 8.03s ± 1.32s with a mean difference of 1.72s ± 0.78s ($p<0.01$). These results powered the ANOVA which translated to an effect size (Cohen's f) of 1.1. It was determined through an *a priori* G-Power repeated measures within factors MANOVA that for an effective size ($f=1.1$) , power of ($1- \beta=0.99$) and $\alpha=0.05$, $n=10$ would be required to measure four variables with approximate correlation between repeated measures of 0.5 (Figure 3.2.1) (Faul, Erdfelder, Lang, & Buchner, 2007). Twelve participants were recruited for this thesis with equal sex distribution.

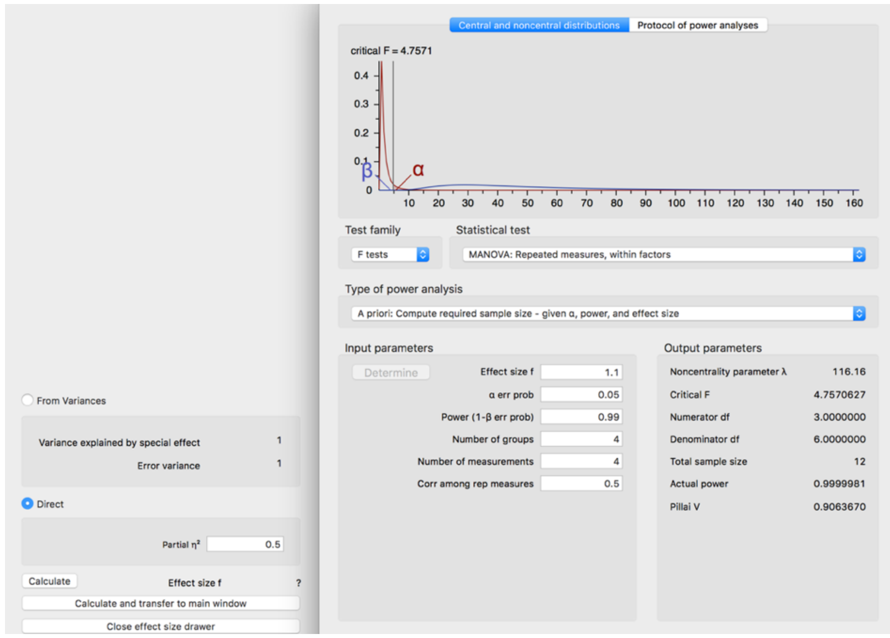

Figure 3.2.1 G*Power Analysis

3.2.3 Inclusion Criteria

In order to be considered for inclusion participants were required to be between the ages of 19 and 45 years and healthy overall. The height restriction was strictly observed based on the recommended dimensions for users of the current Keeogo™ model as per the manufacturer's handbook and as such participants were required to be between 5'4" and 6'2" (Keeogo Manual).

3.2.4 Exclusion Criteria

Upon arrival to the testing session participants were screened using the Physical Activity Readiness Questionnaire (PAR-Q+) for adults, in addition to a health condition screening tool. Self-reported conditions that were considered exclusionary by the secondary health condition screening tool were any musculoskeletal or neurological conditions (diseases and disorders that affect mobility, balance or coordination), lower-extremity amputation, blindness (legally or color-blind), physician diagnosis of an attention deficit spectrum disorder, recent or persisting symptoms of a head concussion, and skin conditions that contraindicate use of orthoses. Sarter, Givens & Bruno (2000) have illustrated a correlation between neural degeneration and decreased performance output during tasks requiring sustained attention.

Additionally, participants were required to score 27 or greater on the Montreal Cognitive Assessment to screen for mild cognitive impairment (ex: recent concussion). MoCA scores less than 27 were considered to be reason for exclusion. Nasreddine and colleagues (2005) analyzed the Montreal Cognitive Assessment (MoCA) tool in comparison to another standard assessment tool of cognitive impairment; the Mini-Mental State Examination (MMSE) and found that the MoCA could identify mild cognitive impairments to a high degree of specificity (90%). Due to the general ability of the population participating in the study, the MoCA was used to screen potential participants for mild cognitive impairment and use a cut-off score of 27/30 (Nasreddine et al., 2005).

3.2.5 Pre-Testing Instructions

Participants were asked to adhere to specific pre-testing instruction to help minimize confounding the data, both between subject and between sessions. On the day of testing participants were asked to refrain from consuming caffeine, alcohol, smoking or vigorous physical activity above and beyond the normal scope of the individual’s capacity on the day of testing. Caffeine, alcohol, and nicotine all present as potential confounding variables (Ehrman, Visich & Keteyian, 2013). Caffeine is a fat-soluble compound that is able to pass through both cell membranes and the blood-brain barrier (Ehrman, Visich & Keteyian, 2013). Caffeine alters the production and/or uptake of neurotransmitters (adenosine and adrenaline with corresponding effects on dopamine acetylcholine, serotonin and norepinephrine) which alter performance, mental and physical energy (Lorist & Tops, 2003). Participants were asked to avoid physical activity above and beyond the normal scope of their regular activity to help prevent delayed onset muscle soreness (DOMS) and associated gait alterations.

3.2.6 Safety

All participants provided informed signed consent before any testing began. The pilot study resulted in no adverse events, and no adverse events have been reported in two other major studies at UNB with this device that tested 25 healthy adults during walking, jogging and other activities (McGibbon et al., 2017; Muggah, Brandon, Brookshaw, Sexton, & McGibbon, 2016). Participants were informed that they were able to end the testing session at any point. Participants were also provided the opportunity to self-disclose any contraindicating conditions to which participation in the study will increase their risk of harm. The physical activity readiness questionnaire (PAR-Q) in addition to the screening measures outlined, and MoCA also served to better ensure the participant's safety.

3.3 Measurement and Evaluation

This section details outcome measures used in the analysis.

3.3.1 Anthropometrics

Anthropometric data was collected from each participant including their sex, age, weight, height, femoral length, tibial length, waist circumference, and thigh girth. The latter variables were required for fitting the Keeogo™. The data collection worksheet was the only piece of information linking the participants name and their participant identification number. The participant completed the consent form in addition to the PAR-Q. Anthropometric measures were taken to account for the physical aspects of the participants and predict limitations (Table 3.3.1).

Table 3.3.1 Participant Anthropometrics

	M	F	Total
Age (y)	23 ± 0.63	24.5 ± 2.81	23.75±2.09
Height (cm)	178.58 ± 5.46	168.42 ± 6.38	173.50±7.76
Weight (kg)	81.67 ± 13.01	70.95 ± 9.0	76.31±12.05
FLength[5] (cm)	52.0 ± 2.97	49.33 ± 4.63	50.67±3.96
TLength[6] (cm)	46.57 ± 1.31	44.0 ± 3.81	45.28±3.03
TG [7] (cm)	50.08 ± 7.10	51.50 ± 4.72	50.79±3.85
WC[8] (cm)	84.83 ± 7.10	82.42 ± 8.53	86.33±7.59
MoCA	29.0 ± 0.63	28.33 ± 1.21	28.67±0.98

3.3.2 Randomization

At the point of successful recruitment participants were randomized to an ID. The ID was associated with a predetermined condition randomization to ensure the maximal number of condition orders would be analyzed in the sample size before any orders were repeated. The ID order was randomized using Excel to which participants were assigned in order of recruitment. For example, if the first three ID's generated were P06, P03, P11

[5] Femoral Length: the distance from the greater trochanter of the femur to the lateral condyle

[6] Tibial Length: the distance from the medial malleolus to the medial condyle

[7] Thigh Girth: calculated after measuring to the distal 1/3 of the femoral length

[8] Waist Circumference: narrowest point between the inferior ribs and iliac crest (approx. 2.5cm superior to umbilicus)

the first three successful participants would have been P06, P03, and P11 respectfully. The condition randomization can be seen in Table 3.3.2.

Table 3.3.2 Participant ID and Condition Order

ID	EXO- RAND	First	Second	Third
mP01	KControl, KPassive, KActive	Control	CL	OC
mP02	KControl, KActive, KPassive	CL	OC	Control
mP03	KPassive, KActive, KControl	OC	Control	CL
mP04	KActive, KPassive, KControl	Control	CL	OC
mP05	KControl, KPassive, KActive	CL	OC	Control
mP06	KControl, KActive, KPassive	OC	Control	CL
fP07	KPassive, KActive, KControl	Control	CL	OC
fP08	KActive, KPassive, KControl	CL	OC	Control
fP09	KControl, KPassive, Active	OC	Control	CL
fP10	KControl, KActive, KPassive	Control	CL	OC
fP11	KPassive, KActive, KControl	CL	OC	Control
fP12	KActive, KPassive, KControl	OC	Control	CL

*participants were randomly assigned to a participant number corresponding to a predetermined condition order upon recruitment

3.3.3 Marker Set

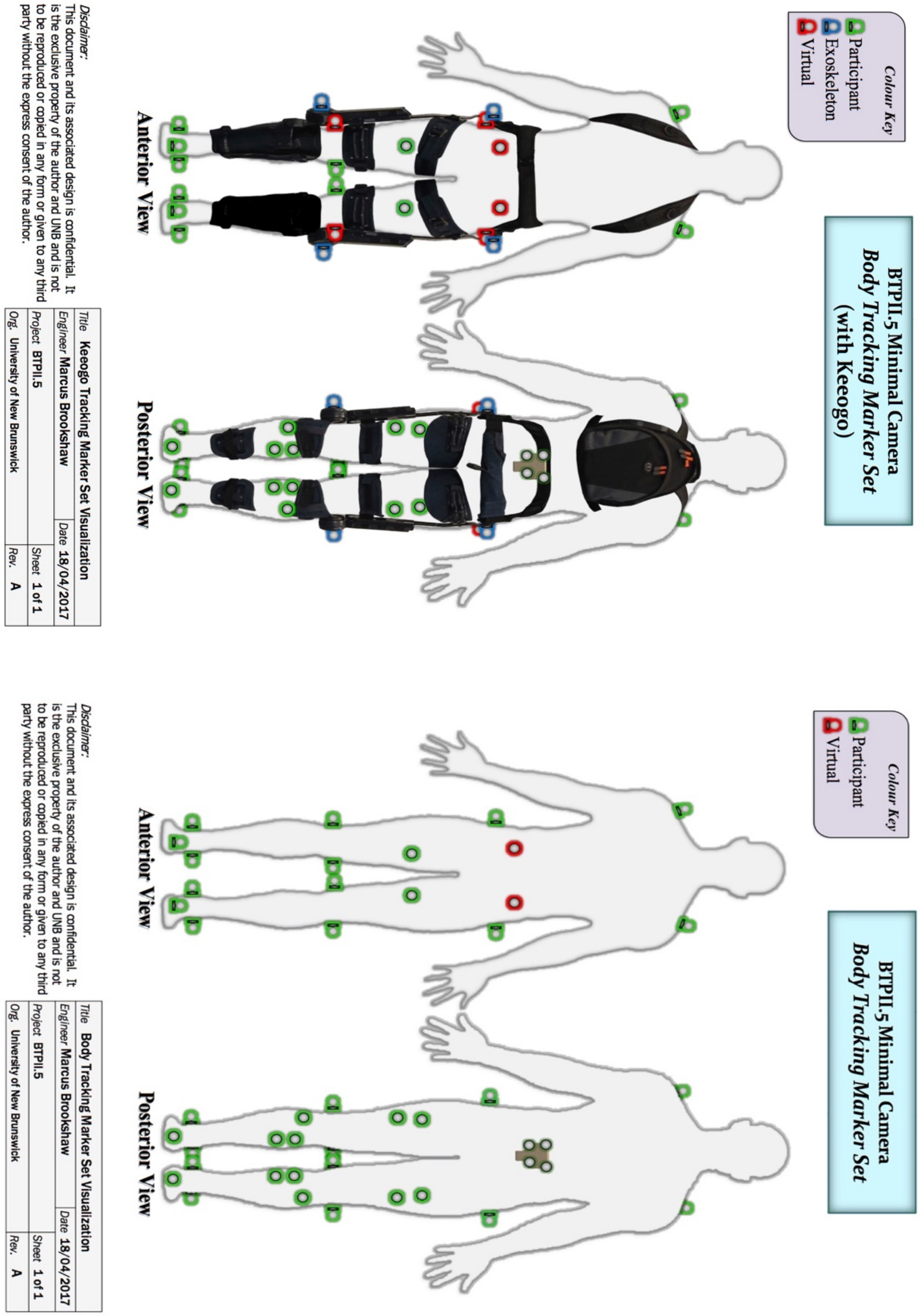

Figure 3.3.1 Markerset for Motion Capture Analysis

3.3.4 Motion Capture

Apparatus included a standard scale, and measuring tape. The Vicon Bonita B3[9] series motion capture system was used as the main outcome measure apparatus. The Bonita B3 Vicon cameras (Figure 3.3.2) have 1.0-megapixel resolution, with a maximal capture speed of 240fps and 0.5mm of translational and rotational error using 9mm markers in a 4m x 4m volume space (Vicon Motion Systems Ltd, 2016). Vicon motion capture was set at a frequency of 100Hz and was processed using Nexus software for labelling and Matlab 2017 for gap filling and determining outcomes.

Apparatus configuration required specific positioning to ensure that apparatus set-up was adequate to capture marker trajectories in the required volume. Camera placement was emphasized to maximize viewing volume. In order to assess the capture capabilities of the camera a simple validation tool was created. Markers were placed on a ruled pole approximately 10cm apart and attached to a wheeled base. The pole was rolled through the viewing volume systematically starting with the perimeter of the viewing rectangle and moving inwards with each ‘lap’ around the capture volume until the entire volume was covered. The analysis of the pole trial determined an RMS error of 1.2235mm for two markers placed 10cm apart. After accepting the accuracy of the volume created by the camera configuration, a model skeleton was rolled through the TUG area to further ensure

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[9] Further specifications of the Vicon Bonita B3 can be found in

Table 2.5.1

good visibility. The primarily sagittal focus and simple gait variables allowed for a large viewing volume to be captured successfully.

Figure 3.3.2 Vicon Bonita B3 Camera (Vicon Motion Systems Ltd., 2004)

3.4 Procedures

This section includes all procedures including tuning and fitting of the Keeogo™.

3.4.1 The Keeogo™ Dermoskeleton

The Keeogo™ lower limb robotic dermoskeleton (DSK) was developed by B-Temia Inc., Quebec City, Quebec, Canada (Figure 1.1.1). The fitting and tuning process was essential to ensure optimal performance with the device. The first portion that was fit to the participant was the waist belt which sits resting on the iliac spine and the back piece flat against the participant's lumbosacral region. The mid-point of the hip chariots were then adjusted to line up with the participant's greater trochanter. At that point the Keeogo™ was clipped into the hip chariots and the appropriate sized straps fastened to the dermoskeleton and loosely attached to the participant. The hip sensor was aligned with the greater trochanter and then the frame was adjusted in length to coordinate with the participant's femur. The length was adjusted so that the knee actuator would be in alignment with the inferior 1/3 of the patella. The thigh straps (slightly inferior to gluteal fold and lower 1/3 of the thigh) and were then tightened to ensure the frame was lateral with no internal or external rotations. Once the thigh portion was secured the tibial straps (superior and inferior ends of the gastrocnemius) were secured with greater tightness than the thigh straps. Alignment was then re-assessed and necessary adjustments were made if alignment had been disturbed.

Once the Keeogo™ was satisfactorily fit to the participant the PI calibrated the device which determined the anatomical position of the sensors and actuators in relation to the participant. During calibration participants stood in anatomical position. Following calibration, the tuning process began in order to customize the tuning parameters to the participant's unique gait cycle. The calibration and tuning process were performed using a tablet computer that was plugged into the Keeogo. The participant began with assistance on high and the tuning parameters were adjusted from there. The participant was asked to walk and the PI adjusted assistance level, damping, extension, and flexion parameters using the tablet as they walked. Adjustments continued until the participant and the PI were satisfied with the natural gait synchronization.

3.4.2 Testing

Prior to the participant's arrival the PI arrived at the Lady Beaverbrook Gym (LBG) soft lab and ensured that all motion capture equipment was initialized and calibrated using the calibration wand before the testing session. At the point of recruitment, participants were informed that data collection would be a single session of approximately 3 hours.

Upon arrival of the participant they were informed of the study verbally, and given a folder of documents (informed consent, nondisclosure, debrief) to read through. The paper folder contained all questionnaires and data collection documents. Each folder number coordinated with a randomization pre-assigned at the point of recruitment to the participant. For example, the first participant would not necessarily be p01; they would be the number they were randomly assigned to upon recruitment. Paper folder indicated which participant number they were assigned. After any questions were answered, participants signed the consent form.

After completing the screening questionnaires (PARQ+, MoCA, health conditions questionnaire) and signing the informed consent and confidentiality forms, the participant was asked to change into the requested appropriate clothing to begin the anthropometric measurements. The participant was then weighed, followed by measurement of height, tibial length, femoral length, and thigh girth (cm). Following the anthropometric assessment, the participant either donned the exoskeleton or testing proceeded without the exoskeleton.

For the EXO conditions with Keeogo™ the PI followed the Keeogo™ User Manual for tuning the parameters (bilateral and unilateral adjustment of level of assistance, torque, knee flexion/extension) and adjusted the exoskeleton to integrate appropriately with the participant's natural gait cycle.

The motion capture system was already calibrated and ready for data collection prior to the participant's arrival. The cameras were oriented in a predetermined format to include the best visibility for full TUG testing range with maximal marker exposure within the field of view. Laboratory configuration can be viewed in Figure 3.4.1.

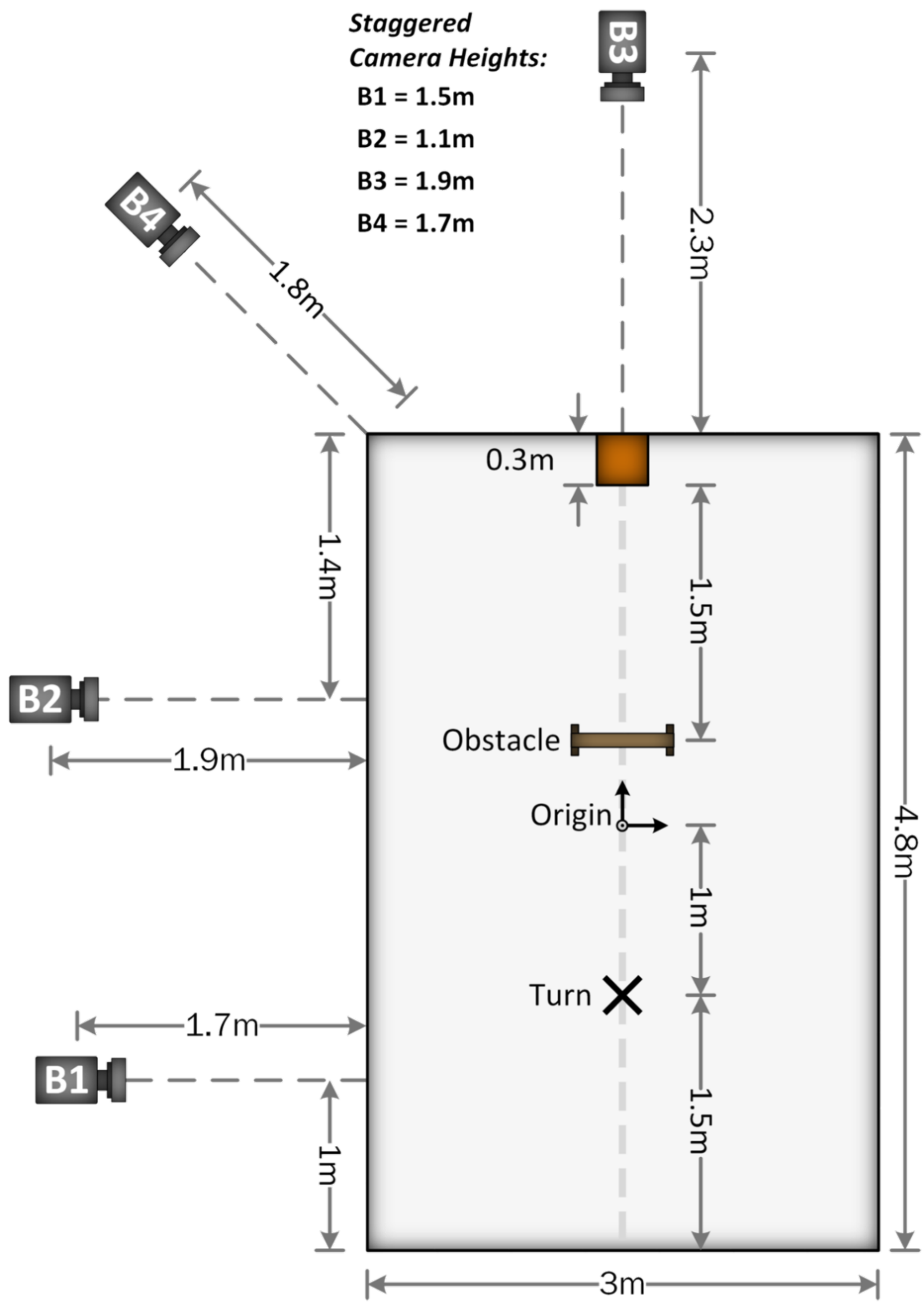

Figure 3.4.1 Laboratory Set-Up

Participants were asked to complete the timed-up-and-go test in KControl (no exoskeleton), in KPassive (unpowered exoskeleton), and KActive (powered exoskeleton) mode wearing the exoskeleton. The order participants wore the device versus not wearing the device was randomly determined using a block randomization. Participants were then asked to either perform TUG in the condition assigned with/without the Keeogo™ three times, with a 10-minute rest between (or the time taken to don the exoskeleton) between the EXO conditions.

The methodology that was used to cognitively load the participants required them to verbally count backwards from a random three-digit number, produced by a random number generator, by intervals of 7. The participant was prompted when to begin, and informed that number of responses and number of correct responses was to be prioritized equally with completing the TUG swiftly as both would be evaluated. Each trial began at a different starting number randomly generated by a random number generator. The list of integers was created using a random number generator and the same list and order of integers was used for all participants. After completion of the testing, participants were debriefed regarding the details of the testing, given a letter describing the study, and had the opportunity to ask any questions which were answered and then they were thanked for their participation. Experimental set-up was then dismantled and equipment put away until the next participant.

3.5 Data Analysis

The data was exported from Nexus software into Matlab for processing. Motion capture data primarily analyzed lower limb kinematics using marker data from the LAcrom, RAcrom, RDPhal3, LDPhal3, LCal, RCal (Table 3.5.1). A cubic spline gap fill was used to fill gaps in the data which applies third degree polynomial interpolation to fill gaps (Howarth & Callaghan, 2010). Gap fill processing was used for gaps in the data less than 40 frames (0.4s). The primary outcome measure was TUG time and secondary outcome measures included turn time, chair rise time, chair sit time, turn radius, stride length, step width, and toe clearance. Cognitive load data was also collected. The total number of responses by the participant was recorded in addition to the number of correct responses for each trial.

Table 3.5.1 Variable Calculation

variable	Markers Used		Figure
t_{TOTALl}: total TUG time	LAcrom, RAcrom	X	Figure 3.5.1
t_{TURN}: turn time	LAcrom,RAcrom	X	Figure 3.5.2
t_{RISE}: chair rise time	LAcrom,RAcrom	Z	Figure 3.5.1
$t_{SIT:}$: chair sit time	LAcrom,RAcrom	Z	Figure 3.5.1
r_{TURN}:turn radius	LAcrom,RAcrom	Y	Figure 3.5.3
ΔL_{STEP}: stride length	RDPhal3,LDPhal3	X	Figure 3.5.4
ΔW_{STEP}: step width	RDPhal 3, LDPhal3	Y	Figure 3.5.5
Δd_{TC}: toe clearance	RDPhal3, LDPhal3	Z	Figure 3.5.6

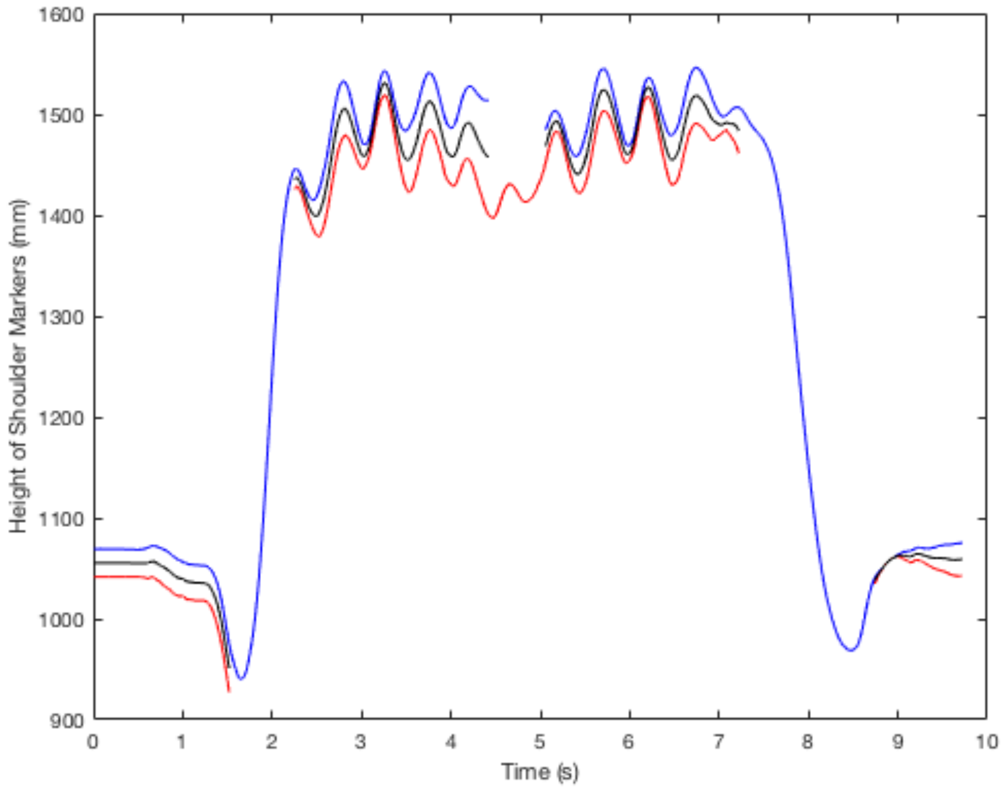

Figure 3.5.1 Shoulder height of left (red) and right (blue) acromial markers and the midpoint (black) used to calculate TUG time (first decrease to the return to the initial height), rise time (first negative slope to first local maxima), and sit time (last local maxima to return initial height)

Chair rise times and chair sit times were calculated using the left and right acromial z-coordinates. Initiation of the TUG was defined as the first point the curves become negative and the termination of the TUG was defined as the last positive slope of the z-coordinate curves. The end of the rise time was defined as the first local maxima after initiating the rise and the beginning of the sit time was defined by the last local maxima prior to the last negative slope before TUG termination as seen in Figure 3.5.1.

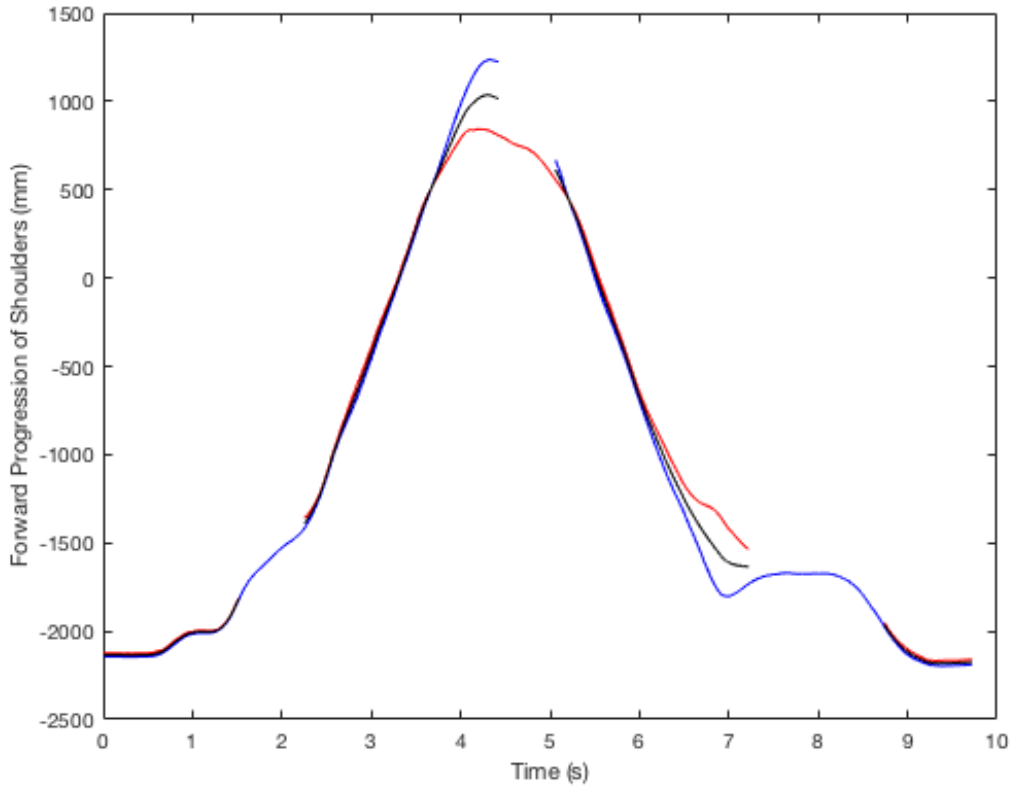

Figure 3.5.2 Shoulder progression of left (red) and right (blue) acromial markers and midpoint (black) where turn time was defined from the divergence of the three curves, to the re-convergence of curves

The turn time was determined by graphing the left and right acromial x-coordinates as well as the mean between the shoulders as seen in Figure 3.5.2. The beginning of turn was defined by the divergence of the x-coordinate curves, the midpoint by the peak of the turn and the end of the turn was defined by the re-convergence of the x-coordinate curve. The time was calculated between beginning and end points defined.

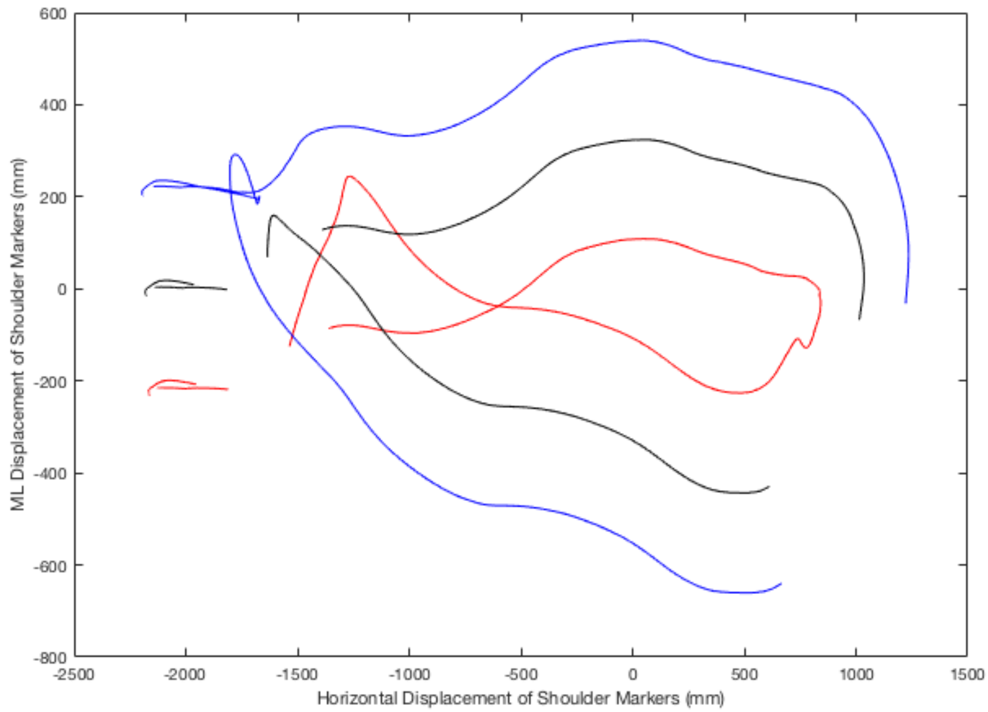

Figure 3.5.3 Forward progression vs mediolateral displacement of left (red) and right (blue) acromial markers where black represents the midpoint between left and right shoulders and turn radius was represented by ½ the distance between the midpoint maxima and midpoint minima

Turn radius was calculated by plotting the X by Y coordinates of the left and right acromial markers and then creating a midpoint curve as the body path. The turn radius was defined as one half of the distance between the absolute maxima of the midpoint curve and the absolute minima of the midpoint curve as seen in Figure 3.5.3.

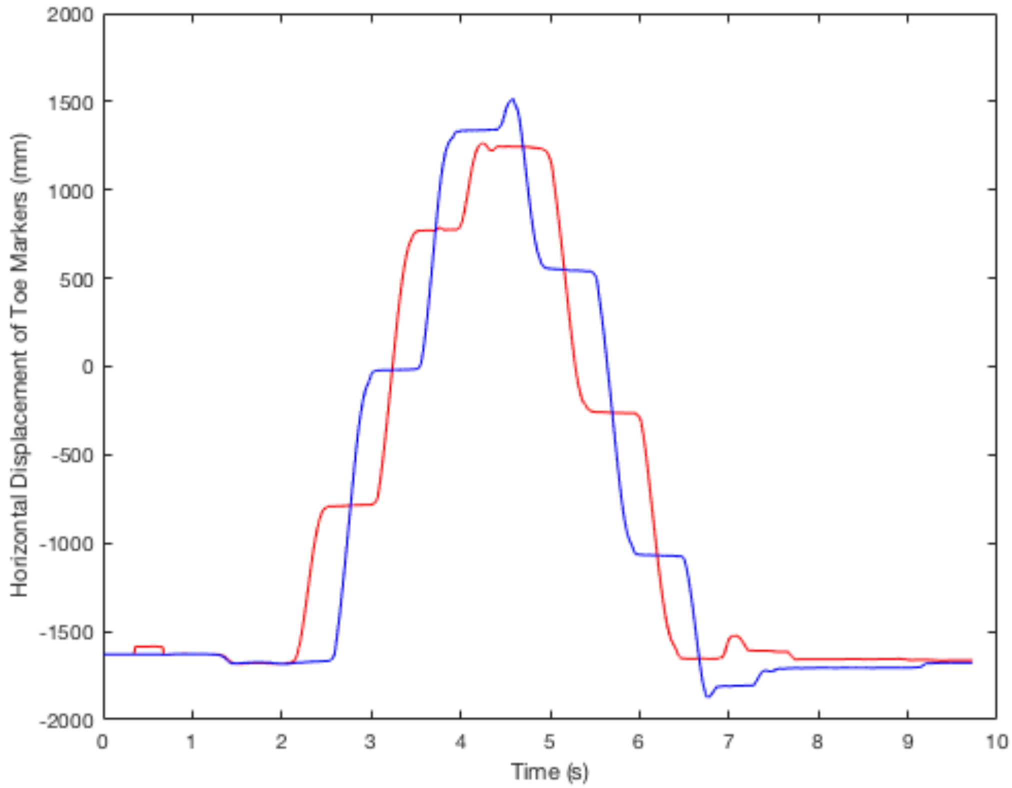

Figure 3.5.4 Progression of LDPhal3 (red) and RDPhal3 (blue) where the mean distance between two plateaus of the same trajectory on each side of the turn (maxima)

Stride length was calculated using the x-coordinates of the RDPhal3 and LDPhal3. The most clearly defined step for each foot prior to the turn and after the turn were calculated by the distance between two plateaus of the x-coordinate graphs. One step was defined for the left foot and one for the right and the mean determined as seen in Figure 3.5.4

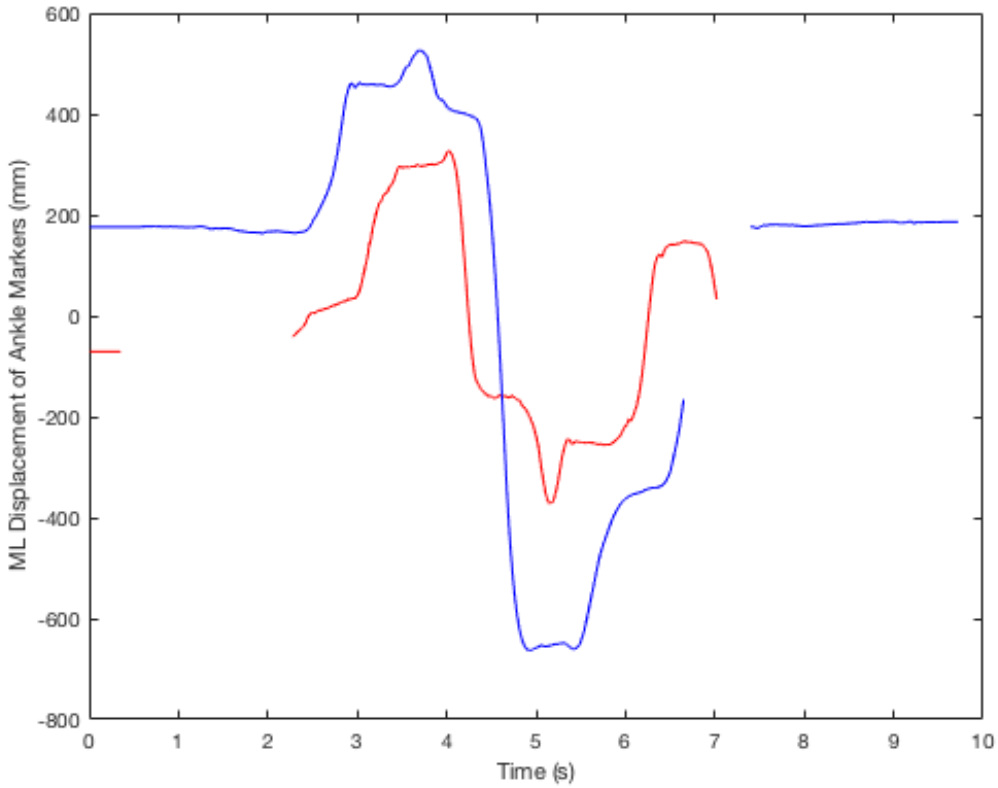

Figure 3.5.5 Mediolateral displacement of left (red) and right (blue) lateral malleoli defining the step width as the mean distance between left and right plateaus before and after the turn

Step width was determined using the y-coordinate of the lateral malleolus. The left and right plateaus prior to the turn defined the first calculation of step width and the left and right plateaus after the turn defined the second calculation of step width and the mean was determined as seen in Figure 3.5.5.

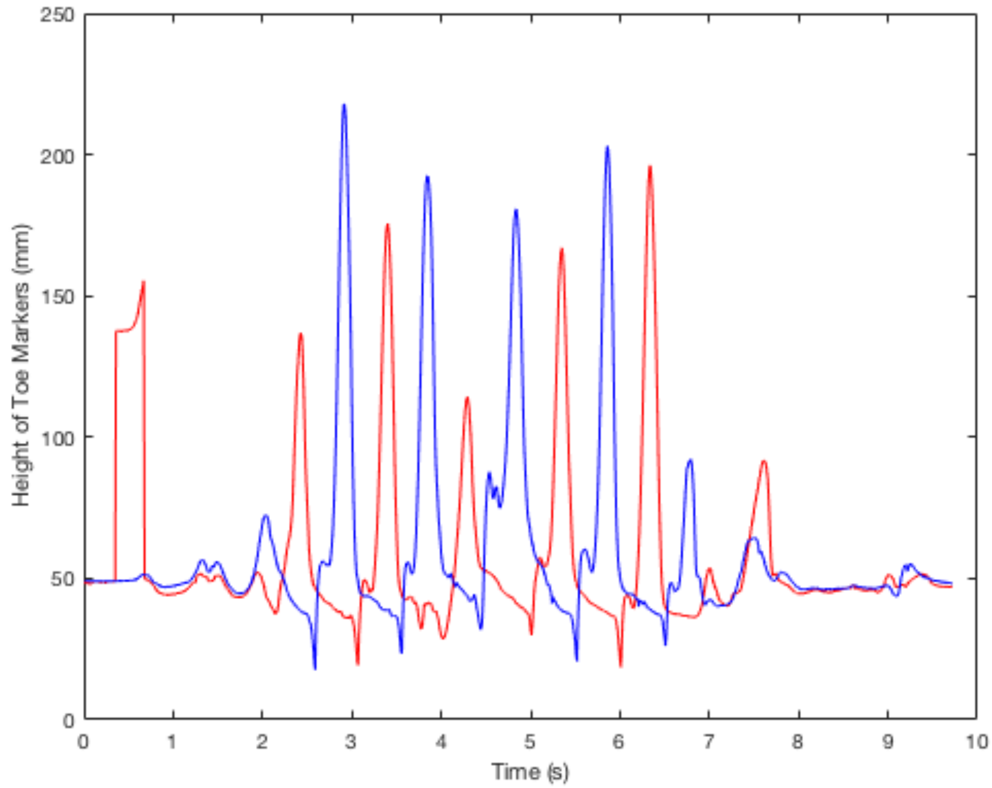

Figure 3.5.6 Height of LDPhal3 (red) and RDPhal3 (blue) markers where toe clearance was represented by the mean height of the LDPhal 3 on one side of the turn and RDPhal 3 maxima on the other side of the turn

Toe clearance was calculated using the z-coordinates of RDPhal3 and LDPhal3. Toe clearance was defined as the maximum z-coordinates of the RDPhal3/LDPhal3 markers on either side of the turn (left on one side, right on the other to maximize height to get true peaks) as seen in Figure 3.5.6.

3.6 Statistical Analysis

Statistical analysis was completed in R version 3.3.2 The first step in the statistical analysis was to examine the assumption of normality. This assumption was tested using Shapiro-Wilk's test for Normality. Q-Q plots revealed some outliers in some variables, but the removal of those participants caused further issues so the outlying participants were included in the analysis. The full dataset (N=12) was therefore found to be acceptable for analysis. The second step in the statistical analysis was testing the assumption of sphericity for the EXO condition, which was done by performing Mauchly's test for sphericity. For violations of sphericity Greenhouse Geisser corrections were made where $\varepsilon<0.75$ and Huynh-Feldt corrections were made where $\varepsilon>0.75$.

A multifactorial analysis of variance was the primary statistical outcome analysis. Data was coded by three independent variables CL (0,1), OC (0,1) and EXO (KControl, KPassive, KActive) (M. A. Lawrence, 2016). Alpha was set to 0.05. Significant main effects were examined with pair-wise comparisons of means, with a Bonferroni correction applied for multiple comparisons. Significant two-factor interaction effects were analyzed with a simple effects analysis, which isolated one independent factor to determine the effect of the other factors. Significant three-way interaction effects were further analyzed by performing additional ANOVAs separated by OC condition. EXO effects were analyzed by comparing KControl, KPassive, and KActive modes through pairwise comparisons divided by OC condition. Pairwise comparisons were also made between OC comparisons for CL.

Chapter 4 Results

Participants

In total 18 participants originally responded regarding recruitment. After making contact three were eliminated due to height restrictions and three decided against participation due to time constraints. The remaining 12 participants (F: n=6, M: n=6) underwent the full protocol. No adverse events were reported.

The data was found to contain two potential outliers within the data during the statistical analysis. Due to the small sample size of the study the statistical analysis was done with the total dataset (N=12) and then modified (n=10) to create a more complete picture of the data[10]. Both the N=12 and n=10 analysis was completed to try and eliminate two apparent outliers in the data (one male, one female) and resolve violations of normality, however upon removing the apparent outliers and re-analyzing the data, different subjects became outliers in the new dataset. This indicated that the removed participants may not be true outliers but only appear so due to the small sample size. In addition, non-parametric measures were excluded from statistical analysis due to the complex number of variable levels within the experimental design. The parametric measures were sufficient in providing evidence to answer the research question despite the small sample size and presence of outliers. The testing protocol did not produce adverse effects with the introduction of the Keeogo™ to novel users or through the research design itself. The appropriate assumptions of Shapiro Wilk's normality and Mauchly's sphericity were tested (with required Greenhouse-Geisser or Hunyh-Feldt corrections made) and the results can

[10] See Appendix IV for detailed statistical analysis of N=12 vs n=10

be found attached in the Appendix II. Statistics will be presented in the following format: F-ratios with degrees of freedom (df) for error and between-groups (F(dfe, dfb), p-value indicating significance (α=0.05) and η_p^2 showing the effect size.

4.1 Timed-Up-and-Go Time

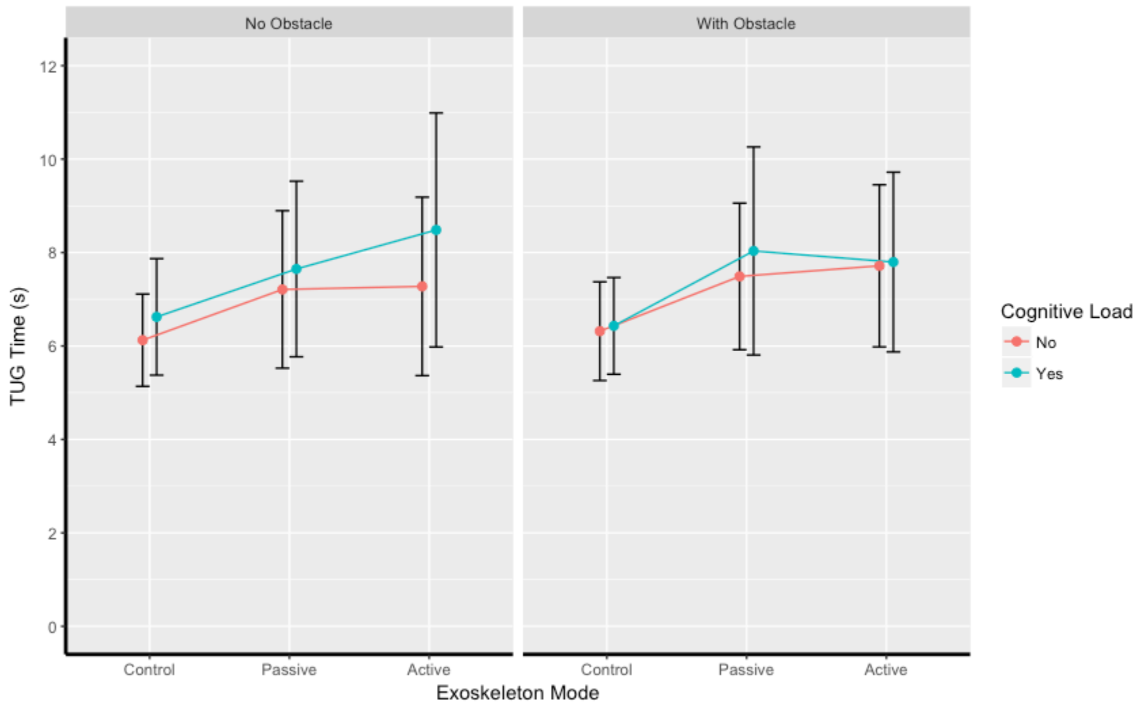

Figure 4.1.1 Total TUG Time (s) for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load condition

The primary effect of a three-way interaction EXO:CL:OC was determined (F(2, 22)=4.99, p=0.02, η_p^2=0.01) as seen in Table 4.1.2. After dissecting this interaction between EXO, CL, and OC it was determined that in the absence of an obstacle there was a significant effect of CL (F(1,11)=16.83, p<0.01, η_p^2=0.04), with the TUG taking longer with the cognitive task. There was no effect of CL in the presence of an obstacle (p=0.091). There was a significant effect of EXO in the absence of an obstacle (F(1.26,13.86)=13.66, p<0.01, η_p^2=0.12) (Table 4.1.3). Post hoc comparisons found no significant differences between KActive (8.48s ±2.50s) and KPassive (7.65s ±1.88s) p=0.13, however both were significantly greater than KControl (6.62s ±1.25s) p<0.01, p<0.01 respectively. There was also a similar effect of EXO in the presence of an obstacle (F(1.2, 13.2)=17.42, p<0.01,

η_p^2=0.15). Post hoc comparisons found no significant differences between KActive (7.80s±1.92s) and KPassive (8.03s±2.23s) p=1.0, conditions and both were significantly higher than KControl (6.43±1.03) $p<0.01$, $p<0.01$ respectively (Table 4.1.4).

Table 4.1.1 TUG Time (s) for participants (N=12) in EXO conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	6.12	0.99	6.62	1.25	6.32	1.06	6.43	1.03
KPassive	7.21	1.69	7.65	1.88	7.49	1.57	8.03	2.23
KActive	7.28	1.91	8.48	2.50	7.72	1.73	7.80	1.92

Table 4.1.2 Analysis of Variance of TUG Time (s)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	267.47	<0.01	0.95
EXO	1.2	13.2	17.77	<0.01*	0.13
CL	1	11	9.00	0.01*	0.02
OC	1	11	0.54	0.48	<0.01
EXO:CL	2	22	0.76	0.48	<0.01
EXO:OC	2	22	2.24	0.13	<0.01
CL:OC	1	11	8.08	0.02*	0.01
EXO:CL:OC	2	22	4.99	0.02*	0.01

Table 4.1.3 TUG Time (s) ANOVA by OC Condition

			OC=0			OC=1		
Effect	**DFn**	**DFd**	**F**	**p**	η_p^2	**F**	**p**	η_p^2
Intercept	1	11	246.62	<0.01	0.95	284.67	<0.01*	0.96
EXO[a]	1.26	13.86	13.66	<0.01*	0.12	17.42	<0.01*	0.15
CL	1	11	16.83	<0.01*	0.04	1.76	0.21	0.01
EXO:CL	2	22	2.40	0.11	0.01	1.76	0.19	<0.01

[a]Greenhouse-Geisser correction for sphericity (OC=0, OC=1); Dfn=1.2, DFd=13.2 for OC=1

Table 4.1.4 Pairwise Comparisons of TUG Time (s) by OC Condition

	OC=0		OC=1	
	KActive	**KControl**	**KActive**	**KControl**
KControl	0.00034*	-	<0.001*	<0.001*
KPassive	0.13367	<0.001*	1	0.13367

Table 4.1.5 Pairwise Comparisons of TUG Time (s) by OC and CL

OC	CL
OC=0	0.00018*
OC=1	0.091

4.2 Turn Time

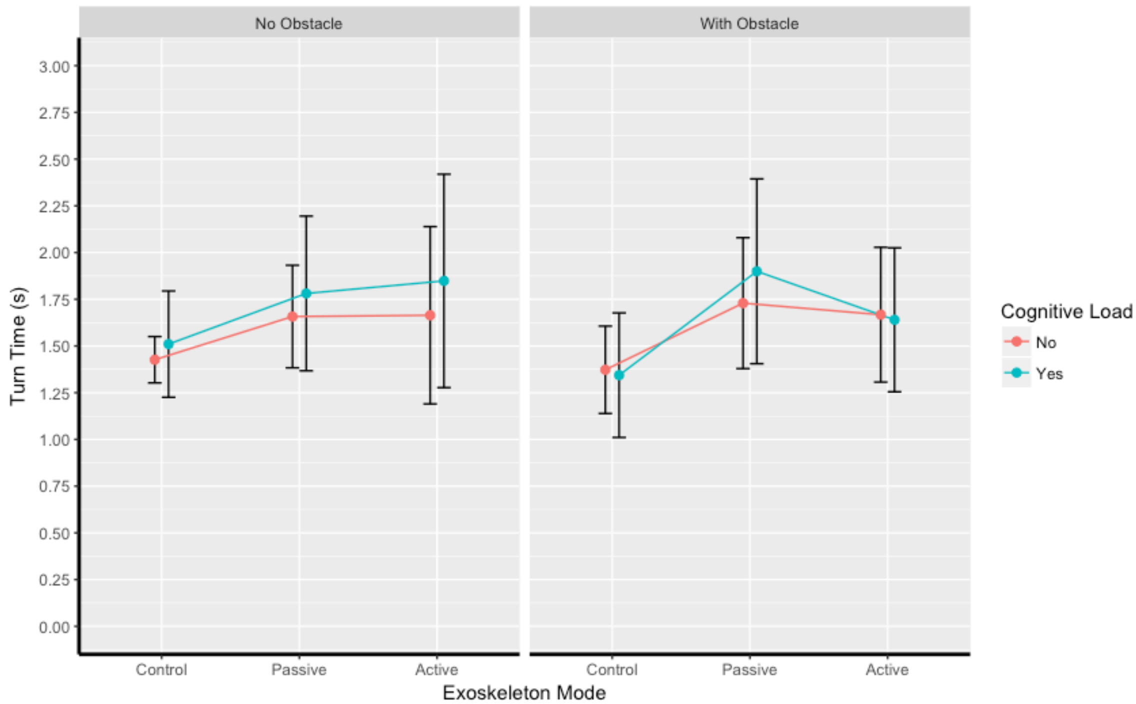

Figure 4.2.1 Turn Time (s) for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

There was a statistically significant effect of EXO mode ($F(2,22)=10.39$, $p<0.01$, $\eta_p^2=0.15$) as seen in Table 4.2.2. KPassive and KActive are statistically similar in both NOC and OC conditions ($p=1.0$, $p=0.31$ respectively), however both are statistically different than KControl in NOC ($p<0.01$, and $p<0.01$ respectively) and OC ($p<0.01$, and $p<0.01$) as seen in Table 4.2.3. There was also a significant main effect of cognitive load on turn time ($F(1,11)= 7.66$, $p=0.02$, $\eta_p^2=0.01$) as seen in Table 4.2.2. Pairwise comparisons reveal a significant effect of CL in the absence of an obstacle ($p=0.01$) as seen Table 4.2.4.

Table 4.2.1 Turn Time (s) for participants (N=12) in EXO conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	1.43	0.12	1.51	0.28	1.37	0.23	1.34	0.33
KPassive	1.66	0.27	1.78	0.41	1.73	0.35	1.90	0.49
KActive	1.66	0.47	1.85	0.57	1.67	0.36	1.64	0.39

Table 4.2.2 Analysis of Variance of Turn Time (s)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	492.96	<0.01	0.95
EXO	2	22	10.39	<0.01*	0.15
CL	1	11	7.66	0.02*	0.01
OC	1	11	0.46	0.51	<0.01
EXO:CL	2	22	0.90	0.42	<0.01
EXO:OC	2	22	1.97	0.16	0.02
CL:OC	1	11	1.29	0.28	<0.01
EXO:CL:OC	2	22	0.80	0.46	0.01

Table 4.2.3 Pairwise Comparisons of Turn Time (s) by OC Condition

	OC=0		OC=1	
	KActive	**KControl**	**KActive**	**KControl**
KControl	0.0046*	-	0.0021*	-
KPassive	1	0.0016*	0.3071	0.0014*

Table 4.2.4 Pairwise Comparisons of Turn Time (s) by OC and CL Conditions

OC	CL
OC=0	0.0091*
OC=1	0.53

4.3 Chair Rise Time

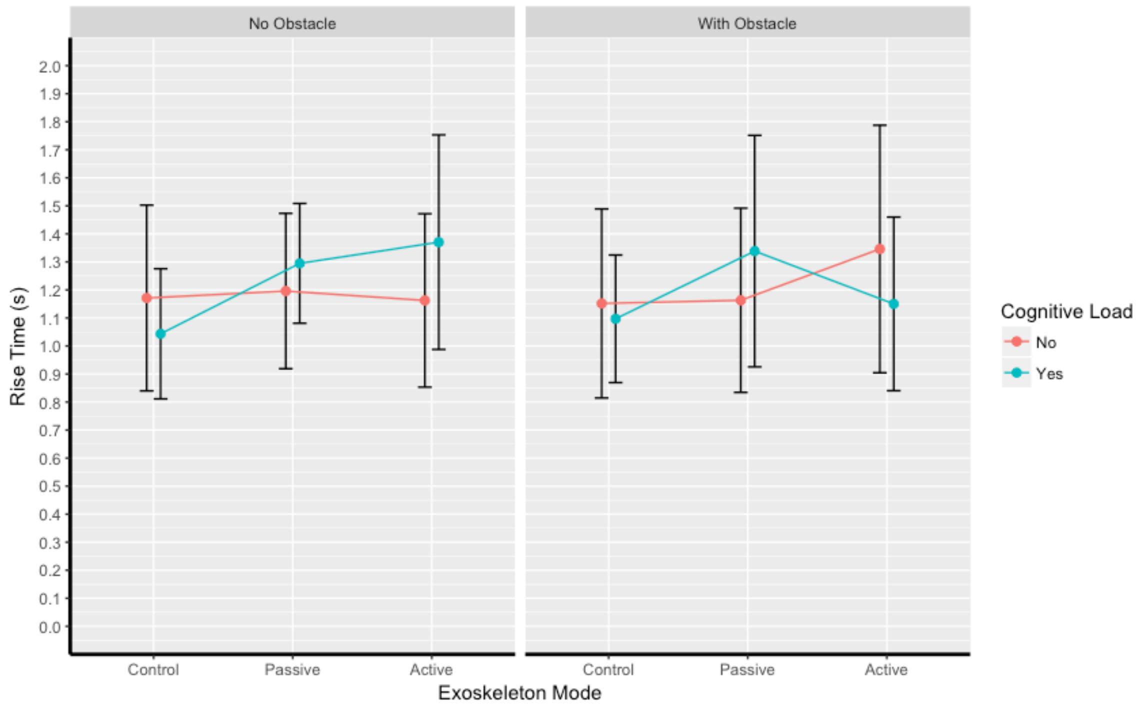

Figure 4.3.1 Chair Rise Time (s) for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

There was a significant three-way interaction effect F(2,22)=6.95, $p<0.01$ η_p^2 =0.03) and a significant interaction of EXO and CL F(2,22)=3.13, p=0.04, η_p^2=0.02) After separating the trials by OC condition a significant interaction effect of EXO and CL was found in the absence of an obstacle (F(2,22)=8.93, $p<0.01$, η_p^2=0.06)) as well as in the presence of an obstacle (F(2,22)=3.70, p=0.04, η_p^2=0.05) as seen in Table 4.3.3. Post-hoc comparisons did not reveal any significant differences between EXO modes without an obstacle or with an obstacle except for KControl and KPassive in the NOC condition (p=0.03) as seen in Table 4.3.4. There was also no significant effect of CL on trials without an obstacle as seen in Table 4.3.5.

Table 4.3.1 Chair Rise Time (s) for Participants (N=12) in EXO Conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	1.17	0.33	1.04	0.23	1.15	0.34	1.10	0.23
KPassive	1.20	0.28	1.29	0.21	1.16	0.33	1.34	0.41
KActive	1.16	0.31	1.37	0.38	1.35	0.44	1.15	0.31

Table 4.3.2 Analysis of Variance of Chair Rise Time (s)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	308.63	<0.01	0.94
EXO	2	22	3.13	0.06	0.04
CL	1	11	0.38	0.55	<0.01
OC	1	11	<0.01	0.96	<0.01
EXO:CL	2	22	3.60	0.04*	0.02
EXO:OC[a]	1.26	13.86	0.06	0.18	<0.01
CL:OC	1	11	1.14	0.31	<0.01
EXO:CL:OC	2	22	6.95	<0.01*	0.03

[a]Greenhouse-Geisser correction for sphericity applied

Table 4.3.3 Chair Rise Time (s) ANOVA by OC Condition

			OC=0			OC=1		
Effect	**DFn**	**DFd**	**F**	**p**	η_p^2	**F**	**p**	η_p^2
Intercept	1	11	324.78	<0.01	0.95	273.82	<0.01	0.93
EXO[a]	1.28	14.08	2.74	0.11	0.06	1.34	0.28	0.03
CL	1	11	1.83	0.2	0.01	0.23	0.64	<0.01
EXO:CL	2	22	8.93	<0.01*	0.06	3.7	0.04*	0.05

[a]Greenhouse-Geisser correction for sphericity applied

Table 4.3.4 Pairwise Comparisons of Chair Rise Time (s) by OC Condition

	OC=0		OC=1	
	KActive	**KControl**	**KActive**	**KControl**
KControl	0.202	-	0.55	-
KPassive	1	0.031*	1	0.46

Table 4.3.5 Pairwise Comparisons of Chair Rise Time (s) by OC and CL Conditions

OC	CL
OC=0	0.18
OC=1	0.68

4.4 Chair Sit Time

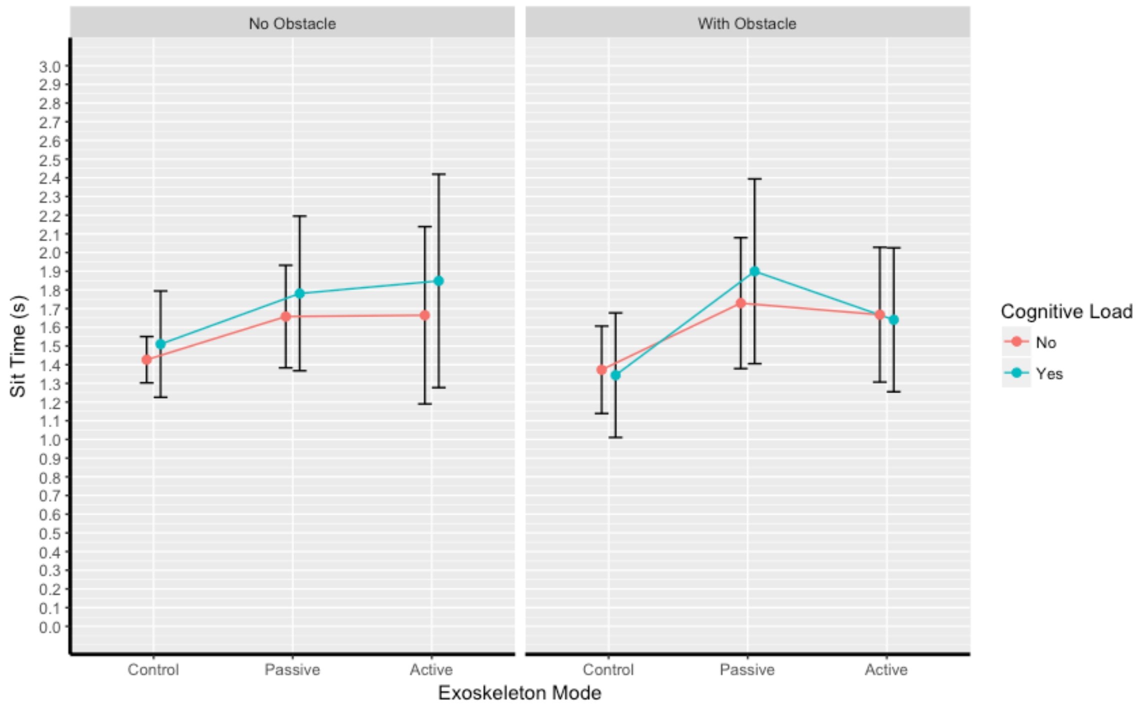

Figure 4.4.1 Chair Sit Time for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

There were no significant differences found for Chair Sit Time (s) variable across CL, OC, and EXO conditions as seen in Table 4.4.2.

Table 4.4.1 Chair Sit Time (s) for Participants (N=12) in EXO Conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	1.20	0.24	1.30	0.34	1.32	0.33	1.20	0.16
KPassive	1.47	0.49	1.55	0.47	1.48	0.38	1.51	0.44
KActive	1.60	0.54	1.80	0.58	1.52	0.30	1.55	0.36

Table 4.4.2 Analysis of Variance of Chair Sit Times (s)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	197.00	<0.01	0.86
EXO[a]	1.26	13.86	2.89	0.11	0.03
CL	1	11	2.30	0.16	0.01
OC	1	11	0.05	0.83	<0.01
EXO:CL[a]	1.1	12.1	0.24	0.66	<0.01
EXO:OC[a]	1.16	12.76	1.81	0.20	0.02
CL:OC	1	11	<0.01	0.99	<0.01
EXO:CL:OC[a]	1.18	12.98	0.51	0.52	<0.01

[a]Greenhouse-Geisser's correction for sphericity applied

4.5 Turn Radius

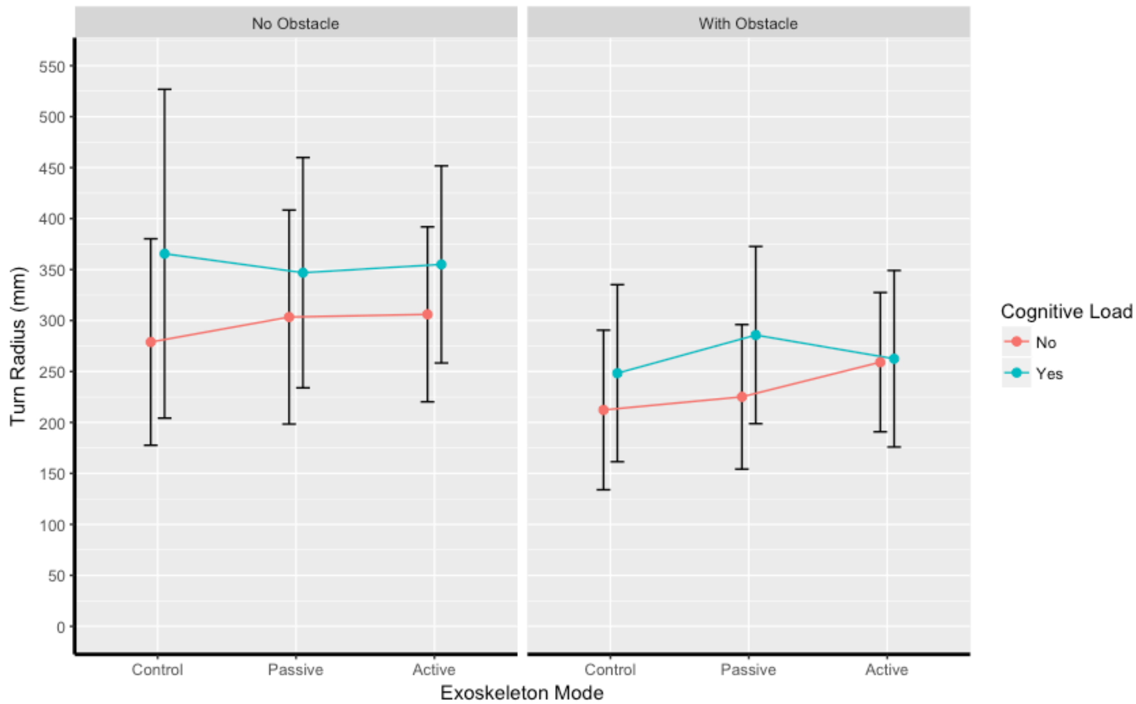

Figure 4.5.1 Turn Radius for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

There was a main effect of CL ($F(1,11)=12.35$, $p<0.01$, $\eta_p^2=0.06$) showing significantly greater turn radii which can be seen in

Table 4.5.2. There was also a main effect of OC ($F(1,11)=50.27$, $p<0.01$, $\eta_p^2=0.14$) which shows significantly smaller turn radii as demonstrated in Table 4.5.1. There was no effect of EXO as seen in

Table 4.5.2.

Table 4.5.1 Turn Radius (mm) of Participants (N=12) for EXO Conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	278.86	101.30	365.51	161.31	212.24	78.27	248.31	86.89
KPassive	303.38	104.96	346.91	112.95	225.11	70.86	285.72	86.96
KActive	306.03	85.81	355.00	96.67	259.13	68.34	262.48	86.58

Table 4.5.2 Analysis of Variance of Turn Radius (mm)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	148.22	<0.01	0.90
EXO	2	22	1.09	0.35	0.01
CL	1	11	12.35	<0.01*	0.06
OC	1	11	50.27	<0.01*	0.14
EXO:CL	2	22	2.02	0.16	0.01
EXO:OC	2	22	0.65	0.53	<0.01
CL:OC	1	11	3.66	0.08	<0.01
EXO:CL:OC	2	22	2.24	0.13	0.01

Table 4.5.3 Pairwise Comparisons of Turn Radius (mm) by OC Condition

	OC=0		OC=1	
	KActive	KControl	KActive	KControl
KControl	1	-	0.071	-
KPassive	1	1	1	0.262

Table 4.5.4 Pairwise Comparisons of Turn Radius (mm) by OC and CL Conditions

OC	CL
OC=0	<0.001
OC=1	0.0052

4.6 Stride Length

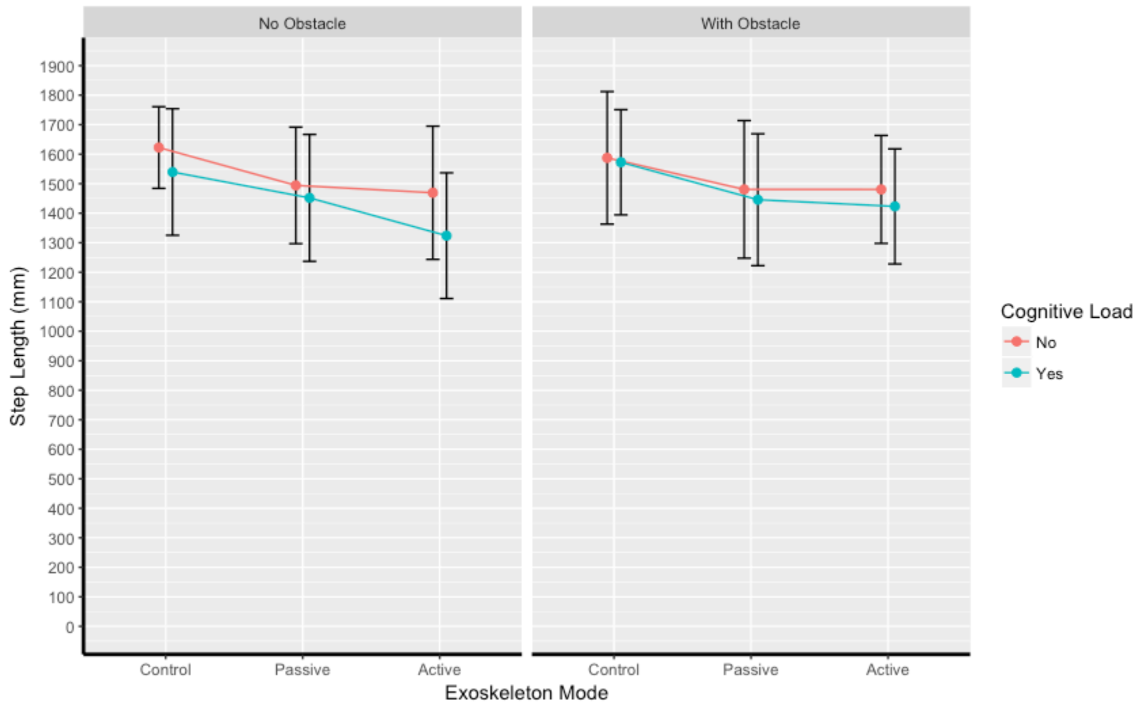

Figure 4.6.1 Stride Length for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

There was a significant main effect of EXO which showed decreasing stride length across EXO conditions ($F(2,22)=11.69$, $p<0.01$, $\eta_p^2=0.10$), which can be seen in Table 4.6.2. KActive and KPassive conditions were found to be statistically the same for OC ($p=1.0$) but not NOC ($p=0.04$) as seen in Table 4.6.3. Both KActive and KPassive were statistically different from KControl for NOC ($p<0.01$, $p<0.01$) and OC ($p=0.02$, $p=0.04$) respectively as seen in Table 4.6.3. There was also a significant effect of CL ($F(1,11)=7.01$, $p=0.02$, $\eta_p^2=0.03$) which shows a decreasing trend in stride length across conditions in the presence of CL as demonstrated in Table 4.6.2. Pairwise comparisons revealed a significant effect of CL in the absence of an obstacle ($p<0.01$) as seen in Table 4.6.4.

Table 4.6.1 Stride Length (mm) for Participants (N=12) in EXO Conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	1622.58	138.38	1539.58	214.43	1587.54	224.68	1572.63	178.24
KPassive	1494.29	197.49	1451.94	215.01	1480.69	233.20	1445.74	223.37
KActive	1469.32	225.79	1323.81	213.0	1480.58	182.95	1423.05	194.98

Table 4.6.2 Analysis of Variance of Stride Length (mm)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	914.10	<0.01	0.98
EXO	2	22	11.69	<0.01*	0.10
CL	1	11	7.01	0.02*	0.03
OC	1	11	1.03	0.33	<0.01
EXO:CL	2	22	1.07	0.36	<0.01
EXO:OC	2	22	1.14	0.34	0.01
CL:OC	1	11	2.18	0.17	<0.01
EXO:CL:OC	2	22	1.18	0.33	<0.01

Table 4.6.3 Pairwise Comparisons of Stride Length (mm) by OC Condition

	OC=0		OC=1	
	KActive	KControl	KActive	KControl
KControl	<0.001*	-	0.017*	-
KPassive	0.03567*	0.00045*	1	0.037*

Table 4.6.4 Pairwise Comparisons of Stride Length (mm) by OC and CL Conditions

OC	CL
OC=0	0.00075*
OC=1	0.16

4.7 Step Width

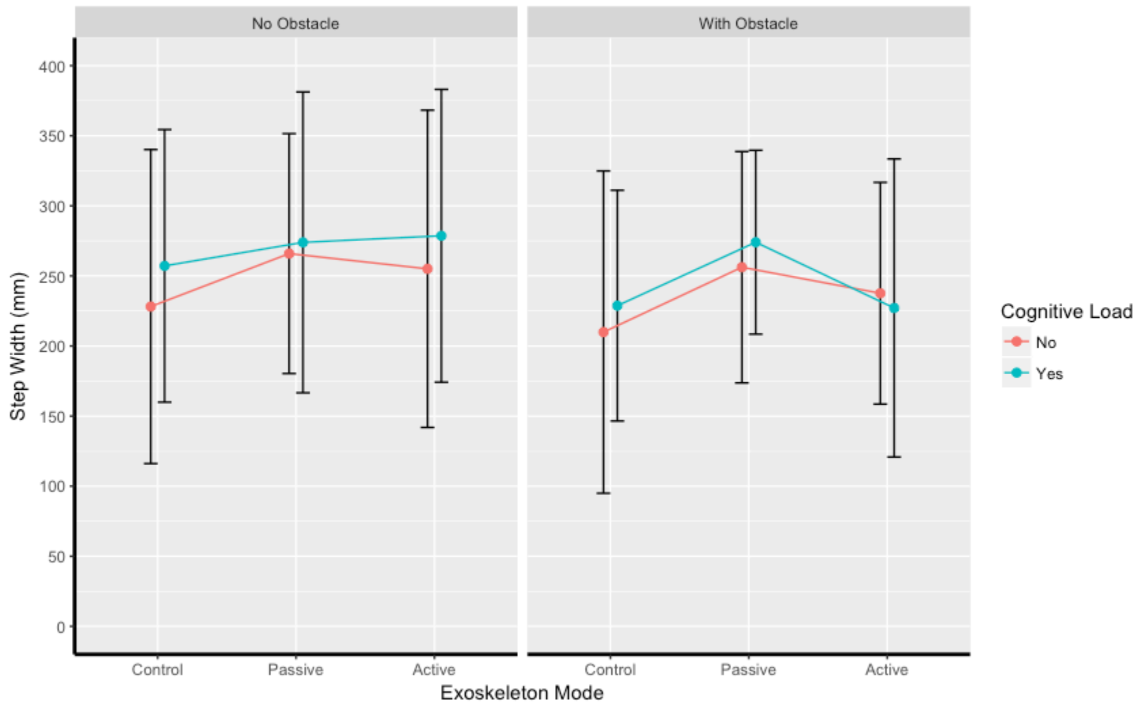

Figure 4.7.1 Step Width for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

As demonstrated in Table 4.7.2 there were no significant differences across CL, OC or EXO conditions.

Table 4.7.1 Step Width (mm) of Participants (N=12) for EXO Conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	228.12	112.01	257.15	97.26	209.90	114.97	228.77	82.31
KPassive	265.92	85.58	273.94	107.32	256.21	82.54	274.03	65.61
KActive	255.05	113.17	278.64	104.44	237.62	79.08	227.12	106.33

Table 4.7.2 Analysis of Variance of Step Width (mm)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	155.12	<0.01	0.88
EXO	2	22	1.73	0.20	0.03
CL	1	11	1.23	0.29	0.01
OC	1	11	3.41	0.09	0.01
EXO:CL	2	22	0.24	0.79	<0.01
EXO:OC	2	22	0.53	0.60	<0.01
CL:OC	1	11	0.71	0.42	<0.01
EXO:CL:OC	2	22	0.43	0.66	<0.01

Table 4.7.3 Pairwise Comparisons of Step Width (mm) by OC Condition

	OC=0		OC=1	
	KActive	**KControl**	**KActive**	**KControl**
KControl	0.94	-	1	-
KPassive	1	0.52	0.34	0.10

Table 4.7.4 Pairwise Comparisons of Step Width (mm) by OC and CL Conditions

OC	CL
OC=0	0.18
OC=1	0.52

4.8 Toe Clearance

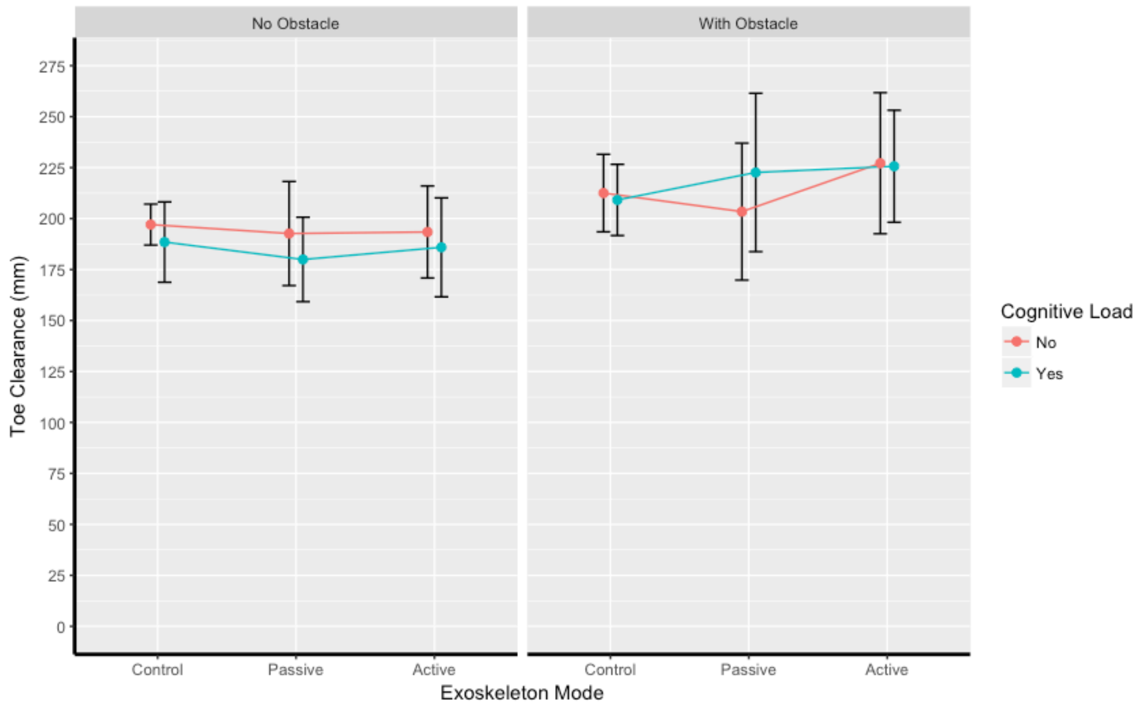

Figure 4.8.1 Toe Clearance for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

There was a significant interaction effect of CLxOC ($F(1,11)=9.97$, $p=0.01$, $\eta_p^2=0.02$) illustrated in Table 4.8.2. There was a significant effect of CL in the absence of an obstacle ($F(1,11)=7.70$, $p=0.02$, $\eta_p^2=0.01$) but not in the presence of an obstacle as seen in Table 4.8.3. Toe Clearance decreased regardless of EXO condition from control to CL. After performing pairwise comparisons there was a statistical difference between KPassive and KActive EXO conditions ($p=0.043$) in the presence of an obstacle while all other EXO conditions were statistically the same as seen in Table 4.8.4.

Table 4.8.1 Toe Clearance (mm) for Participants (N=12) in EXO Conditions (KControl, KPassive, KActive)

EXO	C		CL		OC		CLxOC	
	μ	σ	μ	σ	μ	σ	μ	σ
KControl	197.05	10.04	188.47	19.71	212.52	19.01	209.14	17.45
KPassive	192.66	25.53	179.93	20.70	203.41	33.60	222.62	38.86
KActive	193.42	22.57	185.90	24.27	227.14	34.60	225.66	27.46

Table 4.8.2 Analysis of Variance for Toe Clearance (mm)

Effect	DFn	DFd	F	p	η_p^2
Intercept	1	11	1749.95	<0.01	0.99
EXO[a]	1.22	13.42	3.63	0.07	0.02
CL	1	11	0.51	0.49	<0.01
OC	1	11	19.39	<0.01*	0.23
EXO:CL	2	22	1.20	0.32	0.01
EXO:OC[a]	1.24	13.64	1.90	0.19	0.02
CL:OC	1	11	9.97	0.01*	0.02
EXO:CL:OC	2	22	3.01	0.07	0.02

[a]Greenhouse-Geisser corrections for sphericity

Table 4.8.3 ANOVA of Toe Clearance (mm) by OC Condition

			OC=0			OC=1		
Effect	DFn	DFd	F	p	η_p^2	F	p	η_p^2
Intercept	1	11	1390.24	<0.01	0.99	1163.94	<0.01	0.98
EXO	2	22	2.04	0.15	0.02	2.51	0.10	0.06
CL	1	11	7.70	0.02*	0.05	1.08	0.32	0.01
EXO:CL	2	22	0.26	0.77	<0.01	3.10	0.06	0.03

Table 4.8.4 Pairwise Comparisons of Toe Clearance (mm) by OC Condition

	OC=0		OC=1	
	KActive	**KControl**	**KActive**	**KControl**
KControl	1	-	0.087	-
KPassive	0.85	0.36	0.034*	1

Table 4.8.5 Pairwise Comparisons of Toe Clearance (mm) by OC and CL Conditions

OC	CL
OC=0	0.0043*
OC=1	0.3

4.9 Cognitive Load

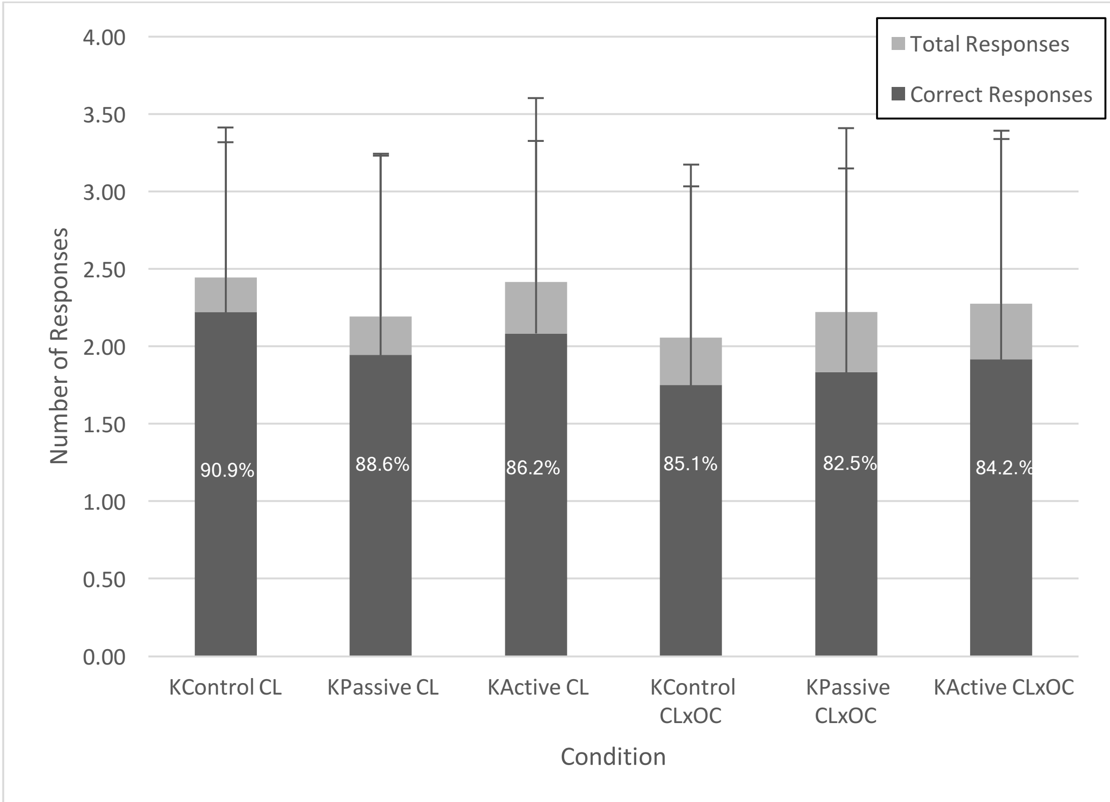

Figure 4.9.1 Responses for participants (n=12) in EXO conditions (KControl, KPassive, KActive) and obstacle-crossing and cognitive load conditions

There were no significant differences in CL responses across CL, OC, and EXO conditions.

Table 4.9.1 Cognitive Load (Serial 7) Responses

	CL						CLxOC					
	Control		Passive		Active		Control		Passive		Active	
	C	T	C	T	C	T	C	T	C	T	C	T
μ	2.22	2.44	1.94	2.19	2.08	2.42	1.75	2.06	1.83	2.22	1.92	2.28
σ	1.10	0.97	1.29	1.05	1.24	1.19	1.29	1.12	1.32	1.19	1.42	1.12

C= correct responses, T= total responses

4.10 Summary of EXO Results

Table 4.10.1 Summary of EXO Results by Variable

KControl=KPassive=KActive	KPassive≠KControl	KPassive=KActive	KPassive≠KActive
Chair Sit (all)	Chair Rise (OC=0)*	TUG Time (OC=0,1)	Stride Length (OC=0)
Turn Radius (all)		Turn Time (OC=0,1)	Toe Clearance (OC=1)
Step Width (all)		Stride Length (OC=1)	

*interaction effect by CL in absence of obstacle where KPassive≠KControl but all others were equal

Chapter 5 Discussion

5.1 Objectives and Major Findings

The objective of this study was to assess the impact of cognitive load on gait biomechanics when using a lower-extremity exoskeleton. This study integrated simple, discrete single-step tasks with complex multi-component tasks to represent and apply the findings to activities of daily living and apply realistic analysis of biomechanical variables during a functional mobility task. The results show that for the hypothesis regarding TUG time H_{01}: $\mu_C = \mu_{CL}$, H_{A1}: $\mu_C \neq \mu_{CL}$ the null hypothesis can be rejected and the alternative hypothesis accepted as there was a significant main effect of CL on TUG times across conditions, however the results found that EXO condition and CL affected TUG times independently. EXO condition was found to impact TUG time regardless of OC condition differently in KPassive/KActive (statistically the same) than KControl. With respect to the secondary hypothesis for gait biomechanics and CL H_{02}: $\mu_C = \mu_{CL}$, H_{A2}: $\mu_C \neq \mu_{CL}$, the null hypothesis can be rejected and the alternative accepted for turn time (s), turn radius (mm), and stride length (mm) which demonstrate main effects of CL independent of EXO condition. EXO condition was found to significantly impact turn time regardless of OC condition when comparing KControl to KPassive/KActive (statistically the same). Additionally, an interaction effect of CL was found by EXO for rise time in the absence of an obstacle where KPassive significantly differed from KControl.

The results regarding third hypothesis for obstacle crossing on TUG times H_{03}: $\mu_C = \mu_{OC}$, H_{A3}: $\mu_C \neq \mu_{OC}$ find statistical main effects of OC on TUG time therefore the null hypothesis may be rejected and the alternative accepted. The presence of the obstacle appeared to mitigate the effect of CL found in the no obstacle condition. There was also a significant effect of EXO when obstacle crossing where KControl was significantly different than KPassive/KActive (statistically equal). With respect to the secondary hypothesis for gait biomechanics and OC H_{04}: $\mu_C = \mu_{OC}$, H_{A4}: $\mu_C \neq \mu_{OC}$ there are main effects of OC on turn radius (mm), stride length (mm), and toe clearance (mm) in addition to interaction effect on rise time (s). Stride length was found to be influenced by the presence of an obstacle and EXO where KControl was significantly different than KPassive/KActive (statistically equal) which was different than in the absence of the obstacle where KPassive and KActive were statistically different. Toe clearance was also found to be significantly different between KPassive and KActive when obstacle crossing.

Overall, the participants were able to adapt and use the Keeogo™ with minimal disturbance and no concerning consequences. None of the participants fell during the trials and the Keeogo™ did not seize or lock during any of the scenarios the participants underwent. There were three instances of obstacle contact (one for one participant, and two for another) where the participant stopped mid-trial and had to restart but did not fall or experience any negative lasting effects. The aforementioned results indicate statistically significant differences, but clinically the difference appears to be minimal and low-risk when comparing to minimal clinical difference of established populations; 3.5s-4.9s for Alzheimer's and Parkinson's patients (Huang et al., 2011; Ries, Echternach, Nof, & Gagnon Blodgett, 2009).

5.2 Interpretation

The impact of cognitive load echoes similar studies performed on healthy populations where the impact of cognitive load dual-task results in detriments to one or both tasks Al-Yahya et al., 2011; Siu, Catena, Chou, van Donkelaar, & Woollacott, 2008). Several studies that have compared young and older healthy adults and found that non-falling older adults and young adults are virtually the same when it comes to dual-tasking (Al-Yahya et al., 2011; Springer et al., 2006).

The presence of the EXO itself seemed to be the primary source of differences between KControl and EXO conditions where pairwise comparisons identified the KPassive and KActive modes as being consistently and statistically equal while being significantly different than KControl. This suggested that the physical presence of the Keeogo™ itself may be the source for the variations and not the Keeogo™ as it acted as an assistive device (KActive). While the results of this study did show statistical differences between EXO modes for TUG time, turn time, rise time, sit time, stride length, and toe clearance, there are no indications that the difference would increase the risk to the user.

5.2.1 Total TUG Time

Decreased gait speed (or increased total TUG time) found in this study was consistent with other research in dual-tasking and gait (Srygley et al 2009), Woolacott, Shumway-Cook, Yogev et al (2005). A similar study which used inertial sensors to examine kinematics in young adults performing TUG and CL-TUG tests found substantially higher TUG times between control and dual-tasking conditions (15.6s±1.4s compared to 17.6±1.7s) (Coulthard, Treen, Oates, & Lanovaz, 2015). This was substantially higher than the comparable KControl values found in this study (6.12s±0.99s) control to (6.62s±1.25s) cognitively loaded. No EXO differences were found which is in agreement with another study performed with the Keeogo™ (McGibbon et al., 2017).

Due to the lack of widespread use of the TUG in healthy or young populations there was no minimal clinically important difference (MCID) established for healthy adults and it has yet to be officially established for each clinical population. A recently published paper by Beyea et al., (2017) indicates an MDC for total TUG time in healthy populations to be 1.5s-2s for trials completed as fast as possible (Beyea, McGibbon, Sexton, Noble, & O'Connell, 2017). For example, Parkinson patients experience a minimal detectable change is 3.5secs as determined by Huang and colleagues (2011) while the minimal detectable change for Alzheimer's patients is 4.09s (Ries et al., 2009). A larger scale study of simple repeated TUG tests would help to establish the MCID for healthy, general population.

There is however, an established cut-off time for high risk fallers (>14s) where participants with TUG times >14s are classified as high risk fallers (Brauer et al., 2001). A cognitively loaded TUG was found by Vance and colleagues to increase the accuracy of distinguishing fallers from non-fallers in Parkinson's patients with a cut-off time of 14.7s with 73.4% specificity. This study used a control TUG, serial 3 TUG, and a manual TUG (carrying a glass of water) and found that the significant difference in gait automaticity between high risk fallers and low risk was performance on the serial 3 TUG where high risk patients exhibited reduced automaticity (75.9%) compared to their lower risk counterparts (83.7%) (Vance, Healy, Galvin, & French, 2015).

Based upon the results and theories of other researchers, future Keeogo™ users may experience favorable performance outcomes from training sessions that include a dual task scenario; specifically the verbal fluency serial 7 task which requires executive function and activates the prefrontal cortex may have beneficial outcomes by passing the brainstem and basal ganglia where automated gait originates (H.-Y. Chen & Tang, 2015).

5.2.2 Turning

This study found that the serial 7 dual-task condition increases turn time which was consistent with an overall increase in TUG time and decrease in gait speed. The study by Coulthard at colleagues analyzed turn time using inertial sensors finding no significant differences between control (1.68s±0.29s) and serial 7 (1.71s±0.31s) conditions (Coulthard et al., 2015). However, the KControl control (1.43s±0.12s) and CL (1.51s±0.28s) conditions in this study found a significant effect of CL across conditions.

There was also a main effect of EXO on turn time which lead to an increase in turn time compared to KControl conditions across C, CL, and OC conditions. This was also consistent with the overall CL by EXO effect on total TUG time where there was a significant interaction effect of cognitive load and EXO in the absence of an obstacle.

When examining the turn radius data, a significant effect of CL can be found where the dual-task condition resulted in increased turn radius. The turn radius was also found to decrease in obstacle-avoidance conditions. The impact of obstacle crossing on turn radius/turn time in this study may be explained through the presence of the obstacle altering the path of the participant as they approach the turn as opposed to the obstacle crossing creating the variation in turn radius or turn time. In addition previous research which used inertial sensors to examine the TUG in young adults, indicates an average of 5 to 8 steps occurring in a 3m TUG (Coulthard et al., 2015).

5.2.3 Chair Rise and Chair Sit

No significant differences were found across conditions for chair sit time. Chair rise (or sit-to-stand) times were found to be statistically the same (2.21s±0.23s) and (2.29s±0.19s) for the study by Coulthard and colleagues (2015) which conflicted with results in this thesis (1.17s±0.33s) and (1.04s±0.23s). The rise times were also substantially greater, which is on trend with increased TUG times and increased turn times, compared to this thesis. Coulthard however, found a significant decrease in turn cadence between control (104.4steps/min ± 11.3steps/min) and CL conditions (97.1steps/min ± 12.4steps/min) (Coulthard et al., 2015).

There was also a significant interaction effect of CL by EXO consistent across obstacle crossing conditions. Rise time increased with cognitive load in the presence of the Keeogo™, however there were no significant differences between KPassive and KActive. Similar to results demonstrated by Gregorczyk et al., where the mechanical presence of the exoskeleton created gait pattern changes regardless of the load carried by the participant (Gregorczyk et al., 2010). While Gregorczyk did not test the exoskeleton in neutral, the consistent alterations across loading conditions suggest the mechanical device creating postural differences or the programmed gait cycle doing so (Gregorczyk et al., 2010). Due to testing the Keeogo™ in KPassive and KActive and finding statistical equality it is highly unlikely the programmed gait cycle of the Keeogo™ is the source of rise time changes. The Keeogo™ was primarily controlled by the participant's initiation/termination and tuned to the participant's gait cycle, thus it is unlikely the programmed gait created the alteration. further study is required to better assess the true source of rise-time variation.

5.2.4 Step Mechanics

Stride Length

This study found that there was a main effect of EXO on stride length which found that the presence of the EXO (regardless of mode KPassive/KActive) significantly decreased stride length. McGibbon et al., (2017) also found significantly decreased step length in the presence of the Keeogo™ in KActive mode (KPassive not tested) compared to KControl condition (McGibbon et al., 2017). The results are reiterated by a study performed in a military population with 3D gait analysis (Birrell & Haslam, 2009). This study also found that step length experienced significant differences from 0kg to 24kg before reaching plateau. One of the explanations postulated by Birrell & Haslam (2009) is the effort to reduce modifications to gait patterns in order to reduce stress on the metatarsal bones of the foot. Other research suggests that the presence of a loaded backpack may lead to decreased stride length strictly at a rapid walking pace due to decreased pelvic rotation in an effort to limit torque through the lumbar spine (LaFiandra, Holt, Wagenaar, & Obusek, 2002; LaFiandra, Wagenaar, Holt, & JP, 2003). However, the Keeogo™ apparatus including the battery enclosed in a backpack only presented a load of 4.5kg and 1.8kg respectively, thus the variations seen in this research may be due to the device's own inertia or the physical bulk of its mechanics.

This study found that there was a significant main effect of cognitive load resulting in decreased stride length in the presence of CL. This study is in accordance with numerous other studies of dual-tasking (Al-Yahya et al., 2011). Single task (55.8mm+14.3mm) steps compared to dual task steps (53.8mm+10.7mm) in fallers, were significantly shorter than non-fallers in single task steps (59.7mm+22.1mm) compared to dual task steps (61.3mm+16.3mm) in both single and dual-task situations (Toulotte et al., 2006).

Obstacle-crossers have been shown to alter stride length as part of a strategy for successfully avoiding an obstacle (Newstead, Walden, & Gitter, 2007; Toulotte, Thevenon, Watelain, & Fabre, 2006). This study does not agree with that idea; there was no significant effect of obstacle crossing on stride length. It is worth noting however, that according to Chen et al. (1991) that a minimum of two steps prior to obstacle crossing are required for motor-planning in young and older adults to create an obstacle avoidance strategy in cases of virtual obstacles (H. C. Chen et al., 1991). Contradictory to these findings, Brown, McKenzie & Doan (2005) more recently found that when using a reaction time cognitive loading methodology, the task of obstacle avoidance required more attentional resources in older adults than younger adults (Brown, McKenzie, & Doan, 2005). Chen also identified two avoidance strategies when approaching the obstacle: short steps or long steps. His study found no age-related preference for step-length in pre-crossing strategy. The mean step length in his cohort of 48 subjects was 761.6mm±86.4mm (OC) were similar (after multiplying by two to apply to stride length) to the values found in this thesis (KControl OC no CL) of 1587.54mm± 224.68mm (H. C. Chen et al., 1991). Newstead, Walden & Gitter (2007) classified older adults into groups of fallers compared to non-fallers and found that the fallers had a distinctive obstacle avoidance strategy where they reduced approach velocity and stride length significantly more than their counterparts (Newstead et al., 2007)

Step Width

This study found no significant differences in step width across conditions, however due to large standard deviations and poor consistent visibility further study is recommended to better assess this variable. This was further demonstrated by McGibbon et al., (2017) who found that stride width was increased in the presence of the Keeogo™ which was not in agreement with this thesis (McGibbon et al., 2017) These results vary from a study by Gregorczyk et al., on military population that found significantly greater step width with the EXO (0.19m compared to 0.15m) and no difference in stride length, however there was a similar weight of 15kg of EXO apparatus. As the soldier was loaded the stride width remained statistically the same as the unloaded EXO condition with 20kg, 40kg, and 55kg. Gregorczyk theorizes that due to a significant increase of 35% in trunk range of motion in the EXO condition and 10% and 18% decreases in range of motion of the knee and ankle respectively, the increase in stride width is an adapative compensation for increased balance. The data collected form the Gregorczyk study also proposes that the main source of reduced range of motion was due to the rigid, relatively heavy mass that constitutes the foot component. It also found that, regardless of load, there is a shorter stance duration and a shorter double-support duration with the EXO than without. Similar to Gregorcyzk's research, this research finds that familiarization will be benefit future research in order to gain the trust of the participants and reduce the perceived need of the user to control the inertia of the device.

According to a study performed by Chen et al there is a significant ($p<0.001$) 21.5% difference between young adults and old adults in step width when crossing a 52mm obstacle. Differences between young and old adults of 21.1% and 23% were found for obstacle crossing heights of 0mm, 25mm, 52mm, and 152mm (H. C. Chen et al., 1991). As no significant differences were found in this population of young adults across conditions future studies on older adult populations may provide insights on the impact of EXO and CL on step width that will more specifically benefit that population.

<u>Toe Clearance</u>

The results found a significant interaction effect of cognitive load by obstacle crossing where there was a significant effect of cognitive loading condition on toe clearance in the absence of an obstacle. Chen and colleagues performed a study on healthy, young and older adults examining obstacle crossing and found that when crossing an obstacle of 52mm the average foot clearance was 91.9mm±31.9mm significantly greater when compared to the average foot clearance for the control 20.2±7.7 (H. C. Chen et al., 1991). The results found by Chen are substantially lower than those found in this study for crossing a 50mm obstacle. However, the Chen study calculated foot clearance differently than in this thesis. The results from a study performed by Kim & Brunt (2007) found results consistent with those in the present study where older adults and younger adults both experienced a decrease in toe clearance during dual-tasking (reaction time) scenarios involving obstacle crossing (Kim & Brunt, 2007). Kim & Brunt also found that older adults had consistently lower toe clearance across conditions than the younger adult group thus increasing their risk of falls (Kim & Brunt, 2007). Due to the increased risk faced by older adults when obstacle-crossing, further research is recommended to further examine the impact of wearing an exoskeleton while obstacle-crossing with and without cognitive load.

5.2.5 Cognitive Loading

Participants in this study were told that both the primary walking task and the secondary serial 7 subtraction task were of equal importance. The participants were told to perform the TUG by walking as quickly as possible but without running. For the CL conditions participants were informed that the PI would be recording all of their responses and that they would be evaluated both on the number of responses and the accuracy. The PI was also clearly visible (facing the participant) noting and evaluating the responses as the participant completed the trial.

No significant differences were reported across conditions for S7 responses, or correct S7 responses. A study performed by Siu and colleagues (2008) examined dual-task obstacle avoidance in young adults and found that in the presence of an auditory Stroop task there were no gait differences compared to the control however, there was a significant detriment to the responses indicating. They suggest a hierarchy of control in dual task obstacle avoidance where obstacle avoidance is the primary receiver of attentional resources and the dual-task receiving as secondary (Siu et al., 2008). However, this study did not find any significant differences in CL responses across conditions. A study performed by Yogev-Seligmann et al., (2010) found that prioritization in young adults undergoing a dual task scenario exhibit sex differences where female participants had significantly greater gait speed when told to prioritize gait speed (compared to no prioritization and CL prioritization conditions) whereas male participants had no significant variations in gait speeds across conditions (G. Yogev-Seligmann et al., 2010).

Yogev-Seligmann et al., (2010) found that in the younger adult group there was no significant differences in the number of words generated across conditions of prioritization which agrees with the findings of this thesis (G. Yogev-Seligmann et al., 2010). Overall, the younger group responded to different prioritization scenarios with smaller changes than the older adult group and were able to maintain very little gait variability in dual task prioritization scenarios (G. Yogev-Seligmann et al., 2010)

With respect to the CL-OC, Siu and colleagues (2008) examined the task prioritization of a dual-task paradigm with obstacle avoidance and found that obstacle management became the primary task in the hierarchy of control when young adults performed a dual-task scenario with obstacle-cross. Reaction times were found to increase as the complexity of the postural task increased. While the performance on the oral Stroop task decreased the gait task did not experience significant changes (Siu et al., 2008).

The primary task (TUG) appeared to be the task that suffered in performance compared to the secondary CL task of serial 7 subtraction. Yogev et al., found significant differences in serial 7 responses in Parkinson's patients when performing a dual task where responses were the secondary task to walking however, control (healthy older adults) did not experience the same decrease in accuracy while also providing significantly greater number of responses (Yogev et al., 2005). Srygley and colleagues determined that there was no difference in serial 3 or serial 7 subtraction in young adults when looking at dual-tasking while walking in either mistaken responses or gait speed (Srygley et al., 2009).

Springer et al., (2006) and Al-Yahya et al., (2011) suggest a significant increase in gait variability in clinical populations compared to healthy populations regardless of age. The Springer study also mentions a decrease in response accuracy in healthy participants which was not found in this study (Al-Yahya et al., 2011; Springer et al., 2006). Interestingly, there are also similarities in the way healthy and clinical populations act in response to cognitive load as when approaching obstacles in mediolateral variables such as swing and torso shift. (Newstead et al., 2007). It has been shown that poorer performance on the MOCA, as a measure of global cognition, is directly and independently related to TUG times (Donoghue et al., 2012).

5.3 Limitations

This study was limited by two primary factors; sample size/generalizability, and technological limitations. This study was a novel investigation into the impact of cognitive load in exoskeleton users thus virtually no prior research existed in this area. The research was performed on a very small sample size (N=12) and as such was limited in its projected effect size. However, the use of a pilot study of TUG times in young, healthy adults served to power the sample size using a G-Power analysis and the corresponding sample size (n=10) was satisfied in this research for an effect size (f=1.1) and a power of (1- β=0.99) to measure 4 variables with an approximate correlation between repeated measures of 0.5. This study recruited 12 participants were recruited for with equal sex distribution and measured a single primary outcome variable, and 8 secondary outcome variables (7 gait related, 1 CL related). Thus, the limitation of small sample size was reasonably mitigated.

The study was also performed on a very specific population of young, healthy adults at University of New Brunswick thus limiting the generalizability of the findings. Almost all exoskeletal research explores exclusively clinical populations or involve carrying out military operations. This study justified the limitation by intending to maximize applicability to both military and clinical populations. It was proposed that by using healthy, young adults the results would be transferrable to the similarly healthy, adult military population that encounter cognitive load and obstacle-crossing in daily activities. The research design also attempted to establish testing protocol that could be performed by clinical populations with minimal risk and produce meaningful results without extensive biomechanical analysis.

The study was also limited by the equipment available. Ideally, cognitive load could have been quantified in the participants through the use of a mobile near-infrared spectroscopy however, no such equipment was available. The addition of the mobile NIRS would have allowed for PFC activity to be measured to quantify the cognitive load effect on the participant. Additionally, the motion capture system used to collect the data, was only able to record accurate data for large-scale movements and unfortunately no advanced joint angle information could be collected.

The four-camera system was limited in viewing volume to capture the timed-up-and-go test therefore, many adjustments and modifications were made to mitigate error through repositioning and refocusing the cameras. Throughout the pre-testing, the lab configuration required skillful positioning and modification of the Bonita cameras to facilitate successful acquisition of data. In order to compensate for the technological barriers additional emphasis was placed on the camera configuration to maximize the viewing volume. In order to establish the viewing volume a validation tool was created. The additional emphasis placed on camera positioning enabled the primarily sagittal capture of a viewing volume far larger than is traditionally captured with four cameras. The configuration allowed for the measures required for the variables outlined to be extracted from the data with accuracy (RMS= 1.2234mm). By limiting the markers analyzed to the ones with the best visibility and optimizing their use for variable calculation, the limitation of equipment was reduced significantly.

The final limitation was the presence of the obstacle altering the path of the participant while performing the timed-up-and-go, specifically approaching and exiting the turn. The results indicated a significant effect of obstacle-crossing on turn radius, however the presence of the obstacle lead the participant to take a partially predetermined path in order to cross the obstacle on the approach to the turn and on the return path. The effect of obstacle-crossing on the outcome measures may have created a false positive by simply altering the natural path of the individual rather that impacting the trial through the crossing of the obstacle itself. A wider obstacle than the 1m obstacle used or a longer TUG such as the 5m TUG would help to clarify the effect of OC on turn radius during a TUG test. According to Chen et al (1994) a minimum of two steps prior to virtual obstacle crossing is required to adequately motor plan and execute a successful obstacle avoidance strategy (H.-C. Chen, Ashton-Miller, Alexander, & Schultz, 1994).

Finally, two participants included in this cohort appeared to have difficulty using Keeogo™ during testing, and demonstrated TUG times well above the group averages, and altered gait biomechanics. The statistical analysis revealed these two participants to be significant outliers thus a full statistical analysis was completed to compare the results with and without the two outliers. One outlier was male and one female thus keeping the sex-ratio the same. However, statistical analysis found that the removal of these two participants did not solve normality violations in the data therefore they were included for the statistical analysis in this thesis. The male outlier appeared to be hesitant when using the device, while the female outlier appeared to be uncomfortable with the physical components. Both individuals made contact with the obstacle and restarted trials. Increasing the size of the cohort will allow for further explanation of these types of participants and determining why certain individuals appear incompatible with Keeogo™.

5.4 Final Comments and Conclusions

This study has provided original research in the field of biomechanics as well the field of exoskeletal technology research. This study was also unique in its ability to dissect the differences between control and exoskeleton conditions and separate the physical presence of the exoskeleton vs the device functioning as an assistive device. This study used the timed-up-and-go in a healthy adult population, used dual-task methodology within the TUG, and implemented a low-risk obstacle crossing condition into the TUG which is a unique research design. This study also used motion capture to identify the initiation and termination of the timed-up-and-go task and used the onset of shoulder momentum (acromial marker acceleration) in the y-axis as the initiation and the termination to be the point of zero acceleration in the acromial marker along the y-axis. Similar methods were used by Coulthard et al., (2015) who used the onset of trunk velocity using inertial sensors as the initiation of TUG.

The study was able to use the timed-up-and-go in a young, healthy adult population and provide meaningful data. The use of the TUG in such populations is uncommon as a clinical outcome measure, however this research provides significant evidence that it may be successfully used as part of a research design. In addition, the TUG was manipulated through the implementation of an obstacle within the test. However, due to the limited volume of the motion capture system, the TUG was constrained to a 3m TUG. An obstacle-crossing TUG may be more meaningful in a 5m TUG to allow the participant to take more steps before obstacle crossing and between the obstacle and the turn, this would allow for a better analysis of approach and exit of the obstacle prior to the turn.

The study's main intent was to assess performance of Keeogo™ users to determine if the presence of the EXO increases CL while engaging in dual-task scenarios or facing simple obstacle-crossing. The results demonstrated that the main variation created by the exoskeleton may come from the presence of the physical components as opposed to the assistance from exoskeleton. Increasing the sample size and diversity as well as performing longer duration testing over time with training/familiarization, may help to better confirm these results. Testing over time, to familiarize the individual to the presence of the Keeogo™, will help determine if there is a decline in the effect of the physical presence of the Keeogo™ in addition to help adjust for test/re-test variability due to the practice effect of the Keeogo™ on gait.

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Chapter 6 Appendices

6.1 First Contact Script

A COMPARATIVE ASSESSMENT OF COGNITIVE LOADING ON GAIT BIOMECHANICS OF LOWER LIMB DERMOSKELETON USERS

PURPOSE
Researchers at the University of New Brunswick, lead by Dr. Chris McGibbon, are looking for individuals to participate in a study investigating cognitive load in users of assistive/voluntary lower limb exoskeletal technology. We hope to gain a better understanding of how the Keeogo™ performs in an activity of daily life. The long term goal is to better understand, develop and refine the exoskeleton to be conducive to activities of daily living.

PROCEDURE
As a participant, you will have to wear shorts or spandex and gym shoes. You will be asked to attend three sessions. A number of instruments will be used to measure your performance. These include: a motion capture system, reflective markers, and an Actigraph accelerometer. You will be asked to perform a timed up and go task, which will involve sitting in a chair, walking, turning, crossing and obstacle, and returning to sitting. You will also be asked to perform simple subtraction. Each visit will last for approximately 1.5-2 hours. An image of the Keeogo ™ lower limb exoskeleton which you will be asked to don is provided below:

RISKS AND DISCOMFORTS
During this experiment, you will be asked to perform walking and obstacle crossing. Minor discomfort due to contact with the Keoogo™ may occur. In addition, some users may experience soreness or chafing from skin contact with the Keeogo™. If you feel discomfort or are at risk you may rest or stop the tests at anytime. Your participation is strictly voluntary, and you may decline to participate at any time before or during your visit without penalty or judgment.

COST/BENEFIT

There is no direct cost to you for participating in the study. You will not directly benefit from participating in this study, but your involvement will help us achieve our short and long term scientific goals.

PRIVACY AND CONFIDENTIALITY
All personal information (names, addresses, email or phone numbers, etc.) gathered for this study that can identify participants will be kept secure to protect their privacy and will never be shared at any time with any person or entity. All personal information linking participants to their data will be destroyed after one year following the completion of the study.

Do you have any questions? (If yes, answer the questions.)

Would you like to participate in the study?
If no,
Thank you very much for your time.
If yes,
SCREENING QUESTIONNAIRE
We are looking for volunteers between the ages of 19-45 years who are in good general health without diagnosed muscle/joint conditions (e.g. arthritis, injury). In order to determine your eligibility I will need to ask you a few questions.
Administer the PARTICIPANT SCREENING QUESIONAIRE – FOR "HEALTHY" ADULT CONTROLS.
If the person is eligible,
Inform the person that they are eligible to volunteer in this study, and if they provide verbal ascent, proceed with testing and schedule remaining testing sessions at the Lady Beaverbrook Gym UNB, Fredericton. Remind the person that participants must bring shorts/spandex and athletic shoes.
If the person is not eligible,
Inform the person that they are not eligible to volunteer in this study and state the reason.

Thank you very much for your time.

Detailed Summary – if more details are requested by potential participant

As a participant you will be asked to take part in a single two-hour session of testing. You will be asked to complete a total of three short questionnaires regarding physical activity readiness and your experience with the Keeogo™. During the first portion of the session, you will be asked to fill out the required forms/questionnaires and you will be fitted with the Keeogo™ exoskeleton. The fitting will involve mechanical adjustments to ensure optimal performance and a personalized fit; and the system calibration will synchronize your unique gait. After fitting and tuning is complete, an Actigraph accelerometer and reflective markers will be placed. You will be asked to sit in a chair, walk three meters, turn around, cross an obstacle, walk back to the chair, resume your seat. You will be required to perform this task under different conditions (with/without counting, with/without the exoskeleton), with three trials per condition. Participants will be asked to complete a simple pain survey directly after completing the session.

This project has been reviewed by the Research Ethics Board of the University of New Brunswick in Fredericton and is on file as REB #2017-039

6.2 Exclusion Criteria

EXCLUSION SCREENING QUESTIONNAIRE – FOR "HEALTHY" ADULT CONTROLS

This questionnaire is to be administered when potential participants make first contact with you. The purpose of the questionnaire is to determine eligibility to participate in the study. When contacted, please be sure to inform the potential participant that in order to determine eligibility you will need to ask a few questions about their medical history. Also inform the potential participant that this questionnaire is for screening purposes ONLY and no records are kept once eligibility has been determined.

Ask potential participant: Do you have a history of one or more of the following?

Heart attack or major rhythm disturbance	Yes ☐	No ☐	Comment:
Renal failure requiring dialysis	Yes ☐	No ☐	Comment:
Recent (<2 yr) cancer with ongoing chemotherapy/radiation therapy	Yes ☐	No ☐	Comment:
Uncontrolled hypertension	Yes ☐	No ☐	Comment:
Uncontrolled diabetes	Yes ☐	No ☐	Comment:
Uncontrolled seizures	Yes ☐	No ☐	Comment:
Recent (<2 yr) foot ulcerations	Yes ☐	No ☐	Comment:
Recent (<2 yr) lower limb fracture	Yes ☐	No ☐	Comment:
Recent (<2 yr) stroke affecting lower limbs	Yes ☐	No ☐	Comment:
Recent (<1 yr) hip or knee replacement or arthroscopic surgery	Yes ☐	No ☐	Comment:
Legal blindness	Yes ☐	No ☐	Comment:
Not ambulatory or regularly uses wheelchair, walker or seeing eye dog to get around	Yes ☐	No ☐	Comment:
Inner ear disease or disorder (vestibulitis, Meniere's)	Yes ☐	No ☐	Comment:
Nerve damage/disease (to legs, torso, neck or eyes)	Yes ☐	No ☐	Comment:
Parkinson's disease	Yes ☐	No ☐	Comment:
Alzheimer's disease	Yes ☐	No ☐	Comment:
Recent (<6 months) concussion	Yes ☐	No ☐	Comment:
Other diseases/conditions (chronic or acute)	Yes ☐	No ☐	Comment:

ELIGIBILITY ASSESSMENT

If answer to ANY question above is Yes, the participant is NOT eligible to participate

Eligible to enter study based on exclusions? Yes ☐ No ☐ Comment:

6.3 Screening Procedures

CSEP approved Sept 12 2011 version

PAR-Q+

The Physical Activity Readiness Questionnaire for Everyone

Regular physical activity is fun and healthy, and more people should become more physically active every day of the week. Being more physically active is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

SECTION 1 - GENERAL HEALTH

	Please read the 7 questions below carefully and answer each one honestly: check YES or NO.	YES	NO
1.	Has your doctor ever said that you have a heart condition OR high blood pressure?	☐	☐
2.	Do you feel pain in your chest at rest, during your daily activities of living, OR when you do physical activity?	☐	☐
3.	Do you lose balance because of dizziness OR have you lost consciousness in the last 12 months? Please answer NO if your dizziness was associated with over-breathing (including during vigorous exercise).	☐	☐
4.	Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)?	☐	☐
5.	Are you currently taking prescribed medications for a chronic medical condition?	☐	☐
6.	Do you have a bone or joint problem that could be made worse by becoming more physically active? Please answer NO if you had a joint problem in the past, but it does not limit your current ability to be physically active. For example, knee, ankle, shoulder or other.	☐	☐
7.	Has your doctor ever said that you should only do medically supervised physical activity?	☐	☐

If you answered NO to all of the questions above, you are cleared for physical activity.

Go to Section 3 to sign the form. You do not need to complete Section 2.

- Start becoming much more physically active – start slowly and build up gradually.
- Follow the Canadian Physical Activity Guidelines for your age (www.csep.ca/guidelines).
- You may take part in a health and fitness appraisal.
- If you have any further questions, contact a qualified exercise professional such as a CSEP Certified Exercise Physiologist® (CSEP-CEP) or CSEP Certified Personal Trainer® (CSEP-CPT).
- If you are over the age of 45 yrs. and NOT accustomed to regular vigorous physical activity, please consult a qualified exercise professional (CSEP-CEP) before engaging in maximal effort exercise.

If you answered YES to one or more of the questions above, please GO TO SECTION 2.

Delay becoming more active if:

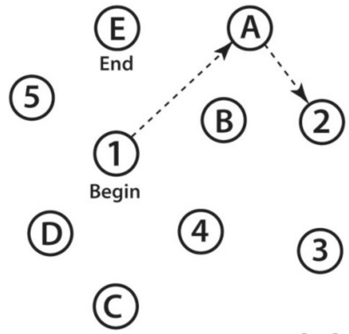
- You are not feeling well because of a temporary illness such as a cold or fever – wait until you feel better
- You are pregnant – talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the PARmed-X for Pregnancy before becoming more physically active OR
- Your health changes – please answer the questions on Section 2 of this document and/or talk to your doctor or qualified exercise professional (CSEP-CEP or CSEP-CPT) before continuing with any physical activity programme.

CSEP | SCPE
THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

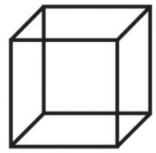
MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 Original Version

NAME :
Education : Date of birth :
Sex : DATE :

	POINTS
VISUOSPATIAL / EXECUTIVE	



[ ]



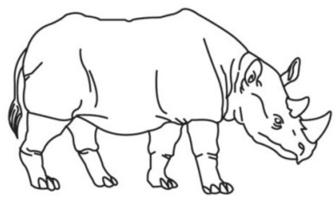
Copy cube [ ]

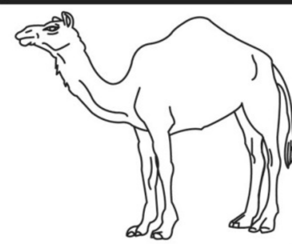
Draw CLOCK (Ten past eleven) (3 points)

[ ] Contour [ ] Numbers [ ] Hands ___/5

NAMING


[ ]


[ ]


[ ] ___/3

MEMORY Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION Read list of digits (1 digit/ sec.). Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2 ___/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors
[ ] F B A C M N A A J K L B A F A K D E A A A J A M O F A A B ___/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65
4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt** ___/3

LANGUAGE Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ] ___/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] _____ (N ≥ 11 words) ___/1

ABSTRACTION Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler ___/2

DELAYED RECALL	Has to recall words **WITH NO CUE**	FACE [ ]	VELVET [ ]	CHURCH [ ]	DAISY [ ]	RED [ ]	Points for UNCUED recall only	___/5
Optional	Category cue							
	Multiple choice cue							

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City ___/6

 www.mocatest.org Normal ≥26 / 30

TOTAL ___/30
Add 1 point if ≤ 12 yr edu

Administered by: ____________________

6.4 Informed Consent

Research Consent Form
University of New Brunswick
Fredericton, N.B.

Project Title: A comparative assessment of cognitive loading on gait biomechanics of lower limb dermoskeleton users

Principal Investigator: Alexa MacDonald MScESS candidate,
Supervising Investigators: Chris McGibbon, PhD, Jeremy Noble, PhD

PURPOSE
We ask for your permission to enroll you as a participant in a research study to investigate the effect of cognitive load (attention) in users of lower limb exoskeletal technology. Our short term goal is to gain a better understanding of how the Keeogo™ (pictured below) performs in an activity of daily life. We hope this information will help us better understand, develop and refine the exoskeletal technology to be conducive to activities of daily living. We will be recruiting

STUDY CONTACTS
If you have any questions regarding project goals, scheduling or other logistics, and research technology, please contact Alexa MacDonald, alexa.macdonald@unb.ca, 506-476-5757.

PROCEDURES
If you choose to participate you will be asked to be involved with a total of three visits. As a participant, you will have to wear shorts or spandex and a t-shirt. These will be worn beneath the Keeogo™ lower limb exoskeleton. Motion capture cameras and adhesive reflective markers will be used to analyze your movements. You will be asked to perform a timed up and go task, which will involve sitting in a chair, standing up, walking, turning, and returning to seated, all done in about 20 seconds.

You will also be asked to step over a clearly indicated compressible foam obstacle. You will also be asked to count backwards by seven.

COSTS
There is no direct cost to you for participating in the. If you feel you have experienced costs to participate that are unreasonable, contact Alexa.

RISKS AND DISCOMFORTS
During this experiment, you will be asked to perform walking and obstacle crossing. Minor discomfort may occur such as soreness or chafing from contact with the Keeogo™. In addition, markers will be attached to the skin or clothing using tape which may cause slight discomfort. If you feel discomfort or at risk you can rest or stop the tests at anytime. Your participation is strictly voluntary, and you may decline to participate at any time before or during your visit without penalty or judgment.

BENEFITS
You will not directly benefit from participating in this study. However, this experiment will provide useful information about gait biomechanics in users of exoskeletal technology and whether the technology is conducive to daily life activities.

PRIVACY AND CONFIDENTIALITY
All personal information (names, addresses, email or phone numbers, etc.) gathered for this study that can identify participants will be kept secure to protect their privacy and will never be shared at any time with any person or entity. Data collected during the study and shared with others will reference participants only by an alphanumeric code. The "master list" linking personal information to the alphanumeric code will not be shared, and will be kept by the study PI in a secure location. All personal information linking participants to their data will be destroyed after one year following the completion of the study. De-identified information gathered from participants will be used and shared with others for research purposes only. These "others" could include researchers at UNB (faculty and graduate students), and collaborators at other universities or research institutions.

Data published in aggregate form (descriptive and inferential statistics) or stored in a data repository (a de-identified database) may be used in future research without your consent. You have the right to request any data gathered from you during this study to be permanently deleted following the study, and to not be entered into a repository. You acknowledge that once data have been released in aggregate form (such as a thesis, published paper or report), or stored in a de-identified database, it is no longer possible to remove records belonging to specific individuals.

PUBLICATION OF RESULTS
The results of this study may be published in a journal or shared at a conference. Your identifiable information will not be used in any publication or other disseminated materials without your specific permission.

You may request a copy of any material made publicly available from the study you participated in. This material may take the form of published journal papers, conference abstracts or internet media. To request this information please contact the researcher listed under Study Contacts on this consent form.

REQUEST FOR MORE INFORMATION

You may ask more questions about the study at any time. The researcher's contact information is listed on this consent form should you have any further concerns about the study. A copy of this consent form will be given to you to keep.

If you want to speak with someone not directly involved in the study about your rights as a research subject, your participation in the study, any concerns you may have about the study, or a research-related injury, contact the UNB Research Ethics Board at (506) 453-5189. You can also contact them if you feel under any pressure to enroll or continue to participate in this study.

REFUSAL OR WITHDRAWAL OF PARTICIPATION

Participation in this study is voluntary. You do not need to sign the consent form. If you do not sign the sign consent form, you cannot participate in the research. You can drop out of the study at any time, without any penalties or judgment.

CONSENT TO PARTICIPATE IN RESEARCH AND AUTHORIZATION TO USE INDIVIDUAL'S PROVIDED HEALTH INFORMATION FOR RESEARCH

I confirm that the purpose of the research, the study procedures, the possible risks and potential benefits that I may experience have been explained to me. All my questions have been answered. I have read this consent form. My signature below indicates my willingness to participate in this research study and my authorization to use and share my de-identified data as described above.

NAME (Please print): **SIGNATURE:**

__________________________ __________________________ __________________

Participant
Date/Time

I have explained the purpose of the research, the study procedures, identifying those that are investigational, the possible risks and discomforts and potential benefits. I have answered any questions regarding the research study to the best of my ability.

Investigator/Individual Obtaining Consent:
Date/Time:

6.5 Data Collection Template

UNB
EST. 1785
UNIVERSITY OF NEW BRUNSWICK

PI: Alexa MacDonald

A COMPARATIVE ASSESSMENT OF COGNITIVE LOADING IN USERS OF LOWER LIMB DERMOSKELETONS

Name: ______________________ Date: ______________________
Contact: ______________________ Start: ______________________
______________________ Finish: ______________________

☐ Charge Keeogo Battery, Tablet Battery & Actigraph Batteries

☐ Calibration of MOCAP
☐ Check charge Keeogo Battery, Tablet Battery & Actigraph Batteries

☐ Admin
PAR-Q+
Additional Screening Questionnaire
Montreal Cognitive Assessment
B-Temia Confidentiality
PVAS Baseline
Informed Consent

Participant ID:	Femoral Length:	Screening Q:
Sex:	Tibial Height:	MOCA Score:
Height:	Waist Circumference:	VAS Pain Score:
Weight:	PARQ+:	OTHER:

☐ Review procedures.
Check Randomization
Generate Randomized numbers
Tuning & Calibration of Keeogo

	Control		**Cognitive Load**		**Obstacle Cross**		**OC x CL**	
	RAND#	*Responses*	*RAND#*	*Responses*	*RAND#*	*Responses*	*RAND#*	*Responses*
Control								
Passive								
Active								

6.6 Participant Anthropometry

A 1 Participant Anthropometry

ID	Sex	Age (yrs)	Height (cm)	Weight (kg)	Femoral Length	Tibial Height	Thigh Girth	WC (cm)	MOCA
P01	M	24	180	80.2	53	47	51.5	89	29
P02	M	23	184.5	97.5	55	47.5	48	90.5	30
P03	M	23	176.5	83.7	50	47	47	92.5	29
P04	M	23	177.5	72.6	54	46.5	48	78	28
P05	M	23	169.5	62.5	47	44	51	75	29
P06	M	22	183.5	93.5	53	47.4	55	84	29
P07	F	23	174	66	52	45	48	71	29
P08	F	29	162	67	42	37	60	93	28
P09	F	23	174.5	75.3	51	47	50	79.5	29
P10	F	23	173.5	87.5	55	47	54	92	27
P11	F	27	160.5	64.5	46	42.5	48	81	30
P12	F	22	166	65.4	50	45.5	49	78	27

6.7 TUG Time Statistics

A 2 Shapiro-Wilk's Test for Normality of TUG Time (s)

TUG TIME						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	***CL***	***OC***	**W**	**p**	**W**	**p**
KActive	-	-	0.79	0.01*	0.97	0.92
	CL	-	0.82	0.02*	0.93	0.44
	-	*OC*	0.79	0.01*	0.94	0.51
	CL	*OC*	0.92	0.30	0.95	0.65
KControl	-	-	0.94	0.50	0.95	0.71
	CL	-	0.91	0.19	0.89	0.18
	-	*OC*	0.96	0.83	0.98	0.98
	CL	*OC*	0.95	0.59	0.87	0.11
KPassive	-	-	0.86	0.05	0.94	0.51
	CL	-	0.85	0.04*	0.84	0.05
	-	*OC*	0.95	0.64	0.93	0.48
	CL	*OC*	0.91	0.22	0.90	0.24

* indicates statistical significance

A 3 Mauchly's test for Sphericity of TUG Time (s)

TUG TIME												
Total Dataset N=12							Modified dataset n=10					
Effect	W	p	GGe	p[GG]	HFe	p[HF]	W	p	GGe	p[GG]	HFe	p[HF]
EXO	0.34	<0.01*	0.60	<0.01	0.64	<0.01	0.86	0.54	0.88	<0.01	1.07	<0.01
EXO:CL	0.77	0.28	0.82	0.46	0.94	0.47	0.90	0.66	0.91	0.33	1.13	0.33
EXO:OC	0.86	0.47	0.88	0.14	1.03	0.13	0.68	0.21	0.76	0.39	0.88	0.40
EXO:CL:OC	0.91	0.62	0.92	0.02	1.09	0.02	0.90	0.65	0.91	0.06	1.13	0.05

* indicates statistical significance

A 4 Mauchly's Test for Sphericity of TUG Time (s) between OC conditions

TUG TIME												
	OC=0						OC=1					
N=12												
Effect	W	p	GGe	p[GG]	HFe	p[HF]	W	p	GGe	p[GG]	HFe	p[HF]
EXO	0.40	0.01*	0.63	<0.01	0.67	<0.01	0.34	<0.01*	0.60	<0.01	0.63	<0.01
EXO:CL	0.71	0.18	0.78	0.13	0.88	0.12	0.97	0.85	0.97	0.20	1.17	0.19
n=10												
EXO	0.74	0.30	0.80	<0.01	0.94	<0.01	0.80	0.41	0.84	<0.01	1.00	<0.01
EXO:CL	0.96	0.84	0.96	0.09	1.21	0.08	0.85	0.53	0.87	0.54	1.06	0.56

* indicates statistical significance

A 5 Analysis of Variance for TUG Time (s)

TUG TIME										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	267.47	<0.01	0.95	1	9	596.07	<0.01	0.98
EXO	2	22	17.77	<0.01*	0.13	2	18	37.25	<0.01*	0.17
CL	1	11	9.00	0.01*	0.02	1	9	6.28	0.03*	0.05
OC	1	11	0.54	0.48	<0.01	1	9	1.66	0.23	<0.01
EXO:CL	2	22	0.76	0.48	<0.01	2	18	1.17	0.33	<0.01
EXO:OC	2	22	2.24	0.13	<0.01	2	18	0.94	0.41	<0.01
CL:OC	1	11	8.08	0.02*	0.01	1	9	5.37	0.05	0.01
EXO:CL:OC	2	22	4.99	0.02*	0.01	2	18	3.49	0.05	0.01

A 6 TUG Time ANOVA by OC Condition

TURN TIME								
			OC=0			OC=1		
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**F**	**p**	**ges**
N=12								
Intercept	1	11	246.62	<0.01	0.95	284.67	<0.01*	0.96
EXO	2	22	13.66	<0.01*	0.12	17.42	<0.01*	0.15
CL	1	11	16.83	<0.01*	0.04	1.76	0.21	0.01
EXO:CL	2	22	2.40	0.11	0.01	1.76	0.19	<0.01
n=10								
Intercept	1	9	616.45	<0.01	0.98	543.36	<0.01*	0.98
EXO	2	18	23.01	<0.01*	0.17	20.25	<0.01*	0.18
CL	1	9	13.11	0.01*	0.11	1.00	0.34	0.01
EXO:CL	2	18	2.85	0.08	0.03	0.59	0.56	<0.01

6.8 Turn Time Statistics

A 7 Shapiro-Wilk's Test for Normality of Turn Time (s)

Turn Time						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	***CL***	***OC***	W	pvalue	W	pval
KActive	-	-	0.76	<0.01	0.76	<0.01
	CL	-	0.78	0.01	0.89	0.15
	-	*OC*	0.88	0.09	0.84	0.05
	CL	*OC*	0.97	0.91	0.95	0.71
KControl	-	-	0.97	0.91	0.97	0.90
	CL	-	0.80	0.01	0.89	0.19
	-	*OC*	0.95	0.66	0.95	0.61
	CL	*OC*	0.93	0.40	0.87	0.09
KPassive	-	-	0.92	0.27	0.83	0.03
	CL	-	0.90	0.17	0.90	0.24
	-	*OC*	0.91	0.20	0.94	0.56
	CL	*OC*	0.90	0.14	0.91	0.31

A 8 Mauchly's Test for Sphericity of Turn Time (s)

TURN TIME												
Total Dataset N=12							Modified dataset n=10					
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.86	0.54	0.88	<0.01	1.07	<0.01	0.70	0.24	0.77	0.01	0.90	0.01
EXO:CL	0.90	0.66	0.91	0.33	1.13	0.33	0.54	0.08	0.68	0.76	0.76	0.78
EXO:OC	0.68	0.21	0.76	0.39	0.88	0.40	0.67	0.21	0.75	0.39	0.87	0.40
EXO:CL:OC	0.90	0.65	0.91	0.06	1.13	0.05	0.88	0.60	0.89	0.21	1.10	0.21

A 9 Analysis of Variance for Turn Time (s)

TURN TIME										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	492.96	<0.01	0.95	1	9	817.41	<0.01	0.97
EXO	2	22	10.39	<0.01*	0.15	2	18	7.17	0.01*	0.19
CL	1	11	7.66	0.02*	0.01	1	9	3.97	0.08	0.01
OC	1	11	0.46	0.51	<0.01	1	9	0.68	0.43	<0.01
EXO:CL	2	22	0.90	0.42	<0.01	2	18	0.18	0.84	<0.01
EXO:OC	2	22	1.97	0.16	0.02	2	18	0.94	0.41	0.01
CL:OC	1	11	1.29	0.28	<0.01	1	9	0.03	0.86	<0.01
EXO:CL:OC	2	22	0.80	0.46	0.01	2	18	1.73	0.21	0.01

6.9 Rise Time Statistics

A 10 Shapiro-Wilk's Test for Normality of Rise Time (s)

RISE TIME						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	***CL***	***OC***	W	pvalue	W	pval
KActive	-	-	0.90	0.18	0.83	0.03*
	CL	-	0.95	0.59	0.93	0.46
	-	*OC*	0.88	0.09	0.92	0.38
	CL	*OC*	0.95	0.60	0.97	0.89
KControl	-	-	0.98	0.97	0.97	0.85
	CL	-	0.92	0.25	0.94	0.51
	-	*OC*	0.86	0.05	0.89	0.18
	CL	*OC*	0.88	0.09	0.84	0.05
KPassive	-	-	0.93	0.39	0.96	0.80
	CL	-	0.97	0.93	0.96	0.80
	-	*OC*	0.93	0.33	0.86	0.07
	CL	*OC*	0.86	0.05	0.88	0.12

A 11 Mauchly's Test for Sphericity of Rise Time (s)

RISE TIME												
Total Dataset N=12							Modified dataset n=10					
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.83	0.39	0.85	<0.01	0.99	<0.01	0.83	0.48	0.86	0.43	1.04	0.44
EXO:CL	0.73	0.20	0.79	0.40	0.89	0.41	0.73	0.29	0.79	0.10	0.93	0.09
EXO:OC	0.41	0.01*	0.63	0.18	0.67	0.18	0.77	0.35	0.81	0.39	0.96	0.40
EXO:CL:OC	0.63	0.10	0.73	0.43	0.82	0.44	0.80	0.41	0.83	0.03	1.00	0.03

A 12 Mauchly’s Test for Sphericity of Rise Time (s) by OC

RISE TIME												
OC=0							OC=1					
N=12												
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.43	0.01*	0.64	0.11	0.68	0.11	0.75	0.24	0.80	0.28	0.92	0.28
EXO:CL	0.79	0.31	0.83	<0.01	0.96	<0.01	0.82	0.37	0.85	0.05	0.99	0.04
n=10												
EXO	0.67	0.21	0.75	0.20	0.87	0.19	0.72	0.27	0.78	0.98	0.92	0.99
EXO:CL	0.49	0.06	0.66	0.02	0.73	0.02	0.85	0.51	0.87	0.14	1.06	0.13

A 13 Analysis of Variance of Rise Time (s)

RISE TIME										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	308.63	<0.01	0.94	1	9	277.52	<0.01	0.95
EXO	2	22	3.13	0.06	0.04	2	18	0.85	0.44	0.01
CL	1	11	0.38	0.55	<0.01	1	9	0.70	0.43	<0.01
OC	1	11	<0.01	0.96	<0.01	1	9	0.01	0.93	<0.01
EXO:CL	2	22	3.60	0.04*	0.02	2	18	2.89	0.08	0.03
EXO:OC	2	22	0.06	0.94	<0.01	2	18	0.97	0.40	0.01
CL:OC	1	11	1.14	0.31	<0.01	1	9	1.98	0.19	0.01
EXO:CL:OC	2	22	6.95	<0.01*	0.03	2	18	4.53	0.03*	0.02

A 14 Analysis of Variance of Rise Time (s) by OC

RISE TIME								
			OC=0			OC=1		
N=12								
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**F**	**p**	**ges**
Intercept	1	11	324.78	0	0.95	273.82	0	0.93
EXO	2	22	2.74	0.09	0.06	1.34	0.28	0.03
CL	1	11	1.83	0.2	0.01	0.23	0.64	0
EXO:CL	2	22	8.93	0	0.06	3.7	0.04	0.05
n=10								
Intercept	1	9	283.4	0	0.95	246.63	0	0.94
EXO	2	18	1.87	0.18	0.03	0.01	0.99	0
CL	1	9	2.31	0.16	0.02	1.05	0.33	0.01
EXO:CL	2	18	6.43	0.01	0.06	2.28	0.13	0.04

6.10 Sit Time Statistics

A 15 Shapiro-Wilk Test for Normality of Sit Time (s)

SIT TIME						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	***CL***	***OC***	W	pvalue	W	pval
KActive	-	-	0.88	0.09	0.90	0.23
	CL	-	0.93	0.33	0.95	0.63
	-	*OC*	0.90	0.17	0.92	0.34
	CL	*OC*	0.94	0.55	0.97	0.90
KControl	-	-	0.94	0.41	0.90	0.21
	CL	-	0.93	0.42	0.89	0.18
	-	*OC*	0.85	0.04	0.86	0.08
	CL	*OC*	0.97	0.88	0.96	0.78
KPassive	-	-	0.94	0.51	0.87	0.11
	CL	-	0.92	0.25	0.94	0.53
	-	*OC*	0.85	0.04*	0.88	0.13
	CL	*OC*	0.94	0.51	0.96	0.78

A 16 Mauchly's Test for Sphericity of Sit Time (s)

SIT TIME												
Total Dataset N=12							Modified dataset n=10					
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.41	0.01*	0.63	0.11	0.67	0.10	0.95	0.80	0.95	<0.01	1.20	<0.01
EXO:CL	0.18	<0.01*	0.55	0.66	0.57	0.66	0.70	0.23	0.77	0.62	0.89	0.65
EXO:OC	0.28	<0.01*	0.58	0.20	0.61	0.20	0.87	0.58	0.89	0.56	1.09	0.57
EXO:CL:OC	0.31	<0.01*	0.59	0.52	0.62	0.53	0.97	0.89	0.97	0.67	1.23	0.67

A 17 Analysis of Variance of Sit Time (s)

SIT TIME										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	197.00	<0.01	0.86	1	9	436.89	<0.01	0.96
EXO	2	22	2.89	0.08	0.03	2	18	12.14	<0.01*	0.15
CL	1	11	2.30	0.16	0.01	1	9	2.93	0.12	0.02
OC	1	11	0.05	0.83	<0.01	1	9	0.22	0.65	<0.01
EXO:CL	2	22	0.24	0.79	<0.01	2	18	0.41	0.67	<0.01
EXO:OC	2	22	1.81	0.19	0.02	2	18	0.57	0.57	0.01
CL:OC	1	11	<0.01	0.99	<0.01	1	9	5.22	0.05	0.01
EXO:CL:OC	2	22	0.51	0.61	<0.01	2	18	0.41	0.67	<0.01

6.11 Turn Radius Statistics

A 18 Shapiro-Wilk's Test for Normality of Turn Radius (mm)

TURN RADIUS						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	***CL***	***OC***	W	pvalue	W	pval
KActive	-	-	0.88	0.08	0.92	0.34
	CL	-	0.98	0.99	0.98	0.94
	-	*OC*	0.95	0.58	0.95	0.64
	CL	*OC*	0.91	0.19	0.94	0.57
KControl	-	-	0.96	0.85	0.94	0.51
	CL	-	0.94	0.56	0.97	0.85
	-	*OC*	0.91	0.22	0.92	0.38
	CL	*OC*	0.95	0.68	0.91	0.29
KPassive	-	-	0.91	0.20	0.92	0.36
	CL	-	0.98	0.97	0.98	0.97
	-	*OC*	0.94	0.56	0.92	0.35
	CL	*OC*	0.98	1.00	0.94	0.55

A 19 Mauchly's Test for Sphericity of Turn Radius (mm)

TURN RADIUS												
	Total Dataset N=12						Modified dataset n=10					
Effect	W	p	GGe	p[GG]	HFe	p[HF]	W	p	GGe	p[GG]	HFe	p[HF]
EXO	0.96	0.82	0.96	0.35	1.16	0.35	0.82	0.46	0.85	0.38	1.03	0.39
EXO:CL	0.87	0.49	0.88	0.16	1.04	0.16	0.90	0.66	0.91	0.40	1.13	0.40
EXO:OC	0.93	0.71	0.94	0.52	1.13	0.53	0.90	0.65	0.91	0.61	1.12	0.63
EXO:CL:OC	0.61	0.08	0.72	0.15	0.80	0.14	0.50	0.06	0.67	0.16	0.74	0.16

A 20 Analysis of Variance of Turn Radius (mm)

TURN RADIUS										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	148.22	<0.01	0.90	1	9	124.07	<0.01	0.90
EXO	2	22	1.09	0.35	0.01	2	18	0.98	0.39	0.01
CL	1	11	12.35	<0.01*	0.06	1	9	8.82	0.02*	0.04
OC	1	11	50.27	<0.01*	0.14	1	9	33.14	<0.01*	0.15
EXO:CL	2	22	2.02	0.16	0.01	2	18	0.96	0.40	<0.01
EXO:OC	2	22	0.65	0.53	<0.01	2	18	0.47	0.63	<0.01
CL:OC	1	11	3.66	0.08	<0.01	1	9	2.91	0.12	0.01
EXO:CL:OC	2	22	2.24	0.13	0.01	2	18	2.21	0.14	0.01

6.12 Stride Length Statistics

A 21 Shapiro-Wilk's Test for Normality of Stride Length (mm)

STRIDE LENGTH						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	***CL***	***OC***	W	pvalue	W	pval
KActive	-	-	0.94	0.47	0.94	0.52
	CL	-	0.96	0.76	0.95	0.71
	-	*OC*	0.93	0.38	0.94	0.59
	CL	*OC*	0.97	0.89	0.94	0.56
KControl	-	-	0.98	1.00	0.96	0.83
	CL	-	0.85	0.04*	0.88	0.14
	-	*OC*	0.88	0.08	0.86	0.07
	CL	*OC*	0.97	0.95	0.98	0.97
KPassive	-	-	0.93	0.35	0.97	0.87
	CL	-	0.96	0.72	0.94	0.60
	-	*OC*	0.94	0.51	0.94	0.55
	CL	*OC*	0.92	0.32	0.92	0.39

A 22 Mauchly's Test for Sphericity of Stride Length (mm)

STRIDE LENGTH												
Total Dataset N=12							Modified dataset n=10					
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.94	0.75	0.95	<0.01	1.14	<0.01	0.77	0.45	0.81	0.43	1.02	0.45
EXO:CL	0.88	0.53	0.89	0.35	1.05	0.36	0.84	0.59	0.86	0.74	1.12	0.77
EXO:OC	0.82	0.36	0.85	0.33	0.98	0.34	0.88	0.68	0.89	0.26	1.18	0.26
EXO:CL:OC	0.83	0.40	0.86	0.32	1.00	0.33	0.46	0.10	0.65	0.22	0.74	0.21

A 23 Analysis of Variance of Stride Length (mm)

STRIDE LENGTH										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	914.10	<0.01	0.98	1	9	110.47	<0.01	0.91
EXO	2	22	11.69	<0.01*	0.10	2	18	0.84	0.45	0.01
CL	1	11	7.01	0.02*	0.03	1	9	6.92	0.03*	0.04
OC	1	11	1.03	0.33	<0.01	1	9	32.58	<0.01*	0.18
EXO:CL	2	22	1.07	0.36	<0.01	2	18	0.26	0.77	<0.01
EXO:OC	2	22	1.14	0.34	0.01	2	18	1.50	0.26	0.01
CL:OC	1	11	2.18	0.17	<0.01	1	9	2.48	0.16	0.01
EXO:CL:OC	2	22	1.18	0.33	<0.01	2	18	1.80	0.20	0.01

6.13 Step Width Statistics

A 24 Shapiro-Wilk Test for Normality of Step Width (mm)

STEP WIDTH						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	*CL*	*OC*	W	pvalue	W	pval
KActive	-	-	0.97	0.89	0.97	0.91
	CL	-	0.93	0.36	0.83	0.04*
	-	*OC*	0.92	0.28	0.91	0.25
	CL	*OC*	0.87	0.07	0.88	0.13
KControl	-	-	0.95	0.59	0.95	0.70
	CL	-	0.98	0.99	0.99	0.99
	-	*OC*	0.92	0.29	0.92	0.34
	CL	*OC*	0.97	0.94	0.96	0.82
KPassive	-	-	0.90	0.15	0.93	0.42
	CL	-	0.94	0.47	0.91	0.31
	-	*OC*	0.93	0.35	0.93	0.50
	CL	*OC*	0.95	0.62	0.95	0.66

A 25 Mauchly's Test for Sphericity of Step Width (mm)

STEP WIDTH												
Total Dataset N=12							Modified dataset n=10					
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.45	0.02	0.65	0.21	0.69	0.21	0.41	0.03	0.63	0.30	0.68	0.30
EXO:CL	0.86	0.46	0.87	0.76	1.03	0.79	0.64	0.17	0.09	0.09	0.84	0.08
EXO:OC	0.86	0.48	0.88	0.57	1.03	0.60	0.74	0.29	0.50	0.50	0.93	0.52
EXO:CL:OC	0.63	0.10	0.73	0.60	0.81	0.62	0.61	0.14	0.79	0.79	0.82	0.82

A 26 Analysis of Variance of Step Width (mm)

STEP WIDTH										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	155.12	<0.01	0.88	1	9	113.07	<0.01	0.87
EXO	2	22	1.73	0.20	0.03	2	18	1.26	0.31	0.02
CL	1	11	1.23	0.29	0.01	1	9	0.29	0.61	<0.01
OC	1	11	3.41	0.09	0.01	1	9	1.94	0.20	0.01
EXO:CL	2	22	0.24	0.79	<0.01	2	18	3.19	0.07	0.01
EXO:OC	2	22	0.53	0.60	<0.01	2	18	0.66	0.53	0.01
CL:OC	1	11	0.71	0.42	<0.01	1	9	0.02	0.89	<0.01
EXO:CL:OC	2	22	0.43	0.66	<0.01	2	18	0.15	0.86	<0.01

6.14 Toe Clearance Statistics (mm)

A 27 Shapiro-Wilk's Test for Normality of Toe Clearance (mm)

TOE CLEARANCE						
COND			Shapiro-Wilk			
			N=12		n=10	
EXO	***CL***	***OC***	W	pvalue	W	pval
KActive	-	-	0.78	0.01*	0.73	<0.01*
	CL	-	0.96	0.80	0.97	0.85
	-	*OC*	0.94	0.49	0.95	0.66
	CL	*OC*	0.87	0.07	0.79	0.01*
KControl	-	-	0.89	0.12	0.87	0.11
	CL	-	0.94	0.53	0.95	0.70
	-	*OC*	0.86	0.06	0.90	0.20
	CL	*OC*	0.90	0.15	0.93	0.43
KPassive	-	-	0.86	0.05	0.88	0.12
	CL	-	0.96	0.76	0.97	0.93
	-	*OC*	0.81	0.01*	0.94	0.55
	CL	*OC*	0.98	0.96	0.96	0.80

A 28 Mauchly's Test for Sphericity of Toe Clearance (mm)

TOE CLEARANCE												
Total Dataset N=12							Modified dataset n=10					
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.35	0.01*	0.61	0.07	0.64	0.07	0.58	0.11	0.70	0.02	0.80	0.01
EXO:CL	0.98	0.92	0.98	0.32	1.20	0.32	0.86	0.54	0.87	0.20	1.07	0.19
EXO:OC	0.37	0.01*	0.62	0.19	0.65	0.19	0.61	0.14	0.72	0.42	0.82	0.44
EXO:CL:OC	0.77	0.28	0.82	0.08	0.94	0.07	0.59	0.12	0.71	0.07	0.80	0.07

A 29 Mauchly's Test for Sphericity of Toe Clearance (mm) by OC

TOE CLEARANCE												
OC=0							OC=1					
N=12												
Effect	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**	**W**	**p**	**GGe**	**p[GG]**	**HFe**	**p[HF]**
EXO	0.84	0.42	0.86	0.16	1.01	0.15	0.28	<0.01*	0.58	0.14	0.61	0.13
EXO:CL	0.86	0.48	0.88	0.74	1.03	0.77	0.94	0.75	0.95	0.07	1.14	0.06
n=10												
EXO	0.77	0.36	0.82	0.30	0.97	0.30	0.49	0.06	0.66	0.11	0.73	0.10
EXO:CL	0.87	0.57	0.88	0.81	1.08	0.84	0.76	0.33	0.80	0.04	0.95	0.04

A 30 Analysis of Variance for Toe Clearance (mm)

TOE CLEARANCE										
	N=12					n=10				
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**DFn**	**DFd**	**F**	**p**	**ges**
Intercept	1	11	1749.95	<0.01	0.99	1	9	1294.68	<0.01	0.99
EXO	2	22	3.63	0.04*	0.02	2	18	6.59	0.01*	0.03
CL	1	11	0.51	0.49	<0.01	1	9	0.03	0.86	<0.01
OC	1	11	19.39	<0.01*	0.23	1	9	16.46	<0.01*	0.18
EXO:CL	2	22	1.20	0.32	0.01	2	18	1.79	0.19	0.01
EXO:OC	2	22	1.90	0.17	0.02	2	18	0.82	0.46	0.01
CL:OC	1	11	9.97	0.01*	0.02	1	9	11.70	0.01*	0.03
EXO:CL:OC	2	22	3.01	0.07	0.02	2	18	3.52	0.05	0.02

A 31 Analysis of Variance for Toe Clearance (mm) by OC

TOE CLEARANCE								
			Control			Obstacle Crossing		
Effect	**DFn**	**DFd**	**F**	**p**	**ges**	**F**	**p**	**ges**
N=12								
Intercept	1	11	1390.24	<0.01	0.99	1163.94	<0.01	0.98
EXO	2	22	2.04	0.15	0.02	2.51	0.10	0.06
CL	1	11	7.70	0.02*	0.05	1.08	0.32	0.01
EXO:CL	2	22	0.26	0.77	<0.01	3.10	0.06	0.03
n=10								
Intercept	1	9	1107.52	<0.01	0.99	1024.36	<0.01	0.99
EXO	2	18	1.29	0.30	0.01	2.85	0.08	0.05
CL	1	9	4.59	0.06	0.04	2.99	0.12	0.02
EXO:CL	2	18	0.18	0.84	<0.01	4.16	0.03*	0.06

Curriculum Vitae

Candidate's full name: Alexa Grace MacDonald

Universities attended: University of New Brunswick, BSc. Kinesiology, 2015

Publications:

Smith, C.A., MacDonald, A.G., & Holahan, M.R., (2011). Acute postnatal exposure to di(2-ethylhexyl) phthalate adversely impacts hippocampal development in the male rat. *Neuroscience. 193,100-108* https://doi.org/10.1016/j.neuroscience.2011.06.082

Conference Presentations:

MacDonald, A., Noble, J., McGibbon, C., (2017) A comparative assessment of cognitive-loading and obstacle-crossing in healthy lower-limb exoskeleton users. Presented at the International Movement Conference, Oxford University, Oxford, United Kingdom.