# THE EFFECTS OF PERCEPTION-ACTION COUPLING ON COMPROMISED HUMAN LOCOMOTION: A PROPOSED RESEARCH PROGRAM

# THE EFFECTS OF PERCEPTION-ACTION COUPLING ON COMPROMISED HUMAN LOCOMOTION: A PROPOSED RESEARCH PROGRAM

By KRISTEN DE MELO, B.Sc.

A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree Master of Science

McMaster University MASTER OF SCIENCE (2021)
Hamilton, Ontario (Department of Kinesiology)

TITLE: The Effects of Perception-Action Coupling on Compromised Human Locomotion: A Proposed Research Program

AUTHOR: Kristen De Melo, B.Sc. (McMaster University)

SUPERVISOR: Professor J.L. Lyons

NUMBER OF PAGES: 169

**ABSTRACT**

There is considerable evidence suggesting an innate linkage between the human perceptual and motor systems, which evolve together and assist one another in the production and coordination of movement. A major contributor to this relationship is *optic flow*, providing movement variables such as navigation, obstacle avoidance, and depth perception. The absence of optic flow leads to the decoupling of perception and action, which has been shown to contribute to decrements in human movement (i.e., negatively impacted locomotion and posture, and slower adaptation to gait perturbations). Despite the importance of maintaining this linkage, optic flow manipulations are often found to be underrepresented in locomotion literature when specifically related to rehabilitation training (i.e., treadmills). This may be a contributor to the lengthy and exhaustive treatment plans. The literature *has* shown instances where reintroducing optic flow into training protocols has shown larger gait improvements in shorter times than typical ambulation protocols, however, the strength of the perception-action linkage in adulthood is still not well understood and its impact not yet fully explored. Therefore, the current research program aims to fill this gap by evaluating how the reintroduction of optic flow into atypical gait training protocols in both healthy and gait compromised individuals may provide evidence that could be used to enhance rehabilitative outcomes. This series of conceptually related experiments explores outcome enhancements through neuromuscular level changes (Study One), the recalibration process of perception-action given newly acquired physical constraints (Study Two), and on larger scale gait cycle performances in a rehabilitation setting (Study Three). It is hypothesized that perception-

action coupling will lead to increases in neuromuscular elicitation in the absence of voluntary movement (Study One), assist the recalibration process to improve measures of spatial awareness and atypical gait parameters (Study Two), and finally, improve rehabilitative outcomes in a spinal cord injury (SCI) ambulation protocol, both objectively (i.e., gait parameters, dynamic balance, SCI measures) and subjectively (i.e., questionnaires) (Study Three).

## ACKNOWLEDGEMENTS

Dr. Jim Lyons, no words can express the gratitude I have towards you. From my undergraduate degree to the present day, you have given me every opportunity that has shaped me as the researcher I am today. You took a chance on me and supported me throughout this entire journey, giving me confidence in my abilities. To me, it is rare to find a supervisor like you – one who believes in and genuinely cares for the growth of their students, not only academically, but also as an individual. I feel lucky to have had these experiences with you. Our journey does not stop here.

Dr. Jim Burkitt, your patience and dedication to helping students is so admirable. I cannot thank you enough for all of the time you spent teaching and supporting me throughout this journey. The long hours and late nights you spent do not go unnoticed. You made a huge difference in this degree for me. From my professor in first year who made every attempt to help and get to know his students, to a fellow researcher that I can count on. Thank you.

To my other committee members, Dr. Mike Carter and Dr. Dylan Kobsar. Thank you for your support and invaluable input throughout this process. You both allowed me to adapt during these unprecedented times, and guided me along the way.

My family: Mom, Dad, & Kyle. Your love and endless support has always carried me through every aspect of my life. Without you, these opportunities would not be possible. You have shaped me into who I am today. Thank you for always being my shoulder to lean on and encouraging me along the way.

Julian, for all of your assistance, support, and love throughout this journey, thank you. I cannot put into words how grateful I am to you. You give me confidence and make me believe in myself.

Last but not least, my friends and lab mates for your endless support and encouragement.

**TABLE OF CONTENTS**

# LIST OF TABLES AND FIGURES

## DECLARATION OF ACADEMIC ACHIEVEMENT

I, Kristen De Melo, declare this thesis to be of my own work. I am the sole author of this document and gathered the literature independently. I was involved in all aspects of the work. To my knowledge, this work does not infringe on the copyrights of others. Dr. Jim Lyons and Dr. Jim Burkitt assisted the conceptualization of the project ideas and the design of the experimental protocols. Both individuals edited and reviewed all written work.

# CHAPTER 1: LITERATURE REVIEW

## 1.0. Introduction

Humans continuously experience multiple and varied forms of visual information that can serve a purpose to movement within our environments. Vision is important for guiding our actions, such as in wayfinding amongst obstacles towards environmental goals (e.g., moving through challenging, rocky terrains on a hike or running to a distant target to accomplish a long jump). Visual information also calibrates our actions to a metric that can be used to gauge locomotion relative to the environment in the event we are without vision (e.g., walking through a dark kitchen at night in search of the fridge for a midnight snack). This process allows us to complete such actions with reasonable accuracy. In this sense, vision for action is also dependent on context and posture, wherein perception of forward visual translation can be paired with different actions and postures (e.g., actively walking through the environment versus sitting in a car or wheelchair and passively moving). These situations result in different stimulus-response interactions as visual information changes with the perception of contextual and postural cues. The idea regarding the nature of human perception, and how stimuli translate directly into responses, is of critical interest to the Ecological Perspective of human movement – and of critical importance to examining how rehabilitation protocols should best leverage this interaction for optimal recovery.

### 1.1. Ecological Theory on Perception-Action

Many multidisciplinary research areas have provided much of our understanding of human behaviour by looking at how humans use sensory information in such a way to serve as a basis for voluntary movement control. A common global conception between researchers in the field is that humans invoke some sort of perceptual process in order to eventually execute a desired action. Interpretations of the process(es) between gathering sensory information and executing actions based on that accumulated information, differ among theoretical constructs, with each proposing their own mechanisms thought to underlie this relationship.

While understanding that the many complexities and subtleties involved in the perception-action literatures opens us to the risk of over simplification, in *general* terms, there are two prevailing theoretical approaches that tackle this idea of how perception becomes action. One of these is termed the *ecological framework* or *ecological approach* to human movement. This ecological framework, first proposed by James Gibson (Gibson, 1966), specifically addresses the interaction between perception and action by attempting to understand and explain the interrelationships that exist between humans, their environment, and how this process changes with injury or disease. Within this framework, constraints play a major role in the development of movement within one's surroundings, as they are a characteristic of a task, an individual, or the environment that can limit or help shape this process (Headrick et al., 2015; Roberton, 1989; Seifert et al., 2017). The ecological perspective heavily stresses the existing interrelationships between these three components. Gibson describes the environment as a composition of natural elements that contain the ability to affect living organisms within that environment (Gibson, 1966). It is suggested that motor control processes exist for animals, including humans, to effectively execute actions necessary to cope and survive within their surroundings, with these actions being geared toward specific variables (i.e., stimuli) within that environment. Therefore, all information that is required to execute a movement can be found within a particular stimulus (e.g., Heft, 2001). This suggests that the ecological perspective is a direct approach meaning, that humans and animals directly perceive information in the environment without the need for, or intervention of, additional assistance from memory, reasoning, or abstract representations to build an understanding of the external world (Hommel et al., 2001; Michaels & Carello, 1981). Thus, the perceptual system allows any information that is accessible within the environment to be used to immediately and directly facilitate interactions with the surroundings (Raiola, 2014; Vaz et al., 2017).

Gibson proposed the perceptual and motor systems evolved together in mammals, not as discrete, independent constructs, but rather in close interrelationship (Gibson, 1966). The two systems grow together and change as an individual develops and gains new visual experiences. Further, perception and action are suggested to be dynamically coupled to "assist" one another in coordinating movements (Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Bertenthal, 1996; Bertenthal et al., 1997; Rossi, Rodrigues, & Forner-Cordero, 2014). In this theoretical context therefore, the development of perception cannot be studied independent of action and vice versa. The linkage between perception and action allows for adaptive behaviours to the surroundings since they are coupled by laws of control relating information variables to the most appropriate parameters of action (Warren, 1990).

An important concept within this framework is what Gibson (1979) termed affordances. Although the definition of an object affordance has changed somewhat over time depending on context, Gibson's original conceptualization of the term refers to object characteristics that automatically provide (i.e., afford) organisms with action possibilities in reference to the environment. In other words, affordances are perceived by the system with this perception in turn suggesting possible executable actions that are appropriate toward those specific affordances. For this reason, affordances are referred to in active terms (Michaels & Carello, 1981). Critically, these are inherent to the system, meaning that there is no preconceived learning required to understand them since all relevant information required to perform an action, even in the absence of movement, is found within the object via its affordances (Gibson, 1979). It is important to note that affordances are usually considered relative to an individual's constraints and provide body-scaled information. For example, an object in a given environment may afford different action possibilities to different people depending on the body dimensions of the individual (Michaels & Carello, 1981; Warren, 1984). Object affordances are encountered in the environment via *optic flow*. Specific processes and mechanisms regarding this concept are described in greater detail in Section 1.3.1, however in general terms, optic flow provides dynamic information about objects and their affordances (e.g., size, shape, approach rate, etc.) within the flow. These variables change as the object moves toward us or individuals move towards them, and the perception of those changes suggests the action response (Gibson, 1979).

A close "cousin" to this ecological framework is the theory of *dynamical systems*. Together, the dynamical systems and ecological theories propose how we move is based on the perceptual information available in the environment with a particular emphasis and focus on the constraints placed upon movements by natural physical properties of the moving body (Garner & Kaplan, 2017). The commonalities between the two theoretical constructs suggest the relationship that exists between perception and action is direct and requires no intervention from higher-order executive functioning. They refute the need for a translatory stage between the perception of sensory information and action response (Garner & Kaplan, 2017). It is believed within these theories that the linkage between perception and action is so intimate that one will often directly trigger the other (termed functional synergy).

The dynamical systems approach to understanding human movement is suggested to have started with the ideas of Nikolai Bernstein (Bernstein, 1967). This theory takes advantage of the physical elements (i.e. gravity, area, etc.) of the environment (Kamm, Thelen, & Jensen, 1990; Schneiberg et al., 2002), and looks at how we learn to martial these effects to produce effective movements within one's surroundings. This theory also suggests that movement control is an emergent property of the constraints that act upon it, meaning that it is not specified by the brain, but rather an interaction of multiple components of the system (Thelen, 1989; Thelen, 2005). Behaviours will therefore emerge based on what is occurring to the organism within a movement context. Under particular conditions, parts of the body (effectors) will self-organize to produce desired movement patterns without having a specific code for the actions (Thelen, 2005) – that is, the human body seeks its greatest level of stability during movements by adapting to or using available constraints (see also Hodges et al., 2005; Holdefer & Miller, 2002; Gagen & Getchell, 2008; Kelso, 1984; Kelso & Schoner, 1988; Smith & Zelaznik, 2004;

Terband et al., 2011; Zariffa et al., 2012). For example, in human locomotion, when one increases their speed while walking, variability in step characteristics (i.e., step length, stride length, stride height) increases which destabilizes the system. Therefore, the system will "automatically" transition to a run in order to reduce variability and return the system to a stable pattern (Kung et al., 2018; Van Hooren, Meijer, & McCrum, 2019). In this example, the running gait is considered to be a behavior to have "emerged" from the walking gait in order to satisfy the new demands placed upon the system.

Together, these two theoretical frameworks follow what is termed a "bottom-up" approach, in which retrieval of information from our sensory environments leads to the development of perceptions automatically. There are, however, "top-down" approaches, where incoming information is interpreted by the brain using cognitive processes that explain the relationship between sensory input and action response. It is important to consider these theories as they contribute to our understanding of this relationship, and create important distinctions between how we automatically process information (i.e., naturally emerging movement changes) versus how we voluntarily choose action responses based on the availability of information. Information processing theory focuses on the latter approach and involves decision-making for movement response.

**1.2. Information Processing Theory**

Information processing theory played a major role in researching motor behaviour prior to the introduction of the ecological perspective. Indeed, much of our understanding of behaviour has originated from working within this framework (Christina, 2017). This theory suggests that human behaviour is a result of a complex interplay between environmental sensory information and cognitive processes to effectively execute a movement (Çeliköz, Erişen & Şahin, 2019). Thus, a fundamental difference between Information Processing models and those positing the direct linkage of perception and action is this intervening higher order contribution of executive function. For example, Information Processing frameworks emphasize the importance of memory and how information is stored and subsequently retrieved when stimulated by the environment – information that is readily available and used as necessary. Here, the human system is viewed as ‘mechanistic’ in nature, suggesting that the system operates similarly to computer programs (Çeliköz, Erişen & Şahin, 2019; Christina, 2017). What primarily differs information processing theory from ecological theory is what occurs between the presentation of a stimulus and the execution of an action response. In information processing, an intermediate step exists between the two stages that acts as a translation from perception to action, where the central executive will analyze the acquired information and send an appropriate action response. Within this translation, three main intervening stages are hypothesized: stimulus-identification (e.g. Chase & Simon, 1973; deGroot, 1978; Starkes & Ericsson, 2003; Zhu, Zhang, & Rio-Tsonis, 2012), response-selection (e.g. Hick, 1952; Hyman, 1953; Kveraga, Boucher, & Hughes, 2002; Lawrence et al., 2008), and response-programming stages (e.g. Christina, 2017; Henry & Rogers, 1960; Senders, 1998).

Although information processing theory has been used as a framework to describe most human movement behaviours, this proposal will limit the scope of discussion of this theory to those elements that are most applicable to the proposed research (i.e., those that pertain directly to human locomotion). A fundamental concept within this theoretical position is that of the Generalized Motor Program (GMP) (Schmidt, 1975). GMPs develop only with experience and considerable practice with the end result of ultimately providing the basis for generating movement sequences within a class of movements that share common "invariant" features directly related to a specific movement goal. Through the process of analyzing sensory information, Schmidt (1975) suggests that the central executive will select an appropriate generalized motor program (GMP) to execute a particular class of action (e.g., walking, running, throwing, etc.). The GMP contains "invariant" features that are fundamental to the movement and do not change between trials (Schmidt, 1976). GMPs are, however, influenced by parameters which alter the output of an action to fit specific environmental characteristics. This outcome will only differ in superficial ways (i.e., absolute speed, size, and time), otherwise, a new GMP must be selected to carry out the required action – a process in which reduces efficiency of performance and expends more energy (Vali Noghondar et al., 2021). Evidence of the use of GMPs have been shown in tasks such as throwing (e.g. Czyż, Zvonař, & Pretorius, 2019; Thomas et al., 2012), kicking (e.g. Hoseini, Sohrabi, & Torbati, 2016; Vera, Alvarez, & Medina, 2008), keyboard and writing movements (e.g. Lai & Shea, 1998; Lashley, 1942), as well as, and of particular importance to this work, locomotion.

Information processing theory suggests that human locomotion involves implementing a GMP to carry out the cyclical pattern of walking. This involves a set of commands which activate the locomotor musculature in a designated sequence (Ivanenko, Poppele, & Lacquaniti, 2006; Summers & Anson, 2009). A conscious decision to perform a specific method of locomotion must be made given the available environmental information. For example, once the GMP for the class of movements associated with walking is selected, it is recalled from memory stores and executed thereby resulting in the activation of the musculature to perform the “walking” gait cycle (Cappellini et al., 2006; Ivanenko, Poppele, & Lacquaniti, 2006; Shapiro et al., 1981). This activation results in various groups of muscles firing at once in relation to specific kinematic events (i.e., the onset of a foot lift; Ivanenko, Poppele, & Lacquaniti, 2006). As speed increases during walking, invariant features (e.g., relative timing of kinematic events) remain, however, the parameter of movement time adjusts to make it shorter (Cappellini et al., 2006; Ivanenko, Poppele, & Lacquaniti, 2006; Shapiro et al., 1981). This has been found to be most efficient between speeds of three to six miles per hour (mph). When a speed of seven mph is achieved, it appears that the human cognitive system *selects* a new GMP to initiate the class of actions associated with running (Shapiro et al., 1981) to fit the new environmental demands. Should the performer decide to switch to a sprint, it is anticipated that a new GMP would be implemented to generate a different pattern (Hay, 1993).

To execute a different GMP necessary to transition from walk to run, sensory information (i.e., vision) is used in the translation step to convert a stimulus to an action response. Light information enters the eye and stimulates different classes of neurons in the retina which will transmit light as electrical impulses to the brain (Pashler, 2004). The impulses will reach the visual cortex where relevant information will be dispersed to different brain areas (Zhu, Zhang, & Rio-Tsonis, 2012). Once sensory information reaches memory, some memorized component or pattern of the stimulus is recognized as previously encountered information (i.e., a stored visual representation; Marr, 1980). It is suggested by David Marr, a prominent researcher who studied the role of vision in stimulus-response relationships, that vision plays a crucial role in the process of solving issues that humans encounter regularly (Marr, 1980). This is accomplished by making decisions based on these stored visual representations; this is where the selection of an appropriate GMP occurs. By understanding and identifying visual stimuli, the brain works to create relevant action responses. From this idea came *Marr's Tri-Level Hypothesis* which looked at three levels of stimuli analysis in the visual system: (1) computational – what does the system do, (2) algorithmic – how does the system perform and manipulate the representations, and (3) implementational – what structures implement the visual system (Dawson, 1998). Through the visual system and the processing of visual information, humans develop these representations that can be accessed for response selection. Marr suggests that there are three stages of vision that allow us to do so: (1) primal sketch – this stage focuses on fundamental feature extraction, (2) 2.5D sketch – textures of the scene start to become acknowledged based on a viewer-centred representation, and finally (3) a 3D model – an object centred description that is on a continuous three-dimensional map (Marr, 1980). In computing these representations, valid constraints of the world are discovered and an idea of how it behaves is established, allowing the performer to recover sufficient information to gain a sense of the expected result (Marr, 1980). Following this level of identification, the system can make a decision on the appropriate action response.

An example of transmitting visual information to GMP selection can be seen in a game of tag. The visual system analyzes the surrounding environment and identifies another player (i.e., your target). The brain will collect information such as the location and speed of the target, and will match these factors with stored mental representations – this will provide an idea of the outcome should you choose to initiate this action response. Based on this analysis, the brain is likely to select a GMP that has a class of actions related to running. Should the target increase in speed as you approach them, this GMP may only be sufficient up until a certain point. Once the threshold for speed is surpassed in this GMP, visual information would then trigger a new GMP to be selected to initiate sprinting patterns based on another stored mental representation.

While information processing theory plays an important role in understanding human interactions with the environment, there are some limitations. To begin, there is the "novelty problem" which looks at how new skills would ever be learned if actions are controlled by learned programs (Muratori, 2013). GMPs attempt to address this problem however they still do not account adequately for the movements made in the early months of life. The human system is able to produce new movements without having experienced them before, which is an essential component to motor programs (Muratori, 2013). There is also the limitation of using the working memory since humans can only store limited information within it at a time, otherwise performance starts to decline (Klingberg, 2000). Information processing theory also places a heavy burden on centres of executive function. In this framework, executive functioning would decide all movements through the processing of perceptual information, which in turn translates into an abundance of neuromuscular commands and the control of musculature (Muratori, 2013). Therefore, the central executive would be in control of all change and movement. This, however, is a very inefficient process to produce movements and would overwhelm the executive. Conversely, the ecological perspective holds that perception is direct and requires no intervention of cognitive processes (Konczak, 1990).

## 1.3. Perception-Action

### *1.3.1. Perception-Action: The Role of Optic Flow*

A more parsimonious explanation of how humans translate perception into action lies with the previously discussed ecological framework, wherein the link between the two components is direct and de-emphasizes the translatory cognitive mediation necessary in Information Processing. The two branches of the ecological theory are complementary in nature, with their underlying components stressing the importance of the linkage for optimal movement performance within the environment. However, the more specific focus of dynamical systems on the physics of movement goes beyond the scope of this proposal, leaving the relationship between perception-action as the main driving theory. A fundamental component of the perception-action approach is optic flow. *Optic flow* is the pattern of motion of the environment caused by the movement between the observer and the visual scene (Warren et al., 2001). It results from an optic array on the eye, defined as changing angles of light rays on the eye as it moves through space, which is then received by the retina. This identifies the nature of the eye's movement, thus identifying one's body in space (Gibson, 1977). Optic flow plays a critical role in navigation (Rand et al., 2019; Redlick, Jenkin, & Harris, 2001; Turton et al., 2009), control amongst obstacles detected in the environment (Franchak & Adolph, 2010; Marigold & Patla, 2008; Matthis, Barton, & Fajen, 2017; Matthis & Fajen, 2014), and depth perception (Koenderink & van Doorn, 1987; McManus, D'Amour, & Harris, 2017; Simpson, 1993; Wexler & Van Boxtel, 2005). Through optical flow fields, we control locomotion with perception-action coupling. It plays a significant role when humans first learn to locomote as our first movements are triggered by our visual scene. Without optic flow, this process becomes decoupled and individuals lack the visual calibration of the action component, leading to slower environmental adaptations (Klostermann & Mann, 2019; Koenderink & van Doorn, 1987; Warren, 1990). There have been many advances in research that have identified how to analyze this visual motion. It is now better understood that to interpret the visual scene, neural cascades from the retina within the visual field are integrated with local motion signals to create more global descriptions of the speed and direction of the object (Pashler, 2004). This visual information received by the retina can come from dynamic and static information. Dynamic information is generated by an individual’s self-motion and the motion of objects in the environment, while static information is received when the observer remains in the same place (Mohapatra & Aruin, 2013).

#### *1.3.2. Association Between Locomotion and Vision*

Development of locomotion begins early in infancy and is initially influenced by visual cues (i.e., dynamic visual flow, head motion, gaze shifts; Di Giorgio et al., 2017; Inman, 1966; Kretch, Franchak, & Adolph, 2014). While locomoting may appear as a simple task, it is rather an “extraordinarily complex skill” requiring years to develop

(Pandy & Andriacchi, 2010). Forward locomotion requires the integration of major walking muscles to move the body in opposition to the downward gravitational pull. There are five muscles that mainly do this: vasti group, gluteus maximus, gluteus medius, gastrocnemius, and soleus. The vasti, gluteus maximus, and medius support the initial portion of the walking stance where feet are separated in the line of progression, while the gastrocnemius and soleus act to accelerate and lift the body into the second half of the walking movement where the back foot propels over the extended leg (Pandy & Andriacchi, 2010). This movement causes the centre of mass to move in a sinusoidal, wave like pattern reaching high and low amplitudes (Borghese et al., 1996; Inman, 1966). The pelvis produces two motions during this movement: rotation along the horizontal plane where the pelvis rotates forward with the swinging leg, and a pelvic drop in the frontal plane on the side of the swinging leg (Borghese et al., 1996; Inman, 1966). The knee and foot work together during locomotion to reduce the height of the centre of mass against gravity (Inman, 1966; Pandy & Andriacchi, 2010). When the heel strikes the ground, the knee will then reach its maximal extension. As the body weight is transferred into the foot through ankle plantarflexion, the knee begins to bend allowing the body to transfer over the leg. Human arms act to help propel the body through the motion by counter-swinging with the legs (Inman, 1966).

Locomotion is regulated with vision both on a global level when it comes to planning a walking route, and on a local level which influences step-by-step patterns (Patla, 1997). Step by step patterns in this case are influenced through pre-planned strategies involving predictive methods that assist in calibration of one's actions (da

Silva, Barbieri, & Gobbi, 2011; Patla & Vickers, 2003). This means that the body is stabilized through inter-segmental maintenance based on estimations of perturbations through visual examination of the oncoming terrain (Higuchi, 2013). Therefore, vision plays an important role when it comes to avoiding potential perturbations. Identifying and avoiding threats to maintain stability are done so through the visual system by altering foot placement to change step width and length, increasing space between the legs in the line of progression to avoid obstacles, changing locomotor direction, or stopping all together when obstacles cannot be avoided (Basili et al., 2013; Fink, Foo, & Warren, 2007; Higuchi, 2013; Menuchi & Gobbi, 2012; Patla, 1997). Optic flow also helps individuals navigate to goals even when the target cannot initially be seen. This is done by navigating stimuli that have no relationship to the target in the surrounding environment (Kirschen et al., 2000; Turano et al., 2005). For example, when navigating to a target in a forested area, individuals will use cues such as dirt pathways and trees to guide them towards an unseen target. This visual information is also used along the route to avoid obstacles that may pose a threat to obtaining the desired target. Should vision be interrupted during locomotion amongst obstacles, it is suggested that humans assume a robotic form due to the lack of information attained from other senses when independent of vision (Rossi, Rodrigues, & Forner-Cordero, 2014). When humans were evaluated on their ability to navigate obstacles with no vision, gait parameters were altered resulting in decreased velocity, higher toe clearance, changes in hip position, and patterns of movement that became more cautious. When compared with trajectories of a robot, humans mimicked their patterns when vision was not available, making the system more inefficient and less in control when producing movement (Rossi, Rodrigues, & Forner-Cordero, 2014). Vision also plays a critical role in locomotion by providing body posture and movement information, and this information often takes precedence over the other sensory modalities (Hartcher-O'Brien, Levitan, & Spence, 2010; Hecht & Reiner, 2009; Patla, 1997). For example, those with visual disorders generally have more unstable postures despite other sensory modalities being fully functional, or even having heightened functionality (Lee, 1980). This stresses the importance of optic flow on locomotion since in the absence of vision, important locomotor factors like posture and gait variables (i.e., step calibration, step length, stride length) start to decline in functionality – this is likely due to the decoupling of perception and action, a relationship that is developed since birth.

*1.3.3. Perception and Action in Children*

The effects of optic flow on movement are evident early in development. Newborns typically exhibit spontaneous general movements and stepping reflexes upon elicitation (Lacquaniti, Ivanenko, & Zago, 2012). These movements are often random, although when optic flow is introduced, they become patterned and cyclic in accordance with what they are observing. An example from a study by Barbu-Roth et al. (2009) examined stepping responses in three-day old infants. Infants were suspended over a horizontal surface that was projected with either a static checkerboard, a translational checkerboard that moved towards the infant, or a rotational checkerboard that circled the infant. Results found that significantly more patterned air steps were taken by infants when exposed to optic flow specifying forward translation, versus the conditions of static and rotational flow. This innate coupling between perception and action demonstrates how visual information is used to initiate self-motion, and more importantly, how it is used at a very early age (Barbu-Roth et al., 2009). In another study, three-day old infants were suspended over a white table projected with either a static checkerboard pattern, a checkerboard pattern that moved either towards or away from the infant, and a tactile condition where infants could put their feet on the checkerboard-projected table (Barbu-Roth et al., 2014). Results showed that infants took more motivated steps in the tactile condition and when presented with a dynamic checkerboard position that moved toward them. This suggests that tactile and visual stimulation may elicit newborn stepping similarly (Barbu-Roth et al., 2014). The coupling of perception and action is evidenced early on in infancy and holds a similar impact on motion as tactile feedback. Here, the strength of the perception-action linkage can be seen through the comparisons of vision and touch; this linkage is innate and develops throughout one's movement experiences. Moreover, another study examined crawling patterns of 3-day old infants placed on a clear, water-filled mattress that had checkerboard patterns projected onto the bottom surface (Forma et al., 2018). Three conditions used to measure crawling patterns included a static, towards, and away condition similar to Barbu-Roth et al. (2014). The results showed that more crawling movements were taken in the optic flow conditions (towards and away) versus the static, but no significant differences were drawn between the towards and away conditions themselves (Forma et al., 2018). This demonstrates the importance of any optic flow on movement execution, as both towards or away conditions resulted in similar step production in infants. This again signifies the innate relationship between perception and action, since the perception of dynamic flow led to increases in movement performance without previous experience.

This early effect of optic flow on movement can also be seen during toddler stages. The moving room experiment by Lee and Aronson (1974) looked at the effects of visual proprioceptive control and its impact on standing in 13-16 month old toddlers. The toddlers were placed in an experimental room that had a ceiling with three moveable walls hanging above a stationary floor (Lee & Aronson, 1974). During trials, the toddler would stand staring at the closed end of the room, and all of the walls would either move toward or away from them. This visual motion would approximate the optic flow associated with forward and backward walking. Results showed that when the walls moved towards them, the child underwent a loss of balance and finished in a sitting position. When the walls moved away from them, the child would lean forward which would cause them to fall (Lee & Aronson, 1974). This demonstrated the strong effect of optic flow on the sensory-motor system of children, and how it affords action responses when experienced by the visual system (see also Bertenthal et al., 1997; Schöner, 1991; Stoffregen et al., 1987). This effect was also evident with adults in the moving room experiment, but to a lesser extent. Adults were found to have body sway that was correlated with the movements of the swinging room (Lee & Lishman, 1975), but the effects were not as significant as found in children. This suggests that as the system develops, other senses (such as proprioception) may begin to minimize the effects of vision alone. However, the perception-action linkage is so significant that it is still evidenced in the developed human system through the body sway response.

*1.3.4. Perception and Action on Postural Control*

It is apparent that vision plays an important role in movement execution, and this concept is further explored when looking more closely at postural control. While Lee and Aronson's (1974) moving room experiment provides compelling evidence of the effect of visual information on static posture (see also Bertenthal et al., 1997; Schöner, 1991; Stoffregen et al., 1987), this effect can also be seen in those with visual impairments versus those with typical vision. The finding by Lee (1980) mentioned previously, suggests that those who are blind typically have a less stable posture than those with typical vision, as they have been found to sway to a greater degree than do sighted individuals with eyes open as they stand. A similar pattern is found when sighted people close their eyes. A review by Alotaibi et al. (2016) addresses this finding by exploring the effect of the absence of vision on posture. It was found that children with visual impairments develop atypical motor patterns and postural reflexes that lead to faulty distributions of muscle force in the body. Without vision, the system undergoes a certain degree of sensory deprivation resulting in imbalances and destabilization, which can be corrected with visual information pertaining to location and body position in space (Alotaibi et al., 2016). Furthermore, the effect of vision on postural stabilization becomes even more important as we age. Poulain and Giraudet (2008) instructed younger (21-31 years of age) and older (44-60 years of age) participants to stand on a stabilometric platform and measured the effect of the visual environment on posture. During trials, participants were presented with a visual recognition task and a rapid serial visual presentation task during different time points. In between sequences of pictures, participants were presented with intervals of darkness where they were to focus on a small point of light. It was found that the older group was more unstable during trials, especially in dark periods. Their stability was more dependent on the properties of the visual environment, and the task constraints within it (Poulain & Giraudet, 2008). This suggests that participants lost their level of stability when vision and attention were taken away. Similar results were also reported in additional studies that examined postural control in elderly participants who completed 'eyes closed' versus 'eyes open' trials in conditions made unstable through different standing supports and varying visual scenes. Postural instability was found to increase with age when visual information was disturbed (i.e., eyes closed trials; Berard et al., 2012; Borel & Alescio-Lautier, 2014; Borger et al., 1999; Perrin et al., 1997; Teasdale et al., 1991).

*1.3.5. Perception and Action on Locomotion*

Visual information also influences locomotion as optic flow provides parameters crucial for movement performance. Locomotion is heavily dependent on our visual scene, as it dictates what obstacles or different terrains one may encounter that can affect their gait. In Ecological terms, this refers to what action possibilities are afforded by the available environmental or task constraints. A study conducted by Antley and Slater (2010) looked at the effect of an immersive virtual environment with changing optical flow patterns on human locomotion. Participants were instructed to walk under three conditions with and without virtual reality: walking on the floor, walking on a narrow ribbon on the floor, and walking on a beam. Electromyography (EMG) measurements were taken on the lower spine muscles and showed higher levels of muscle activation when participants walked on the platform compared to the floor. Higher EMG activation levels were also demonstrated when walking through virtual environments and experiencing changes in optic flow delivery, despite undergoing the same walking conditions. This demonstrates that optic flow can influence locomotion by helping the body prepare for more challenging movement environments (Antley & Slater, 2010). This assistive effect of optic flow was also found in a study completed by Konczak (1994) that explored how inducing changes to the visual scene could affect human locomotion. Younger (mean age of 22.1 years) and older participants (mean age of 74.0 years) were tasked with walking through a hallway while the checker-styled walls around them moved forwards and backwards. They were subjected to six different optic flow conditions, some of which were produced by room movements: eyes open, eyes closed, global backward flow, global forward flow, peripheral forward flow, and central forward flow. Findings in this study suggest that conditions involving eyes open and forward flow had assistive effects on human locomotion, rather than producing a destabilizing effect. It was found that both groups of participants attempted to match their walking speeds to the speed of the visual scene they were experiencing (Konczak, 1994). Optic flow was also found to assist older adults in a dual-task paradigm that investigated declines in cognitive and gait function. After experiencing an immersive virtual environment on a treadmill and simultaneously performing tasks, participants were found to have improvements in gait parameters such as step width (Leeder et al., 2019).

As noted earlier, optic flow patterns play a critical role in how we control our gait parameters to execute locomotion efficiently. Warren et al. (2001) investigated how vision is used to control human walking, whether it be by focusing visually on the goal itself, or by using optic flow to specify locomotion direction. After immersing participants in a virtual environment that displaced optic flow from the walking direction, it was found that participants fixate on a lone target to control locomotion direction, but rely on optic flow when the target is found in a display of items (Warren et al., 2001). This indicates that vision in itself plays a critical role in locomotion, with great importance placed on optic flow to locomote through complex environments. Vision also helps locomotion through apertures by influencing the perception of relative body size compared to aperture width (Stefanucci & Geuss, 2009). As individuals approach apertures such as doorways, the pattern of motion on the eye helps to determine what body position is required to move through the door. It has been determined that the individual must perceive at least an aperture width of 1.3 times their shoulder width, or they will rotate their body to effectively locomote through the doorway (Warren Jr & Whang, 1987). This finding demonstrates how optic flow plays an important role in our perception, and how ultimately this will affect our actions for movement performance.

#### *1.3.6. Effects of Decoupling Perception and Action on Movement Control*

The effects of removing visual cues and disassociating the perception-action linkage can be detrimental to movement performance. The dissociation of perception and action has been explored in the literature in a variety of ways. Visual illusion tasks (i.e., Muller-Lyer, Ponzo, and Ebbinghaus-Titchener illusions) provide evidence for perceptual and behavioural changes that occur when perception and action are unlinked in a complex environment. Some results have shown that when exploring illusions with vision alone, the perceptual system is influenced by the illusion leading to inaccurate spatial measurements (e.g., Biegstraaten et al., 2007; Sperandio et al., 2010; van Doorn, van der Kamp, & Savelsbergh, 2007). However, when the perceptual and motor system are recoupled by having the participant physically interact with the illusion, spatial performance was often left unaffected during these movements (e.g., Carey, 2001; Coello et al. 2007; Glover, 2004; Glover & Dixon, 2001, 2002; van Doorn, van der Kamp, & Savelsbergh, 2007). This demonstrates that when perception and action are linked, it leads to more accurate judgements and movements. Moreover, studies involving brain-injured persons have provided strong evidence supporting the perception-action linkage by demonstrating the effects that occur when they are unlinked. For example, studies have looked at individuals who have experienced damage to specific areas of the brain which are involved in processing visual inputs (Ganel & Goodale, 2019; Goodale et al., 1991; Perenin & Vighetto, 1988). In cases of optic ataxia, patients were unable to move their hand accurately to the object despite being able to identify it (Perenin & Vighetto, 1988). Contrarily, individuals with visual agnosia were unable to identify the object but were able to accurately move towards it (Ganel & Goodale, 2019; Goodale et al., 1991). This provides evidence of the perception-action linkage, and how its dissociation leads to ineffective movements, or movements that are not guided by perceptual goals.

Perceiving visual motion is critical to the locomotive activities of all organisms (Pashler, 2004). It has been shown that simply the presence alone of visual motion can compensate for other deficiencies in visual information. Deficient optic flow, therefore, is more important to have than no optic flow at all. This motion affords the opportunity to collect influential information regarding the physical capacities of surrounding objects, as well as information about the observer relative to their environment in relation to those objects (Pashler, 2004).

## 1.4. Research Program Objectives

### *1.4.1. Literature Gaps*

Despite the demonstrated importance of the perception-action linkage and the various effects on movement that it imposes, there is a line of research that fails to keep these two concepts linked: rehabilitation literature. Rehabilitation practices geared towards improving atypical gait patterns often carry out treatment protocols that unintentionally cause the absence of optic flow during locomotive actions (e.g., Harkema et al., 2012; Hicks et al., 2005; Macko et al., 2005). Looking more specifically at neurological disorders such as spinal cord injury (SCI), rehabilitation treatments often involve the use of physiotherapy. Physiotherapy uses goal-directed exercises aimed at improving functional ambulation impacted by poor motor control, muscle weakness, and contractures (Harvey, 2016). To ensure safety, physiotherapy sessions are primarily held indoors to allow for the use of harnesses and rails. For example, a common practice to retrain walking patterns is the use of a stationary treadmill with overhead suspensions (Harvey, 2016). This provides individuals with a visually static environment, thus removing the previously mentioned effects of dynamic visual stimulation. While this method of training has been shown to boost motor function by improving variables like gait and balance (Hicks et al., 2005; Hicks & Ginis, 2008; Yen et al., 2012), improvements come at the cost of lengthy, expensive, and exhausting treatment plans

(Nas et al., 2015). One reason for this could be due to the deficiency of visual flow in these rehabilitative environments. By using a stationary treadmill, persons with neurological disorders experience locomotion without the perception-action coupling created with optic flow. The process of relearning to walk becomes inconsistent with the perceptual-motor experiences they had when they began to walk as children (Bertenthal et al., 1997; Lee & Aronson, 1974; Schöner, 1991; Stoffregen et al., 1987). Therapists are activating musculature in the absence of visual information that individuals have been linking with locomotion since birth, and are not replicating the movement environments that patients will experience outside of the rehabilitation setting. This also creates new and unwelcomed perceptual-action calibration between the new gait pattern and vision.

For example, Hicks et al. (2005) took a group of 14 incomplete SCI (iSCI) participants through a long-term body-weight supported treadmill training program in order to investigate how adaptations are maintained. Participants completed 144 training sessions within 15 months which entailed sessions of 5-15 minute walking bouts on a stationary treadmill. Results showed lasting effects of this training eight months later, which included improved treadmill walking ability, capacity to walk over ground, and walking speed (Hicks et al., 2005). A similar study carried out by Harkema et al. (2012) took 196 iSCI participants through an intensive locomotor training program using manual facilitation and body-weight supported treadmills. Participants completed a median of 112 sessions consisting of one hour of step training with body weight support, then an assessment lasting 30 minutes. Researchers found improvements in the Berg Balance Scale (BBS), six-minute walk test, and balance following the treatment plan (Harkema et al., 2012). Similar results have also been found in studies looking at the effects of treadmill training on participants following ischemic stroke. A study completed by Macko et al. (2005) took 61 stroke patients with hemiparetic gait through a six month rehabilitation program. Two groups were established that completed either aerobic treadmill training or stretching with a low intensity walk. Both groups completed 40-minute sessions three times a week. Results showed that the aerobic training group saw significant improvements in ambulatory performance and mobility function, while also demonstrating increases in training velocity (Macko et al., 2005). Therefore, in this regard, treadmill training has shown to be effective at improving performance measures and ambulation (see also Duncan et al., 2007; Duncan et al., 2011; Globas et al., 2012; Ivey et al., 2015; Luft et al., 2008; Patterson et al., 2008). However, these study results have come at the cost of intensive and lengthy treatment plans, and improvements may not be optimized in terms of perception-action outcomes. This may be due to the absence of optic flow in this environment, mitigating the development of important locomotive parameters – this includes variables mentioned earlier such as movement accuracy, depth perception, and other gait measures (Koenderink & van Doorn, 1987). These cannot be fully developed without perceptomotor experiences.

The literature has shown instances where reintroducing dynamic visual information, or optic flow, into training protocols have shown larger gait improvements in shorter times than typical exercise protocols. This has been done through overground walking versus treadmill walking protocols (Combs-Miller et al., 2014; Field-Fote & Roach, 2011; Gama et al., 2017), and through uses of virtual reality (VR) in standard therapy protocols (An & Park, 2018; In et al., 2016; Kang et al., 2012; van Dijsseldonk et al., 2018; Villiger et al., 2017). This research, however, is limited in scope and quality, especially for SCI studies (Yeo et al., 2019), and needs significantly more testing. These studies have suggested that the only underlying difference with their protocols from typical treatment is the incorporation of optic flow into their paradigms – an idea that requires further and more in depth exploration. Therefore, the current research program aims to fill this gap by evaluating how the reintroduction of optic flow into atypical gait training protocols can enhance rehabilitative outcomes. This series of studies takes the literature further by looking at outcome enhancements through neuromuscular level changes, the recalibration process of perception-action given one's newly acquired physical constraints, and on larger scale gait cycle performances.

*1.4.2. Study Objectives*

This research program has been developed to explore the strength of the perception-action linkage and its viability as a useful tool for rehabilitation. Specifically, this research series questions how vision contributes on a neuromuscular level to action in different postures, how it can calibrate our actions in typical versus atypical gaits, and how optic flow can be applied to typical therapy protocols for adaptation to altered locomotor constraints in gait-compromised populations. This program will use virtual reality (VR) to incorporate optic flow into what were formerly visually static environments to recouple perception and action.

A series of three independent but conceptually related studies will be performed that each explores an individual component of the overall research question. The purpose of Study One is to determine the strength of the perception-action linkage in adults by testing to see if optic flow will elicit automatic activation of the musculature appropriate for response to the perception of that information, in the absence of voluntary movement. This study will assess lower limb muscle activation in static stance and seated positions when individuals receive virtual reality displaying dynamic motion (optic flow information). Study Two will extend these findings to include a voluntary movement protocol to assess whether this perception-action linkage is beneficial to calibrating spatial updating during locomotion with artificially compromised gait. This study will temporarily compromise the typical gait pattern of typically developed adults through the use of full-leg bracing and will assess measures of gait performance (i.e., action) and global spatial awareness (i.e., perception) prior to and following a training protocol with and without congruent visual information. Finally, Study Three will apply this gathered knowledge to assess the hypothesized linkage of perception and action in a rehabilitative setting. This protocol will include the use of standard therapy protocols, virtual reality, and a population with a neurological disorder: spinal cord injury.

*1.4.3. General Expectations*

In Study One, it is hypothesized that receiving dynamic visual information will elicit an increased neuromuscular response compared to baseline activation levels. More specifically, it is expected that in the standing versus sitting trials, larger increases in neuromuscular response will be experienced due to the perception of a stimulus affording posture. This is anticipated to occur since throughout one’s lifetime, sitting positions become associated with passive movement while standing positions are typically associated with an active stimulus-response relationship developed through the perception-action linkage (Antley & Slater, 2010; Barbu-Roth et al., 2009; Lee & Aronson, 1974). This is also hypothesized due to previous studies demonstrating an existing relationship between stimulation of the visual-sensory system and neuromuscular activation in everyday applications (e.g., subvocalization; Jorgenson, Lee, & Agabont, 2003; Mohanchandra & Saha, 2016; Schultz & Wand, 2010).

In Study Two, it is hypothesized that spatial awareness will be more accurate and measures of gait performance will improve more rapidly in the group provided with dynamic visual information (i.e., optic flow). This is expected due to the calibration process that occurs between the induced atypical gait pattern with visual information, forcing a reconstructed perception-action linkage with one's new physical constraints (Burkitt et al., 2020; Campos et al., 2009).

In Study Three, it is expected, based upon the expected results of studies one and two, that participants with pathologically comprised gait (e.g., SCI) who receive dynamic visual information (i.e., optic flow) will experience enhanced rates and quality of positive rehabilitative outcomes (An & Park, 2018; van Dijsseldonk et al., 2018; Yeo et al., 2019). Optic flow is expected to allow these individuals to obtain environmental information that will assist them in their adaption process to their new physical constraints. They will be able to interact with the environment more consistently with the perceptual-motor experiences they encountered as children (Koenderink & van Doorn, 1987; Lee & Aronson, 1974; Warren, 1990).

# CHAPTER 2: STUDY 1

**2.1. Background**

Perception-action coupling has been demonstrated to be present across the lifespan. Much of the support for this theory has been derived from studies assessing newborn (e.g., Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Forma et al., 2018) and infantile (e.g., Bertenthal et al., 1997; Lee & Aronson, 1974; Stoffregen et al., 1987) stages of development. While there is existing literature surrounding perception-action coupling in adulthood (e.g., Poulain & Giraudet, 2008; Warren et al., 2001), the strength of the relationship requires further exploration in the adult population.

Some examples of how optic flow can influence motion in adults comes from the Lee and Lishman (1975) moving room experiment carried out with 24, 18-30 year old adults. Participants were given instructions to engage in four different stances within trials: standing, standing on a ramp with toes facing downwards, standing on pads, and standing on toes. They were also instructed to have their eyes either open or closed depending on the trial condition (Lee & Lishman, 1975). During some trials, the surrounding room would move forward or backward while the floor remained stationary. Results demonstrated that participant body sway was correlated with the movements of the swinging room. All four stances showed significantly more swaying than the position of a stationary room with eyes open. In addition, all trials showed increases in postural sway compared to the control position of eyes closed with room motion (Lee & Lishman, 1975). This suggests that an innate coupling between perception and action, often demonstrated in children, remains through adulthood and is strong enough to induce a neuromuscular response in the absence of voluntary movement. Our association between vision and locomotion that has developed over a lifetime intimately ties the locomotor response to visual movement cues. Another study by Hoshikawa (1999) looked at how a manmade titling room could affect body sway in 16 undergraduate students. Participants were instructed to stand in an upright position within a room containing a stationary floor and surrounding walls that would tilt to induce visual motion. Body sway was measured during trials using a force plate. It was found that participants swayed forward when the room tilted forward, and swayed backwards as it tilted backwards (Hoshikawa, 1999). This suggests how human posture can be influenced by changing optic flow patterns, due to the intimate tie between perception and action. This standing position affords the possibility of locomotion when visual motion is introduced to the participant, leading to an involuntary postural response. An additional study by Wade et al. (1995) examined how this moving room paradigm affects younger and older adults differently. Forty-five participants were divided into two groups: 20-59 years old, and 60-83 years old. Baseline conditions were taken while the participants and walls were stationary, with eyes open and closed conditions. Experimental conditions involved the walls moving forward or backward to induce optic flow, but only specific walls would move with respect to the condition (i.e., a radial condition where the front wall moved, a lamellar condition where the side walls and ceiling moved, and a global condition where the ceiling, front and side walls moved; Wade et al., 1995). Results were gathered using a force plate and showed that both groups demonstrated more sway in the experimental versus the baseline conditions. Additionally, older adults showed greater instability during the lamellar and global trials compared to the younger group (Wade et al., 1995). Here, elderly individuals appear to rely more on visual information in comparison to younger adults, however, both groups still rely on visual cues for motion control. That is, the perception-action linkage is still evident throughout different stages of life. Chander et al. (2020) took the moving room experiment one step further with the use of virtual reality to mimic the moving walls. VR-induced perturbations were used by changing the direction of the walls in the virtual environment while the participant remained stationary in space. Postural stability and control were evaluated during each trial using force measurements. It was shown that both anticipatory and compensatory responses were made in response to expected and unexpected perturbations induced by the VR, respectively (Chander et al., 2020). These moving room paradigms collectively suggest that the perception-action linkage appears to change from childhood to adulthood. In children, perception of visual motion leads to greater observable movement responses (i.e., falling over) whereas in adults, less of an overt response is evident presumably due to superior multisensory integration. Corrections to stance occur rapidly in adults due to a more well-developed involvement of the proprioceptive system. However, postural swaying in adults is still evident to some degree with perceived visual motion, suggesting that there are neural responses occurring at the level of the muscle.

Virtual reality has been found to be a useful tool for evaluating locomotor tasks and looking at how sensory cues, such as vision, can influence movement (Chander et al., 2020). Considerable evidence for this is reported in a literature review carried out by Barros et al. (2013) that examined how VR can be used for rehabilitation training. It was found that VR successfully simulates real-world situations, providing the advantage of being able to specifically control rates of optic flow (Barros et al., 2013). Additionally, other studies have suggested that virtual environments afford the ability to study these variables of interest with safety, controlled exposure, and conditions that are considered ecologically valid (Bühler & Lamontagne, 2018). In the case of the present study, a variable of interest is optic flow and how it can be used to study the strength of the perception-action linkage within stationary positions. Since this type of dynamic flow would typically require participants to engage in voluntary movement, VR can realistically deliver the same visual information achieved through motion within a stationary environment.

As suggested with the moving room experiments, adults may have better postural resistance than do children to perturbations induced by independent visual motion. This may make the strength of the perception-action linkage appear weaker as one develops. However, this does not mean that optic flow is not impacting other perceptual elements critical to movement (e.g., internal models of postural anticipation; Chander et al., 2020). Therefore, in response to dynamic vision, analyzing lower limb muscle activation via electromyography (EMG) is a method of assessing the strength of the perception-action linkage on movement. When inducing visual cues similar to those experienced during locomotion, EMG responses in the leg should be specific to stationary postures that lend themselves to forward locomotion (i.e., standing versus sitting). Dynamic optic flow during standing is a stimulus that affords walking, while dynamic optic flow in a seated position is a stimulus that affords passive translation (e.g., driving in a car). This perception-action relationship is developed at young age and refines through our perceptomotor experiences (Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Koenderink & van Doorn, 1987; Lee & Aronson, 1974). Additionally, it is suggested that in response to visual cues that are created through expanding retinal images of the approaching environment, individuals elicit preparatory signals to trigger muscle pre-activation (Lee, 1976; Sidaway, McNitt-Gray, & Davis, 1989) to endure the upcoming required motion. This is an important mechanism that relates closely to the availability of optic flow. As mentioned previously, this effect was explored by the Antley and Slater (2010) study that examined how a virtual environment with perceived increasing challenging terrain influences muscle activation. This study demonstrated how changes in optic flow that simulate increases in difficulty can increase EMG activity, and how this activation occurs despite the participants walking the same control path through each trial. That is, new environmental cues lead to more muscular preparation due to our innate perception-action coupling. This is also seen in studies involving subvocalization, which has shown how muscles (i.e., those of the larynx) are capable of low-level activation based on incoming sensory information but in the absence of overt movement (i.e., reading a book or a series of words without speaking them; Jorgenson, Lee, & Agabont, 2003; Mohanchandra & Saha, 2016; Schultz & Wand, 2010). The activation patterns of the muscles shown in these studies are so correlated to what the visual system is experiencing that anticipated speech can be distinguished in the absence of speaking (Schultz & Wand, 2010). This suggests evidence for the strength of the perception-action linkage in adults, as neuromuscular activation results in response to visual cues. More specifically, results such as these suggest that passive sensory reception can "prime" the musculatures appropriate to acting on those sensations, but at a level too low to elicit overt movement.

Few studies using VR have been completed that looked at how the effects of optic flow elicits increases in muscle activity. More specifically, this research has generally only been done in populations who require rehabilitation. The virtual environment provides opportunities for persons with movement disorders to experience optic flow while walking on a stationary apparatus (e.g., treadmill). An example of this is Yoo et al. who explored the effects of a VR game and EMG biofeedback in persons with cerebral palsy (Yoo et al., 2014). Participants were led through a protocol where they were to catch virtual fish with their hands. This task combined VR with EMG biofeedback to improve muscle imbalances in reaching movements. All participants underwent training sessions with the VR and EMG biofeedback combination, and biofeedback alone. After analysis, researchers found improvements both in the activation of hypo-active triceps muscles, and decreased hypertonic or overactive biceps in the VR and biofeedback combination training versus the biofeedback alone (Yoo et al., 2014). This suggests that the provision of optic flow information can have positive effects on rehabilitation protocols as it can provide important variables that are presumably necessary to develop and activate neuromotor control in addition to common training tools. It also suggests how meaningful impacts of optic flow using VR can be made at the level of the muscle for movement performance. Another study by Park et al. (2016) investigated the impact of VR based eccentric training on lower limb muscle activation and balance in individuals who underwent a stroke. Thirty participants were divided into two groups: one used a slow velocity training program while the other used fast velocity. This type of training has been shown to improve lower limb muscle activation in stroke patients compared to concentric training, however, session times were lengthy (i.e., 90 minutes, three days a week for eight weeks; Clark & Patten, 2013). For this study, training was done eight weeks at 30 minutes a day, five days a week (approximately half the previously studied durations). Significant differences in EMG activity were observed in the group participating in slow velocity training with VR in comparison to the fast velocity group (Park et al., 2016). These differences were found in shorter periods of time, suggesting that optic flow provided through VR plays a role in developing neurological changes in combination with standard training regimens. The evidence in these non-walking tasks hints that optic flow in stationary walking conditions (i.e., a treadmill) should be impactful on a neural level, as the lower limbs will activate more readily with visual experiences due to perception-action coupling.

Since the perception-action linkage between walking and dynamic optic flow seems to remain throughout adulthood (Chander et al., 2020; Hoshikawa, 1999; Lee & Lishman, 1975) and can assist in redeveloping movement patterns by eliciting muscle activation responses, Study One of this proposal examines whether leg muscles show different activation levels in the presence of dynamic optic flow in stationary standing versus seated postures. This will provide an understanding of how the perception-action linkage behaves in the absence of voluntary movement, and whether some positions afford more visuomotor possibilities than others. It is hypothesized that upon experiencing dynamic visual information with VR, participants will experience increased muscle activation compared to baseline measures. It is predicted that greater increases above baseline activation will mainly occur in the standing position. This is expected because vision and walking are so inherently linked that it should be most impactful in the posture for which dynamic optic flow is an affordance for walking. The onset of optic flow and the environmental cues expanding on the retina in the standing position should elicit pre-activation patterns in the lower limbs as it mimics typically encountered movement information (Lee, 1976; Sidaway, McNitt-Gray, & Davis, 1989). As a result, the musculature should undergo muscle priming in response to the anticipation of the upcoming terrain compared to static vision (Lee, 1976; Sidaway, McNitt-Gray, & Davis, 1989). In the seated position, it is likely that participants will show increased muscle activation above baseline, however, only at sub-threshold levels. This position is often associated with passive movement (e.g., sitting in a wheelchair) which would mediate the level of activation, but the visual stimulation should still result in increased activation due to the system perceiving a stimulus to be acted upon. Additionally, it is hypothesized that as speeds are increased, muscle activation increases are also predicted to occur. This falls in line with previous research on perception and action response (Antley & Slater, 2010; Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Forma et al., 2018; Lee & Aronson, 1974).

## 2.2. Methods

### *2.2.1. Participants*

This study will adopt a group sequential analysis to allow for more efficient hypothesis testing (Lakens, Pahlke, & Wassmer, 2021). To determine sufficient sample sizes, a Pocock Alpha Spending Function (RPACT Shiny App Software; Appendix A) was used to obtain sample sizes for two interim analyses (33% and 66% of total sample) and at the final analysis (100%). The parameters for the analysis included $\alpha$ at 0.05, $\beta$ at 0.2, *d* at 0.6, and a one-group division. This spending function spends alpha approximately equally across each look (analysis one $\alpha = 0.0226$, analysis two and three $\alpha = 0.0217$) and conserves type I error rates by distributing it equally over the sequential test. The spending function resulted in sample sizes of 10, 19, and 28 for looks at 33%, 66%, and 100%, respectively.

This study will recruit participants aged 18-35 years old from the McMaster University student population and the local Hamilton community. Participants will also be screened to ensure they fit the following inclusion and exclusion criteria: individuals must be self-reported right-hand dominant, have normal or corrected-to-normal vision, have no self-reported neurological disorders that may interfere with muscle activation, and present with no musculoskeletal impairments or injuries. Prior to participating in the study, participants will sign a letter of informed consent outlining the background for the experiment and the protocol to be performed. Upon completion of the study, participants will be compensated $20.00 for their participation.

*2.2.2. Location and Apparatus*

This study will take place in the Sensorimotor and Behavioural Neuroscience Lab (IWC AB104) in the Ivor Wynne Centre at McMaster University. Prior to performing the experiment, participants will be fitted with circular, wired electrodes to the gastrocnemius, soleus, vastus lateralis, tibialis anterior, and vastus medialis muscles

(Pandy & Andriacchi, 2010; Suica et al., 2016; see Figure 1). The muscle bellies will be identified using contraction and palpation techniques. The skin above the muscle belly will be prepared by shaving and rubbing the area with isopropyl alcohol to remove debris and dead skin cells, and minimize the potential for skin reactions. Conductive gel will be placed on the electrode which will then be attached to the skin via adhesive sensor stickers. The electrode placement will run parallel to the muscle fibre orientation (Perotto & Delagi, 2005). A ground electrode will be placed overlying the participant's sacrum (Suica et al., 2016). EMG signals will be collected using the Delsys Bagnoli EMG (Delsys Inc., Massachusetts, USA) system, sampling at a rate of 2500 Hz in alliance with SENIAM surface EMG guidelines (Rose, 2019) and will be differentially amplified. To normalize the EMG data, participants will be instructed to complete three, 10 second quiet trials where they are to remain stationary. This will occur after participants get into both experimental positions and before peak activity trials are recorded. Peak muscle activity will also be used to normalize the data and will be collected three times for five seconds, two minutes apart, following the quiet trials and before experimental trials (Perotto & Delagi, 2005). To obtain this activity in a seated position, participants will be instructed to extend their knees and push up against a researchers hands without overcoming their force. In a standing position, this will be achieved by asking the participant to push their foot into the ground.

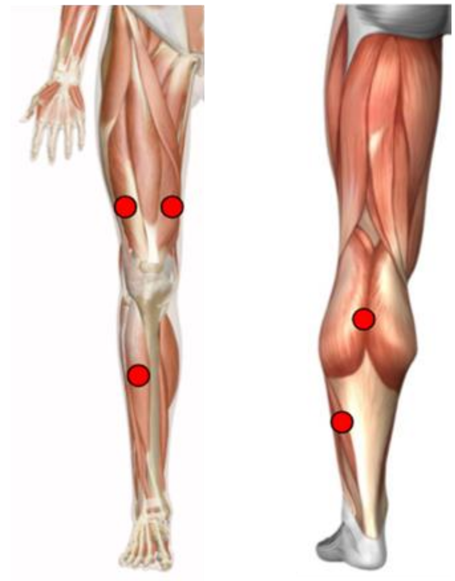

**FIGURE 1.** Anatomical locations of the wired EMG electrodes. Electrodes are superimposed with a red circle for image clarity. Anatomical positions of the wired electrodes include: gastrocnemius, soleus, vastus lateralis, tibialis anterior, and vastus medialis muscles. These muscles will be located with palpation techniques.
*Image: ("Innerbody Research", n.d.)*

*2.2.3. Experimental Procedure*

This experiment is expected to take approximately one hour to complete. Upon entering the lab, participants will be instructed to change into shorts to allow lower limb exposure for EMG electrode placement. This will require palpation of the lower leg muscles and skin preparation as outlined in Section 2.2.2. Once the electrodes are in position participants will be instructed to sit on a designated chair.

Once seated, participants will be outfitted with the Oculus Rift DK1 Virtual Reality Headset (Facebook Technologies, California, USA), henceforth referred to as the VR headset. Straps will be tightened until the headset is comfortably situated over the eyes and resting on the nose. The virtual hallway used in this study will be coded using

Unity 2020.3.0f1 Software and the Unity Hub Platform (Unity Technologies, San Francisco, USA), and will be programmed to display a four foot wide by eight foot tall hallway in absolute coordinates, with aspects such as windows and doors to enhance the realism (see Figure 2). The participant will be shown a practice simulation for a total of two minutes displaying dynamic optic flow at a rate of 1.4 m/s, as this approximates the average speed of human walking (Browning et al., 2006). This is to allow the participant to become familiar with the visual scene while maintaining a stationary posture.

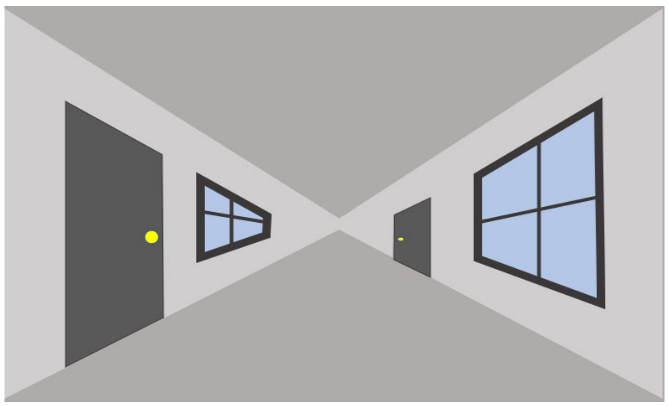

**FIGURE 2.** Example of the virtual 4'x8' hallway presented during experimental trials in the Oculus Rift DK1 Virtual Reality Headset.

Following the practice trial, EMG wiring will be connected to the electrodes and participants will undergo the normalization trials mentioned in Section 2.2.2. while seated in the chair. No VR display will be shown at this time. When peak activity trials are completed as seen in Section 2.2.2., participants will remain in a seated, upright position and not engage in any voluntary muscle contractions. Instructions for the upcoming trials will be to explore the virtual environment with their eyes and imagine the movements associated with what they are experiencing. The VR headset will then turn on and continuous EMG recording will commence.

At the start of every trial, a static display of the virtual hallway will be shown for 10 seconds, after which the VR speed will increase 0.5 m/s every 10 seconds until a VR speed of 3.0 m/s is reached. Ten-second bouts were selected to allow for visual stimulus reception (~20-40 milliseconds) and processing (~180-200 milliseconds) in the brain (Jain et al., 2015). Once 3.0 m/s of VR optic flow has been displayed for 10 seconds, the VR speed will decrease in increments of 0.5 m/s every 10 seconds until a speed of 0.5 m/s is reached. The VR will then display a static virtual hallway for 10 seconds as shown at the beginning of the trial. After this, EMG will stop recording and the VR headset will turn off to allow participants to move into the next seated or standing position. For standing trials, the procedure remains the same except that participants will be instructed to stand upright, head facing forward, arms by their side, and to remain stationary in space.

### *2.2.4. Data and Statistical Analysis*

Custom MATLAB R2021a (The MathWorks Inc., Massachusetts, USA) code will be used to analyze the EMG data. Raw data will be normalized using the collected normalization trials and filtered using a band-pass filter with a low-pass cut-off of 500 Hz and a high-pass cut-off of 20 Hz (Rose, 2019). Muscle activation will be measured as peak activation amplitude (mV) and average activation (mV) per VR speed. Peak amplitude provides the maximal electrical potential of a given muscle per specific time frame. It will provide a measure of reaction to stimulus onset and gives an indication of the immediate effects of changing optic flow speed. Following data normalization and filtering, the peak EMG amplitude will be calculated in relation to the peak activity normalization trial and expressed as a percentage of this contraction (Hibbs et al., 2011). This will quantify the maximal utilization of the muscles as they engage in the protocol. Contrastingly, average EMG activation will provide information about how the musculature reacts to a presented stimulus over time, and whether this activation remains stable, increases, or decreases following a change in VR optic flow speed. This will be calculated by taking the EMG activation graph and dividing it by the time period (Hibbs et al., 2011). Average EMG provides a measure for any submaximal activation that occurs throughout the protocol (Hibbs et al., 2011).

These dependent measures of EMG activation will be analyzed in R for Statistical Analysis (Bell Laboratories, New Jersey, USA) using 2 position (sitting, standing) x 2 speed direction (increasing, decreasing) x 7 VR speed (0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 m/s) repeated measures ANOVA. Alpha will be set at $p < 0.0226$ for interim analysis one and $p < 0.0217$ for analyses two and three (if required). Mauchly's test will be used to test for the assumption of sphericity. Should sphericity not be met, Greenhouse-Geisser correction factor will be applied. Post-hoc comparisons will be done using the Bonferroni post-hoc test, since it is most sensitive to type I errors.

### 2.3. Expected Results

Looking specifically at the standing position, it is expected that the perception-action linkage between optic flow and posture will lead to muscle activation that increases and decreases, respectively, with increasing and decreasing VR optic flow speeds. Specifically, peak amplitudes (mV) in activation should increase almost immediately as the VR optic flow speeds increase, and average activation levels should increase after each speed increase, but plateau over each 10 second bout. Subsequently, as the VR optic flow speeds decrease, peaks activation levels should become smaller and average activation levels should decrease across each 10 second bout. These patterns reflect preparatory signals that would be elicited according to ecological theory, which suggests that optic flow inherently affords that act of locomotion in standing postures. This would allow for the musculature to prepare for the oncoming optic flow condition (Lee, 1976; Sidaway, McNitt-Gray, & Davis, 1989). Compared to the standing trials, sitting trials are anticipated to produce similar patterns of muscle activation above baseline, however, activation is expected to occur to a lesser extent (i.e., significantly below threshold compared to the standing position). This is due to the passive movement experiences typically experienced in this position (e.g., passenger in a car) which may mediate anticipatory muscle activation in the lower limbs (Lee, 1976; Sidaway, McNitt-Gray, & Davis, 1989). Typically, sitting positions may not afford locomotion, but the experience of optic flow alone should trigger the system to respond to oncoming stimuli.

If the hypothesis is supported, this experiment will demonstrate the inherent link between optic flow perception and preparatory action in a posture that affords locomotion. This will provide a theoretical basis for Study Two, in which the perception-action linkage will be taken into a treadmill protocol involving artificially compromised gait. Here, static and dynamic vision will be paired with a novel walking pattern (i.e., asymmetrical gait) to exemplify how dynamic vision impacts the calibration necessary for understanding and developing accurate spatial awareness.

# CHAPTER 3: STUDY 2

### 3.1. Background

Human beings are capable of walking without vision through the environment due to our characteristic spatial awareness. This has been suggested to happen automatically through a process known as iterative spatial updating, which continuously monitors and updates one's position in space, relative to a mental representation of the environment as one locomotes about the environment without vision (Loomis, Klatzky, & Giudice, 2013). This process is heavily influenced by vision, with optic flow being a major contributor to how these mental representations are updated as one moves through their surroundings. In particular, optic flow provides movement information important for spatial updating processes, such as the ability to navigate through the environment amongst obstacles, understanding of depth perception, and the relative closeness of oneself to the environment (Franchak & Adolph, 2010; Koenderink & van Doorn, 1987; Matthis, Barton, & Fajen, 2017; Matthis & Fajen, 2014; Wexler & Van Boxtel, 2005). This visual information gathered from the environment is then converted into spatial orientation cues (e.g., dimensions, direction, speed, and relative placement; Butler, Campos, & Bulthoff, 2015; Campos, Butler, & Bulthoff, 2014; Campos, Ramkhalawansingh, & Pichora-Fuller, 2018; Riecke, Bulthoff, & Cunningham, 2007) to effectively execute actions. These visual cues are suggested to be calibrated with the walking step-cycle, as these underlying visual processes estimate parameters of self-motion such as speed and distance through kinematic parameters (i.e., step length, stride length, and step frequency; Mittelstaedt & Mittelstaedt, 2001; Multon & Olivier, 2013). Therefore, the spatial updating process is responsible for transforming these egocentric, or body centred, representations of the immediate environment during ego-motions (Riecke, Bulthoff, & Cunningham, 2007) to effectively navigate through space.

Some studies have shown that without vision, humans can accurately walk to targets approximately 20 metres away (e.g., Loomis & Philbeck, 2008) due to the spatial updating process. However, no-vision conditions have also been shown to be less accurate when targets are presented at a greater distance; this can include target over- and under-shooting (Commins et al., 2013; Sun et al., 2004). This suggests that as walking extent increases, no-vision conditions may become prone to accumulating error (Commins et al., 2013; Harrison, Kuznetsov, & Breheim, 2013; Lappe, Jenkin, & Harris, 2007). Other factors that may contribute to these findings are: the type of gait, gait kinematics, and static cues during preview of the environment (Mittelstaedt & Mittelstaedt, 2001; Philbeck & Loomis, 1997; Turvey et al., 2009).

Atypical gait patterns may pose situations in which spatial updating may become affected due to the intimate tie between the step-cycle and spatial awareness (Burkitt et al., 2020; Mittelstaedt & Mittelstaedt, 2001; Multon & Olivier, 2013). These patterns of movement can be temporarily induced, or may develop with factors such as aging, injury, or disease (Alsalaheen et al., 2010; Basford et al., 2003; Walker & Pickett, 2007). Atypical gaits contain differing step characteristics that will ultimately change how one moves about their environment (Alsalaheen et al., 2010; Basford et al., 2003; Walker & Pickett, 2007). Their ability to update their mental representations will change, which will reduce its effectiveness in no vision conditions. For example, in a study completed by Turvey et al. (2009), participants conducted no-vision walking trials where they were to move towards a target and then return towards the starting home position. The participants used gaits that either belonged to similar classes of symmetry (e.g., walk-walk or walk-run) or dissimilar symmetry classes (e.g., walk-gallop walk or walk-hesitation walk). Central pattern generators suggested to exist in the spine produce specific signal properties that classify each symmetry class as either primary (e.g., walk and run), which sends similar signals to each leg, or secondary (e.g., gallop-walk and hesitation-walk), which send different signals to each leg. The ability to accurately return home following reaching the target was found to be more accurate when similar classes of symmetry were used, indicating that the perceived distance travelled is specific to the gait-symmetry class (Turvey et al., 2009). These results suggest that atypical gait patterns ultimately affect the spatial updating process, as the system specifies coordination between the two limbs within its mental representation to accurately locomote without vision (see also, Chrastil & Warren, 2014; Turvey et al., 2012). Spatial updating may also be impacted with atypical gait due to an increased frequency of errors resulting from changes within their gait kinematics, a factor relating to inaccurate or low precision updates (Mittelstaedt & Mittelstaedt, 2001).

A method of analyzing a person's ability to iteratively update their spatial location in no vision walking movements is by using a continuous pointing task (Campos et al., 2009). This task allows for the study of spatial updating as it unfolds online during the course of a no-vision walking movement (Campos et al., 2009). The continuous pointing task involves participants continuously pointing their finger toward a target beside the walking path as they locomote forward in a straight line. A reliable measure of perceived distance travelled versus actual distance travelled can be gleaned from the pointing responses throughout the entire walking motion (Burkitt et al., 2020; Campos et al., 2009; Siegle et al., 2009). This task was used more recently in a study by Burkitt et al. (2020) that showed participants under-perceived their actual physical location as they walked without vision further along the walking path, and that this spatial updating process was linked to the early right foot swing phase of the step cycle (Burkitt et al., 2020). This task can be used to understand how static and dynamic vision calibrates spatial updating with novel gait patterns, and how its accuracy can improve with adaptation.

To re-establish accuracy within the spatial updating process of someone with an atypical gait, it is expected that re-engaging in locomotion within dynamic vision conditions will recalibrate their new step-cycle constraints with their visual experiences (Mittelstaedt & Mittelstaedt, 2001; Multon & Olivier, 2013). The effects of recalibration are demonstrated in a study by Rieser et al. (1995) that examined how prolonged exposure to visual-proprioceptive conflict can change spatial updating processes in no-vision walking. The protocol involved participants walking toward targets prior to and following an adaptation period. The adaptation period required participants to walk on a treadmill placed on an open trailer that was pulled through the surroundings via a tractor. The tractor would either pull the treadmill faster than the treadmill speed (i.e., proprioceptive movements) or it would pull it slower, creating a disconnect between visual information and movement speed. Results showed evidence of post-adaptation recalibration, since participants would undershoot target location in no vison conditions following slower tractor speeds, and would overshoot the target following high tractor speeds. These errors occurred without the participant altering their step characteristics, suggesting recalibration altered perceived distance travelled (Rieser, 1995). Optic flow in this case created visual experiences that tied the spatial updating process to their step-cycle, resulting in changes to updating within their mental representations during no-vision walking (see also Mohler et al., 2007). Building off of this idea, it is expected that if individuals with atypical gait retrain their walking patterns with optic flow, new mental representations that are more in-line with their atypical gait patterns versus their previous patterns will be established allowing them to update more accurately. This allows them to re-develop their egocentric representations of the immediate environment for transformation by the spatial updating process during ego-motions (Riecke, Bulthoff, & Cunningham, 2007). This process was demonstrated in a study by Wilson, Foreman, and Stanton (1999) that looked at training spatial awareness in children with physical disabilities such as muscular dystrophy, spina bifida, and cerebral palsy (i.e., populations with atypical gait and inaccurate spatial awareness). Children were randomly allocated into one of two groups (i.e., 2D explorational platform games and 3D virtual environment games) where they completed four 30-minute exploration sessions. Testing involved pointing to various targets within the games and measuring accuracy. Results showed 3D games group decreased significantly in error rates versus the 2D group. These changes were found to be translational into a real-world environment (Wilson, Foreman, & Stanton, 1999). It is likely that this occurred due to the development of spatial awareness variables such as navigation, depth perception, and obstacle avoidance that would only be available in a 3D space with optic flow.

Taken together, the literature in this field of study offer compelling evidence that the calibration of perception and action (i.e., between vision and locomotion) is a necessary process for the complex action of spatial updating. If it is interrupted with a change in walking pattern, iterative spatial updating is hypothesized to benefit from being calibrated with dynamic visual information (i.e., optic flow). Therefore, this experiment aims to evaluate the hypothesis that pairing static and dynamic vision with a novel and recently acquired walking pattern will result in differential impacts on the accuracy of no-vision walking performed after this calibration. It is also not yet understood how the spatial updating process will be affected if atypical walking patterns specifically target the right leg (e.g., in stroke or spinal cord injury populations), since Burkitt et al. (2020) found an association between updating iterations and the right-foot swing in the step cycle. These results suggest that impairment of the right leg may lead to more challenging methods of adapting to the compromise and developing one's spatial awareness. The specific hypothesis for this study is that by coupling congruent perception and action using virtual reality, the group that experiences optic flow will see a more rapid rate of adaptation to gait compromise and a greater accuracy in global spatial awareness compared to the static vision group (Burkitt et al., 2020; Campos et al., 2009). Gait parameters are expected to become more efficient and individual performance is expected to increase. Additionally, measures of spatial awareness will be expected to become more accurate in response to receiving optic flow.

### 3.2. Methods

This study is an adaptation and extension of the Burkitt et al. (2020) study and will follow closely to its experimental procedures, with some protocol changes.

*3.2.1. Participants*

This study will adopt a group sequential analysis to allow for more efficient hypothesis testing (Lakens, Pahlke, & Wassmer, 2021). To determine sufficient sample sizes, a Pocock Alpha Spending Function (RPACT Shiny App Software; Appendix B) was used to obtain sample sizes for two interim analyses (33% and 66% of total sample) and at the final analysis (100%). The parameters for the analysis included $\alpha$ at 0.05, $\beta$ at 0.2, *d* at 0.6, and a two-group division. This spending function spends alpha approximately equally across each look (analysis one $\alpha = 0.0226$, analysis two and three $\alpha = 0.0217$) and conserves type I error rates by distributing it equally over the sequential test. The spending function resulted in sample sizes of 36, 70, and 106 for looks at 33%, 66%, and 100%, respectively.

This study aims to recruit participants aged 18-35 years old from the McMaster University student population and surrounding Hamilton community. Participants will be screened to ensure they meet the following inclusion and exclusion criteria: must have normal or corrected-to-normal vision, have no self-reported neurological disorders, and present no musculoskeletal impairments or injuries. Individuals must also be self-reported right-hand and right-foot dominant. Prior to participating in the study, participants will be asked to sign an informed consent document that will outline the background for the experiment and the experimental protocol. Upon completion of the study, participants will be compensated financially in the amount of $20.00 for their participation.

*3.2.2. Location and Apparatus*

This study will take place in the Sensorimotor and Behavioural Neuroscience Lab in the Ivor Wynne Centre at McMaster University. Participants will be asked to perform the experiment shirtless/wearing tank top (males) or wearing a tank top/sports bra (females), shorts, and running shoes. Participants will be outfitted with 21 retroreflective markers (B & L Engineering, California, USA) with a diameter of 25 mm attached to the following anatomical locations: sternal notch, xyphoid process, left and right anterior superior iliac spines, left and right posterior superior iliac spines, toes of the left and right feet, left and right acromioclavicular joints, right lateral, posterior and anterior shoulder, right lateral and medial epicondyles, right ulnar and radial styloid processes, central right hand, cervical spinous process seven, and the thoracic spinous processes three and seven (see Figure 3; Burkitt et al., 2020). These markers will be attached to the skin through the use of double-sided electrode tape that is designed for skin usage and will be captured during the experimental trials (see below) by 10 Vicon Nexus MX-T40 cameras (Vicon Motion Systems Ltd., Oxford, UK) sampling at a rate of 100 Hz. Participants will also be outfitted with two wooden chopsticks, surrounded in medical tape, affixed to the lateral and medial parts of the index finger and extending proximally down the forearm toward the wrist. This is in efforts to avoid ulnar and finger deviations. Additionally, an iPod Shuffle (Apple Inc., California, USA) will provide white noise to participant during experimental trials to minimize sounds from ambient noises and footsteps that may indicate spatial location. Participants will also be asked to bring a baseball cap to hide ceiling light cues.

**FIGURE 3.** Anatomical locations for the retroreflective markers according to Burkitt et al. (2020). Here, the markers are superimposed with white circles for image clarity. The landmarks of interest for study two are as follows: sternal notch, xyphoid process, left and right anterior superior iliac spines, left and right posterior superior iliac spines, toes of the left and right feet, left and right acromioclavicular joints, right lateral, posterior and anterior shoulder, right lateral and medial epicondyles, right ulnar and radial styloid processes, central right hand, cervical spinous process seven, and the thoracic spinous processes three and seven.

Masking tape will be used to create a six metre walking path along the floor with a target marked as "X" at the end. Tape will also be used to create eight "X" side targets as in the Burkitt et al. (2020) study. To indicate which target will be used for each trial, a green circle covering the selected target will be used for reference. Targets 1-4 will be located two metres beside the walking path and 2.5, 2.7, 3.2, and 3.6 metres along the path, respectively. Targets 5-8 will be located three metres beside and 2.2, 2.6, 3.0, and 3.5 metres along the path, respectively (see Figure 4). Changing the location of the side target creates variability in the trials for the participants in efforts to avoid memorized motor responses. Burkitt et al. (2020) found minimal differences between performance with differing side target locations, so data for the dependent variables will be collapsed along all target locations for the statistical analysis.

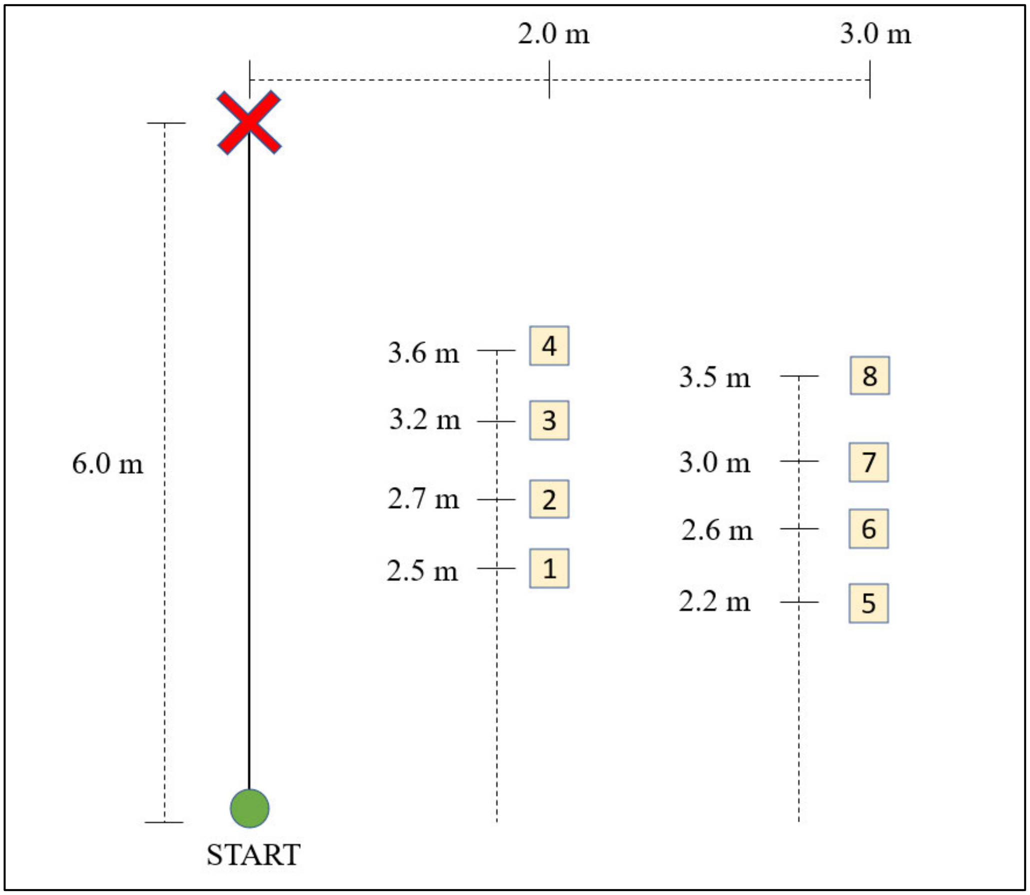


**FIGURE 4.** Overview of the experimental pathway and targets. Green circle marks the start location and red 'X' marks the end target. Solid black line marks the walking path for the continuous pointing task. Yellow boxes mark each of the eight side target locations, marked with target numbers. Targets 1-4 are 2.0 m from the walking path while targets 5-8 are 3.0 m from the walking path. Dashed lines represent measures of distance (adapted from Burkitt et al. (2020)).

A full-leg brace (Hanriver, China) fitted to the right leg will also be required for the experimental protocol (see Figure 5).

**FIGURE 5.** Full leg brace (Hanriver, China) used to artificially compromise gait. Brace contains a hip, knee and ankle immobilizer to restrict joint movement.

*Image: ("Amazon", n.d.)*

*3.2.3. Experimental Procedure*

Upon entering the lab, participants will be randomly assigned to either the control (i.e., static vision group) or experimental group (i.e., optic flow group; see below) and will not be informed of their group allocation. Participants will be asked to change into the required attire (see Section 3.2.2) and the researcher will apply the 21 retroreflective markers (see Section 3.2.2. and Figure 3). Participants will then be fitted with the Oculus Rift DK1 Virtual Reality Headset (Facebook Technologies, California, USA). Straps will be tightened until the headset is properly situated over the eyes and resting on the nose. Participants will be escorted to the treadmill (Horizon T.93, Johnson Health, Tech., Taiwan) where they will be given the opportunity to practice walking with the virtual environment. The virtual environment will be programmed using Unity 2020.3.0f1 Software and the Unity Hub Platform (Unity Technologies, San Francisco, USA), and will display the same virtual four foot wide by eight foot tall hallway in absolute coordinates as in Study One, with aspects such as windows and doors to enhance the realism (see Figure 2). The treadmill speed will be set lower than the average walking speed of 1.4 m/s (i.e., at 1.0 m/s) since walking with a full leg brace will be more challenging (Browning et al., 2006). Participants will concurrently experience either VR optic flow at a rate of 1.0 m/s if in the optic flow group or experience a static visual scene (i.e., 0 m/s) if in the static vision group. They will be provided three minutes of practice with the groups' respective level of optic flow. Once this practice session is completed, participants will be asked to remove the headset, put on their baseball cap, activate the white noise, and move to the designated walking path outlined with masking tape (see Section 3.2.2.).

Participants will perform continuous pointing trials where they will be required to align themselves at the start location of the walking path, assume the anatomical position (i.e. star formation with legs shoulder width apart, arms outstretched by their sides), and remain in this position until instructed by the experimenter (this position is necessary for stationary for marker calibration at the start of each trial). The researcher will then signal the start of each trial with a "thumbs-up", at which point participants will locate the side target, raise and straighten their right arm while ensuring their palm is facing downwards. Their index finger should be pointing at the target. They will then be told to locate the target at the end of the walking path and walk towards it at their own selected speed with a constant velocity, while continuously pointing at the side target. They are to walk forward until they believe they are atop the target, then stop. This will encompass the vision trials (when their eyes are open guiding them to the target location). For no-vision trials, the trial procedure is exactly the same except participants will close their eyes immediately before walking forward. They will be required to keep their eyes closed until they are escorted back to the start location by the experimenter and are signalled to open their eyes with a tap on the shoulder.

Participants will first complete three vision followed by three no-vision practice trials. When the participant is confident in their ability to perform the task, they will complete a block of 10 recorded vision continuous pointing trials followed by a block of 10 recorded no-vision continuous pointing trials. They will then enter a mandatory rest period for the duration of their choosing.

After resting, participants will be fitted with the full leg brace to the right leg (see Figure 5). To practice walking with the brace, they will complete three vision and three no vision practice trials on the continuous pointing task while wearing the brace. When confident walking with the brace, they will complete a block of 10 recorded vision continuous pointing trials followed by a block of 10 recorded no-vision continuous pointing trials. They will then enter a second mandatory rest period for the duration of their choosing.

Following the second mandatory rest period, participants will remove their ball cap, put on the VR headset, and will be escorted to the treadmill where they will complete the experimental manipulation. The experimental manipulation will entail participants walking on the treadmill at 1.0 m/s for a total of 20 minutes while wearing the brace. During the 20 minutes, participants in the optic flow group will experience a virtual walking speed of 1.0 m/s (to match the actual walking speed) and participants in the static vision group will receive a static (i.e., 0 m/s) virtual environment. The safety clip will be connected and participants will be asked to hold onto the rails at all times. The Vicon will record the toe foot markers for one minute durations at minute 0 (0%), 5 (25%), 10 (50%), 15 (75%), and 20 (100%) of the time on the treadmill. Twenty minutes was chosen to capitalize on individuals adapting to the manipulation – the longer one remains in the virtual manipulation, the longer the effects of the manipulation will last (DiZio & Lackner, 2002).

Following the VR experimental manipulation, participants will be instructed to close their eyes and keep them closed while removing the headset, then put their ball cap back on. They will then be escorted off the treadmill with their eyes closed to the starting location of the continuous pointing task. Participants will immediately complete a block of 10 recorded no-vision walking trials, after which they will complete a block of 10 recorded vision walking trials. They will then enter another mandatory rest period where the brace will be removed (total time of one minute). Participants here will be resting on a chair to limit their movement with their eyes open, as there is a potential for recalibration with no-brace walking.

After the third rest period, and without the brace, participants will complete a block of 10 recorded no-vision trials followed by a block of 10 recorded vision walking trials. The total number of trials for the experiment is 80 recorded walking trials. This testing session is projected to take approximately two hours to complete.

*3.2.4. Data and Statistical Analysis*

To process the collected Vicon data, all trials will first be processed using Vicon Nexus 2.12 software (Vicon Motion Systems Ltd., Oxford, UK). The data sets will be reconstructed, and each retroreflective marker will be labelled for every frame of data collection (Burkitt et al., 2020). These data will then be converted to a C3D format and processed using Visual 3D (C-Motion Inc., Ontario, CA). Within Visual 3D, a custom model will be constructed using a static calibration trial and will be attached to the 3D marker data for all trials. Joint centres highlighted in this model include: the thorax, shoulder, shoulder girdle, shoulder anteroposterior joint, elbow, and wrist. This then will create body segments that represent the thorax, pelvis, right forearm, and upper arm. The model can be used to analyze all sets of data by creating a method of measuring joint angles of the trunk, elbow, and shoulder from body segments (Burkitt et al., 2020). From these joint angles, dependent measures can be extracted using a custom MATLAB R2021a program (The MathWorks Inc., Massachusetts, USA). Joint angle and marker data will be filtered using a 6 Hz dual-pass Butterworth filter to minimize the noise within the sample. To determine the start and end of the walking trials, step velocity will be used. That is, when the foot exceeds a velocity of 0.02 m/s and remains above it for 25 frames (i.e., 250 ms), and then returns to a velocity of 0.02 m/s and remains below it for 25 frames. This will allow all dependent variables to be analyzed within each walking trial (Burkitt et al., 2020).

Step Characteristics: Stride Length, Step Length, and Step Velocity

Gait characteristics will be examined for both the continuous pointing task trials and the treadmill walking sessions. Stride length will look at the forward displacement between toe-off and heel-down periods of a single foot in its swing phase, step length refers to the distance between the two feet following a swing phase at the moment of double support, and peak step velocity refers to the maximum change in displacement over time (Burkitt et al., 2020; Multon & Olivier, 2013). To calculate these variables per trial, displacement profiles will be constructed per foot and a three-point finite difference algorithm will be used to obtain velocity profiles. For each left and right stride, peak velocity will be identified. Once identified, the points from the corresponding section of the velocity profile that drop below the allocated step criterion will be selected. That is, velocity start will be measured when the velocity drops below 0.05 m/s on the peak's foreside, and velocity end will be measured when velocity drops below 0.05 m/s on the peak's aft side. Step and stride lengths will be averaged across each of the walking trials (see Burkitt et al., 2020).

Perceived Distance Travelled

To measure perceived distance travelled, an azimuth angle (ϴ) must be calculated. The participant's arm rotation relative to their trunk provides the azimuth angle, which indicates the person's perceived location relative to the target location. Joints necessary to calculate this angle are axial rotation of the trunk and plane of elevation of the shoulder (Burkitt et al., 2020). Rotation in both the shoulder and trunk are expected along the walking path (i.e., 6 metres) in order for participants to keep their finger aligned with the side targets (i.e., 2-3 metres). This can create fluctuations and noise in the perceived distance travelled measure, so therefore must be minimized. To do so, the raw trajectories will be submitted to Fast Fourier Transforms to determine frequency contents of each of the signals. Using their respective frequency contents, these signals will be reconstructed with those less than 0.5 Hz and then summed together (see Burkitt et al., 2020). Using this summed trajectory, perceived distance travelled can be obtained through a series of calculations. Specifically, by knowing the distance of the side target (Y) and the azimuth angle (i.e., summed joint trajectories; Θ), Equation 1 can be completed to determine how far the person perceived themselves to be relative to the side target (ΔX). Then by subtracting ΔX from the target measure ($X_{TARGET}$; Equation 2), instantaneous perceived distance travelled along the walking path is obtained at every frame of data collection (see Figure 6 for detailed image). These instantaneous measures provide a perceived distance travelled trajectory for every frame of data collection, but will only be analyzed at 1.0 metre increments (Burkitt et al., 2020).

**Equation 1:** $X_{TARGET} = Y\tan\Theta$

**Equation 2:** $X_{START} = T - X_{TARGET}$

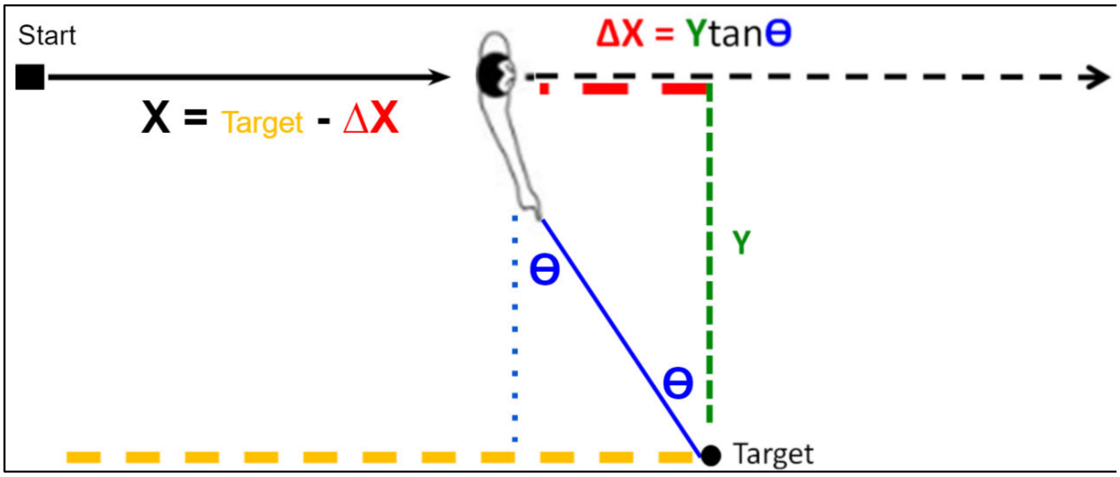


**FIGURE 6.** Overview of the information required to calculate perceived distance travelled using data collected from the continuous pointing task. During trials, participants are to walk forward along the walking path (solid black line) and continuously point (seen with the solid blue line) to the side target location (black dot). The azimuth angle (Θ and blue lines) is measured with the shoulder and trunk rotations. Y, or the green line, measures the distance between the walking path and side target. The yellow line measures the side target distance from the start position. **Δ**X measures perceived distance between the participant and the side target. **Δ**X is then used to calculate **X**, which measures perceived distance travelled along the walking path by the participant (adapted from Burkitt et al. (2020)).

Arm Deviations in Relation to the Step-Cycle

To examine the relationship between the upper limb segments and the step-cycle in the spatial updating process, a trajectory-parsing procedure used in Burkitt et al. (2020) will be used on the raw trajectories of the shoulder plane of elevation. Trunk rotation angles are not used in this process as they contain step-cycle oscillations that do not reflect solely pointing behaviour. The trajectory-parsing procedure will identify shoulder plane of elevation joint angle patterns, since this is the component directly related to the azimuth angle calculations. Within the shoulder trajectory, deviations from the trajectory average can be quantified and used to classify discrete patterns of upper limb control.

This will provide an indication of purposeful changes in control made by the CNS. To obtain shoulder joint velocity and deviations within the trajectory, similar analysis methods to Burkitt et al. (2020; p. 152-154) will be used. After identifying significant arm deviations within the trials, the starts and ends of each deviation will be overlaid with specific phases of the step cycle. More specifically, this will include velocities in the double stance phase before the step-swing (DS), before peak swing (BP), peak swing (PS), and after peak swing (AP). These will be further reduced into four categories: early right foot (ERF), early left foot (ELF), late right foot (LRF), and late left foot (LLF). DS, BP, and PS will be summed and will satisfy the early category, while AP will be used for the late category. This will approximate the phases of toe-off and heel-strike of the step-cycle, which arm deviation frequency counts will be tallied in according to Burkitt et al. (2020). These tallies will be transformed using an arcsine transformation to convert it into parametric data that can later be used for statistical analysis. This measure will provide information as to which phase of the step-cycle the CNS spatially updates its position in space with.

Constant Error Relative to Front Target Location

Constant error is the measure of the position of the walker from the target at the end of each walking movement. To obtain measures of constant error relative to front target location, actual distance of the individual relative to the target can be measured at the end of the walking movement (as previously discussed). This can be collected for every trial, and all calculations can be averaged to examine how it changes pre- and post-test.

Statistical Analyses

To run statistical analysis on the continuous point task data, two separate ANOVAs will be used in R for Statistical Analysis (Bell Laboratories, New Jersey, USA), looking specifically at no-vison data: one for pre-test and one for post-test data. Vision data are not being analyzed since the comparison between vision and no-vision conditions has already been established in the literature (e.g., Burkitt et al. 2020; Campos et al., 2009; Siegle et al., 2009), and does not provide information relevant to the intended research question. A 2 group (static vision, optic flow) x 2 constraint (brace, no brace) x 6 distance (1.0, 2.0, 3.0, 4.0, 5.0, 6.0 m) mixed factors ANOVA with repeated measures on the last two factors will be used to test all of the dependent variables, for both pre- and post-test. On the treadmill manipulation data, a 2 group (static vision, optic flow) x 5 time percentage (0, 25, 50, 75, 100) mixed factors ANOVA with repeated measures on the last factor will be used to examine the dependent variables pertaining to gait characteristics. Alpha will be set at $p < 0.0226$ for interim analysis one and $p < 0.0217$ for analyses two and three (if required). Mauchly's test will be used to test for the assumption of sphericity. Greenhouse-Geisser corrections will be implemented for any violations of sphericity. Post-hoc comparisons will be conducted using the Bonferroni post-hoc test, since it is most sensitive to type I errors.

**3.3. Expected Results**

In line with the hypothesis, it is expected that the group who experienced optic flow matching their walking rate of 1.0 m/s would experience more rapid rates of adaption to gait compromise by showing greater accuracy in perceived distance travelled.

This is expected because optic flow plays a major role in our ability to locomote in our environments, and our first encounters with learning how to walk are associated with our visual scene (Warren, 1990). By relying on visual cues that originally triggered our walking patterns, and by experiencing typical perceptuomotor experiences while rehabilitating locomotion, retraining of walking patterns becomes consistent with our early and everyday locomotor encounters (Warren, 1990). Optic flow assists in developing locomotive variables important for the spatial updating process such as depth perception, navigation, and detecting environmental cues (Franchak & Adolph, 2010; Koenderink & van Doorn, 1987; Rand et al., 2019; Turton et al., 2009).

In terms of the gait variables, it is expected that participants will initially decrease their velocity between the no brace and brace trials as a result of their physical constraints changing due to artificial compromise. As the individual begins to adapt to the compromise and adjust to their new constraints, it is expected that step velocity will increase with adaptation. In addition, it is expected that the gait characteristics of stride length and step length will become more consistent (i.e., less variable) across a trial-to-trial basis. It is also likely that stride length will increase to compensate for the increases in velocity (Gajer, Thepaut-Mathieu, & Lehenaff, 1999). When looking at the spatial awareness measures, it is expected that both the perceived distance travelled and the measure of constant error relative to the target location will improve in the optic flow group due to the calibration of the new atypical walking pattern with dynamic visual information. It is likely that the participants will establish a new mental representation that encompasses their changed physical constraints, leading to more accurate spatial updating.

If these hypotheses are supported, this will provide support for implementing optic flow into rehabilitation protocols. It stresses the importance of the perception-action linkage in improving locomotion using perceptuomotor processes, since the results would suggest that optic flow can aid in recalibration of atypical gaits to improve measures of spatial awareness. This study will also demonstrate the immediacy effects of optic flow on adaptation. In as little as 20 minutes, changes in performance may be demonstrated providing support for shorter training protocols in rehabilitative settings. This will be beneficial as many injuries and diseases that impact locomotion result in patients being unable to participate in training for long periods of time. Current rehabilitation protocols for those with a SCI often use static optic flow to reintegrate gait patterns, but this is shown as an inefficient method through Studies One and Two. For rehabilitation, optic flow can contribute to neuromuscular control and can assist the recalibration between new atypical gait patterns and spatial awareness. Therefore, Study Three takes the perception-action linkage one step further to examine the influence of optic flow, using VR, on a typical rehabilitation protocol involving persons with SCI.

# CHAPTER 4: STUDY 3

## 4.1. Background

Rehabilitation is the process of helping restore an individual's mental, social, and physical states and skills following an injury or illness, in efforts to regain their maximum independence and self-sufficiency (Shiel Jr., 2018). This study will focus specifically on Spinal Cord Injury (SCI), a debilitating disorder resulting from temporary or permanent damage to the spinal cord (Sabapathy et al., 2015). An SCI can be classified as either traumatic or non-traumatic, depending on the nature of the injury. A traumatic SCI is caused by stretch, contusion, or compression of the spinal cord, while non-traumatic injuries are caused by internal dysfunctions that impact the cord (Nas et al., 2015; Sabapathy et al., 2015). The damage can result in either a complete SCI, which is a total loss of muscle function and sensation, or an incomplete SCI (iSCI), meaning some nervous signals can still pass through the injured area (Sabapathy et al., 2015). Regardless of type, this disorder can result in serious physical, psychosocial, and economic disparities, stressing the importance of efficient rehabilitation (Nas et al., 2015). Starting the rehabilitation process early is important to maintain muscle strength, conserve bone density, avoid joint contractures, and ensure that the digestive and respiratory systems maintain their function (Nas et al., 2015). As mentioned previously, SCI is often treated with physiotherapy protocols involving the use of a treadmill, which inherently causes the absence of dynamic visual information. This is hypothesized to be a reason why treatments are intensive, lengthy, and expensive, due to the absence of important perceptuomotor experiences. Research exploring the reintegration of optic flow into rehabilitation protocols for neurological disorders, especially with the SCI population, are limited but promising (e.g., An & Park, 2018; In et al., 2016; Kang et al., 2012; van Dijsseldonk et al., 2018; Villiger et al., 2017). This has included overground training protocols and VR implementation into standard training practices, which will be discussed further.

Rehabilitation protocols involving overground training have shown positive outcomes in comparison to those involving static visual treadmill environments. Overground training entails walking over short distances alongside a therapist who provides gait relevant cues in similar ways as provided during treadmill training (States et al., 2009). These sessions allow for patients to experience optic flow cues. A study by Field-Fote and Roach (2011) looked at locomotor training in persons with spinal cord injuries using either a treadmill-based or overground walking protocol. Participants trained five days a week for a total of 12 weeks and were assessed on speed and distance following the completion of training. Results showed that there were no significant differences between groups when looking at speed, however, the overground training group showed statistically significant distance gains (Field-Fote & Roach, 2011). Another study looked at the effects of body weight-supported treadmill training versus overground walking training in individuals with chronic stroke (Gama et al., 2017). Twenty-eight participants received either treadmill training or overground training and each group completed three sessions a week for six weeks. Although both groups improved in all outcome measures, the overground training group demonstrated significantly greater improvements in step-length and step-symmetry versus the treadmill group (Gama et al., 2017). A similar study examined the effects of body-weight supported treadmill training and overground training in a shorter time period (i.e., two weeks) to assess the immediate effects of each training protocol (Combs-Miller et al., 2014). Twenty participants with chronic stroke were divided into two groups: treadmill training and overground training. Each group completed 30-minute sessions, five times a week for two weeks. Results demonstrated that the overground walking group saw immediate improvements in comfortable walking speed, activity, and gait symmetry parameters following overground training versus the treadmill group. The overground training group also maintained these improvements in a three month follow up (Combs-Miller et al., 2014). These studies have demonstrated the effects of optic flow on similar training protocols, and have shown some superiority for those that include dynamic visual information. It has also provided evidence for immediate and lasting improvements in gait, suggesting that incorporating optic flow may reduce the length of treatment protocols without compromising gains.

However, overground training protocols are not always suitable and treadmill protocols are often the rehabilitation method of choice due to the safety features and feasibility that they offer. Therefore, an alternative method of incorporating optic flow into a common treadmill training protocol must be developed. One way of doing this can be through virtual reality (VR), which can generate immersive virtual environments that act to simulate real environments that an individual can take control over (Calado et al., 2013) in a rehabilitation setting. By adding VR to typical rehabilitation protocols, optic flow can be introduced without changing current effective strategies of treatment and altering safety features. The use of VR, in terms of the ecological perspective, attempts to reintegrate perceptual and biological motion that mimics the perceptual-motor experiences individuals had when they first learned to locomote. Theoretically, these are the movements they are attempting to relearn in training sessions. Individuals will experience a visual scene that is created by the optic array delivered in the virtual environment. Allowing individuals to visually move through the scene at the same rate they are walking will permit them to experience the locomotor effects of optic flow. The goal is to couple the visual perception of walking and action in a rehabilitation environment that normally decouples it.

There are some examples in the literature that have used VR in rehabilitation protocols for the treatment of illness and injury. These studies have focused heavily on how VR therapy can, not only improve locomotor gait variables (i.e., stride length, step length, distance) but also how this type of therapy can improve measures of dynamic balance (e.g., In et al., 2016; Kang et al., 2012; Villiger et al., 2017). Dynamic balance is important to consider after illness and injury as it is a functional attribute that features prominently in everyday life (Niiler, 2018). It is classified as one's ability to balance while in motion, such as when walking or switching positions from sitting to standing. Balance during forward motion relies on the position of one's centre of mass, which is the point where the relative distribution of body mass sums to zero (i.e., no internal forces; Tesio & Rota, 2019). Centre of mass must be maintained within the base of support (i.e., the area within the points of contact with the ground; Hof, Gazendam, & Sinke, 2005), meaning it must be within medial-lateral planes of one's support base to obtain stabilization (Havens, Mukherjee, & Finley, 2018; Young, Wilken, & Dingwell, 2012). When dynamic balance is impaired, it can lead to slower movements to protect the individual from a loss of balance (Niiler, 2018). This will ultimately affect the capacity of an individual to locomote through the environment and requires attention in treatment protocols in addition to typical variables of dynamic locomotor performance. As previously discussed in Section 1.3.4., optic flow plays an important role in how we maintain our posture for balance, providing specific visual cues indicating our position in space. Thus, it is anticipated that including optic flow via VR can improve balance in therapy protocols. For example, Kang et al. (2012) looked at the effects of treadmill training with VR on gait and measures of balance in patients following a stroke. Thirty participants were divided into three groups: treadmill with VR, treadmill only, and a control group. The VR group wore a head mounted display that was synchronous with their walking speed during treadmill training, while the treadmill and control group completed treadmill training and regular therapy, respectively. Each group completed 30-minute sessions, three times a week for four weeks. Performance was measured using a variety of tests including Timed Up-and-Go (TUG), Functional Reach Test (FRT), and other gait measurements including walking velocity. Results show that the treadmill with VR group demonstrated significant improvements in each measurement compared to the control group, and significant improvements compared to the treadmill group except for the functional reach test (Kang et al., 2012). In another study, In et al. (2016) examined the effects of VR reflection therapy (VRRT) on gait and balance. VRRT is an enhanced version of mirror therapy that projects recorded movements of the unaffected limb above the affected limb in a virtual setting. Twenty-five participants were allocated to groups that received either VRRT or a control condition. Both groups completed 30-minutes of conventional rehabilitation, while the VRRT group also performed a VRRT program for an additional 30 minutes. This treatment was performed five times a week for four weeks. Results showed that the VRRT group demonstrated significantly greater improvements in the FRT, Berg Balance Scale (BBS), TUG, and postural sway compared to the control group (In et al., 2016). Another experiment conducted by Kiper et al. (2018) looked at reinforced feedback in a virtual environment (RFVE) for upper limb rehabilitation following a stroke. Participants were divided into a group that received RFVE with conventional rehabilitation and a control group that received conventional rehabilitation. Both groups completed one, two-hour session, five days a week for four weeks. Researchers found that the RFVE group showed greater improvements in walking functional tests, time, peak velocity, and speed (Kiper et al., 2018). While there is considerable evidence supporting VR in the treatment of stroke conditions (see also Afsar et al., 2018; Chen et al., 2016; Choi & Paik, 2018; Corbetta et al., 2015; De Rooij et al., 2016; Lloréns et al., 2015; Malik & Masood, 2017), research examining VR and SCI rehabilitation, especially for the effects on gait, is very limited.

Some examples of the literature pertaining to the effects of VR for SCI rehabilitation explore a variety of factors that contribute to the overall quality of life of afflicted individuals. Heyn et al. (2014) explored how a mixed-reality exercise program could influence enjoyment and engagement levels of individuals with SCI and intellectual disabilities. This pilot study had six participants use endurance training equipment for one hour while immersed in a virtual environment that entailed a first perspective video of a biking/walking trail. Results showed that all participants increased their levels of enjoyment and engagement, while including positive feedback to the researchers (Heyn et al., 2014). It is important for participants to enjoy their experience while training to minimize lack of motivation and drop out. An additional study by Villiger et al. (2017) examined the impact of home-based VR training on lower limb function in iSCI individuals. This was done by providing participants with a VR system that could be used in their own homes to train their lower limbs. The system showed virtual representations of feet and legs in a first-person perspective, teaching them observation and execution. Participants completed 16-20 sessions over 4 weeks, at 30-45 minutes per session. Following training, results showed significant increases in TUG, BBS, and a Lower Extremity Motor Score (LEMS), demonstrating the improvement effects of VR on lower limb function (Villiger et al., 2017). Other studies have looked at the effect of VR on gait mobility and balance. In particular, An and Park (2018) looked at the impact of semi-immersive VR therapy on upright mobility function and balance in iSCI individuals. These participants underwent VR therapy entailing 20 programs such as “soccer” and “volleyball” in 30-minute sessions, three times a week for six weeks. Upon completion, participants showed increases in the BBS, a stability test, TUG, and a walking index score (An & Park, 2018). A similar study by van Dijsseldonk et al. (2018) took 15 iSCI participants through VR training in a Gait Real-Time Analysis Interactive Lab (GRAIL). GRAIL is a virtual interactive environment projected in front of a treadmill showing a variety of activities including obstacle avoidance, precision stepping, and perturbation reactivity. Participants trained in 12 1-hour sessions over a six-week period and demonstrated significant improvements in stride length, walking speed, and stability measures (van Dijsseldonk et al., 2018).

VR in combination with exercise protocols has been shown to result in significant improvements in the mobility and functioning of persons with SCI, demonstrating how optic flow may be added to existing effective treatments to enhance the quality of results. Additionally, VR in combination with treadmill protocols has shown significant results in less time, possibly due to the reintegration of the perception-action linkage. As noted earlier, this perception-action linkage is evident since birth (Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Bertenthal et al., 1997; Forma et al., 2018; Lee & Aronson, 1974), assisting the development of human movement within their environments. As seen in Study One, this protocol capitalizes on this linkage to induce neuromuscular commands in locomotor affording positions. Study two looks at how this link can calibrate novel atypical gait patterns in healthy individuals by making a comparison between static and dynamic visual input. Study Three, therefore, will extend these two studies to assess how this linkage can generate the same visuomotor patterns in a compromised population to enhance treatment outcomes. Including optic flow in a treatment protocol involving persons with SCI should results in the activation of requisite musculature since the perception-action linkage is still viable, and should result in positive behavioural outcomes due to the recalibration of perception with their injury-acquired atypical gait. The literature already exploring this idea is limited in scope and the quality of SCI studies is insufficient (Yeo et al., 2019) and requires significantly more testing. Much of the available literature are pilot studies, especially when it comes to improving gait function in persons with SCI. VR itself also requires more investigation as there is a large gap when looking at how it can impact typical rehabilitation protocols that address SCI walking quality and improvements in gait functioning.

It is hypothesized that if perception and action were to be recoupled using virtual reality, persons with SCI will experience enhanced rates and quality of positive rehabilitative outcomes (An & Park, 2018; van Dijsseldonk et al., 2018; Yeo et al., 2019). With the presence of optic flow, this outcome is expected due to the increased ability for individuals to obtain information and adapt to their environment more consistently with the perceptual-motor experiences they encountered as children (Koenderink & van Doorn, 1987; Warren, 1990). It is expected that gait parameters, muscle signalling, dynamic balance, and measures of rehabilitative performance will increase more rapidly in the group that experiences virtual reality. Moreover, subjective measures are anticipated to increase in this group due to greater levels of enjoyment and satisfaction with performance (Heyn et al., 2014).

## 4.2. Methods

### *4.2.1. Participants*

This study will adopt a group sequential analysis to allow for more efficient hypothesis testing (Lakens, Pahlke, & Wassmer, 2021). To determine sufficient sample sizes, a Pocock Alpha Spending Function (RPACT Shiny App Software; Appendix C) was used to obtain sample sizes for two interim analyses (33% and 66% of total sample) and at the final analysis (100%). The parameters for the analysis included $\alpha$ at 0.05, $\beta$ at 0.2, $d$ at 0.4, and a two-group division. This spending function spends alpha approximately equally across each look (analysis one α = 0.0226, analysis two and three α = 0.0217) and conserves type I error rates by distributing it equally over the sequential test. The spending function resulted in sample sizes of 78, 156, and 232 for looks at 33%, 66%, and 100%, respectively.

Although the a priori power analysis calculation for this experiment suggests a required n of 78, 156, and 232 for looks at 33%, 66%, and 100%, respectively, limitations imposed on participant recruitment occasioned by the specificity of the inclusion criteria for participation may necessitate a smaller sample size, but one that is consistent with the majority of published research in this area, be recruited (e.g., An & Park, 2018; Combs-Miller et al., 2014; Gama et al., 2017; In et al., 2016; Kang et al., 2012; van Dijsseldonk et al., 2018; Villiger et al., 2017). All appropriate cautions regarding the interpretation of data collected on a smaller than statistically recommended sample will be observed. The individuals recruited for this study will involve those aged 50 years old or less to ensure performance is unrelated to the natural aging process (Hall et al., 2017), those who have experienced an iSCI, and are at minimum six months post-injury to ensure injury stability and doctor clearance. Participants must also score a level C or D on the ASIA Impairment Scale, which measures the motor and sensory levels of each side of the body and determines the level of impairment as complete or incomplete SCI (“ASIA Impairment Scale”, n.d.). Specifically, Level C refers to “Motor Incomplete”, where motor function is preserved below the neurological level and less than half of the key locomotor muscles are functioning below the Neurological Level of Injury (NLI). Level D also refers to “Motor Incomplete”, but is where motor function is preserved below the neurological level and at least half of key locomotor muscles are functioning below the NLI ("ASIA Impairment Scale", n.d.). Other inclusion criteria include: no other neurological or lower limb impairments in addition to the iSCI, normal or corrected-to-normal vision, no previous issues with walking and/or balance prior to the iSCI, and no medication influencing therapy. Medication usage will be self-reported. Participants will be compensated $100.00 for their participation.

*4.2.2. Location and Apparatus*

This study will take place in McMaster University's Physical Activity Centre of Excellence (PACE) in Hamilton, Ontario. The protocol requires that a trained physical therapist is present to ensure the safety of participants, carry out regular assessments, and provide proper protocol execution. Experienced PACE volunteers will also be present to assist with any protocol requirements. Prior to engaging in experimental sessions, participants will be asked to change into shorts and comfortable shoes. Participants will then be fitted with rectangular, wireless electrodes to the gastrocnemius, soleus, vastus lateralis, and vastus medialis (see Figure 7; Pandy & Andriacchi, 2010; Suica et al., 2016). The muscle bellies will be identified using contraction and palpation techniques. The skin above the muscle belly will be prepared by shaving and rubbing the area with isopropyl alcohol. This process is in efforts to remove debris and dead skin cells, and minimize the potential for skin reactions as a result of the electrode placement. Conductive gel will be placed on the electrode which will then be attached to the skin via adhesive sensor stickers. The electrode placement will run parallel to the muscle fibre orientation (Perotto & Delagi, 2005).

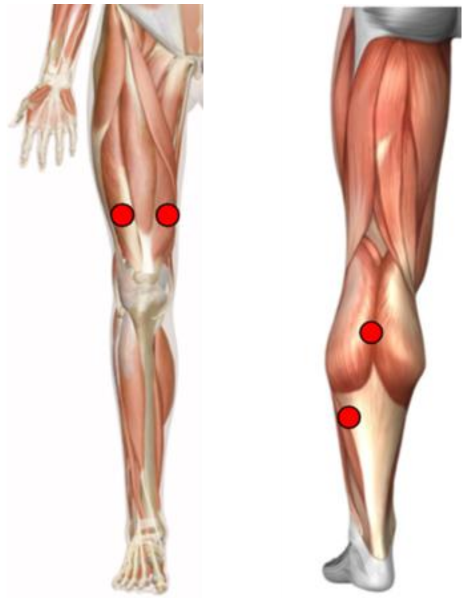

**FIGURE 7.** Anatomical locations of the wireless EMG electrodes. Electrodes are superimposed with a red circle for image clarity. Anatomical positions of the wireless electrodes include: gastrocnemius, soleus, vastus lateralis, and vastus medialis muscles. These muscles will be located with palpation techniques.
*Image: ("Innerbody Research", n.d.)*

EMG signals will be collected using the Delsys Trigno Quattro Multi-Channel EMG + IMU Wireless Senor (Delsys Inc., Massachusetts, USA) system, sampling at a rate of 2500 Hz in alliance with SENIAM surface EMG guidelines (Rose, 2019) and will be differentially amplified. To normalize the EMG data, participants will be instructed to complete three, 10 second quiet trials where they are to remain stationary. This will occur before the training session begins. Following the quiet trials, peak muscle activity will also be used to normalize the data and will be collected for five seconds, three separate times at two minutes apart (Perotto & Delagi, 2005). To obtain this activity in a standing position, this will be achieved by asking the participant to pretend they are forcing themselves into the ground with their legs and engage in full muscle contraction. The purpose of the EMG in this study is to assess if optic flow can trigger muscle activation and sense any changes that may not be seen in step cycle parameters, such as the activation of central pattern generators (Antley & Slater, 2010).

Participants will also be outfitted with two retroreflective markers (B & L Engineering, California, USA) with a diameter of 25 mm attached to the toes of the left and right feet (Burkitt et al., 2020). These markers will be attached to the shoes of the participant via double-sided electrode tape and will be captured during the treatment sessions (see below) by 10 Vicon Nexus MX-T40 cameras (Vicon Motion Systems Ltd., Oxford, UK) sampling at a rate of 100 Hz.

#### *4.2.3. Experimental Procedure*

<u>Pre-Intervention</u>

Prior to commencing the intervention, all participants must undergo initial screening and consent. This includes ensuring that all participants receive medical clearance from their doctors to participate in exercise therapy, and ensuring that participants fit all inclusion criteria outlined for the study. Once cleared to participate, participants will be randomized into either the experimental group (i.e., VR group) or the control group (i.e., static vision). Participants in the VR group will be fitted with the Oculus Rift DK1 Virtual Reality Headset (Facebook Technologies, California, USA) and will receive the VR headset during all treatment sessions. Those in the static vision group will not receive any VR intervention while treadmill walking.

<u>Testing Session</u>

Once assigned, participants will come in to the PACE for a one hour testing session to undergo all initial assessments. Participants will be asked to change into the required attire (see Section 4.2.2) and the researchers will apply the two Vicon retroreflective markers and the Delsys EMG electrodes (see Section 4.2.2.).

Before being fitted to the treadmill, participants will first engage in the Timed Up and Go (TUG) Test. The Center for Disease Control (CDC) recommends the TUG to measure dynamic balance, and it is known to prioritize functional ability in rehabilitation (CDC, n.d.; Niiler, 2018). During the TUG, individuals are tested on their ability to stand from a seated position, walk to a target located three meters away, turn around, walk back towards the chair and sit down (Podsiadlo & Richardson, 1991). Time is taken from the moment the individual leaves the chair and returns to a seated position. The goal is to complete the TUG in as little time as possible, and individuals who take longer to complete it typically have impaired balance and more historical falls (Niiler, 2018). It is important to note that participants are allowed to use walking aids if required, and has shown to be a successful test in individuals with iSCI (e.g., An & Park, 2018). Assessing dynamic balance in patients with iSCI can help gauge how functional their daily movements are and how they are responding to the treatment protocol over time.

Once the TUG test is completed, participants will then be escorted onto a LiteGait Body-Weight Supported (BWS) Treadmill (LG500, LiteGait, USA) by a therapist and will be fitted to the treadmill's overhead harnesses (see Figure 8).


**FIGURE 8.** LiteGait Body Weight Supported Treadmill with overhead harnesses. For each treatment session, participants will be escorted onto the treadmill and connected to the overhead harnesses.

*Image: ("LiteGait Mobility Research", n.d.)*

Baseline activation levels, or the normalization trials (Section 4.2.2.) will be collected next. Once completed, initial performance on spatial-temporal gait parameters (see Section 4.2.4. for full list) will be collected by having participants engage in one 5-15 minute bout of walking on the treadmill. This time range allows for participants to engage in the appropriate amount of activity based on their own functional capacity. The exact time on the treadmill will be determined by the physiotherapist and will be recorded. Vicon and EMG measures will be taken for the entire duration that the participant is engaging in activity. During the 5-15 minute bout, the therapist will determine the appropriate treadmill speed and Body Weight Support Percentage (BWS% - the percentage of body weight the harnesses have to support during training) to start at per participant based on their capabilities.

Upon completion of the testing session, participants in the control group will be escorted off the treadmill while participants in the VR group will be asked to remain on the treadmill. Straps of the VR headset will be tightened until the headset is properly situated over the eyes and resting on the nose. Participants will enter a two minute practice session where they can walk with the headset moving at a virtual speed that matches the speed of the treadmill. This will allow participants to familiarize themselves with the virtual environment. The virtual environment will be programmed using Unity 2020.3.0f1 Software and the Unity Hub Platform (Unity Technologies, San Francisco, USA), and will display the same virtual four foot wide by eight foot tall hallway in absolute coordinates as in Study One and Two, with aspects such as windows and doors to enhance the realism (see Figure 2). The visual flow speed will be programmed to match the speed set on the treadmill by the physiotherapist. VR speed will adjust with changing speeds of the treadmill to give the illusion that participants are walking through space. Speeds will be adjusted at the discretion of the therapist.

Once the practice session is complete, the VR headset will be removed and the VR group participants will be escorted off the treadmill and sat down in a chair. At this point, all participants will be asked to complete subjective questionnaires (see Section 4.2.4.) while the EMG system and Vicon markers are removed by the researcher. When all questionnaires are complete, participants will set up a schedule of days to come in for training with the researcher and therapist. Training sessions will be three, one-hour sessions per week for eight weeks. This coincides with the VR literature time frames (e.g. An & Park, 2018; van Dijsseldonk et al., 2018; Villiger et al., 2017).

<u>Intervention</u>

At the commencement of the intervention, participants will return to the PACE on their allocated training days. At the beginning of every session, participants in the VR group will be fitted with the headset to use during every training period. Participants in both groups will then be escorted on the treadmill by a therapist and fitted to the harnesses where the appropriate BWS% will be set.

The intervention itself is an adaptation of a previously completed study by Hicks et al. (2005). This study will use the same protocol, but over a shorter time frame to test the efficiency of recoupling perception and action. Once participants are ready, the therapist will adjust the speed of the treadmill to the previously recorded tolerance and the optic flow speed in the VR will match the allocated speed. Each session will entail three, 5 -15 minute bouts of walking on the body weight supported treadmill. Time per bout will be determined by the participants' ability to withstand the treatment. During training, participants will be encouraged to hold onto the rails until they feel comfortable enough to walk without them. Therapists will be informed to increase the duration of the bouts, increase the speed of the treadmill, and decrease BWS% when they feel the participant has improved enough to do so. Between each bout of exercise, participants in the VR group will have the headset removed and all participants will be given a chair on the treadmill for a break period, allowing sufficient time to recuperate. At the end of each session, participants will be escorted off the treadmill and the VR group will remove the headset.

<u>Mid-Way and Post Testing</u>

Assessments completed in the pre-intervention stage ("Testing Session", Section 4.2.3.) will be re-administered halfway through the intervention. Participants at the four week mark will be asked to come in for another one-hour testing session to assess their changes in performance. This should occur within one week of their last fourth week training session. At the end of the intervention, all assessments completed pre- and mid-way through the intervention will be repeated post-intervention. Participants will be asked to come in for a final one-hour testing session within one week of their last training session. This will assess the effectiveness of the experimental protocol at the end of the eight weeks.

*4.2.4. Data and Statistical Analysis*

Gait parameters will be analyzed using the captured Vicon data. These parameters include: stride length, step length, number of steps, average walking speed, and distance travelled. This information will be extracted using the MATLAB code developed in Section 3.2.4. in line with the Burkitt et al. (2020) study, with the exception of only using two retroreflective markers. The Vicon system will record the entirety of each exercise bout during testing sessions. These measures will provide an indication of the level of locomotor improvement.

Measures of dynamic balance, important for locomotor control, will be assessed via the TUG test score. The scoring is based off of the time taken to complete the entirety of the test (see Appendix D for sample scoring sheet). A score greater than 14 seconds indicates poorer dynamic balance and a higher risk for falls in this population ("Timed Up and Go Test (TUG)", n.d.).

Measures directly assessing SCI improvement include measures of BWS% and the Modified Wernig Scale provide an assessment of the level of independence of the participant following injury. BWS% assesses how much body weight an individual can support while standing on their own in an upright position. The Modified Wernig Scale developed by Hicks et al. (2005) assesses gait quality and the level of assistance required to locomote. This can include help from another person, a walking assistive device, or no device requirement (see Table 1 for a sample of the scale). The outcome measurement of this scale is a quantitative value that can be compared across time.

Since the recruited population still has some level of muscle innervation, this study will examine the level of muscle activation in the lower limbs and how this innervation changes over time with the introduction of optic flow. Measures of peak amplitude (mV) and average activation (mV) will be extracted from the data collected by Delsys EMG system using the same MATLAB code developed in Section 2.2.4. EMG will be recorded throughout the entirety of each exercise bout during testing sessions.

Subjective measures of performance will assess how participants feel prior to and following the intervention. The Ferrans and Powers Quality of Life Index for SCI (QOLI-SCI; see Appendix E and F) will be used to assess a variety of factors that make up one's quality of life, such as physical, social, and emotional aspects. This is an important measure especially in those with chronic disorders, as it looks at the impact of health care methods in their everyday functioning (Burckhardt & Anderson, 2003). This scale outputs a quantitative score between 0-30, with 30 being the highest rating of QOL. Subsections of the questionnaire can be scored to focus on areas that require specific treatment attention. This can be scored and assessed at different time points of the protocol (Ferrans & Powers, 1992). A researcher-developed questionnaire (see Appendix G) will be used to assess parameters of the intervention itself. It will look at how the participants enjoyed the protocol, how they feel during the intervention, and if they feel themselves improving. This will also provide an overall value that can be scored at different time points.

Using R for Statistical Analysis (Bell Laboratories, New Jersey, USA), a 2 group (VR group, static vision) x 3 time (pre, mid, post-intervention) mixed factors ANOVA with repeated measures on the last factor will be used to analyze all dependent variables. Alpha will be set at $p < 0.0226$ for interim analysis one and $p < 0.0217$ for analyses two and three (if required). Mauchly's test will be used to test for the assumption of sphericity. Should sphericity not be met, a Greenhouse-Geisser correction factor will be applied. Post-hoc comparisons will be done using the Bonferroni post-hoc test, since it is most sensitive to type I errors.

**4.3. Expected Results**

In accordance with the hypothesis, the expected results favour the group receiving optic flow through the VR headset. The VR group is anticipated to see more rapid and greater improvements in gait parameters, increased performance on the TUG test, increased and less variable muscle activation, and greater improvements in self-report measures. This set of participants will be provided with visual cues through optic flow that are more consistent with the dynamic visual experiences they had before their injuries. This can trigger motor responses in response to visual stimuli, associating walking variables with aspects of the environment (Antley & Slater, 2010; Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Forma et al., 2018; Lee & Aronson, 1974). These visual cues can in turn, create more stable perceptuomotor experiences resulting in more positive locomotor outcomes.

As a result of the re-establishment of the perception-action linkage through optic flow, gait parameters are expected to improve at a faster and more amplified rate than the control group. This would be evidenced by increases in gait speed, increases in the number of steps taken, and a greater distance covered in response to more stable walking patterns. Stride length and step length, as mentioned in Study Two, will also become less variable and may increase to accommodate faster walking speeds (Gajer, Thepaut-Mathieu, & Lehenaff, 1999) and as a result of visual cues leading them to familiar walking strides. This is expected to conform with the findings of Study Two suggesting that optic flow can recalibrate atypical gait with vision to produce more stable movement patterns.

Optic flow is anticipated to provide posture relevant visual cues that are important for dynamic balance (e.g., Alotaibi et al., 2016; Berard et al., 2012; Poulain & Giraudet, 2008). As a result, optic flow is expected to lead to greater improvements in dynamic balance in the optic flow group versus the static vision group. That is, scores on the TUG test are hypothesized to decrease more significantly in the optic flow group suggesting overall improvements in dynamic balance.

When looking at the dependent variable of EMG activity, it is likely that participants in the VR group will experience increases in muscle activation and it will become less random. That means, participants will reach higher peak amplitudes and average activation will be more consistent. Individuals with ASIA scores of C or D have below normal neurological functioning ("ASIA Impairment Scale", n.d.), which suggests that the electrical activity of the musculature is variable and insufficient upon injury. However, studies have shown that volitional muscle function can be recovered in SCI patients (Calancie, Molano, & Broton, 2004). Therefore, using the theoretical basis of optic flow triggering muscle activation in preparation for the visual scene they are experiencing (e.g., Study One results; Antley & Slater, 2010; Sidaway, McNitt-Gray, & Davis, 1989), it is likely that this restoration will occur at more rapid rates in the VR group versus the control.

As a result of the changes in gait parameters and EMG muscle activity, it is likely that the VR group will see improvements in the SCI measures. Increases in EMG activity leads to increases in muscle function, which would allow for the participants to support more of their body weight while walking in an upright position, leading to decreases in BWS%. Additionally, these changes will lead to greater improvements in overall locomotor functioning, allowing them to be more independent with their walking. This will lead to better scores on the Modified Wernig Scale.

Finally, after experiencing the predicted improvements in their walking abilities, it is likely that participants will score better results on the QOLS as they will gain more independence in their everyday life. It is also likely that participants in the VR group will score better results on the researcher questionnaire due to increased enjoyment levels and increased satisfaction with their own performance (Heyn et al., 2014). This overall positive outcome from the intervention could support the implementation of VR into rehabilitative settings more regularly to induce optimal benefits in shorter time periods.

**Table 1:** Modified Wernig Scale (Hicks et al., 2005)

| Score | Classification |
|---|---|
| 0 | No walking capability, even with help of two therapists |
| 1 | Capable of walking <5 steps with the help of two therapists OR along parallel bars |
| 2 | Capable of walking ≥ 5 steps with the help of two therapists OR along parallel bars |
| 3 | Capable of walking >1 length of the parallel bars, requiring assistance to turn |
| 4 | Capable of walking >1 length of the parallel bars, turning independently |
| 5 | Capable of walking along railing (<5 steps) with the help of one therapist |
| 6 | Capable of walking along railing (>5 steps) with the help of one therapist |
| 7 | Capable of walking with a rolling walking frame >5 steps |
| 8 | Capable of walking with canes or crutches >5 steps |
| 9 | Capable of walking without devices >5 steps |

# CHAPTER 5: GENERAL DISCUSSION

## 5.1. Summary of the Research Program

In summary, this research program aims to explore the strength of the perception-action linkage, further develop theoretical models of perception-action coupling, and test the viability of these models as a useful tool for rehabilitation. Specifically, this research series questions how vision contributes on a neuromuscular level to action in different postures, how it can calibrate our actions in typical versus atypical gaits, and how optic flow may be applied to typical therapy protocols for adaptation to altered locomotor constraints in gait-compromised populations. This program uses virtual reality (VR) to incorporate optic flow into what were formerly visually static environments to recouple perception and action. This program hopes to give rise to virtual reality as an effective tool for use in rehabilitation protocols, where dynamic visual settings cannot be met. As seen throughout the program's background, optic flow plays an important role in the development of the perception-action linkage. These two components are dynamically coupled, developing together and assisting one another in movement control (Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Bertenthal, 1996; Bertenthal et al., 1997; Rossi, Rodrigues, & Forner-Cordero, 2014). It is through the visual system that information variables are related to the most appropriate parameters of action (Warren, 1990).

Optic flow's role in the linkage is critical, as it plays a role in developing locomotor variables crucial for movement performance (Franchak & Adolph, 2010; Koenderink & van Doorn, 1987; Marigold & Patla, 2008; Matthis, Barton, & Fajen, 2017; Matthis & Fajen, 2014; McManus, D'Amour, & Harris, 2017; Rand et al., 2019; Redlick, Jenkin, & Harris, 2001; Simpson, 1993; Turton et al., 2009; Wexler & Van Boxtel, 2005).

It is through optical flow fields that perception and action can couple to produce locomotor control. Without optic flow, this linkage becomes decoupled, resulting in less controlled actions and inefficient rates of adaptation (Klostermann & Mann, 2019; Koenderink & van Doorn, 1987; Warren, 1990). Negative effects on performance can be seen in the absence of visual cueing (e.g. Alotaibi et al., 2016; Lee, 1980; Poulain & Giraudet, 2008). However, rehabilitation literature has been found to carry out training protocols that cause the absence of optic flow, negatively mitigating all of the positive influence dynamic visual information has on performance. This can lead to more lengthy, expensive, and inefficient treatment plans (Nas et al., 2015). It was shown that by reintroducing optic flow into these programs, greater results may be seen in less time (An & Park, 2018; Combs-Miller et al., 2014; Field-Fote & Roach, 2011; Gama et al., 2017; In et al., 2016; Kang et al., 2012; van Dijsseldonk et al., 2018; Villiger et al., 2017).

As a result, this research program contains a sequence of three studies that each use optic flow to test the impact of the perception-action linkage on movement performance. Study One looks at determining the strength of the linkage in adulthood by testing to see if this relationship alone can elicit muscle activation in the appropriate musculature, even in the absence of voluntary movement. It is hypothesized that results in the standing position will demonstrate an increase in peak activation every time optic flow speed is increased, and decreases in peak activation when speed is decreased. This is expected due to the standing position being a stimulus-affording posture for locomotion (i.e., it is the first stance made when beginning to locomote). Additionally, it is anticipated that average muscle activation will remain above baseline levels when individuals experience speeds greater than static vision. Average muscle activation should also increase and decrease when optic flow increases and decreases, respectively. In the seated position specifically, it is expected that both peak activation and average muscle activation will encounter similar patterns to the standing position, but to a lesser extent. Muscle activation is anticipated to increase above baseline, however, it should remain significantly below threshold levels. This position is associated with passive movement (e.g., sitting in a wheelchair) in our every-day environments, which would mediate the level of activation. This would ultimately differ the results from the standing position (Antley & Slater, 2010; Sidaway, McNitt-Gray, & Davis, 1989). Study One demonstrates the inherent link between optic flow perception and preparatory action in postures that affords locomotion. This provides a theoretical basis for Study Two, in which the perception-action linkage is taken into a treadmill protocol involving artificially compromised gait. Here, static and dynamic vision is paired with a novel walking pattern (i.e., asymmetrical gait) to exemplify how dynamic vision impacts the calibration necessary for understanding and developing accurate spatial awareness.

Study Two aims to assess the linkage on a voluntary movement protocol and whether it can prove to be beneficial in calibrating spatial updating with artificially compromised gait. This study temporarily compromises the typical gait pattern through the use of full-leg bracing and assesses measures of gait performance (i.e., action) and global spatial awareness (i.e., perception) prior to and following a training protocol with and without congruent visual information. The hypothesis states that individuals who received optic flow in the manipulation protocol will see a more rapid rate of adaptation to gait compromise and a greater accuracy in global spatial awareness compared to the static vision group (Burkitt et al., 2020; Campos et al., 2009). This means that the tested gait measures (stride length, step length, and velocity) will demonstrate less variability and increases as individuals become more accustomed to their new physical constraints. This is expected to happen more rapidly in the optic flow group due to the introduction of visual cues controlling movement performance. Spatial awareness measures of constant error relative to target location and perceived versus actual distance travelled are expected to become more accurate in the optic flow group due to introduced visual cues such as depth perception, obstacle avoidance, and control (Koenderink & van Doorn, 1987; Matthis, Barton, & Fajen, 2017; Matthis & Fajen, 2014; McManus, D'Amour, & Harris, 2017; Redlick, Jenkin, & Harris, 2001; Wexler & Van Boxtel, 2005).

Finally, Studies One and Two are expected to provide support for the introduction of optic flow into a rehabilitative setting (Study One demonstrating how optic flow plays a role in neuromuscular control of movement, and Study Two demonstrating the importance of the perception-action linkage in improving locomotion using perceptuomotor processes). Therefore, Study Three tests the effectiveness of the perception-action linkage in a rehabilitative setting by introducing optic flow through virtual reality in a locomotor protocol for those with a SCI. It is hypothesized that individuals in the VR group will see increased rates of performance and the quality of rehabilitative outcomes will increase (An & Park, 2018; van Dijsseldonk et al., 2018; Yeo et al., 2019). In terms of gait parameters (stride length, step length, number of steps, average walking speed, and distance travelled), these measures will see greater increases and will become more stable throughout the intervention. With the introduction of optic flow, individuals will have increased ability to obtain information and adapt to their environment more consistently with the perceptual-motor experiences they encountered as children (Koenderink & van Doorn, 1987; Warren, 1990). Dynamic balance is anticipated to improve following the introduction of optic flow, resulting in decreased time scores on the TUG test. Muscle activation, both peak amplitude and average activation, should increase as a result of muscle priming and familiarity of perceptuomotor cues consistent with events prior to injury onset (Antley & Slater, 2010; Sidaway, McNitt-Gray, & Davis, 1989). Persons with SCI have shown to obtain some level of volitional muscle control following the injury (Calancie, Molano, & Broton, 2004), so this is anticipated to occur more rapidly with experiences of optic flow. Increased gait performance and neuromuscular control should result in greater walking independence, leading to decreased BWS% and increased scoring on the Modified Wernig Scale. Finally, subjective measures of performance should increase as a result of improvements in performance, This should boost their confidence and make them feel more independent within their everyday tasks (Heyn et al., 2014). These results should be demonstrated via increased scores on the QOLS and the researcher questionnaire.

**5.2. Impact of the Research Program**

This research program has the potential to make an impact on both a theoretical and practical basis. Looking at its theoretical implications, this research will extend the theoretical underpinnings of the perception-action linkage. This will provide evidence for the perception-action linkage into adulthood, and will support the influence of optic flow on human motor performance. More specifically, Study One is expected to provide support for the innate perception-action linkage on a neuromuscular level without voluntary movement. It will also speak to the linkage being effective in positions that afford specific actions. Study Two will extend the literature by speaking to the calibration of atypical gaits with dynamic visual information for spatial updating processes. It will stress the importance of dynamic versus static visual information for this calibration process. Study Three is expected to support the rehabilitation literature, providing a study in which looks at optic flow for enhancing locomotor performance.

There is great importance for the practical implications of this research program. Incorporating optic flow into already established gold-standard methods provides an alternative way to strengthen the protocol without adjusting major factors such as space required, safety devices and protocols. Virtual reality is a relatively inexpensive way to provide optimal benefits in a more enjoyable and shorter time frame. This means that increases in performance may be generated without major alterations to existing practices and without compromising the safety of patients, while still leveraging this interaction for optimal recovery in decreased time. This reduces the overall cost of rehabilitation, decreases time commitments from patients, and results in less exhaustive treatment plans.

**5.3. Limitations**

A limitation to the implementation of the perception-action linkage into a rehabilitative setting is that it may not be applicable to every neurological disease or injury etiology. In cases where the affected mechanisms involve portions of the brain that are associated with perceptual cognition, the perception-action linkage may not persist.

For example, in disorders such as brain injuries or stroke that may directly target areas of the brain related to perception (i.e. areas such as the visual cortex, posterior parietal cortex, inferotemporal cortex), the disorder may cause damage or decreased nerve functioning to the point where the system will not be able to perceive visual cues to relate information variables to parameters of action. However, since the brain is capable of neuroplasticity (Demarin, Morovic, & Bene, 2014), it may be able to reroute this function by establishing new connections and using other neural pathways, but this will result in more challenging and longer rehabilitative times and the linkage may never approach full functioning capacity.

### 5.4. Future Directions

Future directions for this research include changing the clinical population and seeing the effects of the protocol with different disease aetiologies. Additionally, studies should look at developing the virtual reality system to display environments that include obstacles, more challenging terrains, or game play with targeted goals. Obstacle avoidance is an important locomotive variable to move within the environment (Koenderink & van Doorn, 1987; Warren, 1990), more challenging terrains have been shown to increase muscle activation (Antley & Slater, 2010), and game play can increase motivation (Novak et al., 2014), all having positive effects on movement performance. Future studies should also consider the process of multi-sensory integration for locomotor control. That is, include more sensory cues within the training protocol such as audition and proprioception. For example, previous studies have demonstrated the effects of audition on movement control throughout development (e.g. Fischel, 1982; Muir & Field, 1979; Phillips-Silver & Trainor, 2005) and within the context of rehabilitation settings (e.g. del Olmo & Cudeiro, 2005; Opoku-Baah, Hou, & Wallace, 2020; Schaffert et al., 2019), showing similar effects as vision on locomotor control. Other studies have started to examine how by combining different senses, walking performance starts to increase. An example of this is by Roy et al. (2017) which found a benefit to multimodal sensory stimulation versus unimodal sensory stimulation for locomotor control. This area of research has so much potential and should be explored further.

# References

Afsar, S. I., Mirzayev, I., Yemisci, O. U., & Saracgil, S. N. C. (2018). Virtual reality in upper extremity rehabilitation of stroke patients: a randomized controlled trial. *Journal of Stroke and Cerebrovascular Diseases, 27*(12), 3473-3478.

Alotaibi, A. Z., Alghadir, A., Iqbal, Z. A., & Anwer, S. (2016). Effect of absence of vision on posture. *Journal of physical therapy science, 28*(4), 1374-1377.

Alsalaheen, B. A., Mucha, A., Morris, L. O., Whitney, S. L., Furman, J. M., Camiolo-Reddy, C. E., ... & Sparto, P. J. (2010). Vestibular rehabilitation for dizziness and balance disorders after concussion. *Journal of Neurologic Physical Therapy*, *34*(2), 87-93.

*American Spinal Cord Injury Association (ASIA) Impairment Scale.* (n.d.). Retrieved November 23, 2020, from https://www.physio-pedia.com/American_Spinal_Cord_Injury_Association_(ASIA)_Impairment_Scale.

An, C. M., & Park, Y. H. (2018). The effects of semi-immersive virtual reality therapy on standing balance and upright mobility function in individuals with chronic incomplete spinal cord injury: a preliminary study. *The journal of spinal cord medicine*, *41*(2), 223-229.

Antley, A., & Slater, M. (2010). The effect on lower spine muscle activation of walking on a narrow beam in virtual reality. *IEEE transactions on Visualization and Computer Graphics, 17*(2), 255-259.

Barbu-Roth, M., Anderson, D. I., Desprès, A., Provasi, J., Cabrol, D., & Campos, J. J. (2009). Neonatal stepping in relation to terrestrial optic flow. *Child development, 80*(1), 8-14.

Barbu-Roth, M., Anderson, D. I., Desprès, A., Streeter, R. J., Cabrol, D., Trujillo, M., ... & Provasi, J. (2014). Air stepping in response to optic flows that move toward and away from the neonate. *Developmental Psychobiology, 56*(5), 1142-1149.

Barros, H. O., Soares, M. M., Rolim Filho, E. L., Correia, W., & Campos, F. (2013, July). Virtual Reality Immersion: An Important Tool for Diagnostic Analysis and Rehabilitation of People with Disabilities. In *International Conference of Design, User Experience, and Usability* (pp. 337-344). Springer, Berlin, Heidelberg.

Basford, J. R., Chou, L. S., Kaufman, K. R., Brey, R. H., Walker, A., Malec, J. F., ... & Brown, A. W. (2003). An assessment of gait and balance deficits after traumatic brain injury. *Archives of physical medicine and rehabilitation, 84*(3), 343-349.

Basili, P., Sağlam, M., Kruse, T., Huber, M., Kirsch, A., & Glasauer, S. (2013). Strategies of locomotor collision avoidance. *Gait & posture*, *37*(3), 385-390.

Berard, J., Fung, J., & Lamontagne, A. (2012). Impact of aging on visual reweighting during locomotion. *Clinical neurophysiology, 123*(7), 1422-1428.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements.* Pergamon Press.

Bertenthal, B. I. (1996). Origins and early development of perception, action, and representation. *Annual review of psychology, 47*(1), 431-459.

Bertenthal, B. I., Rose, J. L., & Bai, D. L. (1997). Perception–action coupling in the development of visual control of posture. *Journal of Experimental Psychology: Human Perception and Performance, 23*(6), 1631.

Biegstraaten, M., de Grave, D. D., Brenner, E., & Smeets, J. B. (2007). Grasping the Müller–Lyer illusion: not a change in perceived length. *Experimental Brain Research*, *176*(3), 497-503.

Borel, L., & Alescio-Lautier, B. (2014). Posture and cognition in the elderly: interaction and contribution to the rehabilitation strategies. *Neurophysiologie Clinique/Clinical Neurophysiology, 44*(1), 95-107.

Borger, L. L., Whitney, S. L., Redfern, M. S., & Furman, J. M. (1999). The influence of dynamic visual environments on postural sway in the elderly. *Journal of Vestibular Research, 9*(3), 197-205.

Borghese, N. A., Bianchi, L., & Lacquaniti, F. (1996). Kinematic determinants of human locomotion. *The Journal of physiology, 494*(3), 863-879.

Browning, R. C., Baker, E. A., Herron, J. A., & Kram, R. (2006). Effects of obesity and sex on the energetic cost and preferred speed of walking. *Journal of applied physiology, 100*(2), 90-398.

Bühler, M. A., & Lamontagne, A. (2018). Circumvention of pedestrians while walking in virtual and physical environments. *IEEE transactions on neural systems and rehabilitation engineering, 26*(9), 1813-1822.

Burckhardt, C. S., & Anderson, K. L. (2003). The Quality of Life Scale (QOLS): reliability, validity, and utilization. *Health and quality of life outcomes, 1*(1), 1-7.

Burkitt, J. J., Campos, J. L., & Lyons, J. L. (2020). Iterative Spatial Updating During Forward Linear Walking Revealed Using a Continuous Pointing Task. *Journal of Motor Behavior, 52*(2), 145-166.

Butler, J. S., Campos, J. L., & Bülthoff, H. H. (2015). Optimal visual–vestibular integration under conditions of conflicting intersensory motion profiles. *Experimental brain research, 233*(2), 587-597.

Calado, A. V. S., Soares, M. M., Campos, F., & Correia, W. (2013, July). Virtual reality applied to the study of the interaction between the user and the built space: A literature review. In *International Conference of Design, User Experience, and Usability* (pp. 345-351). Springer, Berlin, Heidelberg.

Calancie, B., Molano, M. R., & Broton, J. G. (2004). EMG for assessing the recovery of voluntary movement after acute spinal cord injury in man. Clinical neurophysiology, 115(8), 1748-1759.

Campos, J. L., Butler, J. S., & Bülthoff, H. H. (2014). Contributions of visual and proprioceptive information to travelled distance estimation during changing sensory congruencies. *Experimental brain research, 232*(10), 3277-3289.

Campos, J. L., Ramkhalawansingh, R., & Pichora-Fuller, M. K. (2018). Hearing, self-motion perception, mobility, and aging. *Hearing Research, 369*, 42–55.

Campos, J. L., Siegle, J. H., Mohler, B. J., Bülthoff, H. H., & Loomis, J. M. (2009). Imagined self-motion differs from perceived self-motion: evidence from a novel continuous pointing method. *PLoS One, 4*(11), e7793.

Cappellini, G., Ivanenko, Y. P., Poppele, R. E., & Lacquaniti, F. (2006). Motor patterns in human walking and running. *Journal of neurophysiology*, *95*(6), 3426-3437.

Carey, D. P. (2001). Do action systems resist visual illusions? *Trends in Cognitive Sciences, 5*, 109-113.

Çeliköz, N., Erisen, Y., & Sahin, M. (2019). Cognitive Learning Theories with Emphasis on Latent Learning, Gestalt and Information Processing Theories. *Online Submission, 9*(3), 18-33.

*Centres for Disease Control (CDC): STEADI Materials for Health Care Providers (STEADI)* (n.d.). Retrieved September 24, 2021, from http://www.cdc.gov/steadi/materials.html

Chander, H., Kodithuwakku Arachchige, S. N., Turner, A. J., & Knight, A. C. (2020). Is it me or is the room moving? Recreating the classical "moving room" experiment with virtual reality for postural control adaptation. *Adaptive Behavior*, 1059712320971372.

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive psychology, 4*(1), 55-81.

Chen, L., Lo, W. L. A., Mao, Y. R., Ding, M. H., Lin, Q., Li, H., ... & Huang, D. F. (2016). Effect of virtual reality on postural and balance control in patients with stroke: a systematic literature review. *BioMed research international*, 2016.

Choi, Y. H., & Paik, N. J. (2018). Mobile game-based virtual reality program for upper extremity stroke rehabilitation. *JoVE (Journal of Visualized Experiments)*, (133), e56241.

Chrastil, E. R., & Warren, W. H. (2014). Does the human odometer use an extrinsic or intrinsic metric?. *Attention, Perception & Psychophysics, 76,* 230–246.

Christina, R. W. (2017). Motor control and learning in the North American Society for the Psychology of Sport and Physical Activity (NASPSPA): The first 40 years. *Kinesiology Review*, *6*(3), 221-231.

Clark, D. J., & Patten, C. (2013). Eccentric versus concentric resistance training to enhance neuromuscular activation and walking speed following stroke. *Neurorehabilitation and neural repair*, *27*(4), 335-344.

Coello, Y., Danckert, J., Blangero, A., & Rossetti, Y. (2007). Do visual illusions probe the visual brain? Illusions in action without a dorsal visual stream. *Neuropsychologia*, *45*, 849-1858.

Combs-Miller, S. A., Kalpathi Parameswaran, A., Colburn, D., Ertel, T., Harmeyer, A., Tucker, L., & Schmid, A. A. (2014). Body weight-supported treadmill training vs. overground walking training for persons with chronic stroke: a pilot randomized controlled trial. *Clinical rehabilitation*, *28*(9), 873-884.

Commins, S., McCormack, K., Callinan, E., Fitzgerald, H., Molloy, E., & Young, K. (2013). Manipulation of visual information does not change the accuracy of distance estimation during a blindfolded walking task. *Human movement science*, *32*(4), 794-807.

Corbetta, D., Imeri, F., & Gatti, R. (2015). Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review. *Journal of physiotherapy*, *61*(3), 117-124.

Czyż, S. H., Zvonař, M., & Pretorius, E. (2019). The development of generalized motor program in constant and variable practice conditions. *Frontiers in psychology, 10,* 2760.

da Silva, J. J., Barbieri, F. A., & Gobbi, L. T. B. (2011). Adaptive locomotion for crossing a moving obstacle. *Motor control*, *15*(3), 419-433.

Dawson, M. R. (1998). *Understanding cognitive science*. Blackwell Publishing.

deGroot, A.D. (1978). *Thought and choice in chess*. The Hague: Mouton.

del Olmo, M. F., & Cudeiro, J. (2005). Temporal variability of gait in Parkinson disease: Effects of a rehabilitation programme based on rhythmic sound cues. *Parkinsonism & related disorders, 11*(1), 25-33.

Demarin, V., Morovic, S., & Bene, R. (2014). Neuroplasticity. *Periodicum biologorum, 116*(2), 209-211.

De Rooij, I. J., Van De Port, I. G., & Meijer, J. W. G. (2016). Effect of virtual reality training on balance and gait ability in patients with stroke: systematic review and meta-analysis. *Physical therapy, 96*(12), 1905-1918.

Di Giorgio, E., Lunghi, M., Simion, F., & Vallortigara, G. (2017). Visual cues of motion that trigger animacy perception at birth: the case of self‐propulsion. *Developmental science*, *20*(4), e12394.

DiZio, P., & Lackner, J. R. (2002). Proprioceptive adaptation and aftereffects. In *Handbook of virtual environments* (pp. 791-812). CRC Press.

Duncan, P. W., Sullivan, K. J., Behrman, A. L., Azen, S. P., Wu, S. S., Nadeau, S. E., ... & Hayden, S. K. (2011). Body-weight–supported treadmill rehabilitation after stroke. *New England Journal of Medicine, 364*(21), 2026-2036.

Duncan, P. W., Sullivan, K. J., Behrman, A. L., Azen, S. P., Wu, S. S., Nadeau, S. E., ... & Tilson, J. K. (2007). Protocol for the Locomotor Experience Applied Post-stroke (LEAPS) trial: a randomized controlled trial. *BMC neurology, 7*(1), 39.

Ferrans, C. E., & Powers, M. J. (1992). Psychometric assessment of the Quality of Life Index. *Research in nursing & health, 15*(1), 29-38.

Field-Fote, E. C., & Roach, K. E. (2011). Influence of a locomotor training approach on walking speed and distance in people with chronic spinal cord injury: a randomized clinical trial. *Physical therapy, 91*(1), 48-60.

Fink, P. W., Foo, P. S., & Warren, W. H. (2007). Obstacle avoidance during walking in real and virtual environments. *ACM Transactions on Applied Perception (TAP)*, *4*(1), 2-es.

Fischel, J. E. (1982). The organization of human newborn sucking and movement during auditory stimulation. *Infant Behavior and Development*, *5*(1), 45-61.

Forma, V., Anderson, D. I., Goffinet, F., & Barbu-Roth, M. (2018). Effect of optic flows on newborn crawling. *Developmental psychobiology*, *60*(5), 497-510.

Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. *Vision research*, *50*(24), 2766- 2774.

Gagen, L., & Getchell, N. (2008). Applying Newton's apple to elementary physical education: An interdisciplinary approach. *Journal of Physical Education, Recreation & Dance*, *79*(8), 43-51.

Gajer, B., Thepaut-Mathieu, C., & Lehenaff, D. (1999). Evolution of stride and amplitude during course of the 100 m event in athletics. *New Studies in Athletes, 14*(1), 43-50.

Gama, G. L., Celestino, M. L., Barela, J. A., Forrester, L., Whitall, J., & Barela, A. M. (2017). Effects of gait training with body weight support on a treadmill versus overground in individuals with stroke. *Archives of physical medicine and rehabilitation, 98*(4), 738-745.

Ganel, T., & Goodale, M. A. (2019). Still holding after all these years: An action-perception dissociation in patient DF. *Neuropsychologia*, *128*, 249-254.

Garner, J. K., & Kaplan, A. (2017). An ecological, dynamical systems perspective on teacher learning and professional development. In *Annual Meeting of the American Educational Research Association*.

Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Boston: Houghton Mifflin.

Gibson, J. J. (1977). On the analysis of change in the optic array. *Scandinavian Journal of Psychology*.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.

Globas, C., Becker, C., Cerny, J., Lam, J. M., Lindemann, U., Forrester, L. W., ... & Luft, A. R. (2012). Chronic stroke survivors benefit from high-intensity aerobic treadmill exercise: a randomized control trial. *Neurorehabilitation and neural repair*, *26*(1), 85-95.

Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences, 27*, 3-78.

Glover, S. and Dixon, P. (2001). Dynamic illusion effects in a reaching task: Evidence for separate visual representations in the planning and control of reaching. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 560-572.

Glover, S. and Dixon, P. (2002). Dynamic effects of the ebbinghaus illusion in grasping: Support for a planning/control model of action. *Perception & Psychophysics*, *64*, 266-278.

Goodale, M.A., Milner, A.D., Jakobson, L.S., & Carey, D.P. (1991). A neurological dissociation between perceiving objects and grasping them. *Nature, 349*, 154-156.

Hall, K. S., Cohen, H. J., Pieper, C. F., Fillenbaum, G. G., Kraus, W. E., Huffman, K. M., ... & Morey, M. C. (2017). Physical performance across the adult life span: correlates with age and physical activity. *The Journals of Gerontology: Series A, 72*(4), 572-578.

Harkema, S. J., Schmidt-Read, M., Lorenz, D. J., Edgerton, V. R., & Behrman, A. L. (2012). Balance and ambulation improvements in individuals with chronic incomplete spinal cord injury using locomotor training–based rehabilitation. *Archives of physical medicine and rehabilitation, 93*(9), 1508-1517.

Harrison, S. J., Kuznetsov, N., & Breheim, S. (2013). Flexible kinesthetic distance perception: When do your arms tell you how far you have walked?. *Journal of Motor Behavior, 45*, 239–247.

Hartcher-O'Brien, J., Levitan, C., & Spence, C. (2010). Extending visual dominance over touch for input off the body. *Brain research*, *1362*, 48-55.

Harvey, L. A. (2016). Physiotherapy rehabilitation for people with spinal cord injuries. *Journal of physiotherapy, 62*(1), 4-11.

Havens, K. L., Mukherjee, T., & Finley, J. M. (2018). Analysis of biases in dynamic margins of stability introduced by the use of simplified center of mass estimates during walking and turning. *Gait & posture, 59*, 162-167.

Hay, J.G. (1993). *The biomechanics of sport technique*. 4th ed. Prentice Hall.

Headrick, J., Renshaw, I., Davids, K., Pinder, R. A., & Araújo, D. (2015). The dynamics of expertise acquisition in sport: The role of affective learning design. *Psychology of Sport and Exercise*, *16*, 83-90.

Hecht, D., & Reiner, M. (2009). Sensory dominance in combinations of audio, visual and haptic stimuli. *Experimental brain research*, *193*(2), 307-314.

Heft, H. (2001). *Ecological psychology in context: James Gibson, Roger Barker, and the legacy of William James's radical empiricism*. Psychology Press.

Henry, F. M., & Rogers, D. E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *31*(3), 448-458.

Heyn, P., Baumgardner, C., McLachlan, L., & Bodine, C. (2014). Mixed-reality exercise effects on participation of individuals with spinal cord injuries and developmental disabilities: a pilot study. *Topics in Spinal Cord Injury Rehabilitation*, *20*(4), 338-345.

Hibbs, A. E., Thompson, K. G., French, D. N., Hodgson, D., & Spears, I. R. (2011). Peak and average rectified EMG measures: which method of data reduction should be used for assessing core training exercises?. *Journal of Electromyography and Kinesiology*, *21*(1), 102-111.

Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of experimental psychology*, *4*(1), 11-26.

Hicks, A. L., Adams, M. M., Ginis, K. M., Giangregorio, L., Latimer, A., Phillips, S. M., & McCartney, N. (2005). Long-term body-weight-supported treadmill training and subsequent follow-up in persons with chronic SCI: effects on functional walking ability and measures of subjective well-being. *Spinal cord*, *43*(5), 291-298.

Hicks, A. L., & Ginis, K. A. M. (2008). Treadmill training after spinal cord injury: it's not just about the walking. *Journal of Rehabilitation Research & Development*, *45*(2).

Higuchi, T. (2013). Visuomotor control of human adaptive locomotion: understanding the anticipatory nature. *Frontiers in psychology*, *4*, 277.

Hodges, N. J., Hayes, S., Horn, R. R., & Williams, A. M. (2005). Changes in coordination, control and outcome as a result of extended practice on a novel motor skill. *Ergonomics*, *48*(11-14), 1672-1685.

Hof, A. L., Gazendam, M. G. J., & Sinke, W. E. (2005). The condition for dynamic stability. *Journal of biomechanics, 38*(1), 1-8.

Holdefer, R. N., & Miller, L. E. (2002). Primary motor cortical neurons encode functional muscle synergies. *Experimental Brain Research*, *146*(2), 233-243.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and brain sciences*, *24*(5), 849-878.

Hoseini, S. M., Sohrabi, M., & Torbati, H. T. (2016). The Effect of Speed, Accuracy and Effector on Generalizability of Motor Program. *Biosciences Biotechnology Research Asia*, *13*(4), 2089-2099.

Hoshikawa, T. (1999). Effects of room tilting on body sway: Adaptation and strategies for maintaining a standing posture. *Japanese Psychological Research, 41*(3), 186-192.

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of experimental psychology*, *45*(3), 188.

In, T., Lee, K., & Song, C. (2016). Virtual reality reflection therapy improves balance and gait in patients with chronic stroke: randomized controlled trials. *Medical science monitor: international medical journal of experimental and clinical research, 22*, 4046.

Inman, V. T. (1966). Human locomotion. *Canadian Medical Association Journal, 94*(20), 1047.

Ivanenko, Y. P., Poppele, R. E., & Lacquaniti, F. (2006). Motor control programs and walking. *The Neuroscientist*, *12*(4), 339-348.

Ivey, F. M., Stookey, A. D., Hafer-Macko, C. E., Ryan, A. S., & Macko, R. F. (2015). Higher treadmill training intensity to address functional aerobic impairment after stroke. *Journal of Stroke and Cerebrovascular Diseases, 24*(11), 2539-2546.

Jain, A., Bansal, R., Kumar, A., & Singh, K. D. (2015). A comparative study of visual and auditory reaction times on the basis of gender and physical activity levels of medical first year students. *International Journal of Applied and Basic Medical Research, 5*(2), 124.

Jorgensen, C., Lee, D. D., & Agabont, S. (2003, July). Sub auditory speech recognition based on EMG signals. In *Proceedings of the International Joint Conference on Neural Networks, 2003*. (Vol. 4, pp. 3128-3133). IEEE.

Kamm, K., Thelen, E., & Jensen, J. L. (1990). A dynamical systems approach to motor development. *Physical therapy, 70*(12), 763-775.

Kang, H. K., Kim, Y., Chung, Y., & Hwang, S. (2012). Effects of treadmill training with optic flow on balance and gait in individuals following stroke: randomized controlled trials. *Clinical rehabilitation, 2*6(3), 246-255.

Kelso, J. A. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 246*(6), R1000-R1004.

Kelso, J. S., & Schöner, G. (1988). Self-organization of coordinative movement patterns. *Human Movement Science, 7*(1), 27-46.

Kiper, P., Szczudlik, A., Agostini, M., Opara, J., Nowobilski, R., Ventura, L., ... & Turolla, A. (2018). Virtual reality for upper limb rehabilitation in subacute and chronic stroke: a randomized controlled trial. *Archives of physical medicine and rehabilitation, 99*(5), 834-842.

Kirschen, M. P., Kahana, M. J., Sekuler, R., & Burack, B. (2000). Optic flow helps humans learn to navigate through synthetic environments. *Perception, 29*(7), 801-818.

Klingberg, T. (2000). Limitations in information processing in the human brain: neuroimaging of dual task performance and working memory tasks. *Progress in brain research, 126*, 95-102.

Klostermann, A., & Mann, D. L. (2019). Current Issues in Perceptual Training: Facing the Requirement to Couple Perception, Cognition, and Action in Complex Motor Behavior. *Frontiers in psychology, 10*, 2680.

Koenderink, J. J., & van Doorn, A. J. (1987). Facts on optic flow. *Biological cybernetics, 56*(4), 247-254.

Konczak, J. (1990). Toward an ecological theory of motor development: the relevance of the Gibsonian approach to vision for motor development research. *Advances in motor development research, 3,* 3-17.

Konczak, J. (1994). Effects of optic flow on the kinematics of human gait: a comparison of young and older adults. *Journal of motor behavior, 26*(3), 225-236.

Kretch, K. S., Franchak, J. M., & Adolph, K. E. (2014). Crawling and walking infants see the world differently. *Child development, 85*(4), 1503-1518.

Kung, S. M., Fink, P. W., Legg, S. J., Ali, A., & Shultz, S. P. (2018). What factors determine the preferred gait transition speed in humans? A review of the triggering mechanisms. *Human movement science, 57,* 1-12.

Kveraga, K., Boucher, L., & Hughes, H. C. (2002). Saccades operate in violation of Hick's law. *Experimental Brain Research, 146*(3), 307-314.

Lacquaniti, F., Ivanenko, Y. P., & Zago, M. (2012). Development of human locomotion. *Current opinion in neurobiology, 22*(5), 822-828.

Lai, Q., & Shea, C. H. (1998). Generalized motor program (GMP) learning: Effects of reduced frequency of knowledge of results and practice variability. *Journal of motor behavior*, *30*(1), 51-59.

Lakens, D., Pahlke, F., & Wassmer, G. (2021). *Group Sequential Designs: A Tutorial*.

Lappe, M., Jenkin, M., & Harris, L. R. (2007). Travel distance estimation from visual motion by leaky path integration. *Experimental Brain Research, 180*, 35–48.

Lashley, K.S. (1942). The problem of cerebral organization in vision. In J. Cattell (Ed.), *Biological symposia. Vol. VII. Visual mechanisms* (pp. 301-322). Lancaster, PA: Jaques Cattell Press.

Lawrence, B. M., John, A. S., Abrams, R. A., & Snyder, L. H. (2008). An anti-Hick's effect in monkey and human saccade reaction times. *Journal of Vision*, *8*(3), 26-26.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5*(4), 437-459.

Lee, D.N. (1980). Visuo-motor coordination in space-time. In G.E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 281-295). Amsterdam: North-Holland.

Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Perception & Psychophysics, 15*(3), 529-532.

Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of human movement studies.*

Leeder, T., Fallahtafti, F., Schieber, M., Myers, S. A., Boron, J. B., & Yentes, J. M. (2019). Optic flow improves step width and length in older adults while performing dual task. *Aging Clinical and Experimental Research*, *31*(8), 1077-1086.

Lloréns, R., Noé, E., Colomer, C., & Alcañiz, M. (2015). Effectiveness, usability, and cost-benefit of a virtual reality–based telerehabilitation program for balance recovery after stroke: A randomized controlled trial. *Archives of physical medicine and rehabilitation, 96*(3), 418-425.

Loomis, J. M., Klatzky, R. L., & Giudice, N. A. (2013). Representing 3D space in working memory: Spatial images from vision, hearing, touch, and language. In *Multisensory imagery* (pp. 131-155). Springer, New York, NY.

Loomis, J. M., & Philbeck, J. W. (2008). Measuring spatial perception with spatial updating and action. In *Carnegie Symposium on Cognition, 2006, Pittsburgh, PA, US*. Psychology Press.

Luft, A. R., Macko, R. F., Forrester, L. W., Villagra, F., Ivey, F., Sorkin, J. D., ... & Hanley, D. F. (2008). Treadmill exercise activates subcortical neural networks and improves walking after stroke: a randomized controlled trial. *Stroke, 39*(12), 3341-3350.

Macko, R. F., Ivey, F. M., Forrester, L. W., Hanley, D., Sorkin, J. D., Katzel, L. I., ... & Goldberg, A. P. (2005). Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke: a randomized, controlled trial. *Stroke, 36*(10), 2206-2211.

Malik, A. N., & Masood, T. (2017). Effects of virtual reality training on mobility and physical function in stroke. JPMA. *The Journal of the Pakistan Medical Association, 67*(10), 1618-1620.

Marigold, D. S., & Patla, A. E. (2008). Visual information from the lower visual field is important for walking across multi-surface terrain. *Experimental Brain Research*, *188*(1), 3-31.

Marr, D. (1980). Visual information processing: The structure and creation of visual representations. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, *290*(1038), 199-218.

Matthis, J. S., & Fajen, B. R. (2014). Visual control of foot placement when walking over complex terrain. *Journal of experimental psychology: human perception and performance*, *40*(1), 106.

Matthis, J. S., Barton, S. L., & Fajen, B. R. (2017). The critical phase for visual control of human walking over complex terrain. *Proceedings of the National Academy of Sciences*, *114*(32), E6720-E6729.

McManus, M., D'Amour, S., & Harris, L. R. (2017). Using optic flow in the far peripheral field. *Journal of vision*, *17*(8), 3-3.

Menuchi, M. R. T. P., & Gobbi, L. T. B. (2012). Optic flow contribution to locomotion adjustments in obstacle avoidance. *Motor control, 16*(4), 506-520.

Michaels, C. F., & Carello, C. (1981). *Direct perception.* Englewood Cliffs, NJ: Prentice-Hall.

Mittelstaedt, M. L., & Mittelstaedt, H. (2001). Idiothetic navigation in humans: estimation of path length. *Experimental Brain Research, 139*(3), 318-332.

Mohanchandra, K., & Saha, S. (2016). A communication paradigm using subvocalized speech: translating brain signals into speech. *Augmented Human Research, 1*(1), 1-14.

Mohapatra, S., & Aruin, A. S. (2013). Static and dynamic visual cues in feed-forward postural control. *Experimental brain research, 224*(1), 25-34.

Mohler, B. J., Thompson, W. B., Creem-Regehr, S. H., Willemsen, P., Pick, Jr, H. L., & Rieser, J. J. (2007). Calibration of locomotion resulting from visual motion in a treadmill-based virtual environment. *ACM Transactions on Applied Perception (TAP), 4*(1), 4-es.

Muir, D., & Field, J. (1979). Newborn infants orient to sounds. *Child development,* 431-436.

Multon, F., & Olivier, A. H. (2013). Biomechanics of walking in real world: naturalness we wish to reach in virtual reality. In *Human walking in virtual environments* (pp. 55-77). Springer, New York, NY.

Muratori, L. M., Lamberg, E. M., Quinn, L., & Duff, S. V. (2013). Applying principles of motor learning and control to upper extremity rehabilitation. *Journal of Hand Therapy*, *26*(2), 94-103.

Nas, K., Yazmalar, L., Şah, V., Aydın, A., & Öneş, K. (2015). Rehabilitation of spinal cord injuries. *World journal of orthopedics, 6*(1), 8.

Niiler, T. (2018). Measures to determine dynamic balance. In *Handbook of human motion* (pp. 887-913). Springer International Publishing.

Novak, D., Nagle, A., Keller, U., & Riener, R. (2014). Increasing motivation in robot-aided arm rehabilitation with competitive and cooperative gameplay. *Journal of neuroengineering and rehabilitation, 11*(1), 1-15.

Opoku-Baah, C., Hou, B., & Wallace, M. (2020). A multisensory perspective on low vision rehabilitation: audition facilitates visual learning of contrast detection. *Investigative Ophthalmology & Visual Science, 61*(7), 4269-4269.

Pandy, M. G., & Andriacchi, T. P. (2010). Muscle and joint function in human locomotion. *Annual review of biomedical engineering, 12,* 401-433.

Park, S. K., Yang, D. J., Uhm, Y. H., Heo, J. W., & Kim, J. H. (2016). The effect of virtual reality-based eccentric training on lower extremity muscle activation and balance in stroke patients. *Journal of physical therapy science, 28*(7), 2055-2058.

Pashler, H. (2004). *Stevens' handbook of experimental psychology, sensation and perception* (Vol. 1). John Wiley and sons.

Patla, A. E. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & posture, 5*(1), 54-69.

Patla, A. E., & Vickers, J. N. (2003). How far ahead do we look when required to step on specific locations in the travel path during locomotion?. *Experimental brain research*, *148*(1), 133-138.

Patterson, S. L., Rodgers, M. M., Macko, R. F., & Forrester, L. W. (2008). Effect of treadmill exercise training on spatial and temporal gait parameters in subjects with chronic stroke: a preliminary report. *Journal of rehabilitation research and development*, *45*(2), 221.

Perenin, M. T., & Vighetto, A. (1988). Optic ataxia: A specific disruption in visuomotor mechanisms: I. Different aspects of the deficit in reaching for objects. *Brain, 111*(3), 643-674.

Perotto, A., & Delagi, E.F. (2005). *Anatomical guide for the electromyographer: the limbs and trunk.* Charles C Thomas Publisher.

Perrin, P. P., Jeandel, C., Perrin, C. A., & Bene, M. C. (1997). Influence of visual control, conduction, and central integration on static and dynamic balance in healthy older adults. *Gerontology, 43*(4), 223-231.

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception and Performance, 23*(1), 72.

Phillips-Silver, J., & Trainor, L. J. (2005). Feeling the beat: movement influences infant rhythm perception. *Science, 308*(5727), 1430-1430.

Podsiadlo, D., & Richardson, S. (1991). The timed "Up & Go": a test of basic functional mobility for frail elderly persons. *Journal of the American geriatrics Society, 39*(2), 142-148.

Poulain, I., & Giraudet, G. (2008). Age-related changes of visual contribution in posture control. *Gait & posture, 27*(1), 1-7.

Raiola, G. (2014). Motor control and learning skills according to cognitive and ecological dynamic approach in a vision on behaviorism, cognitive, Gestalt and phenomenology theories. *Mediterranean Journal of Social Sciences*, *5*(15), 504-504.

Rand, K. M., Barhorst-Cates, E. M., Kiris, E., Thompson, W. B., & Creem-Regehr, S. H. (2019). Going the distance and beyond: simulated low vision increases perception of distance traveled during locomotion. *Psychological research*, *83*(7), 1349-1362.

Redlick, F. P., Jenkin, M., & Harris, L. R. (2001). Humans can use optic flow to estimate distance of travel. *Vision research*, *41*(2), 213-219.

Riecke, B. E., Cunningham, D. W., & Bülthoff, H. H. (2007). Spatial updating in virtual reality: the sufficiency of visual information. *Psychological research, 71*(3), 298-313.

Rieser, J. J., Pick, H. L., Ashmead, D. H., & Garing, A. E. (1995). Calibration of human locomotion and models of perceptual-motor organization. *Journal of Experimental Psychology: Human Perception and Performance, 21*(3), 480.

Roberton, M. A. (1989). Motor development: Recognizing our roots, charting our future. *Quest*, *41*, 213-223.

Rose, W. (2019). Electromyogram analysis. *Online course material. University of Delaware.* Retrieved July 14, 2021.

Rossi, L. F., Rodrigues, S. T., & Forner-Cordero, A. (2014, August). Do humans walk like robots when crossing an obstacle without visual information?. In *5th IEEE RAS/EMBS international conference on biomedical robotics and biomechatronics* (pp. 216-220). IEEE.

Roy, C., Lagarde, J., Dotov, D., & Dalla Bella, S. (2017). Walking to a multisensory beat. *Brain and cognition, 113,* 172-183.

Sabapathy, V., Tharion, G., & Kumar, S. (2015). Cell therapy augments functional recovery subsequent to spinal cord injury under experimental conditions. *Stem Cells International, 2015.*

Schaffert, N., Janzen, T. B., Mattes, K., & Thaut, M. H. (2019). A review on the relationship between sound and movement in sports and rehabilitation. *Frontiers in psychology, 10*, 244.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological review*, *82*(4), 225.

Schmidt, R. A. (1976). Control processes in motor skills. *Exercise and sport sciences reviews*, *4*(1), 229-262.

Schneiberg, S., Sveistrup, H., McFadyen, B., McKinley, P., & Levin, M. F. (2002). The development of coordination for reach-to-grasp movements in children. *Experimental Brain Research*, *146*(2), 142-154.

Schöner, G. (1991). Dynamic theory of action-perception patterns: the “moving room” paradigm. *Biological cybernetics, 64*(6), 455-462.

Schultz, T., & Wand, M. (2010). Modeling coarticulation in EMG-based continuous speech recognition. *Speech Communication, 52*(4), 341-353.

Seifert, L., Araújo, D., Komar, J., & Davids, K. (2017). Understanding constraints on sport performance from the complexity sciences paradigm: An ecological dynamics framework. *Human movement science*, *56*, 178-180.

Senders, J. W. (1998). Analysis of an intersection. *Ergonomics in Design, 6*(2), 4-6.

Shapiro, D. C., Zernicke, R. F., Gregor, R. J., & Diestel, J. D. (1981). Evidence for generalized motor programs using gait pattern analysis. *Journal of motor behavior, 13*(1), 33-47.

Shiel Jr., W. C. (2018, December 27). Definition of Rehabilitation. Retrieved November 20, 2020, from https://www.medicinenet.com/rehabilitation/definition.htm

Sidaway, B., McNitt-Gray, J., & Davis, G. (1989). Visual timing of muscle preactivation in preparation for landing. *Ecological Psychology, 1*(3), 253-264.

Siegle, J. H., Campos, J. L., Mohler, B. J., Loomis, J. M., & Bülthoff, H. H. (2009). Measurement of instantaneous perceived self-motion using continuous pointing. *Experimental Brain Research, 195*(3), 429-444.

Simpson, W. A. (1993). Optic flow and depth perception. *Spatial vision*.

Smith, A., & Zelaznik, H. N. (2004). Development of functional synergies for speech motor coordination in childhood and adolescence. *Developmental psychobiology, 45*(1), 22-33.

Sperandio, I., Savazzi, S., & Marzi, C. A. (2010). Is simple reaction time affected by visual illusions?. *Experimental brain research, 201*(2), 345-350.

Starkes, J. L., & Ericsson, K. A. (2003). *Expert performance in sports: Advances in research on sport expertise*. Human Kinetics.

States, R.A., Pappas, E., & Salem, Y. (2009). Overground physical therapy gait training for chronic stroke patients with mobility deficits. *Cochrane database of systematic reviews,* (3).

Stefanucci, J. K., & Geuss, M. N. (2009). Big people, little world: The body influences size perception. *Perception, 38*(12), 1782-1795.

Stoffregen, T. A., Schmuckler, M. A., & Gibson, E. J. (1987). Use of central and peripheral optical flow in stance and locomotion in young walkers. *Perception, 16*(1), 113-119.

Suica, Z., Romkes, J., Tal, A., & Maguire, C. (2016). Walking with a four wheeled walker (rollator) significantly reduces EMG lower-limb muscle activity in healthy subjects. *Journal of bodywork and movement therapies, 20*(1), 65-73.

Summers, J. J., & Anson, J. G. (2009). Current status of the motor program: Revisited. *Human Movement Science, 28*(5), 566-577.

Sun, H. J., Campos, J. L., Young, M., Chan, G. S., & Ellard, C. G. (2004). The contributions of static visual cues, nonvisual cues, and optic flow in distance estimation. *Perception, 33*(1), 49-65.

Teasdale, N., Stelmach, G. E., & Breunig, A. (1991). Postural sway characteristics of the elderly under normal and altered visual and support surface conditions. *Journal of Gerontology, 46*(6), B238-B244.

Terband, H., Maassen, B., Van Lieshout, P. H. H. M., & Nijland, L. (2011). Stability and composition of functional synergies for speech movements in children with developmental speech disorders. *Journal of Communication Disorders, 44*(1), 59-74.

Tesio, L., & Rota, V. (2019). The motion of body center of mass during walking: a review oriented to clinical applications. *Frontiers in neurology, 10,* 999.

Thelen, E. (1989). The (re) discovery of motor development: Learning new things from an old field. *Developmental psychology*, *25*(6), 946.

Thelen, E. (2005). Dynamic systems theory and the complexity of change. *Psychoanalytic dialogues*, *15*(2), 255-283.

Thomas, J., Alderson, J., Thomas, K., Campbell, A., Edwards, B., Meardon, S., & Elliott, B. (2012). Is there a general motor program for right versus left hand throwing in children?. *Journal of Biosensors and Bioelectronics*, *2011*(1), 1-4.

*Timed Up and Go Test (TUG)*. (n.d.). Retrieved September 24, 2021, from https://www.physio-pedia.com/Timed_Up_and_Go_Test_(TUG).

Turano, K. A., Yu, D., Hao, L., & Hicks, J. C. (2005). Optic-flow and egocentric-direction strategies in walking: Central vs peripheral visual field. *Vision research*, *45*(25-26), 3117-3132.

Turton, A. J., Dewar, S. J., Lievesley, A., O'Leary, K., Gabb, J., & Gilchrist, I. D. (2009). Walking and wheelchair navigation in patients with left visual neglect. *Neuropsychological rehabilitation*, *19*(2), 274-290.

Turvey, M. T., Harrison, S. J., Frank, T. D., & Carello, C. (2012). Human odometry verifies the symmetry perspective on bipedal gaits. *Journal of Experimental Psychology: Human Perception and Performance, 38*(4), 1014.

Turvey, M. T., Romaniak-Gross, C., Isenhower, R. W., Arzamarski, R., Harrison, S., & Carello, C. (2009). Human odometer is gait-symmetry specific. *Proceedings of the Royal Society B: Biological Sciences*, *276*(1677), 4309-4314.

Vali Noghondar, N., Sohrabi, M., Taheri, H. R., Kobravi, H. R., & Khodashenas, E. (2021). Pre-programming in overhand throwing of children with Down syndrome: role of the generalized motor program. *International Journal of Developmental Disabilities, 67*(3), 229-235.

van Dijsseldonk, R. B., De Jong, L. A., Groen, B. E., Vos-Van Der Hulst, M., Geurts, A. C., & Keijsers, N. L. (2018). Gait stability training in a virtual environment improves gait and dynamic balance capacity in incomplete spinal cord injury patients. *Frontiers in Neurology, 9*, 963.

van Doorn, H., van der Kamp, J., & Savelsbergh, G. J. (2007). Grasping the Müller-Lyer illusion: The contributions of vision for perception in action. *Neuropsychologia*, *45*(8), 1939-1947.

Van Hooren, B., Meijer, K., & McCrum, C. (2019). Attractive gait training: applying dynamical systems theory to the improvement of locomotor performance across the lifespan. *Frontiers in physiology*, *9*, 1934.

Vaz, D. V., Silva, P. L., Mancini, M. C., Carello, C., & Kinsella-Shaw, J. (2017). Towards an ecologically grounded functional practice in rehabilitation. *Human Movement Science*, *52*, 117-132.

Vera, J. G., Alvarez, J. C. B., & Medina, M. M. (2008). Effects of different practice conditions on acquisition, retention, and transfer of soccer skills by 9-year-old schoolchildren. *Perceptual and motor skills*, *106*(2), 447-460.

Villiger, M., Liviero, J., Awai, L., Stoop, R., Pyk, P., Clijsen, R., ... & Bolliger, M. (2017). Home-based virtual reality-augmented training improves lower limb muscle strength, balance, and functional mobility following chronic incomplete spinal cord injury. *Frontiers in neurology, 8*, 635.

Wade, M. G., Lindquist, R., Taylor, J. R., & Treat-Jacobson, D. (1995). Optical flow, spatial orientation, and the control of posture in the elderly. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *50*(1), P51-P54.

Walker, W. C., & Pickett, T. C. (2007). Motor impairment after severe traumatic brain injury: a longitudinal multicenter study. *Journal of rehabilitation research and development*, *44*(7), 975.

Warren Jr, W. H., & Whang, S. (1987). Visual guidance of walking through apertures: body-scaled information for affordances. *Journal of experimental psychology: human perception and performance, 13*(3), 371.

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of experimental psychology: Human perception and performance, 10*(5), 683.

Warren, W. H. (1990). The perception-action coupling. In *Sensory-motor organizations and development in infancy and early childhood* (pp. 23-37). Springer, Dordrecht.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature neuroscience*, *4*(2), 213-216.

Wexler, M., & Van Boxtel, J. J. (2005). Depth perception by the active observer. *Trends in cognitive sciences*, *9*(9), 431-438.

Wilson, P. N., Foreman, N., & Stanton, D. (1999). Improving spatial awareness in physically disabled children using virtual environments. *Engineering Science & Education Journal, 8*(5), 196-200.

Yen, S. C., Schmit, B. D., Landry, J. M., Roth, H., & Wu, M. (2012). Locomotor adaptation to resistance during treadmill training transfers to overground walking in human SCI. *Experimental brain research*, *216*(3), 473-482.

Yeo, E., Chau, B., Chi, B., Ruckle, D. E., & Ta, P. (2019). Virtual reality neurorehabilitation for mobility in spinal cord injury: a structured review. *Innovations in Clinical Neuroscience, 16(*1-2), 13.

Yoo, J. W., Lee, D. R., Sim, Y. J., You, J. H., & Kim, C. J. (2014). Effects of innovative virtual reality game and EMG biofeedback on neuromotor control in cerebral palsy. *Bio-medical materials and engineering*, *24*(6), 3613-3618.

Young, P. M. M., Wilken, J. M., & Dingwell, J. B. (2012). Dynamic margins of stability during human walking in destabilizing environments. *Journal of biomechanics*, *45*(6), 1053-1059

Zariffa, J., Steeves, J., & Pai, D. K. (2012). Changes in hand muscle synergies in subjects with spinal cord injury: characterization and functional implications. *The journal of spinal cord medicine*, *35*(5), 310-318.

Zhu, J., Zhang, E., & Del Rio-Tsonis, K. (2012). Eye Anatomy. *eLS.*

# APPENDICES

# Appendix A

Sample Size Calculation for Study 1 Using Pocock Spending Function on RPACT

R Command

```
design <- getDesignGroupSequential(typeOfDesign = "asP", informationRates = c(0.33333333,
  0.66666667, 1), alpha = 0.05, twoSidedPower = TRUE, sided = 2)
summary(getSampleSizeMeans(design, alternative = 0.6, groups = 1))
```

☐ Show default parameters

R Output    Summary

```
Sample size calculation for a continuous endpoint

Sequential analysis with a maximum of 3 looks (group sequential design), overall
significance level 5% (two-sided).
The sample size was calculated for a one-sample t-test, H0: mu = 0,
H1: effect = 0.6, standard deviation = 1, power 80%.

Stage                                  1      2      3
Information rate                   33.3%  66.7%   100%
Efficacy boundary (z-value scale)   2.279  2.295  2.296
Overall power                      0.2982 0.6015 0.8000
Expected number of subjects          19.5
Number of subjects                    9.3   18.6   27.8
Cumulative alpha spent             0.0226 0.0382 0.0500
Two-sided local significance level 0.0226 0.0217 0.0217
Lower efficacy boundary (t)        -0.917 -0.584 -0.462
Upper efficacy boundary (t)         0.917  0.584  0.462

Legend:
  (t): treatment effect scale
```

# Appendix B

Sample Size Calculation for Study 2 Using Pocock Spending Function on RPACT

R Command

```
design <- getDesignGroupSequential(typeOfDesign = "asP", informationRates = c(0.33333333,
  0.66666667, 1), alpha = 0.05, twoSidedPower = TRUE, sided = 2)
summary(getSampleSizeMeans(design, alternative = 0.6))
```

☐ Show default parameters

R Output    Summary

```
Sample size calculation for a continuous endpoint

Sequential analysis with a maximum of 3 looks (group sequential design), overall
significance level 5% (two-sided).
The sample size was calculated for a two-sample t-test, H0: mu(1) - mu(2) = 0,
H1: effect = 0.6, standard deviation = 1, power 80%.

Stage                                   1      2      3
Information rate                    33.3%  66.7%   100%
Efficacy boundary (z-value scale)   2.279  2.295  2.296
Overall power                      0.2982 0.6015 0.8000
Expected number of subjects          73.1
Number of subjects                   34.8   69.6  104.4
Cumulative alpha spent             0.0226 0.0382 0.0500
Two-sided local significance level 0.0226 0.0217 0.0217
Lower efficacy boundary (t)        -0.811 -0.563 -0.456
Upper efficacy boundary (t)         0.811  0.563  0.456

Legend:
  (t): treatment effect scale
```

# Appendix C

Sample Size Calculation for Study 3 Using Pocock Spending Function on RPACT

R Command

```
design <- getDesignGroupSequential(typeOfDesign = "asP", informationRates = c(0.33333333,
  0.66666667, 1), alpha = 0.05, twoSidedPower = TRUE, sided = 2)
summary(getSampleSizeMeans(design, alternative = 0.4))
```

☐ Show default parameters

R Output | Summary ▾

```
Sample size calculation for a continuous endpoint

Sequential analysis with a maximum of 3 looks (group sequential design), overall
significance level 5% (two-sided).
The sample size was calculated for a two-sample t-test, H0: mu(1) - mu(2) = 0,
H1: effect = 0.4, standard deviation = 1, power 80%.

Stage                                  1      2      3
Information rate                   33.3%  66.7%   100%
Efficacy boundary (z-value scale)   2.279  2.295  2.296
Overall power                      0.2982 0.6015 0.8000
Expected number of subjects         162.4
Number of subjects                   77.3  154.6  231.9
Cumulative alpha spent             0.0226 0.0382 0.0500
Two-sided local significance level 0.0226 0.0217 0.0217
Lower efficacy boundary (t)        -0.529 -0.373 -0.304
Upper efficacy boundary (t)         0.529  0.373  0.304

Legend:
  (t): treatment effect scale
```

## Appendix D

Sample Scoring Sheet for Timed Up and Go Test ("Timed Up and Go Test (TUG)", n.d.)

Timed Up and Go Test (TUG)—Scoring sheet

Date: ___________

Time (seconds): ______

Assistive Device Used:
- none: ____
- cane: ____
- walker:____
- other: ____

Other:
- stopped to rest: ____
- impaired cognition:____

Risk for Falls:
- High Risk (>13.5 seconds): ____
- None/low/moderate: (<13.5 seconds):____

## Appendix E

Figure E1: Ferrans and Powers Quality of Life Index for SCI (QOLI-SCI) Questionnaire

**Ferrans and Powers**
**QUALITY OF LIFE INDEX©**
**SPINAL CORD INJURY VERSION - III**

PART 1. For each of the following, please choose the answer that best describes how ***satisfied*** you are with that area of your life. Please mark your answer by circling the number. There are no right or wrong answers.

| **HOW *SATISFIED* ARE YOU WITH:** | Very Dissatisfied | Moderately Dissatisfied | Slightly Dissatisfied | Slightly Satisfied | Moderately Satisfied | Very Satisfied |
|---|---|---|---|---|---|---|
| 1. Your health? | 1 | 2 | 3 | 4 | 5 | 6 |
| 2. Your health care? | 1 | 2 | 3 | 4 | 5 | 6 |
| 3. The amount of pain that you have? | 1 | 2 | 3 | 4 | 5 | 6 |
| 4. The amount of energy you have for everyday activities? | 1 | 2 | 3 | 4 | 5 | 6 |
| 5. Your ability to take care of yourself without help? | 1 | 2 | 3 | 4 | 5 | 6 |
| 6. Your ability to go places outside your home? | 1 | 2 | 3 | 4 | 5 | 6 |
| 7. Your ability to clear your lungs? | 1 | 2 | 3 | 4 | 5 | 6 |
| 8. The amount of control you have over your life? | 1 | 2 | 3 | 4 | 5 | 6 |
| 9. Your chances of living as long as you would like? | 1 | 2 | 3 | 4 | 5 | 6 |
| 10. Your family's health? | 1 | 2 | 3 | 4 | 5 | 6 |
| 11. Your children? | 1 | 2 | 3 | 4 | 5 | 6 |
| 12. Your ability to have children? | 1 | 2 | 3 | 4 | 5 | 6 |
| 13. Your family's happiness? | 1 | 2 | 3 | 4 | 5 | 6 |
| 14. Your sex life? | 1 | 2 | 3 | 4 | 5 | 6 |
| 15. Your spouse, lover, or partner (if you have one)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 16. Not having a spouse, lover or partner (if you do not have one)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 17. Your friends? | 1 | 2 | 3 | 4 | 5 | 6 |

(Please Go To Next Page)



Page 1

## Appendix E

Figure E2: Ferrans and Powers Quality of Life Index for SCI (QOLI-SCI) Questionnaire

| HOW *SATISFIED* ARE YOU WITH: | Very Dissatisfied | Moderately Dissatisfied | Slightly Dissatisfied | Slightly Satisfied | Moderately Satisfied | Very Satisfied |
|---|---|---|---|---|---|---|
| 18. The emotional support you get from your family? | 1 | 2 | 3 | 4 | 5 | 6 |
| 19. The emotional support you get from people other than your family? | 1 | 2 | 3 | 4 | 5 | 6 |
| 20. Your ability to take care of family responsibilities? | 1 | 2 | 3 | 4 | 5 | 6 |
| 21. How useful you are to others? | 1 | 2 | 3 | 4 | 5 | 6 |
| 22. The amount of worries in your life? | 1 | 2 | 3 | 4 | 5 | 6 |
| 23. Your neighborhood? | 1 | 2 | 3 | 4 | 5 | 6 |
| 24. Your home, apartment, or place where you live? | 1 | 2 | 3 | 4 | 5 | 6 |
| 25. Your job (if employed)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 26. Not having a job (if unemployed, retired, or disabled)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 27. Your education? | 1 | 2 | 3 | 4 | 5 | 6 |
| 28. How well you can take care of your financial needs? | 1 | 2 | 3 | 4 | 5 | 6 |
| 29. The things you do for fun? | 1 | 2 | 3 | 4 | 5 | 6 |
| 30. Your chances for a happy future? | 1 | 2 | 3 | 4 | 5 | 6 |
| 31. Your peace of mind? | 1 | 2 | 3 | 4 | 5 | 6 |
| 32. Your faith in God? | 1 | 2 | 3 | 4 | 5 | 6 |
| 33. Your achievement of personal goals? | 1 | 2 | 3 | 4 | 5 | 6 |
| 34. Your happiness in general? | 1 | 2 | 3 | 4 | 5 | 6 |
| 35. Your life in general? | 1 | 2 | 3 | 4 | 5 | 6 |
| 36. Your personal appearance? | 1 | 2 | 3 | 4 | 5 | 6 |
| 37. Yourself in general? | 1 | 2 | 3 | 4 | 5 | 6 |

(Please Go To Next Page)



Page 2

## Appendix E

Figure E3: Ferrans and Powers Quality of Life Index for SCI (QOLI-SCI) Questionnaire

PART 2. For each of the following, please choose the answer that best describes how ***important*** that area of your life is to you. Please mark your answer by circling the number. There are no right or wrong answers.

| **HOW *IMPORTANT* TO YOU IS:** | Very Unimportant | Moderately Unimportant | Slightly Unimportant | Slightly Important | Moderately Important | Very Important |
|---|---|---|---|---|---|---|
| 1. Your health? | 1 | 2 | 3 | 4 | 5 | 6 |
| 2. Your health care? | 1 | 2 | 3 | 4 | 5 | 6 |
| 3. Having no pain? | 1 | 2 | 3 | 4 | 5 | 6 |
| 4. Having enough energy for everyday activities? | 1 | 2 | 3 | 4 | 5 | 6 |
| 5. Taking care of yourself without help? | 1 | 2 | 3 | 4 | 5 | 6 |
| 6. Being able to go places outside your home? | 1 | 2 | 3 | 4 | 5 | 6 |
| 7. Your ability to clear your lungs? | 1 | 2 | 3 | 4 | 5 | 6 |
| 8. Having control over your life? | 1 | 2 | 3 | 4 | 5 | 6 |
| 9. Living as long as you would like? | 1 | 2 | 3 | 4 | 5 | 6 |
| 10. Your family's health? | 1 | 2 | 3 | 4 | 5 | 6 |
| 11. Your children? | 1 | 2 | 3 | 4 | 5 | 6 |
| 12. Being able to have children? | 1 | 2 | 3 | 4 | 5 | 6 |
| 13. Your family's happiness? | 1 | 2 | 3 | 4 | 5 | 6 |
| 14. Your sex life? | 1 | 2 | 3 | 4 | 5 | 6 |
| 15. Your spouse, lover, or partner (if you have one)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 16. Having a spouse, lover or partner (if you do not have one)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 17. Your friends? | 1 | 2 | 3 | 4 | 5 | 6 |

(Please Go To Next Page)



Page 3

## Appendix E

Figure E4: Ferrans and Powers Quality of Life Index for SCI (QOLI-SCI) Questionnaire

| **HOW *IMPORTANT* TO YOU IS:** | Very Unimportant | Moderately Unimportant | Slightly Unimportant | Slightly Important | Moderately Important | Very Important |
|---|---|---|---|---|---|---|
| 18. The emotional support you get from your family? | 1 | 2 | 3 | 4 | 5 | 6 |
| 19. The emotional support you get from people other than your family? | 1 | 2 | 3 | 4 | 5 | 6 |
| 20. Taking care of family responsibilities? | 1 | 2 | 3 | 4 | 5 | 6 |
| 21. Being useful to others? | 1 | 2 | 3 | 4 | 5 | 6 |
| 22. Having no worries? | 1 | 2 | 3 | 4 | 5 | 6 |
| 23. Your neighborhood? | 1 | 2 | 3 | 4 | 5 | 6 |
| 24. Your home, apartment, or place where you live? | 1 | 2 | 3 | 4 | 5 | 6 |
| 25. Your job (if employed)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 26. Having a job (if unemployed, retired, or disabled)? | 1 | 2 | 3 | 4 | 5 | 6 |
| 27. Your education? | 1 | 2 | 3 | 4 | 5 | 6 |
| 28. Being able to take care of your financial needs? | 1 | 2 | 3 | 4 | 5 | 6 |
| 29. Doing things for fun? | 1 | 2 | 3 | 4 | 5 | 6 |
| 30. Having a happy future? | 1 | 2 | 3 | 4 | 5 | 6 |
| 31. Peace of mind? | 1 | 2 | 3 | 4 | 5 | 6 |
| 32. Your faith in God? | 1 | 2 | 3 | 4 | 5 | 6 |
| 33. Achieving your personal goals? | 1 | 2 | 3 | 4 | 5 | 6 |
| 34. Your happiness in general? | 1 | 2 | 3 | 4 | 5 | 6 |
| 35. Being satisfied with life? | 1 | 2 | 3 | 4 | 5 | 6 |
| 36. Your personal appearance? | 1 | 2 | 3 | 4 | 5 | 6 |
| 37. Are you to yourself? | 1 | 2 | 3 | 4 | 5 | 6 |



Page 4

# Appendix F

Figure F1: Ferrans and Powers Quality of Life Index for SCI (QOLI-SCI) Scoring Instructions

**Description of Scoring for the Ferrans and Powers Quality of Life Index (QLI)**

*NOTE: This is a description of the steps for calculating the five scores of the Quality of Life Index: total scale, health and functioning subscale, social and economic subscale, psychological/spiritual subscale, and family subscale. To calculate the scores, we recommend using the computer syntax for SPSS-PC, which is included in this web site.*

| | STEPS | DESCRIPTION |
|---|---|---|
| **OVERALL QLI SCORE (overall quality of life)** | | |
| 1. | Recode satisfaction scores | To center the scale on zero, subtract 3.5 from satisfaction response for each item. (This will produce responses of –2.5, -1.5, -.5, +.5, +1.5, +2.5.) |
| 2. | Weight satisfaction responses with the paired importance responses. | Multiply the recoded satisfaction response by the raw importance response for each pair of satisfaction and importance items. |
| 3. | Obtain preliminary sum for the overall (total) score. | Add together the weighted responses obtained in step 2 for all of the items. |
| 4. | Obtain final overall (total) QLI score. | To prevent bias due to missing data, divide each sum obtained in step 3 by the number of items answered by that individual. (At this point the possible range for scores is –15 to +15.) Next, to eliminate negative numbers for the final score, add 15 to every score. This will produce the final overall (total) QLI score. (Possible range for the final scores = 0 to 30). |

**SUBSCALE SCORES**

*The same steps are used to calculate subscale scores as total scores. The only difference is that the calculations are performed using subsets of items, rather than on all of the items.*

| | | |
|---|---|---|
| 1. | Recode satisfaction scores | To center the scale on zero, subtract 3.5 from the satisfaction response for each item. (This will produce responses of –2.5, -1.5, -.5, +.5, +1.5, +2.5.) *This is exactly the same step as #1 above.* |
| 2. | Weight satisfaction responses with | Multiply the recorded satisfaction response by |

1

## Appendix F

Figure F2: Ferrans and Powers Quality of Life Index for SCI (QOLI-SCI) Scoring Instructions

| | | |
|---|---|---|
| | the paired importance responses. | the raw importance for each pair of satisfaction and importance items. *This is exactly the same step as # 2 above.* |
| 3. | Obtain preliminary sum for the subscale score. | Add together the weighted responses obtained in step 2 *for the items that compose the subscale*. |
| 4. | Obtain final subscale score. | To prevent bias due to missing data, divide each sum obtained in step 3 by the number of items answered *in that subscale* for that individual. (At this point the possible range for score is –15 to +15. *This is the possible range for all four of the subscales and for the overall (total) score. The possible range is the same for all five scores even though they have different numbers of items, because we have divided the preliminary sum by the number of items answered for each one.*) Next, to eliminate negative numbers for the final score, add 15 to every score. *It is always the number 15 that is added, regardless of which subscale score is being calculated.* This will produce the final subscale score. (Possible range for the final scores = 0 to 30.) *The possible range for the final scores is the same for all four subscales and for the overall (total) score.* |

2

## Appendix G

Researcher Developed Questionnaire Assessing Level of Enjoyment and Satisfaction

1. I enjoyed my experience in the training sessions (0 at no point – 5 all of the time)
0 1 2 3 4 5

2. During the training sessions, I felt like I was stuck in a lab (0 at no point – 5 all of the time)
0 1 2 3 4 5

3. I felt like I was actually moving through my surroundings during the training (0 at no point – 5 all of the time)
0 1 2 3 4 5

4. How often would you exercise given the equipment during this training? (0 rarely – 5 everyday)
0 1 2 3 4 5

5. I look forward to and I am motivated to come to training sessions (0 at no point – 5 all of the time)
0 1 2 3 4 5

6. I enjoy the presence of the therapists (0 at no point – 5 all of the time)
0 1 2 3 4 5

7. Would you recommend this program to another person? (0 never – 5 to everyone)
0 1 2 3 4 5

8. This exercise experience made the time seem quicker than other treatments (0 at no point – 5 all of the time)
0 1 2 3 4 5

9. I see changes in my performance from the start of the program (0 none – 5 huge difference)
0 1 2 3 4 5

10. I feel good about myself following training (0 at no point – 5 all of the time)
0 1 2 3 4 5

11. My confidence to perform tasks on my own is improving (0 same confidence – 5 I perform significantly more tasks on my own)
0 1 2 3 4 5

12. I feel more stable and balanced when I walk through my environment (0 at no point – 5 all of the time)

| | | | | | |
|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 |

# Appendix H

Figure H1: NSERC Postgraduate Scholarship (PGS D) Application

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

**Application for a Postgraduate Scholarship or Postdoctoral Fellowship (FORM 201)**

| | |
|---|---|
| AID | |
| CTTEE | |
| Date | 2021/09/08 |

| Type of Award | Reference No. |
|---|---|
| PGS D | [redacted] |

| Family name of applicant | Given name | Initial(s) of all given names | Personal identification no. (PIN) |
|---|---|---|---|
| De Melo | Kristen | [redacted] | [redacted] |

**ADDRESSES.** Changes to any of the information below must be sent to schol@nserc-crsng.gc.ca.

Current mailing address
1280 Main Street W
Hamilton, ON
CANADA L8S 4L8

If current mailing address is temporary, indicate leaving date

| Telephone number | Facsimile number | E-mail address NSERC will use this information as the initial point of contact. |
|---|---|---|
| 905 (525) 9140 | | [redacted] |

**CITIZENSHIP**

[X] Canadian citizen [ ] Permanent resident of Canada [ ] Protected person

Date of issue as stated on official immigration document

**LANGUAGE OF CORRESPONDENCE**

I wish to receive my correspondence in:

[X] English [ ] French

**University responsible for the internal selection process (Not applicable for PGS applications submitted directly and PDF applications.)**

Form 201 (2011 W), Cover page | Personal information collected on this form and appendices will be stored in the Personal Information Bank for the appropriate program. | Version française disponible

Canada | PROTECTED B WHEN COMPLETED | Not Completed

# Appendix H

Figure H2: NSERC Postgraduate Scholarship (PGS D) Application

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

Page 1 of 7

**Application for a Postgraduate Scholarship or Postdoctoral Fellowship (FORM 201)**

| | |
|---|---|
| AID | |
| CTTEE | |
| Date | 2021/09/08 |

| Type of Award |
|---|
| PGS D |

| Family name of applicant | Given name | Initial(s) of all given names | Personal identification no. (PIN) |
|---|---|---|---|
| De Melo | Kristen | [redacted] | [redacted] |

**ACADEMIC BACKGROUND (include only current and past degree programs)**

| Degree | Name of discipline | Department, institution and country | Month and year started | Month and year awarded/expected |
|---|---|---|---|---|
| Bachelor's | | Kinesiology McMaster, CANADA | [redacted] | |
| Master's | | Kinesiology McMaster, CANADA | [redacted] | |

Form 201 (2011 W) PROTECTED B WHEN COMPLETED Version française disponible

Canadä

## Appendix H

Figure H3: NSERC Postgraduate Scholarship (PGS D) Application

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

Page 2 of 7

**Application for a Postgraduate Scholarship or Postdoctoral Fellowship (FORM 201)**

| Type of Award | | AID | CTTEE | Date |
|---|---|---|---|---|
| PGS D | | | | 2021/09/08 |

| Family name of applicant | Given name | Initial(s) of all given names | Personal identification no. (PIN) |
|---|---|---|---|
| De Melo | Kristen | [redacted] | [redacted] |

ACADEMIC, RESEARCH AND OTHER RELEVANT WORK EXPERIENCE

| Position held and nature of work (begin with current) Full Time – Part Time | Organization and department | Supervisor | Period (mm/yyyy-mm/yyyy) |
|---|---|---|---|
| [redacted] | | | |

Form 201 (2011 W) PROTECTED B WHEN COMPLETED Version française disponible

Canadä

# Appendix H

Figure H4: NSERC Postgraduate Scholarship (PGS D) Application



| Personal identification no. (PIN) | Family name, given name and initial(s) of applicant |
|---|---|
| [redacted] | De Melo, Kristen [redacted] |

**AWARD APPLIED FOR**

| Type of award | Proposed starting date of award |
|---|---|
| Postgraduate Scholarships - PGS D | 2022/09 |

| Proposed degree program (e.g. Masters, Doctorate) | Proposed field of study/research | Research subject code |
|---|---|---|
| Doctorate | Kinesiology | 5502 |

Title of proposed research
THE EFFECTS OF PERCEPTION-ACTION COUPLING ON COMPROMISED HUMAN LOCOMOTION: A PROPOSED RESEARCH PROGRAM

List ten (10) key words that describe your proposed research.
Optic Flow, Perception, Action, Dynamic Vision, Spatial Updating, Locomotion, Ecological Theory,

**PROPOSED LOCATION(S) OF TENURE (in order of preference)**

| Institution/organization | Department | Program of study | Proposed supervisor |
|---|---|---|---|
| McMaster, | Kinesiology | | |
| Toronto, | Rehabilitation Science Institute | | |

Are any of your proposed programs of study:

Clinically-oriented? [X] Yes [ ] No Joint programs with a professional degree (e.g., MD/PhD)? [ ] Yes [ ] No

**SECTION TO BE COMPLETED BY PGS APPLICANTS ONLY**

Indicate the total number of months of graduate studies (master's and doctoral) you have completed as of December 31 of the year of application in the natural sciences and engineering.

[redacted] months of full-time studies ____ months of part-time studies

Indicate the number of months of studies you have completed, as of December 31 of the year of application, **in the program for which you are requesting funding.**

0 months of full-time studies ____ months of part-time studies

Indicate if you are attending university at the time of application.

[X] Attending full time [ ] Attending part time [ ] Not attending

Form 201 (2011 W) PROTECTED B WHEN COMPLETED Version française disponible

Canadä

# Appendix H

Figure H5: NSERC Postgraduate Scholarship (PGS D) Application

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

Page 4 of 7

**Application for a Postgraduate Scholarship or Postdoctoral Fellowship (FORM 201)**

| Type of Award | Personal Identification no. (PIN) | Family name, given name and initial(s) of applicant |
|---|---|---|
| PGS D | [redacted] | De Melo, Kristen [redacted] |

**SCHOLARSHIPS AND OTHER AWARDS OFFERED (start with most recent and include NSERC awards)**

| Name of Award | Value (CDN$) | Level Institutional, Provincial, National, International | Type Academic, Research, Leadership, Communication | Location of tenure | Period held (yyyy/mm – yyyy/mm) |
|---|---|---|---|---|---|
| [redacted] | | | | | |

Form 201 (2011 W)

Canada

Version française disponible

PROTECTED B WHEN COMPLETED

# Appendix H

Figure H6: NSERC Postgraduate Scholarship (PGS D) Application



| Type of Award | Personal identification no.(PIN) | Family name, given name and initial(s) of applicant |
|---|---|---|
| PGS D | [redacted] | De Melo, Kristen [redacted] |

**THESIS COMPLETED OR IN PROGRESS**

| 1. Degree | Supervisor | Date degree requirements completed |
|---|---|---|
| Masters of Science | Dr. Jim Lyons | 09/2021 |

Title of thesis
THE EFFECTS OF PERCEPTION-ACTION COUPLING ON COMPROMISED HUMAN LOCOMOTION: A PROPOSED RESEARCH PROGRAM

| 2. Degree | Supervisor | Date degree requirements completed |
|---|---|---|
| | | |

Title of thesis

**SUMMARY OF THESIS MOST RECENTLY COMPLETED OR IN PROGRESS**

Do not reproduce abstract of thesis.

To understand how humans interact and navigate about their environment, and how this process may change with injury or disease, it has been suggested that one must grasp the interrelationships that exist between the environment, the task, and the individual (Gibson, 1966; Roberton, 1989; Headrick et al., 2015; Seifert et al., 2017). These relationships develop through a direct linkage that exists between the human perceptual and motor systems. Research indicates that these systems are dynamically coupled and assist one another in coordinating movements (Bertenthal, 1996; Bertenthal et al., 1997; Barbu-Roth et al., 2009; Barbu-Roth et al., 2014), therefore suggesting that they cannot be studied independently. The perception-action linkage allows for adaptive behavior to the surroundings since they are coupled by laws of control that relate information variables to the most appropriate parameters of action (Warren, 1990).
A major component of this framework is optic flow, which is the pattern of the environment on the eye caused by the movement between the observer and the visual scene (Warren et al., 2001). Optic flow plays a critical role in obstacle avoidance, navigation, and depth perception (e.g., Turton et al., 2009; Rand et al., 2019; Franchak & Adolph, 2010; Matthis & Fajen, 2014; Koenderink & van Doorn, 1987; Wexler & Van Boxtel, 2005). Without optic flow, the relationship between perception and action becomes decoupled, leading to downfalls in human behaviour (i.e., challenges with posture, locomotion, atypical reflexes; Lee, 1980, Warren, 1990; Poulain & Giraudet, 2008; Berard et al., 2012; Alotaibi et al., 2016). Despite the demonstrated importance of maintaining the perception-action linkage, rehabilitation literature often carries out protocols where the opportunity to experience optic flow is absent (i.e., stationary treadmills; Hicks et al., 2005; Macko et al., 2005; Harkema et al., 2012). This absence is predicted to be the reason for lengthy, expensive, and exhausting treatment plans (Nas et al., 2015).
Instances in the literature have shown that the reintroduction of optic flow into protocols has resulted in more rapid and greater improvements in human movement (Field-Fote & Roach, 2011; Gama et al., 2017; Combs-Miller et al., 2014). These studies have suggested that the only underlying difference with their protocols from typical treatment is the incorporation of dynamic vision into their paradigms. This idea requires more in-depth exploration to examine how this link between perception and action behaves in adult locomotion, providing a further expansion of the ecological theory as it relates to human motion. Therefore, the current research program aims to fill this gap by evaluating how the reintroduction of optic flow into atypical gait training protocols can enhance movement performance. This series of studies takes the literature further by first exploring the strength of the perception-action linkage through neuromuscular level changes, how it can benefit the human recalibration process given one's newly acquired physical changes, and finally, how it can impact larger scale gait cycle performances.

Form 201 (2011 W) PROTECTED B WHEN COMPLETED Version française disponible

Canadä

# Appendix H

## Figure H7: NSERC Postgraduate Scholarship (PGS D) Application

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

Page 6 of 7

**Application for a Postgraduate Scholarship or Postdoctoral Fellowship (FORM 201)**

| Type of Award | | Personal identification no. (PIN) | Family name, given name and initial(s) of applicant |
|---|---|---|---|
| PGS D | | [redacted] | De Melo, Kristen [redacted] |

**DIVERSITY CONSIDERATIONS IN RESEARCH DESIGN**

Are diversity considerations including, but not limited to, sex and gender taken into account in the research design, methods, analysis and interpretation, and/or dissemination of findings?

X Yes    No

**NOTE**

If you answer "yes" to the question above, please ensure that diversity considerations are incorporated throughout your proposal (i.e. research design, methods, analysis and interpretation, and/or dissemination of their findings).

If you answer "no" to the question above, please use the text box provided to explain why diversity considerations are not relevant to your research design.

Form 201 (2020 W) PROTECTED B WHEN COMPLETED Version française disponible

Canadä

# Appendix H

## Figure H8: NSERC Postgraduate Scholarship (PGS D) Application



Ecological theory of human movement has guided our understanding of human behaviour as it relates to our surroundings. It focuses more readily on how humans use sensory information to serve as a basis for voluntary movement control. This framework addresses the interaction between perception and action by attempting to explain interrelationships that exist between humans and their environment (Gibson, 1966). Specific factors related to a task, an individual, and the surroundings can help shape this process (Headrick et al., 2015; Seifert et al., 2017). It is suggested that motor control processes exist to allow animals, including humans, to survive and cope with their surroundings. Vision plays a crucial role in this process, gearing these actions towards specific variables (i.e., stimuli) within that environment (Heft, 2001).

The perceptual and motor systems are suggested to have evolved not as discrete, independent constructs, but rather in a close interrelationship (Gibson, 1966). The two systems grow together and change as an individual develops and gains new visual experiences. Perception and action are suggested to be dynamically coupled and assist one another in coordinating movements (Bertenthal, 1996; Bertenthal et al., 1997; Barbu-Roth et al., 2009; Barbu-Roth et al., 2014; Rossi, Rodrigues, & Forner-Cordero, 2014). This link allows for adaptive behaviours to the surroundings since they are coupled by laws of control relating information variables to the most appropriate parameters of action (Warren, 1990). A critical component to this relationship is optic flow, which is the pattern of motion of the environment caused by the movement between the observer and the visual scene (Warren et al., 2001). Optic flow plays a critical role in navigation (Turton et al., 2009; Rand et al., 2019), control amongst obstacles (Marigold & Patla, 2008; Franchak & Adolph, 2010; Matthis & Fajen, 2014), and depth perception (Koenderink & van Doorn, 1987; Wexler & Van Boxtel, 2005; McManus, D'Amour, & Harris, 2017). The effects of different optical flow fields on movement can be seen in early development, demonstrating an innate reliance on the perception-action linkage (Lee & Aronson, 1974; Barbu-Roth et al., 2014; Forma et al., 2018). Without optic flow, this linkage becomes decoupled and individuals lack the visual calibration of the action component, leading to slower environmental adaptations (Warren, 1990; Klostermann & Mann, 2019).

The effects of decoupling the perception-action linkage has been shown in the literature to produce downfalls in human behaviour (i.e., challenges with posture, locomotion, atypical reflexes; Lee, 1980, Warren, 1990; Poulain & Giraudet, 2008; Berard et al., 2012; Alotaibi et al., 2016). Despite the considerate level of research demonstrating these decoupling effects, there are various ambulation protocols (more specifically in rehabilitation) carried out in research where the opportunity to experience optic flow is absent (e.g., Hicks et al., 2005; Macko et al., 2005; Harkema et al., 2012). This absence is predicted to cause lengthy and exhaustive treatment plans due to sub-optimal locomotor conditions (Nas et al., 2015). The literature has shown instances where reintroducing dynamic visual information (optic flow) into training protocols produces more rapid gait improvements in shorter times than typical ambulation protocols (Field-Fote & Roach, 2011; Gama et al., 2017; Combs-Miller et al., 2014; An & Park, 2018; van Dijsseldonk et al., 2018). These studies have suggested that the only underlying difference with their protocols from typical paradigms is the incorporation of visual stimulation. It is evident that there is a disconnect in the literature between understanding the existing perception-action relationship in adulthood, the strength of its effects on movement control, and how it can contribute to human locomotion training. Therefore, the current research program aims to fill this gap by evaluating

# Appendix H

## Figure H9: NSERC Postgraduate Scholarship (PGS D) Application



how the reintroduction of optic flow into gait training protocols can enhance locomotor outcomes. These studies take the literature further by looking at outcome enhancements through neuromuscular level changes, the recalibration process of perception-action given newly acquired physical changes, and larger scale gait cycle performances. The overall research question looks at how vision contributes to action on a neuromuscular level, and how it can calibrate our actions in atypical gaits to improve movement performance.

The purpose of *study one* is to determine the strength of the perception-action linkage in adults by testing to see if optic flow will elicit activation of the musculatures appropriate for response to the perception of that information, in the absence of voluntary movement. This study will place healthy adults in a virtual environment using a virtual reality (VR) headset that will display a moving hallway with windows and doors. Participants will be fitted with EMG sensors to the major walking muscles of the leg, and will be asked to perform seated and static stance positions. During trials, the VR headset will adjust in speed (i.e., increasing 0.5 m/s every 10 seconds from 0 m/s to 3.0 m/s, then decreasing in the opposite direction) and muscle activation levels (i.e., peak and average activation) will be measured. It is hypothesized that receiving optic flow will elicit an increased neuromuscular response compared to baseline activation levels. More specifically, it is expected that in the standing versus sitting trials, larger increases in neuromuscular response will be experienced. This is anticipated to occur since throughout the lifespan, sitting positions become associated with passive movements (i.e., passenger in a car) while standing positions are typically associated with active movements (i.e., walking; Lee & Aronson, 1974; Barbu-Roth et al., 2009; Antley & Slater, 2010).

The purpose of *study two* is to assess whether the perception-action linkage is beneficial to calibrating spatial awareness during locomotion with artificially compromised gait. Gait will be temporarily compromised in typically developing adults through full-leg bracing. Participants will be divided into two groups and will engage in 20-minute treadmill walking with VR while wearing the brace. If in the optic flow group, participants will receive optic flow at the walking speed rate. If in the static vision group, participants will see a static virtual environment. The subsequent influence of optic flow on forward overground walking will be evaluated by measuring global spatial awareness (i.e., perception) using a continuous pointing paradigm encompassing vision and no vision trials (with and without the brace; Campos et al., 2009; Burkitt et al., 2020), and gait parameters (i.e., action). It is hypothesized that spatial awareness will be more accurate and measures of gait performance will improve more rapidly in the group provided with optic flow. This is expected due to the calibration process that occurs between the induced atypical gait pattern with visual information (Campos et al., 2009; Burkitt et al., 2020), forcing a reconstructed perception-action linkage with one's new physical conditions.

This research program will develop and expand the theoretical underpinnings of the perception-action literature and provide evidence for the use of optic flow in locomotor research paradigms. This would lead to significant practical implications of this work. For example, should the hypotheses be supported, this provides evidence for implementing VR (or optic flow) into rehabilitation protocols that use static vision (i.e., body weight supported training). It can be used in treatment protocols involving participants with compromised gait (e.g., spinal cord injury), and would demonstrate how optic flow can create optimal conditions for training of these individuals, leading to greater and more rapid movement improvements.

# Appendix H

Figure H10: NSERC Postgraduate Scholarship (PGS D) Application

References

Alotaibi, A. Z., Alghadir, A., Iqbal, Z. A., & Anwer, S. (2016). Effect of absence of vision on posture. *Journal of physical therapy science, 28*(4), 1374-1377

An, C. M., & Park, Y. H. (2018). The effects of semi-immersive virtual reality therapy on standing balance and upright mobility function in individuals with chronic incomplete spinal cord injury: a preliminary study. *The journal of spinal cord medicine, 41*(2), 223-229.

Antley, A., & Slater, M. (2010). The effect on lower spine muscle activation of walking on a narrow beam in virtual reality. *IEEE transactions on Visualization and Computer Graphics, 17*(2), 255-259.

Barbu-Roth, M., Anderson, D. I., Desprès, A., Provasi, J., Cabrol, D., & Campos, J. J. (2009). Neonatal stepping in relation to terrestrial optic flow. *Child development, 80*(1), 8-14.

Barbu-Roth, M., Anderson, D. I., Desprès, A., Streeter, R. J., Cabrol, D., Trujillo, M., ... & Provasi, J. (2014). Air stepping in response to optic flows that move toward and away from the neonate. *Developmental Psychobiology, 56*(5), 1142-1149.

Berard, J., Fung, J., & Lamontagne, A. (2012). Impact of aging on visual reweighting during locomotion. *Clinical neurophysiology, 123*(7), 1422-1428.

Bertenthal, B. I. (1996). Origins and early development of perception, action, and representation. *Annual review of psychology, 47*(1), 431-459.

Bertenthal, B. I., Rose, J. L., & Bai, D. L. (1997). Perception–action coupling in the development of visual control of posture. *Journal of Experimental Psychology: Human Perception and Performance, 23*(6), 1631.

Burkitt, J. J., Campos, J. L., & Lyons, J. L. (2020). Iterative Spatial Updating During Forward Linear Walking Revealed Using a Continuous Pointing Task. *Journal of Motor Behavior, 52*(2), 145-166.

Campos, J. L., Siegle, J. H., Mohler, B. J., Bülthoff, H. H., & Loomis, J. M. (2009). Imagined self-motion differs from perceived self-motion: evidence from a novel continuous pointing method. *PLoS One, 4*(11), e7793.

Combs-Miller, S. A., Kalpathi Parameswaran, A., Colburn, D., Ertel, T., Harmeyer, A., Tucker, L., & Schmid, A. A. (2014). Body weight-supported treadmill training vs. overground walking training for persons with chronic stroke: a pilot randomized controlled trial. *Clinical rehabilitation, 28*(9), 873-884.

Field-Fote, E. C., & Roach, K. E. (2011). Influence of a locomotor training approach on walking speed and distance in people with chronic spinal cord injury: a randomized clinical trial. *Physical therapy, 91*(1), 48-60.

## Appendix H

Figure H11: NSERC Postgraduate Scholarship (PGS D) Application

Forma, V., Anderson, D. I., Goffinet, F., & Barbu-Roth, M. (2018). Effect of optic flows on newborn crawling. *Developmental psychobiology, 60*(5), 497-510.

Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. *Vision research*, *50*(24), 2766-2774.

Gama, G. L., Celestino, M. L., Barela, J. A., Forrester, L., Whitall, J., & Barela, A. M. (2017). Effects of gait training with body weight support on a treadmill versus overground in individuals with stroke. *Archives of physical medicine and rehabilitation, 98*(4), 738-745.

Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Boston: Houghton Mifflin.

Harkema, S. J., Schmidt-Read, M., Lorenz, D. J., Edgerton, V. R., & Behrman, A. L. (2012). Balance and ambulation improvements in individuals with chronic incomplete spinal cord injury using locomotor training–based rehabilitation. *Archives of physical medicine and rehabilitation, 93*(9), 1508-1517.

Headrick, J., Renshaw, I., Davids, K., Pinder, R. A., & Araújo, D. (2015). The dynamics of expertise acquisition in sport: The role of affective learning design. *Psychology of Sport and Exercise*, *16*, 83-90.

Heft, H. (2001). *Ecological psychology in context: James Gibson, Roger Barker, and the legacy of William James's radical empiricism*. Psychology Press.

Hicks, A. L., Adams, M. M., Ginis, K. M., Giangregorio, L., Latimer, A., Phillips, S. M., & McCartney, N. (2005). Long-term body-weight-supported treadmill training and subsequent follow-up in persons with chronic SCI: effects on functional walking ability and measures of subjective well-being. *Spinal cord, 43*(5), 291-298.

Klostermann, A., & Mann, D. L. (2019). Current Issues in Perceptual Training: Facing the Requirement to Couple Perception, Cognition, and Action in Complex Motor Behavior. Frontiers in psychology, 10, 2680.

Koenderink, J. J., & van Doorn, A. J. (1987). Facts on optic flow. *Biological cybernetics, 56*(4), 247-254.

Lee, D.N. (1980). Visuo-motor coordination in space-time. In G.E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 281-295). Amsterdam: North-Holland.

Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Perception & Psychophysics, 15*(3), 529-532.

Macko, R. F., Ivey, F. M., Forrester, L. W., Hanley, D., Sorkin, J. D., Katzel, L. I., ... &

## Appendix H

Figure H12: NSERC Postgraduate Scholarship (PGS D) Application

Goldberg, A. P. (2005). Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke: a randomized, controlled trial. *Stroke, 36*(10), 2206-2211.

Marigold, D. S., & Patla, A. E. (2008). Visual information from the lower visual field is important for walking across multi-surface terrain. *Experimental Brain Research*, *188*(1), 23-31.

Matthis, J. S., & Fajen, B. R. (2014). Visual control of foot placement when walking over complex terrain. *Journal of experimental psychology: human perception and performance*, *40*(1), 106.

McManus, M., D'Amour, S., & Harris, L. R. (2017). Using optic flow in the far peripheral field. *Journal of vision*, *17*(8), 3-3.

Nas, K., Yazmalar, L., Şah, V., Aydın, A., & Öneş, K. (2015). Rehabilitation of spinal cord injuries. *World journal of orthopedics, 6*(1), 8.

Poulain, I., & Giraudet, G. (2008). Age-related changes of visual contribution in posture control. *Gait & posture, 27*(1), 1-7.

Rand, K. M., Barhorst-Cates, E. M., Kiris, E., Thompson, W. B., & Creem-Regehr, S. H. (2019). Going the distance and beyond: simulated low vision increases perception of distance traveled during locomotion. *Psychological research*, *83*(7), 1349-1362.

Rossi, L. F., Rodrigues, S. T., & Forner-Cordero, A. (2014, August). Do humans walk like robots when crossing an obstacle without visual information?. In *5th IEEE RAS/EMBS international conference on biomedical robotics and biomechatronics* (pp. 216-220). Ieee.

Seifert, L., Araújo, D., Komar, J., & Davids, K. (2017). Understanding constraints on sport performance from the complexity sciences paradigm: An ecological dynamics framework. *Human movement science*, *56*, 178-180.

Turton, A. J., Dewar, S. J., Lievesley, A., O'Leary, K., Gabb, J., & Gilchrist, I. D. (2009). Walking and wheelchair navigation in patients with left visual neglect. *Neuropsychological rehabilitation*, *19*(2), 274-290.

van Dijsseldonk, R. B., De Jong, L. A., Groen, B. E., Vos-Van Der Hulst, M., Geurts, A. C., & Keijsers, N. L. (2018). Gait stability training in a virtual environment improves gait and dynamic balance capacity in incomplete spinal cord injury patients. *Frontiers in Neurology, 9*, 963.

Warren, W. H. (1990). The perception-action coupling. In *Sensory-motor organizations and development in infancy and early childhood* (pp. 23-37). Springer, Dordrecht.

# Appendix H

Figure H13: NSERC Postgraduate Scholarship (PGS D) Application

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature neuroscience*, *4*(2), 213-216.

Wexler, M., & Van Boxtel, J. J. (2005). Depth perception by the active observer. *Trends in cognitive sciences*, *9*(9), 431-438.

## Appendix H

Figure H14: NSERC Postgraduate Scholarship (PGS D) Application

Natural Sciences and Engineering Research Council of Canada | Conseil de recherches en sciences naturelles et en génie du Canada

Page 7 of 7

**Application for a Postgraduate Scholarship or Postdoctoral Fellowship (FORM 201)**

| Type of Award | Personal identification no. (PIN) | Family name, given name and initial(s) of applicant |
|---|---|---|
| PGS D | [redacted] | De Melo, Kristen [redacted] |

**SPECIAL CIRCUMSTANCES**

Due to COVID-19, access to the lab and completing human-based data collection has not been permitted or was very limited. This situation has been ongoing since March 2020 and lasted until the near end of my Master's degree. This has prevented data collection and the progression of the noted studies. This has also limited my experience with data analysis and running studies independently. Changes to degree requirements were made to assist students in similar positions to mine. However, attempts have been made to keep up with aspects such as data analysis, by taking courses to understand concepts and basic programs, using old data sets to practice, and learning from peers on what these processes would look like.

Form 201 (2020 W) | PROTECTED B WHEN COMPLETED | Version française disponible

Canadä

# Appendix I

Figure I1: ICORD Seed Grants Funding Sample Application

icord seed grants

**DUE 9 JUNE 2021**

ICORD Seed Grants are designed to provide seed funding for novel research projects proposed by Principal Investigators and Investigators within ICORD, and enable ICORD faculty members to generate pilot data for future applications for multi-year operating grants (especially Tricouncil) as a result of receiving a Seed Grant. Given the competitiveness of securing Tricouncil funding and the mandatory requirement for pilot data in these applications, it is the intent of these seed funds to foster future funding success for new projects.

A total of **$200,000** is available to be awarded each year over two annual competitions (with five projects–approximately $20K each–funded in each competition). The scope of the projects must be aligned with ICORD's Mission and SCI Research Platform and projects must have a strong likelihood of leading to a new sustainable research program. Proposals may only be submitted by ICORD Principal Investigators or Investigators in good standing.

ICORD members may submit only one application as the primary applicant per round of funding.

Applications will be reviewed by an adjudication committee using a five-point scale (akin to CIHR, with 5 being the best) To maintain a standard of excellence, no applications rated 3.5 or below will be funded. The adjudication committee will include:

- Dr. Lowell McPhail, ICORD Managing Director
- Three or more of the previous Seed Fund competition awardees.

**Application Procedures:**

Submit your applications files (this form, optional one-page attachment, and CV of any non-ICORD co-applicants) **online** at https://icord.org/funding-opportunities/seed-grants/

If you do not receive a confirmation message within two hours of submission, please **contact admin@icord.org.** We anticipate that the competition results will be announced within one month of the deadline.

**Eligibility:**

- **Applicants must be ICORD members (Principal Investigator or Investigator level).** Associate Members, Research Associates and post-doctoral fellows are not eligible to apply as the primary applicant, but may be co-applicants. Applicants must be pursuing a new novel area of research that requires seed funding to generate pilot data to apply for a Tricouncil or other operating funding grant applications as a result of receiving the Seed Grant. Priority will be given to those who will use the data towards attaining their first multi-year Tricouncil grant as PI, followed by those applying to a different Tricouncil agency (in which they have not held funding as a PI), and then to those applying for renewals or other funding types (e.g., Heart and Stroke Foundation).
- Only one seed grant application can be submitted each round by the primary applicant. Collaborative applications are encouraged and there is no limit to the number of applications one can be listed as a co applicant.

**Judging Criteria for the proposals include**:

- The appropriateness of the **research plan**, including its feasibility and the use of the best available methodology;
- The **significance/impact** of the work proposed and its **originality**, or novelty of the concepts, ideas or hypotheses being pursued in the application;
- The suitability of the **research environment**, including the availability of facilities, personnel, and time, required to complete the work proposed;
- The **alignment** of the proposed research with ICORD's Mission & Research Platform and the **likelihood** that a successful proposal will lead to a sustainable program.

# Appendix I

## Figure I2: ICORD Seed Grants Funding Sample Application

**Conditions of Award:**

- Grants must be activated within 6 months of notice of award (including all necessary approvals), if the grant is not activated; the funds may revert back to ICORD and may be awarded to other applicants.
- An interim report is be due one year from the award date, and a final report will be due no later than 26 months after the award date. Any unspent funds remaining at that time will be returned to ICORD. A report template will be provided along with the award notifications.
  - Please send your report to Dr. Lowell McPhail (mcphail@icord.org). If the due date falls on a holiday or weekend, your report will be due the following workday.
- Award winners may be required to assist in the adjudication of applications in the next cycle.
- Award winners must report annually on grant applications submitted, and/or funding received as a result of seed grant-supported pilot data or preliminary work.

**Mission & research platform:**

ICORD's mission is to conduct research and training towards the development and translation of more effective strategies promoting prevention of spinal cord injury, functional recovery, and improved quality of life after SCI. Our vision is broad, and therefore, our strategy is not to focus solely on a narrow definition of 'cure' for SCI, but rather, to foster excellence across the entire research continuum that affects the lives of those with SCI. This includes preclinical discovery science, the development of therapies for acute and chronic SCI, and solutions for successful and fulfilled living with SCI.

ICORD's research activities revolve around these four strategic goals:

1. Prevention of SCI
2. Acceleration of SCI cures/treatments
3. Improving the quality of life for people with SCI
4. Supporting activities of our partners

generously supported by

Rick Hansen Foundation

# Appendix I

Figure I3: ICORD Seed Grants Funding Sample Application

icord seed grants

## Principal Applicant

(must be an ICORD Principal Investigator or Investigator and must have submitted an Annual Report for the previous year to ICORD Administration before submitting this application)

**Name** (Surname, Given Names): Kristen De Melo
**Affiliation:** McMaster University

| Department (s) | Institution |
|---|---|
| Kinesiology | McMaster Univerity |

---

**Co-Applicant(s):** If co-applicants are not ICORD PIs/Investigators, please upload short CV
**Name** (Surname, Given Names): N/A
Affiliation (Department / Institution):

**Name** (Surname, Given Names): N/A
Affiliation (Department / Institution):

**Name** (Surname, Given Names): N/A
Affiliation (Department / Institution):

**Project title:** THE EFFECTS OF PERCEPTION-ACTION COUPLING ON COMPROMISED HUMAN LOCOMOTION: A PROPOSED RESEARCH PROGRAM

---

**Amount requested:** N/A

---

**Applicant's Signature:**

[redacted] September 21, 2021
Signature Date

**Research summary (for lay public)**
Please provide a summary of the project's objective(s) potential results and impact for people with SCI. Use language appropriate for the lay public. (1500 characters including spaces & punctuation).
This research project attempts to optimize current treatment protocols for individuals with SCI while maintaining the current degree of safety and effectiveness. To do so, this protocol is built using previous research suggesting vision plays an important role in movement control and performance. Human perceptual and motor systems have shown to be intimately tied together, as they develop simultaneously and affect one another. When they are decoupled, human movement experiences downfalls (i.e., aspects such as posture, balance, and reflexes are negatively impacted). Rehabilitation protocols often carry out treatment in the absence of dynamic visual information (i e., stationary treadmills, body weight supported treadmills), which would suggest the negative effects of decoupling of perception and action are experienced. This may account for lengthy, expensive, and exhausting treatment plans. Therefore, this study wishes to incorporate dynamic vision into regular treatment plans using virtual reality to examine the effects of vision on rehabilitative outcomes. By recoupling our perceptual and motor systems, it is expected that individuals with

# Appendix I

Figure I4: ICORD Seed Grants Funding Sample Application

SCI will experience enhanced rates and positive performance changes throughout the treatment compared to those without virtual reality. This will lead to increases in locomotor capabilities in reduced time commitments, resulting in greater independence and quality of life of persons with SCI.

**Research summary (for peer review committee)**

Please provide a summary of the project's objective(s) hypothesis and research plan. Use language appropriate for a peer review committee. (2000 characters including spaces & punctuation).

The objective of this project aims to optimize current treatment protocols for individuals with SCI, while still maintaining gold standard methods and safety regimes. This project is built using previously established literature within the ecological theory of human movement, which suggests that human perceptual and motor systems develop simultaneously in a close interrelationship (Gibson, 1966). They are dynamically coupled and assist one another in coordinating movements (Bertenthal, 1966; Barbu-Roth et al., 2009). This linkage allows for adaptive behaviours to the environment since they are coupled by laws of control relating information variables to the most appropriate parameters of action (Warren, 1990). An important component to this linkage is optic flow (OF), which provides visual information about the observer relative to their motion within the environment (Warren et al., 2001). OF plays a critical role in navigation, depth perception, and obstacle avoidance (e.g., Rand et al., 2019; Franchak & Adolph, 2010). Without OF, the perception-action (P-A) linkage becomes decoupled, leading to downfalls in movement performance (e g., impacted posture, locomotion; Lee, 1980; Alotaibi et al., 2016). However, much of the rehabilitation literature carries out training protocols in the absence of OF (e.g., stationary treadmills; Hicks et al., 2005; Macko et al., 2005), ultimately decoupling P-A and possibly resulting in lengthy, exhaustive, and expensive treatment plans (Nas et al., 2015). Thus, this project plans to implement OF, using virtual reality (VR) into a standard training program for persons with incomplete SCI. Two groups will be used (OF vs. no OF) to compare the effects of OF on gait parameters and subjective measures of performance. It is hypothesized that the OF group will see enhanced rates and quality of positive rehabilitative outcomes, both objectively (i e., gait parameters) and subjectively (i.e., questionnaires) compared to the no OF group.

# Appendix I

## Figure I5: ICORD Seed Grants Funding Sample Application

### Research proposal

Provide a clear  concise description of the research proposal. Maximum of one page (5000 characters including spaces and punctuation). You may upload **one** additional page of references  figures tables  charts  or photographs.

This research project aims to develop a method of optimizing current treatment protocols for persons with SCI, while maintaining safety practices and gold standard methods. To do so, it is hypothesized that this can be done by implementing strategies related to the ecological theory of human movement, with a more specific focus on the relationship between perception and action. This framework focuses heavily on the interactions that exist between the environment and the individual, and how these interactions shape our movements (Gibson, 1966). It is suggested that motor processes exist for humans to effectively execute actions necessary to survive and cope within their surroundings. These actions are geared toward specific variables within that environment, as all information to execute a movement can be found within a stimulus (Gibson, 1966; Heft, 2001). The relationship between the perceptual and motor systems assist in this process, by relating information variables found within the surroundings to the most appropriate parameters of action (Warren, 1990). These two systems evolved together in mammals not as discrete, independent constructs, but rather in a close interrelationship (Gibson, 1966). The ecological theory indicates that these systems are dynamically coupled and assist one another in the coordination of movements (Bertenthal, 1966; Barbu-Roth et al., 2009). Critical to this relationship is optic flow, which provides visual information about the observer relative to their motion within the environment (Warren et al., 2001). Optic flow plays a critical role on movement factors such as obstacle detection (e g., Franchak & Adolph, 2010; Matthis & Fajen, 2014), navigation (e.g., Turton et al., 2009; Rand et al., 2019), and depth perception (e g., Wexler & Van Boxtel, 2005; McManus, D'Amour, & Harris, 2017). Without optic flow, perception and action become decoupled leading to slower environmental adaptations due to the lack of visual calibration (Koenderink & van Doorn, 1987; Klostermann & Mann, 2019). This serves as a negative implication to something like rehabilitation, where rapid adaptation to newly acquired physical conditions (i.e., SCI) is crucial to regaining everyday independence. Rehabilitation practices, however, often carry out treatment protocols in the absence of optic flow which may be related to the often lengthy, exhaustive, and expensive treatment plans put in place (Nas et al., 2015). Therefore, this study aims to assess whether incorporating optic flow, using virtual reality (VR), into a typical incomplete SCI (iSCI) ambulation protocol will lead to enhancements in rehabilitative outcomes.

To carry out this study, persons with iSCI (ASIA score C or D) will be recruited to participate in an eight-week body weight supported (BWS) treadmill training intervention. Participants will be divided into two groups: no optic flow and optic flow. Participants in the optic flow group will receive a VR headset during all bouts of training, while participants in the no optic flow group will not receive a headset. VR will be used to create a visual scene that mimics typical walking patterns (i.e., a hallway), and will move at the same rate the participant is moving. Participants will engage in three, 5-15 minute bouts of treadmill walking (Hicks et al., 2005), three days a week. Measures will be taken pre-, mid-, and post-intervention. These include measures of muscle activity using EMG (to determine neuromuscular changes), spatial-temporal measures of gait parameters (i.e., stride length, stride height) using Vicon Motion Capture, measures of SCI changes (i e., Modified Wernig Scale, BWS), and subjective questionnaires (i.e., Quality of Life Scale). It is hypothesized that if optic flow using VR recouples perception and action, persons with iSCI will experience enhanced rates and quality of positive rehabilitative outcomes (An & Park, 2018; van Dijsseldonk et al., 2018; Yeo et al., 2019). With the presence of optic flow, this outcome is anticipated due to the increased ability for individuals to obtain information and adapt to their environment more consistently with the perceptual-motor experiences they encountered throughout their lifespan (Koenderink & van Doorn, 1987; Warren, 1990). It is expected that gait parameters, muscle signaling, subjective measures, and measures of rehabilitative performance will increase more rapidly in the group that experiences VR. Subjective measures are anticipated to increase more significantly in the optic flow group due to greater levels of enjoyment and satisfaction with performance (Heyn et al., 2014).

This study will lead to overall increased quality of life for participants as they will experience increases in performance and independence in more enjoyable and shorter treatment durations. This falls in line with previous research exploring similar effects of VR on rehabilitation (e.g., In et al., 2016; Gama et al., 2017; An & Park, 2018).

# Appendix I

Figure I6: ICORD Seed Grants Funding Sample Application

NEW! **Will this research be conducted in partnership with *research users*?**
Yes ☐ No☒

If you answered **yes**, please provide details about
(a) who the **research user partners** on the project will be: N/A (maximum 600 characters)
b) **when** and **how** each partner will be engaged: N/A (maximum 600 characters)
(c) **expected contributions** to the research process from each partner:N/A (maximum 600 characters)

Note: **Research users** are individuals or groups that will use or benefit from the research. These groups are different than research participants and include but are not limited to persons with lived experience of SCI, policy-makers, health and/or service providers, other researchers, professional organizations, funders, and industry partners. The partnership should carefully consider who the right research user(s) is/are for its project.
**Research partnerships** have emerged as an approach to help address the research to practice gap by involving research users throughout the research process. *ICORD is dedicated to improving the quantity and quality of SCI research partnerships and will be evaluating how approaches to partnership within ICORD evolve over time.* This evaluation will be conducted by ICORD PI Dr. Heather Gainforth and her team, and will involve looking at past and present ICORD Seed Grant applications. This application will be shared with them. All team members will sign a confidentiality agreement prior to accessing the grants. The data from this evaluation may be shared via publications, reports and presentations to both the scientific and broader community, but any such presentations will be of general findings only related to partnerships. None of your experiments or methods will be discussed in the presentations. Further, no identifiable information will be included in the presentations, and we will not breach your confidentiality.

**Alignment with ICORD's Mission and Research Platform**
Provide a concise explanation of how the proposed project aligns with ICORD's Mission and Research Platform as outlined in the Strategic Directions Implementation Plan. (maximum 600 characters)
The proposed project aligns with ICORD's missions as it works to improve current training methods for individuals with SCI, while maintaining saftey measures. It will provide an alternative, relatively inexpensive method to optimize treatment protocols through the use of VR. Overall, this project determines a way to improve the functionality, independence, and quality of life following SCI, while minimizing treatment durations, expenses, and exhaustion. Although it does not 'cure' SCI, it finds a way for individuals to cope and better their injury, and advances SCI rehabilitation literature.

**Plan to Secure Future External Funding**
Provide a concise description of how completion of the proposed project will lead to future funding from external granting or other sources. (maximum 600 characters)
N/A

**Itemized Budget + Justification**
Provide estimates for the research project. Each budget item should be supported by a short justification statement and include applicable taxes. Maximum 1 page (5000 characters).
N/A

**Total Requested: $ <u>0</u>**

TOTAL APPLICATION LENGTH MAY NOT EXCEED EIGHT PAGES

## Appendix I

Figure I7: ICORD Seed Grants Funding Sample Application


Alotaibi, A. Z., Alghadir, A., Iqbal, Z. A., & Anwer, S. (2016). Effect of absence of vision on posture. *Journal of physical therapy science, 28*(4), 1374-1377

An, C. M., & Park, Y. H. (2018). The effects of semi-immersive virtual reality therapy on standing balance and upright mobility function in individuals with chronic incomplete spinal cord injury: a preliminary study. *The journal of spinal cord medicine, 41*(2), 223-229.

Barbu-Roth, M., Anderson, D. I., Desprès, A., Streeter, R. J., Cabrol, D., Trujillo, M., ... & Provasi, J. (2014). Air stepping in response to optic flows that move toward and away from the neonate. *Developmental Psychobiology, 56*(5), 1142-1149.

Bertenthal, B. I. (1996). Origins and early development of perception, action, and representation. *Annual review of psychology, 47*(1), 431-459.

Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. *Vision research, 50*(24), 2766-2774.

Gama, G. L., Celestino, M. L., Barela, J. A., Forrester, L., Whitall, J., & Barela, A. M. (2017). Effects of gait training with body weight support on a treadmill versus overground in individuals with stroke. *Archives of physical medicine and rehabilitation, 98*(4), 738-745.

Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Boston: Houghton Mifflin.

Heft, H. (2001). *Ecological psychology in context: James Gibson, Roger Barker, and the legacy of William James's radical empiricism*. Psychology Press.

Heyn, P., Baumgardner, C., McLachlan, L., & Bodine, C. (2014). Mixed-reality exercise effects on participation of individuals with spinal cord injuries and developmental disabilities: a pilot study. *Topics in Spinal Cord Injury Rehabilitation, 20*(4), 338-345.

Hicks, A. L., Adams, M. M., Ginis, K. M., Giangregorio, L., Latimer, A., Phillips, S. M., & McCartney, N. (2005). Long -term body-weight-supported treadmill training and subsequent follow-up in persons with chronic SCI: effects on functional walking ability and measures of subjective well-being. *Spinal cord, 43*(5), 291-298.

In, T., Lee, K., & Song, C. (2016). Virtual reality reflection therapy improves balance and gait in patients with chronic stroke: randomized controlled trials. *Medical science monitor: international medical journal of experimental and clinical research, 22*, 4046.

Klostermann, A., & Mann, D. L. (2019). Current Issues in Perceptual Training: Facing the Requirement to Couple Perception, Cognition, and Action in Complex Motor Behavior. *Frontiers in psychology, 10*, 2680.

Koenderink, J. J., & van Doorn, A. J. (1987). Facts on optic flow. *Biological cybernetics, 56*(4), 247-254.

Lee, D.N. (1980). Visuo-motor coordination in space-time. In G.E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 281-295). Amsterdam: North-Holland.

Macko, R. F., Ivey, F. M., Forrester, L. W., Hanley, D., Sorkin, J. D., Katzel, L. I., ... & Goldberg, A. P. (2005). Treadmill exercise rehabilitation improves ambulatory function and cardiovascular fitness in patients with chronic stroke: a randomized, controlled trial. *Stroke, 36*(10), 2206-2211.

Matthis, J. S., & Fajen, B. R. (2014). Visual control of foot placement when walking over complex terrain. *Journal of experimental psychology: human perception and performance, 40*(1), 106.

McManus, M., D'Amour, S., & Harris, L. R. (2017). Using optic flow in the far peripheral field. *Journal of vision, 17(8)*, 3-3.

Nas, K., Yazmalar, L., Şah, V., Aydın, A., & Öneş, K. (2015). Rehabilitation of spinal cord injuries. *World journal of orthopedics, 6*(1), 8.

Rand, K. M., Barhorst-Cates, E. M., Kiris, E., Thompson, W. B., & Creem-Regehr, S. H. (2019). Going the distance and beyond: simulated low vision increases perception of distance traveled during locomotion. *Psychological research, 83*(7), 1349-1362.

Turton, A. J., Dewar, S. J., Lievesley, A., O'Leary, K., Gabb, J., & Gilchrist, I. D. (2009). Walking and wheelchair navigation in patients with left visual neglect. *Neuropsychological rehabilitation, 19*(2), 274-290.

van Dijsseldonk, R. B., De Jong, L. A., Groen, B. E., Vos-Van Der Hulst, M., Geurts, A. C., & Keijsers, N. L. (2018). Gait stability training in a virtual environment improves gait and dynamic balance capacity in incomplete spinal cord injury patients. *Frontiers in Neurology, 9*, 963.

Warren, W. H. (1990). The perception-action coupling. In *Sensory-motor organizations and development in infancy and early childhood* (pp. 23-37). Springer, Dordrecht.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature neuroscience, 4*(2), 213-216.

Wexler, M., & Van Boxtel, J. J. (2005). Depth perception by the active observer. *Trends in cognitive sciences, 9*(9), 431-438.

Yeo, E., Chau, B., Chi, B., Ruckle, D. E., & Ta, P. (2019). Virtual reality neurorehabilitation for mobility in spinal cord injury: a structured review. *Innovations in Clinical Neuroscience, 16*(1-2), 13.