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An Exploratory Approach to Manipulating Dynamic Stability: Investigating the Role of Visual Control during a Precision Foot Placement Task

Russell CG Kennedy
Wilfrid Laurier University, kenn8670@mylaurier.ca

An Exploratory Approach to Manipulating Dynamic Stability: Investigating the Role of Visual Control during a Precision Foot Placement Task

By: Russell Kennedy

Supervisor: Dr. M. Cinelli

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ABSTRACT

Background: The visual system provides the body with an accurate sensory system; designed to gather information at a distance and acts as a feedforward control mechanism during human locomotion. By doing so, visual information contributes coordination of the head-arm-trunk (HAT) segment and modulating foot placement. The purpose of this study was to examine the effects of a constrained pathway during a complex navigational stone-stepping task on HAT segment control and how the visual system guides locomotion during a complex foot placement task.

Methods: Nine university-aged females (Mean age: 22.5 years old +/-1.75) participated in this study. Participants were instrumented with four rigid bodies (4x3 IRED markers) on the head, trunk and feet and two IRED markers on the wrists in order to measure kinematic data, collected by Optotrak system (NDI, Waterloo, Canada). Additionally, each participant was outfitted with an ASL H7-HS High Speed Head Mounted Optics (ASL, Bedford, USA) eye tracking unit to assess gaze behaviours. The experimental protocol required participants to perform 40 walking trials across four conditions (i.e., constrained and self-selected pathways; starting with either the left or the right foot), on a 7.2m x 1.2m raised-target platform. The platform consisted of 60 sloper-style rock climbing holds, whose location was designed to satisfy one of three criterion: 1) in line with natural footfall locations (e.g. normal step length and/or width dimensions of 60cm by 10cm); 2) greater or less than one of the dimensions of a natural step length or width; or 3) to act as a possible option/distractor on the pathway. The two constrained pathways were indicated with a high-contrasting moldable material placed inside each hold's screw hole. Measurements were compared across conditions (i.e., constrained versus unconstrained), time points (e.g. first, middle, and last trial performed of each condition), and segment (Segment 1: first 3m of path or

Segment 2: last 3m of path). The measurements included: horizontal and vertical pupil velocity RMS; average walking speed; trunk rotations about the hip (i.e., pitch and roll), and whole-body movement (i.e., ML COM variability).

Results: Findings revealed that there was a significant difference between conditions such that: 1) the constrained vertical pupil RMS velocity was higher than the unconstrained ($F_{(3,24)}$=4.71; p= .04; d=.46); 2) the unconstrained horizontal pupil RMS velocity was higher than the unconstrained ($F_{(3,24)}$=4.40; p= .03; d=.36); 3) the constrained average walking speed was greater than the unconstrained ($F_{(3,24)}$=23.27; p=0.04; d=.30); 4) the constrained trunk roll was greater than the unconstrained ($F_{(3,21)}$=4.84; p=0.01; d=.45); and 5) the unconstrained dynamic stability margin minimum (DSMmin) was greater than the constrained ($F_{(3,21)}$=4.89; p= .01; d=.41).

Conclusions: The complex nature of the raised-target foot placement task challenged individuals from the start of each condition, forcing participants to learn how to control body movements—especially in the AP direction. During constrained condition, there was evidence to suggest that there was a greater regulation of trunk control than during unconstrained trials. This was attributed to the conditional demands of predetermined pathway to follow. However, during unconstrained trials, individuals were able to choose footholds, which were most likely based on their current state of stability. And thus, conditional demands of the pathway influenced gaze behaviours, such that during the constrained condition participants used a scanning behaviour (i.e., greater vertical pupil velocity RMS) whereas participants used more of a sampling behaviour (i.e., greater horizontal and slower vertical pupil velocities) during the free choice pathway condition. Therefore, the finding from this study suggest that gaze behaviours are influenced by stepping characteristics and these different gaze behaviours have different effects on trunk control.

LIST OF FIGURES

LIST OF ABREVIATIONS

ANOVA	**Analysis of Variance**
AP	**Anterior-Posterior**
BOS	**Base of Support**
CNS	**Central Nervous System**
COM	**Centre of Mass**
COP	**Centre of Pressure**
HAT	**Head-Arm-Trunk**
IRED	**Infrared Light-Emitting Diodes**
ML	**Medial-Lateral**
NDI	**Northern Digital Inc.**
REB	**Research Ethics Board**
SD	**Standard Deviation**

1.0 INTRODUCTION

An Introduction to Adaptive Locomotion

Walking, just one example of locomotion, is one of the most integral parts of human life. Walking—commonly referred to as locomotion—requires the individual to accommodate for a variety of internal and external perturbations, such as avoiding obstacles, anticipatory postural adjustments, navigating complex surfaces (e.g. an icy sidewalk, narrow path, a sloping hill, etc.), and selecting a path towards a goal (e.g. stepping on river stones). Throughout the course of a step (and gait) cycle, individuals make adjustments and modifications to behaviour to perform successful steps. These kinds of adjustments and accommodations are referred to as adaptive locomotion [Patla & Shumway-Cook, 1997; Andriacchi, T. & Alexander, E., 2000; Patla, 2004]. As a result, humans learn to adapt and modify movements of the body in order to avoid objects, select secure footholds, and maintain upright locomotion.

Underlining adaptive locomotion properties are the principles of locomotion. Das and McCollum (1988) first discussed the three principles of locomotion as the essential elements of adaptive locomotion: 1) postural control; 2) progression; and 3) adaptation. Postural control is characterized by the maintenance of upright stability of body segments in a manner that attempts to counteract perturbations that act on the body [Das & McCollum, 1988]. Essentially, postural control refers to one's ability to remain upright and able to move as a dynamic system. Progression is simply moving from that hypothetical 'point A' to 'point B', or more simply, towards an intended goal. Whether there is an obstacle in the way or an alternative stepping strategy to perform, progression is simply getting to the goal, beginning from gait initiation to termination. However, as a part of human nature, progression towards the goal is often performed in a manner that is as efficient as possible [Inman, 1966]. Adaptation is the process in which response measures are altered according to the demands of the task [Das & McCollum, 1988]. This particular element is influenced by the environment, stability of the individual, attention demands, along with a variety of other factors that may come into play.

The process of locomotion produces internal perturbations and the individual must overcome and counteract those perturbations in order to remain upright. Regardless of the source of the perturbation, a common effect has been noted: the main cause of falls and increasing the risk of falling is as a result of the center of mass (COM) moving outside of the base of support (BOS) and the control of the center of pressure (COP) in a fast manner: COM can be defined as the distribution of mass that takes into account the total mass of the body and its segments; BOS refers to the area beneath a person outlined by every point of contact that makes the supporting surface; COP is defined as the point of application of ground reaction forces, acting as the sum of all forces acting between the individual and the supporting surface [Lee & Farley, 1998; Chou *et al*., 2003; Popovic, Goswami, & Hugh, 2005; Benda, Riley, & Krebs, 1994].

The process of adaptive locomotion can be broken down into the simpler terms of describing the biomechanical forces present which act on the body. Winter (1991) describes the relationship of COM, BOS, and COP in figure 1 below: note that COM is referred to as center of gravity (C of G) and COP is referred to as C of P. In the figure, the COM travels towards the medial border of the right foot whereas the COP extends beyond the COM to control and corral the COM towards the potential new footfall location of the left foot, following right heel strike and left toe off. COP is essentially acting here as a regulatory mechanism to keep the COM within the confines of the BOS. This is where maintaining dynamic stability during locomotion comes into the picture. For the remaining portion of this review, I will be introducing ideas and concepts related to adaptive locomotion and control strategies used to coordinate body movement.

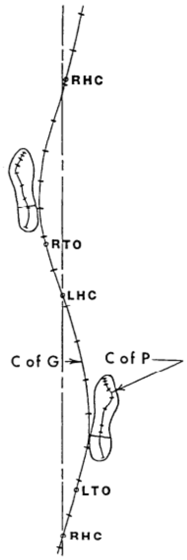


Figure 1- Centre of Gravity (C of G) and Centre of Pressure (C of P) under the support foot of flat ground walking [Winter, 1991]. This figure visually represents the sheep and sheep dog relationship between COM, COP, and BOS: the COP accelerates to the medial border of the foot, acting on the COM direct towards the new support foot during single support in order to keep the COM within the confines of the BOS.

Modulation of Stability During Locomotion

Stability is crucial to locomotion and maintaining stability is considered a constant battle with each step; from a static perspective, each step is unstable. To maintain stability, the central nervous system (CNS) coordinates the body and its segments to control the COM from moving outside an ever-changing BOS. In order to do so, the CNS acts on muscles to change the size and/or location of the BOS to control the movement and direction of the COM to fall within the new BOS, aligning with what is referred to as postural control [Winter, 1991]. However, in order to coincide with the principles of locomotion, individuals use some combination of reactive, predictive, and proactive control mechanisms [Patla, 2004].

Reactive control strategies are described as a response elicited following the detection of a perturbation by the sensory systems [Patla, 2004]. In other words, the body senses a disruption to its stability and responds accordingly. For instance, during a slip a series of complex sensorimotor transformations occur in order to maintain stability in the perturbed and the unperturbed limb [Tang, Woollacott, & Chong, 1998]. Tang and colleagues (1998) examined the role that proximal trunk and hip muscles (e.g. biceps femoris, rectus femoris) play in a reactive balance control study. In order to determine the latency of muscle activation, EMG was used to record muscle activity for biceps femoris, rectus femoris, and gastrocnemius during an anterior slip during locomotion. However, the results did not support the hypothesis that proximal leg muscles activate earlier and longer than distal leg muscles. In fact, the results revealed that distal and intermediate leg and thigh muscles are crucial to reactive balance control strategies. This study was one of many studies that suggested the importance of interlimb coordination during locomotion. Knowing and understanding the importance of interlimb coordination is crucial to studies conducted with an objective of examining whole body biomechanics and strategies used to accomplish such coordinated movements.

Predictive control strategies are described as responses elicited prior to the detection of a known perturbation based on ongoing movement [Patla, 2004]. Essentially, predictive control strategies rely on modifying current movements of the body to predict movement outcome as a result of an upcoming perturbation in which the individual is expecting and relies heavily on feedforward control; feedforward control is where external information is used as the input to elicit a preset response, producing an action until the information is no longer available [Stanfield, 2012]. One main mechanism of predictive control is through joint moments that counteract the known perturbations of locomotion [Winter, 1991]. Winter (1991) has described and connected movements that begin in the trunk and extend distally to foot placement and regulation of each mechanism. Winter (1991) also explained each strategy and its respective control/regulating mechanism, starting with: pitching the trunk, as regulated by the acceleration and deceleration of each step as controlled by moments about the hip joint; tipping the trunk to the unsupported side—regulated by the hip abductors; preventing a collapse in the vertical direction—as controlled by moments about the knee joint; decelerating the swing limb—hamstrings decrease the speed of the swing limb in order to produce precise and gentle foot placement [Winter, 1991]. Winter (1991) is suggesting here that trunk control is crucial to the control and maintenance of dynamic stability as a predictive control strategy.

Proactive control strategies are described as responses elicited and mediated at a distance due to pertinent information [Patla, 2004]. Proactive control strategies are deemed as one of the most powerful control strategies in controlling dynamic stability during locomotion. With this particular strategy, humans have the power to acquire information—mainly through the visual system—and develop a plan to modify body movements according to the task [Patla, 2004]. By identifying possible threats to the body and stability, information can be used to avoid obstacles, plan a route, and/or perform precise foot placement.

Within locomotion-focused research, there has been a shift to investigate the role and the mechanisms underlying proactive control strategies to contribute to the current understanding within literature. Patla and colleagues (1999) demonstrated the weighting of body control was examined during a simple walking task. Using whole body kinematics, they monitored the onsets of body movements as participants changed directions according to visual cues. The results revealed that the CNS controls the onset of movement such that body segment reorientation was initiated sequentially, beginning with the head, trunk, and then feet, referred to as a top down adjustment (refer to figure 2 below) [Patla, Adkin, & Ballard, 1999]. It was believed that by initiating head movements first allowed the individual to gather visual information about their future path, whereas trunk and foot movements controlled the COM in the direction of travel. This finding is essentially suggesting that the body tends to coordinate movements in response to perturbations, initiated in the head, trunk, and then in the foot placement. Furthermore, this study highlights the importance of two key concepts: 1) the role of the visual system with respect to body coordination—the body is controlled in a top-down approach, starting with the head; and 2) the effect of head and trunk stability and the influence of foot placement—as a proactive/reactive means stabilizing the head/trunk, foot placement is the 'last line of defense' with respect to body coordination during adaptive locomotion.

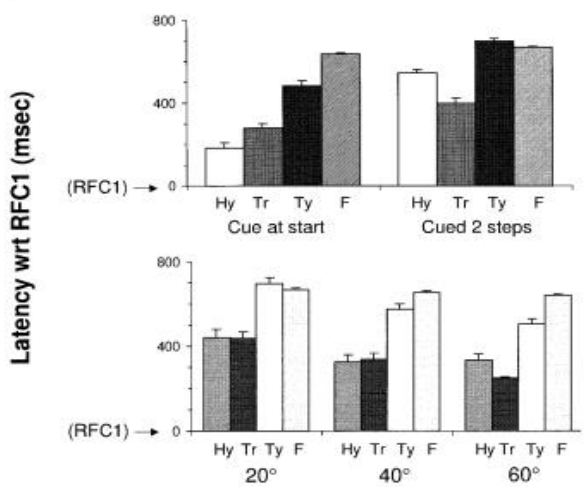


Figure 2- Initiation of head yaw (Hy), trunk roll (Tr), trunk yaw (Ty), and foot medio-lateral displacement (F) with respect to transition stride (RFC1) as a function of visual cue time (top graph) and direction change magnitude (bottom graph). The top graph demonstrates a segmental approach to the initiation of body movements, beginning with head yaw, trunk roll, trunk yaw, and then foot displacement. The bottom graph displays a similar representation.

The initial understanding of how individuals control balance and posture stems from the work conducted by Winter (1991). Winter treated the body and all of the moving segments as a dynamic, biomechanical system, to understand how the body is able to move the way it does.

Winter (1991) suggested that the hip, knee, and ankle joints produce moments of force in order to counteract perturbations experienced by the body during locomotion. In a follow up study, Winter and colleagues (1993) performed two-dimensional assessments of trunk movement (angle and hip moments) in the sagittal plane during natural walking. The results indicated a predominant pitching motion (i.e., rotation about the horizontal axis) of the trunk accelerated and decelerated in each step cycle [MacKinnon & Winter, 1993]. This trunk movement was controlled by moments at the hip and trunk musculature [Winter, 1991]. However, to remain stable, the CNS activates the muscles around the knee and ankle in order to produce moments necessary to counteract the movement of the trunk [Winter, 1991]. For instance, as the hip begins to generate an extensor moment, the knee and ankle follows suit by generating extensor moments. Once again, trunk movements present themselves as control strategy used to counteract perturbations created via locomotion.

Previous research also indicated that ankle muscle activation is a first responder to perturbations, acting to refine movement of the lower limb in response to changes with each step cycle [Horak & Nasher, 1986; MacKinnon & Winter, 1993]. By doing so, movements about the knee and ankle can co-vary with the hip to adapt the overall movement of the lower limb. As a result, activating muscles of the trunk and hip regulate flexion and extension, coinciding with the top-down approach to the coordination of the body that ultimately treats each step on a step-by-step basis (i.e. adaptive locomotion) [Winter, 1991; MacKinnon & Winter, 1993]. However, stabilization of the system (i.e. the body) presents itself as an issue as a result of a few major reasons: a narrow BOS, a small contact surface with the ground, and the fact that two-thirds of our body mass is distributed above two-thirds of the distance above the ground [MacKinnon & Winter, 1993]. The last point is of interest because the majority of body mass is a far distance away from the two small contact points (i.e. feet) and yet individuals are able control this mass and move about space without falling over.

To further illustrate this point, work by MacLellan and Patla (2006) examined the adaptations made during a walking task on a compliant surface. Participants were asked to perform walking trials under two conditions: flat ground and compliant surface walking. When walking on the compliant surface (e.g. a giant foam mat), participants performed particular gait strategies to increase stability—such as stepping wide and stepping long to increase BOS [MacLellan & Patla, 2006]. Additionally, strategies to regulate dynamic stability were assessed and it was found that there was increased variability about the hips in the anterior-posterior (AP) direction [MacLellan & Patla, 2006]. Thus, it was suggested that the main method to regulate dynamic stability was through a series of constant overcompensation and corrections of the COM to control trunk movements in response to the compliant surface.

Knowing how individuals control their body and in what fashion is vital to understanding how to challenge people. Researchers like Fajen, Patla, and Winter (and their respective colleagues) demonstrated that control strategies used to counteract perturbations created as a result of human locomotion follow a top-down approach; relying heavily on trunk movement to control the accurate placement of one's feet such that the COM is controlled and dynamic stability is maintained. Once again, dynamic stability control is maintained by trunk stability (e.g. trunk pitch/roll, trunk acceleration/deceleration, etc.), we can then further challenge individuals to determine whether these strategies emerge during a complex foot placement task, such as a stone stepping task. For example, in comparison to a flat ground foot placement task, a raised ground foot placement task should provide an added element of complexity to the design of the experiment and challenge the individual's dynamic stability control even further. In the next section, I will be discussing the role of the visual system as it pertains to where and when we look.

Where Do We Look and When?

As an integral part to proactive control strategies, the visual system is a predominate system used to gather information. Vision is used as a coordinator for whole body movements, collecting information about movements and positioning in order to reorganize and maintain upright locomotion. Much of one's knowledge about the environment's properties and layout are through the visual system, which in turn guides movements [Patla, 2004]. In a pioneering paper reviewing the roles of vision in human locomotion, Patla (1997) describes visual control as the dominate force behind the establishment of initial body posture in order to initiate locomotion through producing rhythmic and coordinated movements, all the way to termination of locomotion [Patla, 1997]. As individuals navigate, visual information is used almost as a feedback system to inform the individual about the body and its segments.

Additionally, vision acts as a feedforward control of exproprioceptive information—vision is used to contribute knowledge acquired through past experiences and current limb position and movement in space (exproprioceptive information). Conversely, vision acts as an on-line control mechanism of exproprioceptive information about limb position—in order to fine-tune the swing limb, limb movement information is gathered via the visual system to monitor swing limb trajectory and potential landing position of the swing limb. And finally, vision is relied upon heavily to sample the terrain—in order to monitor where to move about in the environment, the visual system plays a major role in assessing and detecting relevant cues [Patla, 1997].

Another role of vision is to assess and survey the environment. From varying terrains to different conditions, vision is used to gather information about the current and upcoming environmental demands. However, the role vision plays differs when varying degrees of complex terrain: when individuals walk along a flat and uncluttered surface, there really is no need to use the visual system to guide each foot placement; in more complex terrains, the visual system is used to fixate on possible future footholds [Lands, 2006].

In order to establish a stable foothold, three main sensory systems are used to help guide the swinging limb to a secure and stable location: vestibular, somatosensory, and vision. Out of all the senses, vision is arguably the dominant sensory system as it is able to collect information at a distance. Vision is a unique sense as it has the abilities to attend to an area that may be more local (e.g. step-by-step basis) or a global (e.g. route planning) with respect to the individual [Patla, 1997]. This aspect of vision comes into play when individuals are navigating the environment, especially when it comes to regulating locomotive patterns [Patla, 1997]. Across the literature, vision was found to be the primary mechanism of control of adaptive locomotion [Patla, 1997; Patla, 2004; Patla & Vickers, 2003]. During locomotion, the visual system is constantly searching and fixating (i.e., stabilizing gaze on a particular location for more than 100ms) on objects and areas within the environment to plan a path per se.

Within the literature, Patla and Vickers (2003) found that people tend to fixate on objects in their path two steps ahead or 800-1000ms in travel time of where their limb is placed. In this study, participants were asked to step on 17 irregularly or regularly spaced footprints along a 10m path; regular spacing fell within natural footfall dimensions of a natural step (e.g. 10cm wide and 60cm long). As the figure below demonstrates, regardless of the spacing of the footprints, people tend to fixate (>99ms) on the footprints that are two steps away from their current position. Fixating on objects two steps ahead allows the individual to update information (e.g. internal and external cues) in order to modulate behaviour (e.g. trunk movements, foot placement, etc.).

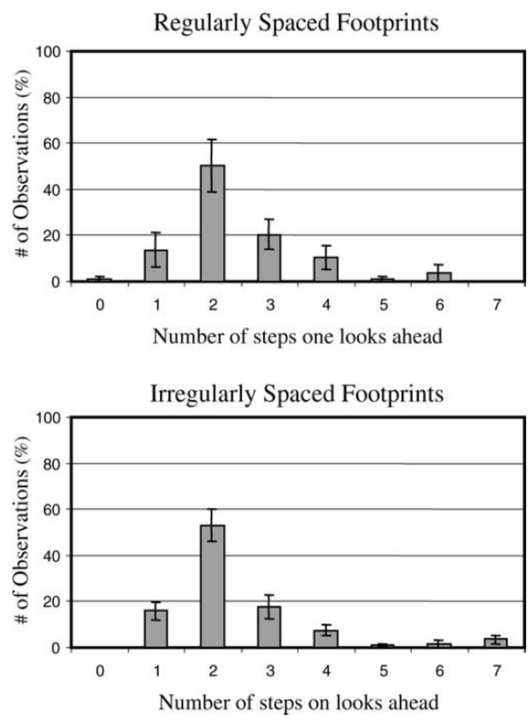


Figure 3- Histograms of the number of observations and the number of steps one looks ahead for regular spaced footprints and irregular spaced footprints. The frequency histograms demonstrate the overall finding that people tend to look two steps ahead of their current position [Patla & Vickers, 2003].

Patla and colleagues go on to describe visual control strategies categorized into two divisions: travel fixation and footprint fixation. Travel fixation is characterized by an individual holding a steady gaze out in front, surveying the environment in their respective field of vision [Hollands, Patla & Vickers, 2002]. The travel fixation strategy follows the previous findings of assessing the local environment around 800-1000ms ahead, doing so at a fixed distance. One could look at this proposed strategy as a ‘flashlight model’: during a simple walking task, the individual uses their eyes—the bulb of the flashlight—as the working part of the system whereas the area of focus—the beam of the flashlight—is used to illuminate and take in environmental cues at roughly two steps ahead. However, differing from a fixed, stable gaze of travel fixation, footprint fixation strategies align themselves on future footfall locations [Patla, 1997; Patla & Vickers, 2003]. As the individual walks, their gaze tends to prioritize possible footholds—an area of interest that is considered to be a possible area of foot placement [Yamada et al, 2012]. Similar to travel fixation, footprint fixation occurs approximately 800-1000ms, or roughly two steps, away from the individual [Patla, 1997; Patla & Vickers, 2003]. This is in order to plan for and accommodate according to potential foothold locations.

With this understanding of where and how long people look while navigating a pathway, Mathis & colleagues (2015) examined the role of visual information with respect to a precision foot placement task during locomotion over a complex terrain. In this study, participants walked along a 5m path of six irregularly-spaced targets. However, this study differs from the Patla & Vickers (2003) study in setup of visual constrains: during a trial, vision was either occluded during the step to the target or during the step prior to placing the foot on the target. This experimental design was in place to determine at which step leading up to the precise foot placement is most important with respect to visual information. As figure 4 demonstrates, there is a significant increase in stepping error when the target becomes nonvisible prior to toe off of the foot being placed on the target; the figure below represents the overall stepping error up to two steps prior to precise foot placement on the target. It is suggested that vision is critical in this phase of the step as it is a control phase in the gait cycle [Mathis, Barton, & Fajen, 2015].

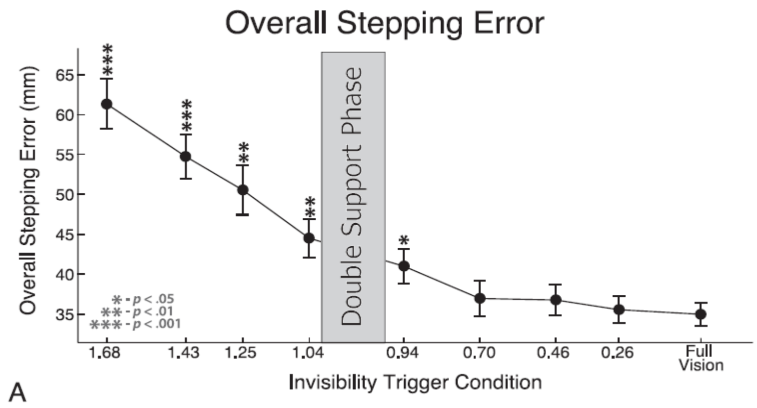


Figure 4- Stepping error measured in two dimensions. Double support phase represents the transition from N-2 to N-1; prior to one step away, an increase in stepping error is observed, indicating that vision is crucial during the step prior to toe off.

In order to explain this, we must turn to previous work conducted by Mathis and Fajen (2013) which found that humans were able to use vision to exploit biomechanical efficiency. However, in this study, participants were required to avoid the obstacles rather than step on the targets either with full vision of limited vision conditions. The results agreed with previous findings that people tended to require two steps of information. When performing flat, free walking trials, foot placement was determined by the COM movement; when obstacles were present, vision proved to be the main mechanism of control, modifying the movement of COM according to restrains of the environment [Mathis & Fajen, 2013]. With two steps of information, participants were able to visually guide foot placement and redirect COM towards the available footfall locations that promoted energetic efficiency (e.g. proactive control strategy).

Mathis and colleagues furthered this study by examining visual control of locomotion during a precise foot placement task [Mathis & Fajen, 2014; Mathis, Barton, & Fajen, 2015]. In this particular study, participants were required to step along six planar footholds along a pathway with vision occluded at various stages during the swing phase. Mathis and colleagues suggest that the reason as to how individuals exploit the biomechanical properties of locomotion is using visual control strategies up to the point of opposite leg toe-off to guide foot placement [Mathis & Fajen, 2014; Mathis, Barton, & Fajen, 2015]. As the figure below shows, the critical phase of visual control of foot placement is just prior to two steps away in order to exploit passive properties of locomotion and ensure foot placement accuracy.

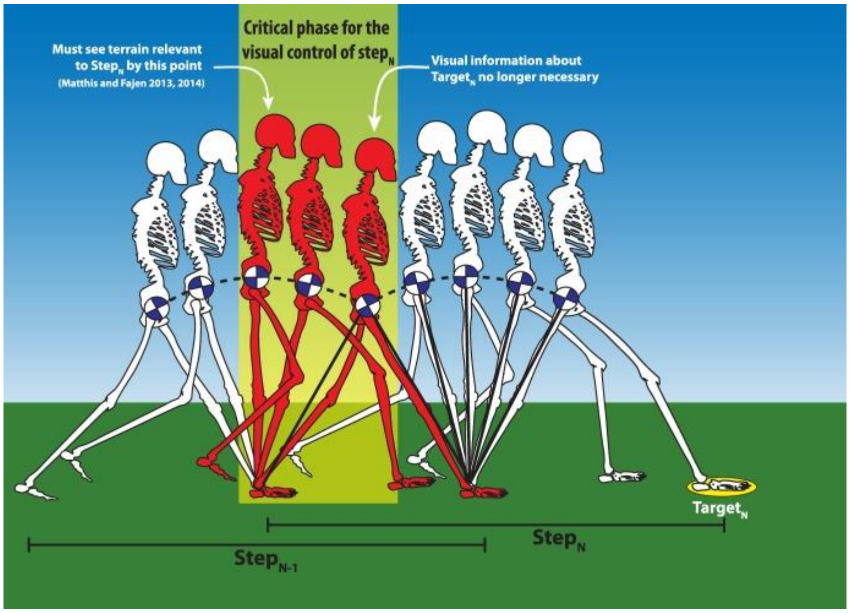


Figure 5- The figure depicts the critical phase for visual control of foot placement occurs during the latter half of the preceding step. This figure is from the findings that suggest that in order to fixate two steps ahead and to exploit the passive properties of locomotion; the window of critical visual control is just prior to Step$_N$, or approximately two steps away from the future foothold [Mathis & Fajen, 2014; Mathis, Barton, & Fajen, 2015].

Furthering this study was an experiment conducted by Marigold & Patla (2008). In this particular study, participants were required to navigate predetermined pathways, crossing nine potential 0.5m by 0.5m blocks of multi-surface complex terrain (e.g. slippery, compliant, tilt, and rocky terrain) in order to get to a goal. The main results discussed the importance of the lower visual field of view but more importantly, Marigold and Patla (2008) suggested that the complex nature of the multi-surface terrain resulted in the participants performing altered gait patterns and visual control strategies.

From these highlighted studies, it is known that individuals need at least two steps of visual information in order to exploit the mechanical forces of human locomotion. However, in to order successfully exploit such forces, vision is needed up to the point at which toe off of one step away is about to be performed. This is known across experimental designs that incorporate obstacle avoidance and precision foot placement tasks. Furthermore, the role of vision changes with task demands. In an environment with greater terrain demands (e.g. cracked sidewalks, river stones, etc.), visual control strategies differ. One possible suggestion could align with previous discussion of head/trunk movements or another could suggest the influence of foot placement strategies.

Foot Placement Strategies

When an individual must choose where to place the foot in a short period of time, the individual must: 1) quickly and accurately assess environmental risks; 2) compare potential contact surfaces for a preferential landing spot of the swing foot (e.g. flat, stable, even ground); 3) coordinate head and body movements in a manner that controls the COM in the direction of the swing foot's future position; and 4) prepare the body with an anticipatory postural adjustment in order to ensure a stable foothold [Das & McCallum, 1988]. Seeing as though foot placement tasks require a significant amount of sensory integration and information processing, countless studies have examined the effects of paradigms that require individuals to selectively place their foot on a given location (e.g. target selection tasks).

In this area of research, alternative foot placement strategies arise when individuals must deviate from their normal footfall location. For instance, Patla and colleagues (1999) determined factors that guided individuals to select alternate foot placement strategies. This study set the precedence of alternative foot placement strategies in order to determine what individuals do and why. It was found that individuals will choose to minimize their displacement of the foot such that in the event of a perturbation, their alternative foot placement location is as close to their normal foot fall location as possible to help maintain stability [Patla et al., 1999]. As a result of minimizing foot displacement, muscle activity and thus, locomotive movement is limited in interruptions and promotes continuous stepping behaviours.

Following up that study, Moraes and colleagues determined that if response choices satisfied minimizing foot displacement, then people will generally follow three alternate foot placement strategies: 1) placing the foot along the plane of progression; 2) choosing to take a longer step than a shorter step; and 3) selecting a more medial foot placement opposed to a lateral foot placement [Moraes, Lewis, & Patla, 2006; Moraes & Patla, 2004]. However, foot placement strategies, such as stepping more medial or placing the foot along the plane of progression seem to be counterintuitive in the sense that these strategies may compromise the dynamic stability of the individual. With the reduced BOS, the individual has a limited area to control their COM, which may increase the risk of losing balance, leading to an increased risk of falling [Hak et al., 2012]. A way to combat this risky stepping behaviour has been to increase the stability margin (i.e. stepping laterally to increase the BOS) [Hak et al., 2013]. By doing so, a more conservative approach to a foot placement strategy is performed, resulting in a decrease risk of falls. Thus, suggesting that stability is taken into the highest of priorities in effort to stay upright and injury-free; as previously mentioned, stability is one of the three essential elements of locomotion [Das & McCallum, 1988].

Research examining foot placement has shifted to assessing strategies used during the navigation of complex terrains. Complex terrains can include elements of uneven, challenging surfaces that require individuals to assess future foot placement locations to a much greater degree. Within literature, there have been a few examples of complex terrain, ranging from shortened multi-surface terrain to a few irregularly spaced target footholds. Marigold and Patla (2008), participants were required to walk across six varying types of ground terrain (two solid, three compliant three rocky, three irregular, three tilt, and one slippery); the design was setup in a way where only the middle portion challenged individuals with its multi-surface terrain. The researchers reported findings of increased variability with respect to step, trunk, and head when comparing multi-surface terrain to flat ground walking and young to older adults (Marigold & Patla, 2008). However, the step, trunk, and head variability could have been due to the layout of the experiment itself opposed to the multi-surface terrain: with each square of the multi-surface terrain being 0.5m and the average step length of a young adult being 0.6m, the variability could be as a result of unnatural stepping dimensions of the required pathway—or some may be avoided completely, unless told otherwise.

Throughout navigational locomotion tasks (e.g. target selection tasks), literature demonstrates the importance of the visual system with respect to foot placement strategies. Vision is required to gather information about the environment and find safe, secure foothold locations; secure foot placement is required to adjust and regulate one's stability in efforts to remain upright during locomotion. Mathis and Fajen (2015 describe the role of vision up to the point of opposite foot toe off during a navigational task, suggesting that the reason is to exploit mechanical properties of locomotion, but never really suggests the interaction between postural and visual control with respect to foot placement.

CURRENT STUDY

As the previous section highlighted, several research projects and articles stand out in the adaptive locomotion field of research. Researchers such as: Patla, Winters, and Fajen—just to name a few—contributed to the current study in some fashion; whether providing insight into results and/or building upon experimental design to further explore visual control of locomotion. In particular, three main studies have provided the foundation to the current study.

The first study by MacLellan and Patla (2006) examined the stability control strategies (e.g. adaptations of stepping patterns, COM movement, and lower limb muscle activity) of young adults while walking on a compliant surface. In order to maintain upright locomotion with a highly variable COM movement, individuals tended to increase their BOS by choosing to step wide and long. This study provided a great amount of insight into the operation of the CNS with respect to organizing muscle activities in order to control constant overcompensation and subsequent correction strategies as a means to control the COM. Furthermore, this particular study contributed to the understanding and implementation of assessing the dynamic stability margin of an individual during a difficult walking task.

The second influential study was by Marigold and Patla (2008) in which they designed a study with the objective of determining the importance of vision while navigating a 2.5m multi-surface complex terrain. As previously mentioned, this study contained two main research design flaws: 1) the 0.5m by 0.5m blocks of terrain is less than the average step length (i.e. ~60cm), therefore, an individual could step over a terrain in one step, unless otherwise instructed; and 2) a 2.5m pathway is not long enough to suggest that participants were able to achieve what is deemed a steady state of locomotion. Rietdyk and Drifmeyer (2009) argue that during an accurate foot targeting task, the visual system is scanning to gather information in order to contribute to an overall plan in the first four steps. Therefore, to accurately assess visual control strategies of complex terrain (and to ensure the individual reaches steady state locomotion), the pathway should incorporate more than four steps.

The final influential study was by Mathis and colleagues (2015) who examined the role of vision and its influence on whole body mechanics during a pathway walking task, using six targets across 5m. The participants were exposed to the same path for 200 trials with no variation in target placement, which could suggest a learning effect from start to finish. However, this experimental design did highlight a key finding: individuals tend to use a visual-guidance of foot placement within two steps away—and up to toe off of opposite foot—in order to exploit biomechanical forces of the body when performing a precision foot placement task [Mathis, Barton, & Fajen, 2015; Mathis & Fajen, 2014; 2013]. This finding significantly contributed to the understanding of why people tend to look two steps ahead during a complex navigational task.

Based on these previous studies, some questions are left unanswered. The current study forced individuals to place their feet on the superior surface of irregularly shaped objects (e.g. rock climbing holds), moving from stone to stone. Participants navigated these stones following a predetermined pathway (e.g. constrained) or self-selecting the pathway (e.g. unconstrained). This study was designed with the notion of answering the following questions:

1) How is control of the head and trunk affected when individuals choose their own path opposed to following a predetermined path?

2) What are the differences in visual control strategies exhibited when self-selecting a pathway opposed to following a predetermined path? And how is the DSM of an individual affected?

The purpose of this study is to further understand the postural and visual control mechanisms during a complex navigational task (e.g. stone stepping) and whether either were affected by the type of path (i.e., free or constrained) one walked. The current study assessed the role of visual control during a complex navigational task and strategies used. Furthermore, the study was designed to examine the stability of individuals during a predetermined path opposed to a self-selected path, incorporating the challenging task of precision foot placement. With a task such as stone stepping, it was unknown whether the level of task difficulty would influence the visual control strategies, coinciding with previous work or not.

HYPOTHESES

For this study, two main hypotheses emerge, centralizing around the conditions of the pathways (e.g. whether it they are predetermined or self-selected). The primary hypothesis includes a comparison of the whole-body control, focusing on the HAT segment with respect to the condition of the trials.

I. It is hypothesized that the constrained will cause individuals to exhibit greater variability—in the form of trunk movements about the hip—when compared to the unconstrained task. For instance, during the constrained trials, individuals should produce greater trunk movements in effort to control the HAT segment as a result of the unnatural foothold locations of the predetermined path. In comparison, unconstrained trials enable individuals to choose their path based on their current state of postural control, thus showing less trunk movements about the hip (e.g. trunk pitch and trunk roll).

II. According to the conditions of the pathway (e.g. constrained versus unconstrained), it is hypothesized that individuals will not perform the previously reported strategy of using visual information from two steps away. This notion comes as a result of the complexity of the task; previous literature reasoned that individuals fixate two steps away to exploit biomechanical factors of human locomotion during a simple pathway walking task [Mathis & Fajen, 2013; 2014; Mathis, Barton, & Fajen, 2015]. However, with a difficult paradigm—such that of the current study—the body may be greatly challenged. In order to remain upright and on the raised-ground path, visual control strategies may differ from the travel fixation strategies of more than two steps away [Hollands, Patla, & Vickers, 2002; Patla & Vickers, 2003]. Instead, it is hypothesized that fixations will occur on more immediate foothold locations as a way to compensate for the variable trunk movements and modulate foot placement to ensure accuracy.

2.0 METHODS

2.1 Participants

Nine university-aged females (mean age: 22.5 years old +/-1.75, range 20-24 years) volunteered for participation in this study. Inclusion criteria was designed and outlined as follows: 1) participants must not have any neurological, muscular, or joint disorders that could affect their performance and/or behaviour in this study; 2) participants must not have received any formal, sport-specific training within the past five years and/or be rostered to a competitive club/university field sport (e.g. rugby, soccer, field hockey, etc.) in order to have the most homogenous group as possible; 3) participant must have a shoe size smaller than US size 9 females (size 7 males) in order to allow for roughly 70% of the entire foot to fit on a single rock climbing hold; and 4) participants have normal or corrected-to-normal vision. Please note: during pilot testing, the working inclusion criteria became a focal point as it was noted that males with a foot size larger than US size 9 would not work for two main reasons: 1) the foot was too large and would make contact with the plywood surface, offering a point of stabilization; and 2) the foot was too large that it would cover up to three rock climbing holds at once, offering a point of stabilization. For these reasons, females were recruited, with an inclusion criterion of women's US size 9 or smaller. Once it was decided that females would be recruited as participants for the study, the placement of the rock climb holds were selected based on average step length and width for females.

The current experiment has received ethical approval from the Wilfrid Laurier University Research Ethics Board (REB #4246).

2.2 Experimental Set Up

Each participant was outfitted with four rigid bodies which contained three infrared emitting diodes (IREDs) in a triangular formation, allowing for thirteen digitized points (refer to Figure 6). One rigid body was placed on the occipital region (back of the head), mounted on the posterior head strap of the ASL gaze tracking system, with two corresponding digitized points located at both the left and right external ear; another rigid body was placed on the right scapula, specifically on the infraspinous fossa, with five digitized points corresponding with the rigid body: bilateral intertubercular grooves of the humerus, spinous process of T10, and both posterior superior iliac spines (PSIS); and one rigid body on each of the posterior aspects of the foot, specifically on the calcaneal region, corresponding with digitized points of the outer bounds of the 1st and 5th metatarsals as well as the anterior ankle (i.e. anterior aspect of the ankle, situated directly between both malleoli). Additionally, one marker was placed on the styloid processes of each the left and right ulna in order to show movements of the arm—and for COM calculations. Kinematic data were collected at a sampling frequency of 120Hz.

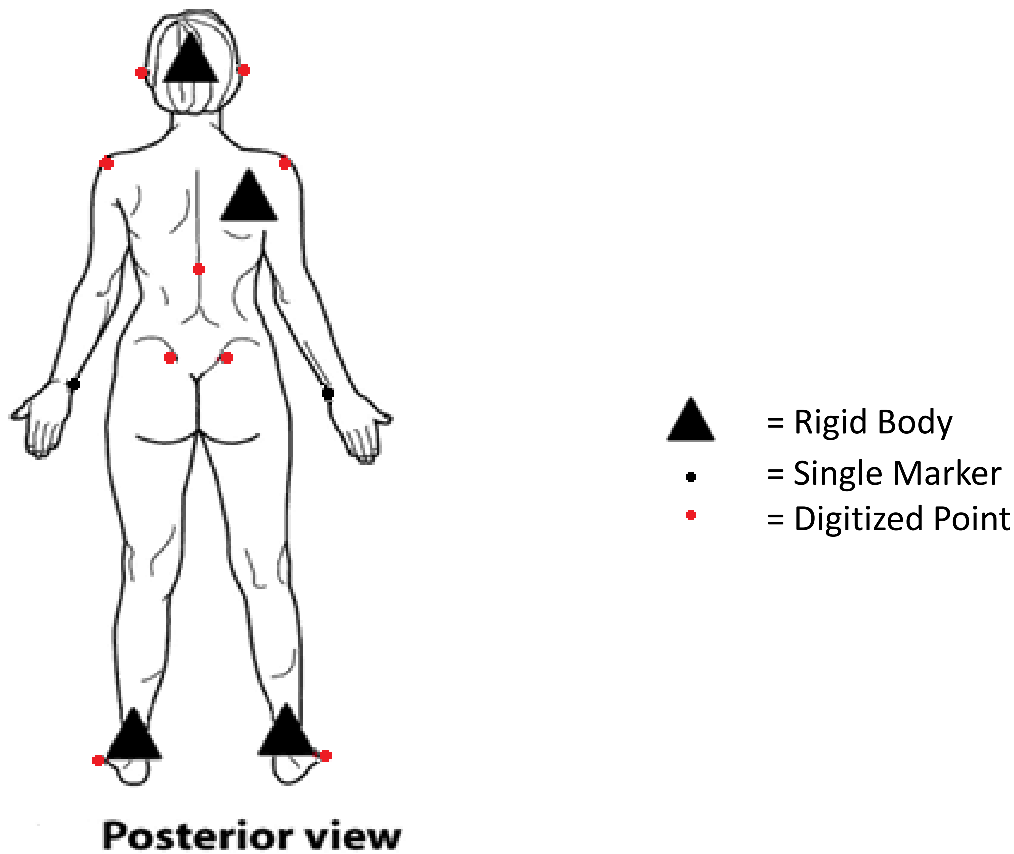


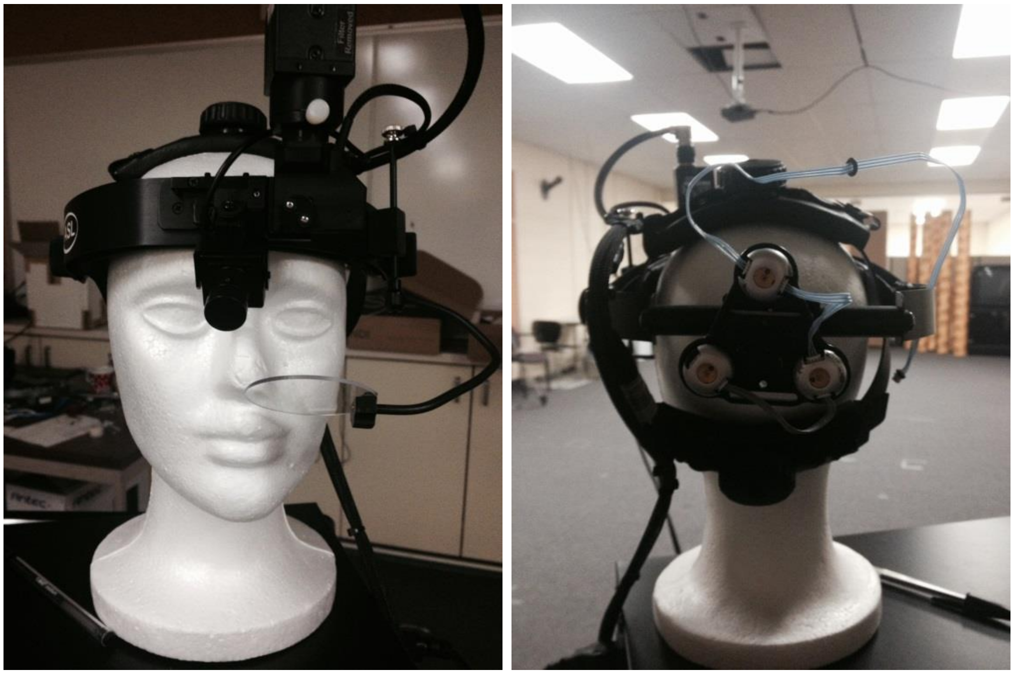
Figure 6- The location of the rigid bodies and digitized points; markers will be captured by three Optotrak camera systems (Northern Digital Inc., Waterloo, Ontario) in order to represent the body in space. The black triangles represent the four of the rigid bodies, located on the occipital lobe (mounted on ASL eye tracker); the black dots represent markers on both styloid processes of the ulna; the red dots represent nine (of the thirteen) digitized points on the TMJs, intertubercular grooves, T10, PSIS, and 5th metatarsals—the digitized points missing from this figure are: anterior ankles, and 1st metatarsals.

Five OPTOTRAK position sensors (Northern Digital Inc.; Waterloo, Ontario, Canada) were positioned to the surroundings of the participant, in a semicircular shape in order to collect rear facing IRED markers as the individuals walked from the start of the pathway toward the end (refer to Figure 7 for setup). This particular setup was used to assess whole-body movements, with an emphasis on rotational trunk movements about the hip (e.g. trunk angles). Trunk angles were calculated using the displacement of the digitized points on the left and right glenohumeral joints and T10.

$$\boldsymbol{Pitch}: \emptyset = \tan^{-1}[\frac{midpoint\ of\ GH\ joints_{ML} - T10_{ML}}{midpoint\ of\ GH\ joint_{Vertical} - T10_{Vertical}}]$$

$$\boldsymbol{Roll}: \emptyset = \tan^{-1}[\frac{midpoint\ of\ GH\ joints_{AP} - T10_{AP}}{midpoint\ of\ GH\ joint_{Vertical} - T10_{Vertical}}]$$

Additionally, gaze behaviours were monitored and recorded with the ASL H7-HS High Speed Head Mounted Optics eye tracking unit (Applied Science Laboratory; Bedford, Massachusetts, USA). One of the five rigid bodies was secured on the posterior portion of the head mounting unit (refer to figure 7). The gaze data was collected at a sampling frequency of 120Hz. In order to calibrate the gaze tracker, participants were instructed to stand 1m away from the platform to ensure the entire first piece of the 7.2m by 1.2m plywood was fully visible to the participant and the scene camera. Using the ASL Results Plus software in calibration mode, the participant was instructed to just move eyes to the points indicated on the platform. Nine points were used on the first piece of plywood of the 7.2m pathway to calibrate: points 1, 3, 7, and 9 were at all four corners of the 2.4m x 1.2m sheet of plywood; points 2 and 8 were directly in the middle of points 1/3 and 7/9, respectively; and points 4, 5, & 6 were outlined by finding the halfway point between 1/7, 2/8, and 3/9. Once fixation occurred at each of these points, the participant was directed to the next point of interest to fixate on. If calibration was not successful, the monocle and/or the pupil camera was adjusted and calibration was attempted again; calibration was considered to be unsuccessful if there was excessive movement of the pupil cursor when fixating on points of interest in addition to the experimenter being unsure of the exact point of interest (e.g. when asked to fixate on a rock, the experimenter was unsure of the exact rock due to inaccurate pupil cursor location).



A) Anterior View of ASL H7 B) Posterior View of ASL H7

Figure 7- The ASL H7-HS High Speed Head Mounted Optics eye tracking unit (Applied Science Laboratory; Bedford, Massachusetts, USA). The head mounted unit contains two adjustable claps to ensure fit and comfort; the unit is also equipped with two cameras, an adjustable monocle, and wire that is positioned down the back left side of the unit. Figure 6a shows the anterior view of the head mounted system with two visible cameras: the scene camera is used to record the environmental surroundings (e.g. the scene) while the eye camera is positioned in accordance to the monocle in order to record eye movements. One of the adjustable clasps is visible from this angle along. Figure 6b shows the posterior view of the head mounted system with one of the rigid bodies used during this paradigm. The rigid body was in place to collect movement about the head during the stone stepping task. The second adjustable clasp and the cable connected to ASL software are visible from this perspective.

The study was conducted in a 13m x 9m room, virtually unconfined when it comes to a navigational task (refer to Figure 8). The current study focused on raised-target pathway walking, with 60 rock climbing holds secured to superior surfaces of three consecutive pieces of plywood with a total measurement of 7.2m x 1.3m x 0.012m.

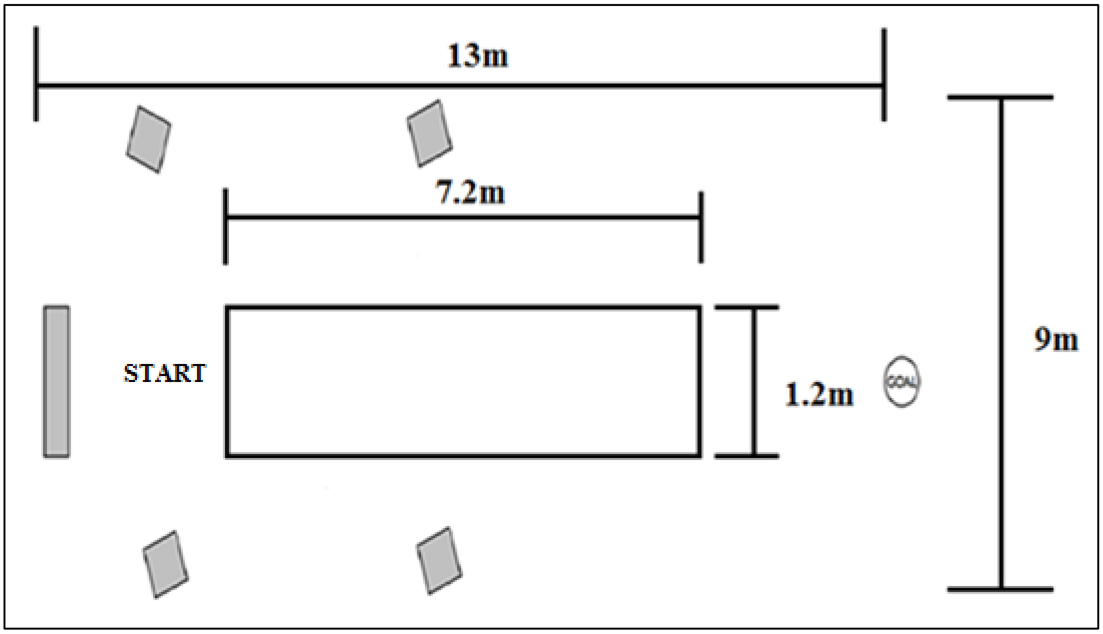


Figure 8- The experiment took place in a 13m by 9m space, with full lighting. Within this space was the 7.2m by 1.2m pathway which contained the raised rock climbing holds. Five Optotrak cameras were positioned in a semicircular formation in order to capture full-body kinematics of the participants throughout the entire pathway.

2.3 Experimental Design

The raised ground walking task was performed on a platform containing 60 rock climbing holds. Each hold was placed strategically to fulfill one of three criterion: 1) in line with natural footfall locations (e.g. normal step length and/or width dimensions of 60cm by 10cm); 2) greater or less than one of the dimensions of a natural step length or width; or 3) to act as a possible option/distractor on the pathway (refer to Figure 9).

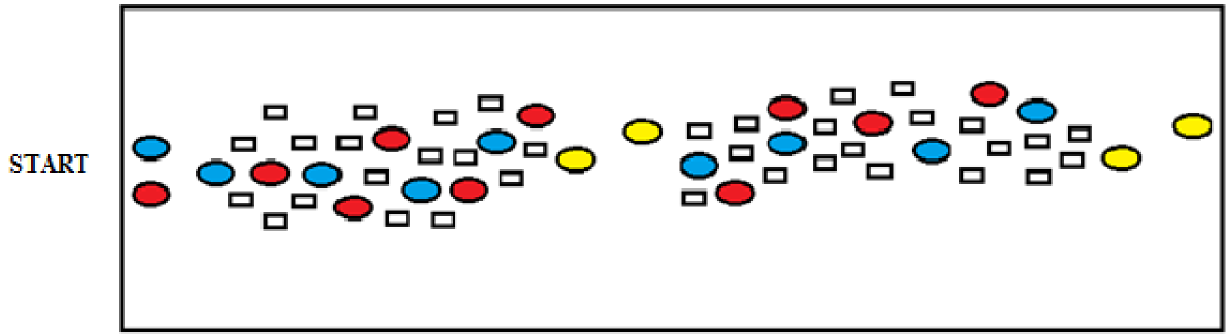


Figure 9- An aerial view of the raised pathway in which participants were instructed to walk along. The ovals and the small rectangles within the space represent the 60 rock climbing holds which made up the possible foot placement targets. The red and blue ovals represent the right and left respectively predetermined paths in which the participants had to follow during constrained walking trials. The small rectangles represent the additional stones placed as options for the participants to step on during unconstrained walking trials and act as distractors during the constrained walking trials. The yellow ovals are the four planned foot placements in which the participants had to step on every trial, regardless of condition (i.e. constrained or unconstrained). On each trial the participants were required to place their right foot on the first yellow oval followed by placing their left foot on the second target. The participants began each trial by stepping on either the first red or blue oval and continued to the last set of planned yellow ovals.

Two pathways (i.e., left foot start or right foot start) were constructed along the pathway in order to rule out any effects of starting with one foot over the other. Furthermore, the two pathways were mirror images of each other, manipulating the same dimension, just different direction. For instance, the blue path below begins by manipulating natural step length to decrease the step length by 33.3%; the next step manipulated natural step width by decreasing step width by 50%; followed by manipulating the natural step length by increasing step length by 33.3%; increasing step width by 50%; and decreasing step length by 33.3%. And the red pathway begins by manipulating natural step width to decrease the step width by 50%; the next step manipulated natural step width by decreasing step length by 33.3%; followed by manipulating the natural step width by increasing step width by 50%; increasing step length by 33.3%; and decreasing step width by 50%. Each of the previously described pathways is only one segment, consisting of five steps each approaching the first set of preplanned foot placements secured at a natural step length of 60cm and a natural step width of 20cm. The segments were then repeated in the same order for the second segment of the platform (Table 1).

With each step, one dimension was manipulated with the other dimension remaining consistent with a natural step. Thus, to increase step length, the subsequent stone was placed 80cm in the AP direction and 10cm in the ML direction away from the previous stone; 80cm being roughly 33% longer than the average person's step length and 10cm being the average person's step width. Conversely, to decrease step length, the subsequent stone was placed 40cm in the AP direction and 10cm in the ML direction away from the previous stone; 40cm being roughly 33% shorter than the average person's step length and 10cm being the average person's step width. To increase step width, the subsequent stone was placed 20cm in the ML direction and 60cm in the AP direction away from the previous stone; 20cm being roughly 50% wider than the average person's step width and 60cm being the average person's step width. Conversely, to decrease step width, the subsequent stone was placed 5cm in the ML direction and 60cm in the AP direction away from the previous stone; 5cm being roughly 50% narrower than the average person's step width and 60cm being the average person's step width.

Table 1- A summary of step manipulations for both the red and blue pathways, separated into two segments by the preplanned foot placements; the preplanned foot placements were fastened at a natural step length dimension of 60cm and a natural step width dimension of 20cm. Each pathway contains ten manipulations in total, with five manipulations (i.e. steps) in the first segment and five in the second segment. The Blue pathway begins by manipulating decreasing step length by 33.3%; decreasing step width by 50%; increasing step length by 33.3%; increasing step width by 50%; and decreasing step length by 33.3%. And the red pathway begins by decreasing step width by 50%; decreasing step length by 33.3%; increasing step width by 50%; increasing step length by 33.3%; and decreasing step width by 50%. The segments were then repeated in the same order for the second segment of the platform.

Step	**Blue Pathway**	**Red Pathway**
N (starting)	Left Foot Start	Right Foot Start
N_{+1} (step one)	Decrease step length by 33.3%	Decrease step width by 50%
N_{+2} (step two)	Decrease step width by 50%	Decrease step length by 33.3%
N_{+3} (step three)	Increase step length by 33.3%	Increase step width by 50%
N_{+4} (step four)	Increase step width by 50%	Increase step length by 33.3%
N_{+5} (step five)	Decrease step length by 33.3%	Decrease step width by 50%
N_{+6} (step six): Preplanned Step	60cm step length by 20 cm step width	60cm step length by 20 cm step width
N_{+7} (step seven): Preplanned Step	60cm step length by 20 cm step width	60cm step length by 20 cm step width
N_{+8} (step eight)	Decrease step length by 33.3%	Decrease step width by 50%
N_{+9} (step nine)	Decrease step width by 50%	Decrease step length by 33.3%
N_{+10} (step ten)	Increase step length by 33.3%	Increase step width by 50%
N_{+11} (step eleven)	Increase step width by 50%	Increase step length by 33.3%
N_{+12} (step twelve)	Decrease step length by 33.3%	Decrease step width by 50%

The two sets of planned foot placements (represented as the yellow ovals in Figure 8) were placed 2.4m and 6m from the starting positions. The position of these foot holds fell in line with one's natural step length and width dimensions (i.e., 60cm step length and 10cm step width). This was done for a few reasons: 1) to increase the level of control—regardless of condition, participants were instructed to incorporate a right-left stepping behaviour on the set of planned foot placements for post-hoc analysis of gait parameters; 2) the two sets of planned placements were designed to analyze the Dynamic Stability Margin (DSM) at those four rocks to help ensure that all participants had similar stepping parameters across all trials; and 3) to act as a divider, separating the pathway into two separate segments. The purpose of the segments was to compare the effects of segments and to compare whether or not both segments had the same effect on the participants and that they were unaffected by the planned foot placements. The four planned foot placements were clearly marked with high-contrasting moldable material (i.e., pink Play-Doh) placed within the bolt hole of the rock climbing hold, visible from a minimum of four steps away.

The superior surfaces of the rock climbing holds were flat enough to allow the participants to make contact with the pads and the arches of their feet (refer to Figure 10). In order to control for shoe mechanics and contacting surface area, each participant wore canvas style Converse Chuck Taylor shoes because of their flat rubber sole bottoms that offered limited ankle support and possess a medium density insole.

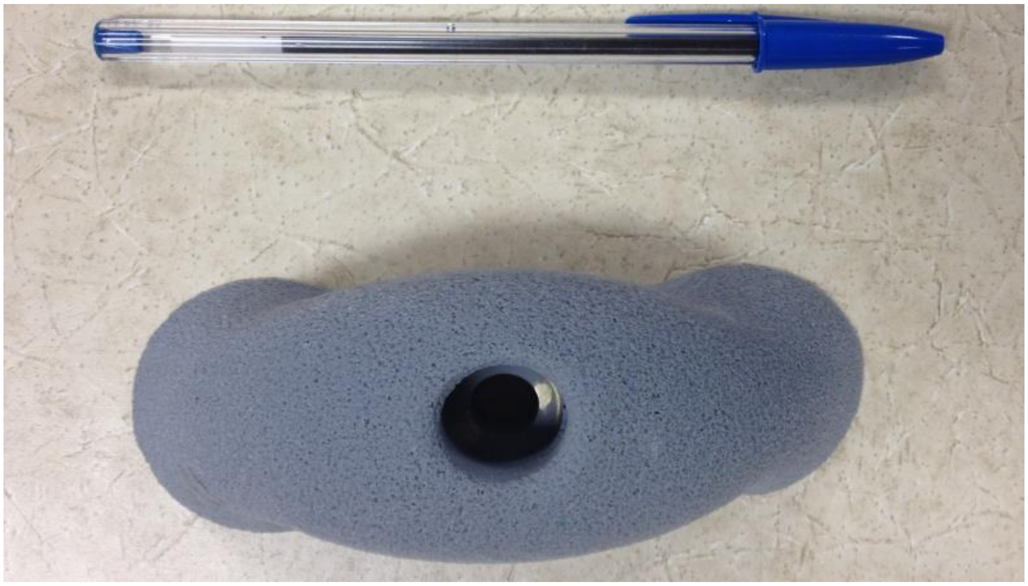


Figure 10- Picture of rock climbing hold used in current study alongside a standard-size ballpoint pen. The rock was fastened to the wood platform with a 2 ½" bolt and secured with carpenter's glue. Each rock was laid out in a specific location to either fall in line with a natural footfall location, to larger or smaller than one of the dimensions of a natural step length or step width, or act as an additional option/distractor. Participants were instructed to place each of their feet on the superior surface of the stone without spanning across more than one and/or making contact with the wood platform. A high-contrasting moldable substance was placed in the bolt hole of the superior surface of rocks to indicate to individuals which stones to step on; one of the starting stones and all four planned foot placements always had the high-contrasting moldable substance to ensure that participants always stepped on those rocks.

2.4 Experimental Procedure

Prior to the start of data collection, all participants were given the same set of instructions:

> *Before the start of every trial, an experimenter will calibrate your vision to ensure accuracy of the ASL gaze tracking equipment. Prior to the 'go' command, you will face the opposite direction of the walkway and one experimenter indicate whether the upcoming trial is a free choice or forced trial and which foot to start with. When you hear the experimenter say "go", you will turn around to face the walkway and you will begin*

walking as 'normal' as possible, placing your feet on the top of each stone without spanning across more than one stone at a time and/or making contact with the board.

Each participant walked at a self-selected pace and performed a total of 40 randomized trials of the following four conditions: 1) constrained predetermined path, starting with left foot; 2) constrained predetermined path, starting with right foot; 3) unconstrained self-selected path, starting with left foot; and 4) unconstrained self-selected path, starting with right foot. The constrained pathways were differentiated from the unconstrained ones using a high-contrasting moldable material (e.g. pink Play-Doh) on the superior surfaces of designated rocks, according to the given trial.

Trials were redone if participant fell off of the stones completely and/or they failed to conform to the above-mentioned "rules" (i.e., do not let foot come in contact with platform).

2.5 Data Analysis

In order to answer the research questions at hand, the data was analyzed as two separate entities: Gaze Behaviours and Kinematics. However, with two separate units and unsynchronized software, the start of the data analysis window was defined as the frame in which the first foot broke the positive X/Y plane. With +X/+Y plane setup such that the anterior-posterior (A-P) and medial-lateral (M-L) axes of the board, corresponded to the X+ and Y+ axes respectively. The first positive value in the X direction indicated the starting frame; the origin of the global axis coordinate system was located in the bottom left corner of the platform. The analysis window ended once the individual reached 7.2m in the X direction.

Using this defined analysis window, gaze behaviours and kinematics were further broken down into segment number, condition, and time.

Segment number was divided into two portions: Segment 1 which began at heel contact during the first stone of the pathway and ended just prior to heel contact with the first stone of the first set of predetermined footholds; Segment 2 began at heel contact with the first stone of the pathway after the first set of predetermined footholds and ended just prior to heel contact of the first stone of the second set of predetermined footholds.

Condition was characterized by the task demands as well as starting foot. For instance, if the participant was asked to start the trial with their left foot and follow the pathway, that trial would be classified as a ControlLeft (CL). Conversely, if the participant was asked to start with their right foot and choose their own path, that trial would be classified as FreeRight (FR). Therefore, with two starting foot options and two conditional demands, there are four conditions: ControlLeft (CL), ControlRight (CR), FreeLeft (FL), and FreeRight (FR).

Time was measured at three separate time points throughout the experimental protocol and characterized by the number of completed trials of a particular condition. For all four conditions, the first, the middle (i.e., 5th), and the last (i.e., 10th) trials successfully completed were taken into account when analyzing each dependent variable. For instance, for the condition CR which had a total number of ten trials completed, trial number one, five, and ten were highlighted to extract any values from to measure across segments and conditions. This characterization of time point was used to assess whether learning occurred from the beginning of the experimental protocol through the end.

2.5.1 Gaze Behaviours

The gaze data was first viewed real-time playing speed to qualitatively assess observable gaze strategies of each trial performed by all participants. Number of fixations and fixation durations (ms) were analyzed to determine if there were any differences in the processing time of individuals between the two conditions. Then, average pupil velocity was calculated using output from ASL H7-HS High Speed Head Mounted Optics eye tracking unit, separating velocity values (pixels/s) into vertical and horizontal components. To gain an understanding into the fluctuation of velocity values about a mean, the root mean square (RMS) of horizontal and vertical values were calculated across all trials using the following equation:

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + \ldots + x_n^2)}$$

Horizontal and vertical pupil velocity values were used as a means to determine how quickly individuals fixated between points. Horizontal and vertical pupil velocity values were analyzed to provide a quantitative approach to describing observable gaze strategies. For instance, a higher velocity value suggests greater movement of the pupil (and eye). However, a greater velocity value also suggests that an individual moved quickly from one fixation point (i.e., foothold) to another. With respect to the vertical component, a greater velocity value may be indicative of producing a visual control strategy similar to the documented travel fixation strategy [Hollands, Patla, & Vickers, 2002]. The travel fixation strategy incorporates the use of a scanning pupil behaviour that travels ahead to locate possible future footholds and returns to more immediate footholds, fixating in this sort of scanning pattern. Conversely, with greater velocity values in the horizontal component may be indicative of more of a sampling fixation strategy [Wilkie & Wann, 2003]. The sampling fixation strategy is essentially that—the eye is sampling the environment and relevant possible foothold locations to discriminate between attractive and unattractive foothold locations.

However, these analyses failed to indicate where the individual was looking with respect to potential foothold locations. In order to gain insight into a possible location, a representative of the group of participants was selected for a frame-by-frame analysis of fixation location.

2.5.2 Kinematics

Kinematic data was collected using a five positioning OPTOTRAK camera systems with the use of four rigid bodies and two individual IRED markers (refer to Figure 5). Raw data was processed using Optofix software (Mishac Kinetics, Waterloo, Canada); a cubic spline interpolation was used to filter any missing data at a threshold of 15 frames. All kinematic data was then filtered further using a 4th order low-pass Butterworth filter with a 3Hz cutoff—to be conservative and remove step-by-step variability, a 1Hz cutoff was used for average walking velocity.

Kinematic data was characterized based on the dependent measure being assessed. In order to depict the most informative understanding of the results of the current study, six dependent measures were analyzed.

I. Average walking speed (cm/s)

Average walking speed was calculated based on the average of the instantanoues speeds during segment one and segment two of the platform. Average walking speed of Segment 1 was calculated from heel contact of the starting foot to heel contact of the first predetermined right heel contact. Average walking speed of Segment 2 was measured from heel contact of the first stone following the first set of predetermined foot placements to right heel contact of the second set of predetermined foot placements. The purpose of analyzing walking speed was to gain an understanding of the amount of time an individual took to complete both segments of the task. The comparison of walking speed across conditions could be used as an indirect measure the level of difficulty of each condition (i.e., slower velocity equals a more difficult task).

II. *Medial-Lateral Centre of Mass Variability (cm)*

Medial-lateral centre of mass variability (ML COMvar) was analyzed as a means to describe whole body kinematic data. In order to do so, the weighted whole body COM was calculated using a formula derived from Winter (2008) for the x, y, and z planes and the standard deviation of the average position during each segment was calculated as follows:

*COM = 0.46 *((Left Glenohumeral Joint + Right Glenohumeral Joint + T10) / 3) + 0.22 * ((Left PSIS + Right PSIS) / 2) + 0.16 * (0.625 * Left PSIS + 0.375 * Left Ankle) + 0.16 * (0.625 * Right PSIS + 0.375 * Right Ankle)*

$$ML\ COMvar = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

This equation was used to provide insight into the variability in linear movement of the whole body COM as a measure over the two segments.

III. *Trunk Pitch and Roll (degrees)*

Trunk pitch and roll was used to assess rotational trunk movement abouth the hip joint in the sagiital and frontal planes, adding to the descriptive understanding of trunk control during the task. However, with this concentration of trunk movements, we extend work by Winter (1991; 1995) as well as MacKinnon and Winter (1993) that assessed the rotation about the hip and the movement of what is commonly referred to as the inverted pendulum. RMS of trunk pitch and roll were analyzed to show how the trunk was moving about the mean and provide further insight into control strategies used.

IV. Trunk-Head Control

Trunk-Head control is a measure of providing further insight into angluar head control relative to trunk angular control in both the sagittal and frontal planes. Trunk-head control assesses the level of segmental control that the body uses to coordinate movements of the head-arm-trunk (HAT) segment. In order to assess this level of control, head movements (e.g. pitch and roll) were subtracted from the repsective trunk movements (e.g. pitch and roll), equating an integer. This integer was then assessed based on the relationship to the integer less than or greater than 0: if the trunk-head value was greater than zero, the level of segmental control was predominently the trunk; if the trunk-head value was less than zero, the level of segmental control was predominently the head; if the trunk-head value was 0, trunk and head movements were occuring together as a means to segmental control.

V. Dynamic Stability Margin minimum (cm)

The DSMmin is a measure of medialateral (ML) stability within a particular time window; DSM in the ML direction was measured from the lateral border of the BOS to the COM at heel contact, added to the instantaneous ML velocity of the COM, divided by the square root of height to the COM divided by gravity [Hof *et al*., 2005; MacLellan & Patla, 2006]. More simply put, DSMmin was measured during single support and was calculated as the M-L difference between the COM and the lateral border of the BOS (i.e., 5^{th} metatarsal) [Denomme et al., 2014; Perry et al., 2008]. DSMmin was chosen as the value of interest because it represents the closest that the COM is allowed to get to the lateral border of the BOS before it is redirected. Larger DSMmin values are indicative of better dynamic stability than smaller values (refer to figure 11).

In order to highlight any differences in DSM leading up to the first set of preplanned foot placements, the DSM was characterized with an additional factor of foot (i.e. right foot versus left foot). This was with the intention of understanding how individuals treated the first preplanned foot placement with respect to the second preplanned foot placement.

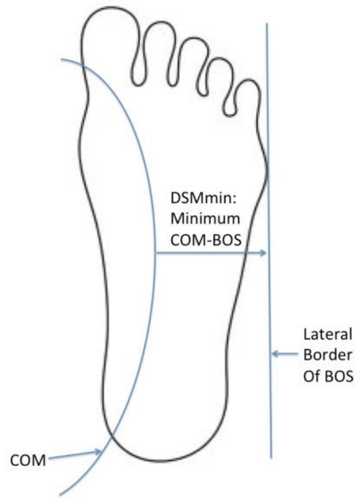


Figure 11- Representation of the DSMmin that demonstrates the control of the COM as it approaches the borders of the BOS [Maki *et* al., 2008]. The stability margin can be estimated by measuring the minimum distance the COM moves in relation to the lateral bounds of the BOS; a larger DSMmin suggests a greater dynamic stability.

2.6 Statistical Analysis

In order to determine significant effects across all dependent variables (e.g. horizontal pupil velocity RMS, vertical pupil velocity RMS, average walking speed, trunk pitch, trunk roll, trunk-head control, and DSMmin), a 2 (Segment 1 vs. Segment 2) by 4 (constrained left foot start, constrained right foot start, unconstrained left foot start, unconstrained right foot start) by 3 (trial 1, 5, and 10) repeated measures ANOVA was used.

3.0 RESULTS

All nine participants completed all experimental trials. Across all trials, only 16 falls were observed where the participant remained upright but failed to remain on the stone pathway. All failed trial attempts were redone at the end of the scheduled protocol. Specific outcomes of both gaze and kinematic behaviours are outlined below.

3.1. Gaze Behaviours

3.1.1. Vertical Pupil Velocity RMS (pixels/s)

The analysis of vertical pupil velocity RMS (in pixels/s) was calculated to determine participants' quick eye movements in the vertical direction (indicative of scanning behaviours) the results revealed that there was no significant interaction effect of segment and condition ($F_{(3,24)}$=2.27; p= .11; d=.22); no significant interaction of condition and time ($F_{(6,48)}$=1.76; p= .13; d=.18; no significant interaction of segment and time ($F_{(2,16)}$=3.29; p= .06; d=.29); and there was no significant interaction of condition and segment and time ($F_{(6,48)}$=.88; p= .52; d=.10).

As for main effects, the analysis revealed a significant main effect of condition ($F_{(3,24)}$=4.71; p= .04; d=.46). Post hoc analysis revealed that the mean vertical velocity RMS of both the right and left foot starts during the constrained trials ($\bar{x}_{Rconstrained}$=1859.46 pixels/s, SD=395.45; $\bar{x}_{Lconstrained}$=2002.23 pixels/s, SD=226.39) were greater than that of the velocity RMS of right and left foot starts for unconstrained trials ($\bar{x}_{Runconstrained}$=1494.23 pixels/s, SD=305.46; $\bar{x}_{Lunconstrained}$=1483.66 pixels/s, SD=226.64) (refer to Figure 12).

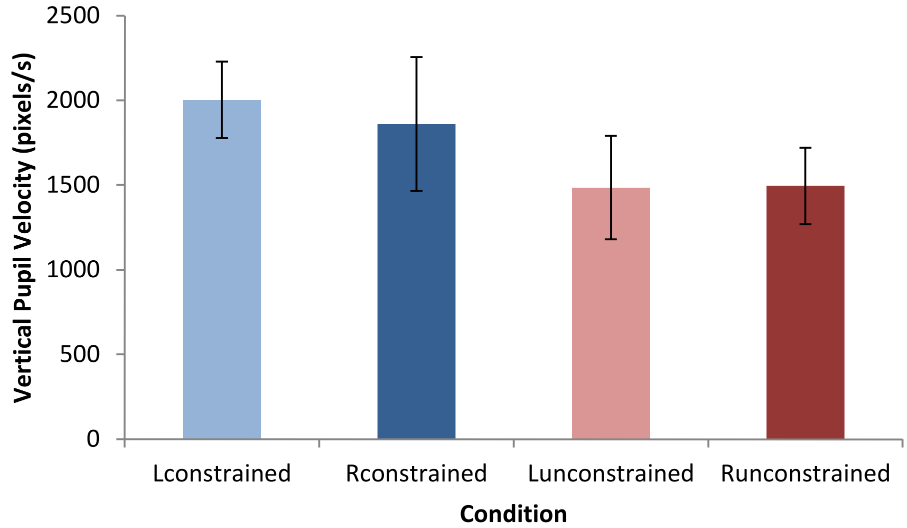


Figure 12- Vertical pupil velocity RMS was significantly affected by condition, such that the constrained trials (left and right start) were greater than the unconstrained trials ($F_{(3,24)}$=4.71; p= .04; d=.46).

However, the analysis revealed that Segment 1 was not different from Segment 2 ($F_{(1,8)}$=1.21; p=.31; d=.13) and pupil velocity RMS was consistent from the first trial to the last (i.e., time) ($F_{(2,16)}$=0.44; p=.65; d=.05).

3.1.2. Horizontal Pupil Velocity RMS (pixels/s)

Similar to the vertical pupil velocity, the horizontal pupil velocity RMS (in pixels/s) was calculated to determine the velocity that participants' eyes moved horizontally (i.e., scanning between right and left foot placements), the results revealed that there was no significant effect of segment number on condition ($F_{(3,24)}$=1.14; p= .35; d=.13); no significant interaction of condition and time ($F_{(6,48)}$=1.82; p= .13; d=.19); no significant interaction of segment and time ($F_{(2,16)}$=.90; p= .46; d=.10); and no significant interaction condition and segment and time ($F_{(6,48)}$=1.95; p= .09; d=.20).

As for main effects, the analysis revealed that Segment 1 was not different from Segment 2 ($F_{(1,8)}$=.50; p= .50; d=.06) nor was the first trial significantly different from the middle or last trial (i.e., time) ($F_{(2,16)}$=1.37; p= .28; d=.15). However, there was a significant main effect of condition ($F_{(3,24)}$=4.40; p= .03; d=.36). Post hoc analysis revealed that the mean horizontal velocity RMS of both the right and left foot starts during the unconstrained trials ($\bar{x}_{Runconstrained}$=2695.53 pixels/s, SD=476.31; $\bar{x}_{Lunconstrained}$=2826.66 pixels/s, SD=835.59) were greater than that of the velocity RMS of right and left foot starts for constrained trials ($\bar{x}_{Rconstrained}$=2012.46 pixels/s, SD=451.31; $\bar{x}_{Lconstrained}$=1925.25 pixels/s, SD=255.80) (refer to Figure 13).

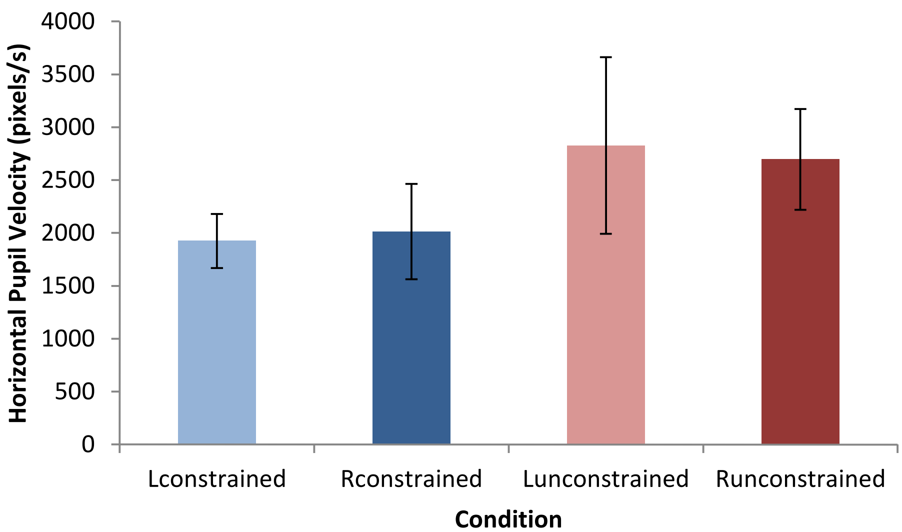


Figure 13- The results from the horizontal pupil velocity RMS revealed that the constrained trials (left and right start) were significantly greater than the unconstrained trials ($F_{(3,24)}$=4.40; p= .03; d=.36).

3.1.3. Number and Duration of Gaze Fixations

The total number of fixations (i.e., gaze remained fixed for >100ms) and the mean duration of each fixation for each trial for all participants were recorded via the ASL H7-HS

High Speed Head Mounted Optics eye tracking unit. The number of fixations and the duration of fixations were separated based on condition (i.e. constrained and unconstrained).

On average, the participants performed more gaze fixations during the unconstrained trials ($\bar{x}_{unconstrained}$=31.65; SD=16.25) than during the constrained trials ($\bar{x}_{constrained}$=30.26; SD=17.95). However, the mean number of fixations did not show a significant conditional effect ($t_{(53)}$=0.65, p=0.52) and thus, we can conclude that there was not a significant difference in the number of fixations between conditions and participants.

On average, the participants performed a similarly with respect to gaze fixation duration during unconstrained trials ($\bar{x}_{unconstrained}$=0.16s; SD=0.017) when compared constrained trials ($\bar{x}_{constrained}$=0.16s; SD=0.021). Therefore, the mean duration of fixations did not reveal a significant conditional effect ($t_{(53)}$=-0.61s, p=0.54) and thus, we can conclude that there was not a significant difference in the duration of fixations between conditions and participants.

3.1.4. Approximate Fixation Location: A Representative Participant

One participant was randomly selected to represent the participant group in order to suggest the approximate fixation location during constrained and unconstrained trials. A frame-by-frame analysis was performed and fixations were categorized based on condition and steps away from the individual (i.e. one, two, or three steps away).

There was a significant association between the condition and the location of fixation being one, two, or three steps away from the individual $x^2_{(2)}$=1362.64, p<0.001. This seems to suggest that a conditional effect is present based on approximate location of the gaze during constrained and unconstrained trials.

3.2. Kinematic

3.2.1 Average Walking Speed (cm/s)

The analysis for average walking speed revealed that there were no significant interactions found: there was not a significant interaction of condition and time ($F_{(6,48)}$=2.24; p=0.06; d=.22); there was not a significant interaction of condition and segment ($F_{(3,24)}$=0.34; p=0.80; d=.04); there was not a significant interaction of time and segment ($F_{(2,16)}$=4.33; p=0.07; d=.35); nor was there a significant interaction of condition and time and segment ($F_{(6,48)}$=1.38; p=0.28; d=.15).

However, there was a main effect of condition ($F_{(3,24)}$=23.27; p=0.04; d=.30). Post hoc analysis revealed that the average walking speeds of both right and left foot starts during the constrained trials ($\bar{x}_{Rconstrained}$=80.51 cm/s, SD=5.45; $\bar{x}_{Lconstrained}$=81.98 cm/s, SD=4.53) were greater than that of the average walking speeds of right and left foot starts for unconstrained trials ($\bar{x}_{Runconstrained}$=69.71 cm/s, SD=4.60; $\bar{x}_{Lunconstrained}$=67.48 cm/s, SD=4.16) (Figure 14).

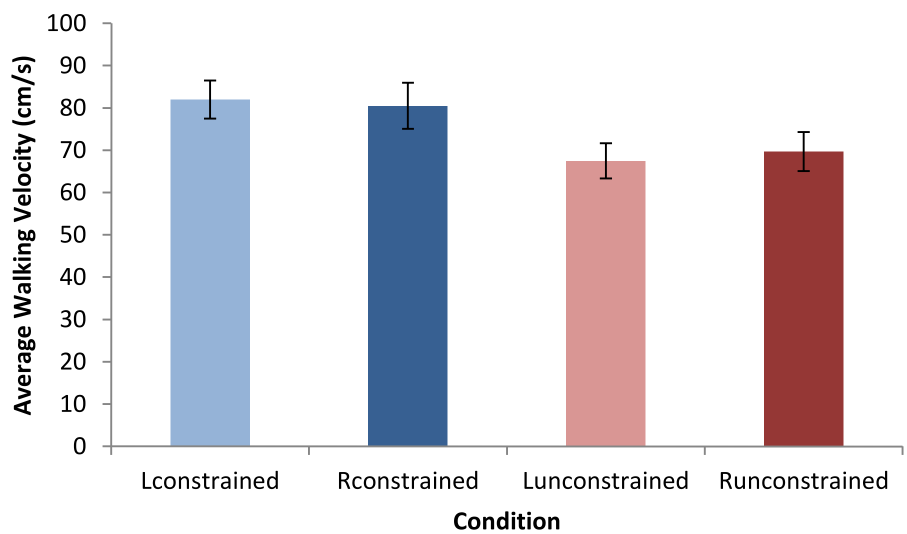


Figure 14- The results revealed that average walking speed during the constrained conditions (left and right foot starts) were significantly faster than the unconstrained conditions ($F_{(3,24)}$=4.40; p= .03; d=.36).

Additionally, there was a main effect of time ($F_{(2,16)}$=23.27; p< .001; d=.74). Post hoc analysis revealed that the first trial ($\bar{x}_{time1}$=66.16 cm/s, SD=5.62) and the middle trial ($\bar{x}_{time2}$=74.09 cm/s , SD=4.39) were significantly slower than that of the mean walking speed of the last trial ($\bar{x}_{time3}$=90.51 cm/s , SD=3.96) (refer to Figure 15). Furthermore, average walking speed was not different during Segment 1 ($\bar{x}_{segment1}$=75.96 cm/s, SD=4.66) as compared to Segment 2 ($\bar{x}_{segment2}$=77.88 cm/s, SD=3.88).

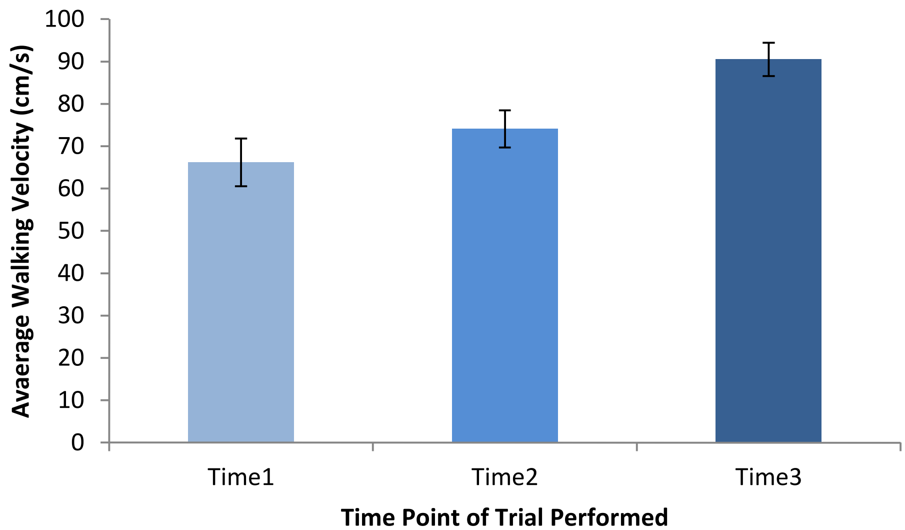


Figure 15- Average walking speed was significantly affected by the trial number (time) ($F_{(2,16)}$=23.27; p<0.001; d=.74) such that the first (Time1) and middle (Time2) trials were significantly slower than the last trial (Time 3) completed.

3.2.2 Medial-Lateral Centre of Mass Variability (cm)

The analysis of the ML COMvar was calculated to determine the participants' medial-lateral linear stability during the trials. The results did not reveal any significant interactions: there was no significant interaction of segment and condition ($F_{(3,24)}$=.82; p= .50; d=.09); there was no significant interaction of condition and time ($F_{(6,48)}$=.67; p= .67; d=.08); there was no significant interaction of segment and time ($F_{(2,16)}$=1.19; p= .33; d=.13); and no significant interaction condition and segment and time ($F_{(6,48)}$=.78; p= .59; d=.09).

Additionally, there was no significant main effects observed: there was not a significant main of condition ($F_{(3,24)}$=.45; p= .72; d=.05); there was not a significant main effect of segment ($F_{(1,8)}$=1.12; p= .32; d=.12); nor was there a significant main effect of time ($F_{(2,16)}$=1.39; p= .28; d=.15).

3.2.3 Trunk Roll (degrees)

The analysis of the trunk roll was calculated to determine whether or not the walking conditions produced different levels of sagittal angular trunk control. A paired-samples t test was performed to determine whether mean trunk roll was significantly different between the two conditions; we fail to reject the null ($t_{(constrained)}$=0.42; p=0.34) and conclude that mean trunk roll during constrained trials ($\bar{x}_{constrained}$=6.84°) was not significantly different than the mean trunk roll of the unconstrained trials ($\bar{x}_{unconstrained}$=9.42°).

RMS of trunk roll was analyzed to assess trunk variability about the mean. There were no significant interactions: there was no significant interaction of segment and condition ($F_{(3,18)}$=.34; p= .80; d=.05); there was no significant interaction of condition and time ($F_{(6,36)}$=1.00; p= .44; d=.14); there was no significant interaction of segment and time ($F_{(2,12)}$=1.70; p= .22; d=.22); and no significant interaction condition and segment and time ($F_{(6,36)}$=1.25; p= .30; d=.18).

Additionally, trunk roll angles were not significantly affected by trial number ($F_{(2,12)}$=1.10; p=0.37; d=.16) nor segment number ($F_{(1,6)}$=1.32; p=0.29; d=.18). However, trunk roll angle was significantly affected by condition ($F_{(3,21)}$=4.84; p=0.01; d=.45). Post hoc analysis revealed that the mean trunk roll of both the right and left foot starts during the unconstrained trials ($\bar{x}_{Runconstrained}$=9.71°, SD=1.15; $\bar{x}_{Lunconstrained}$=9.26°, SD=.88) were greater than that of the mean trunk roll of right and left foot starts for constrained trials ($\bar{x}_{Rconstrained}$=7.34°, SD=.59; $\bar{x}_{Lconstrained}$=7.02°, SD=.73) (refer to Figure 16).

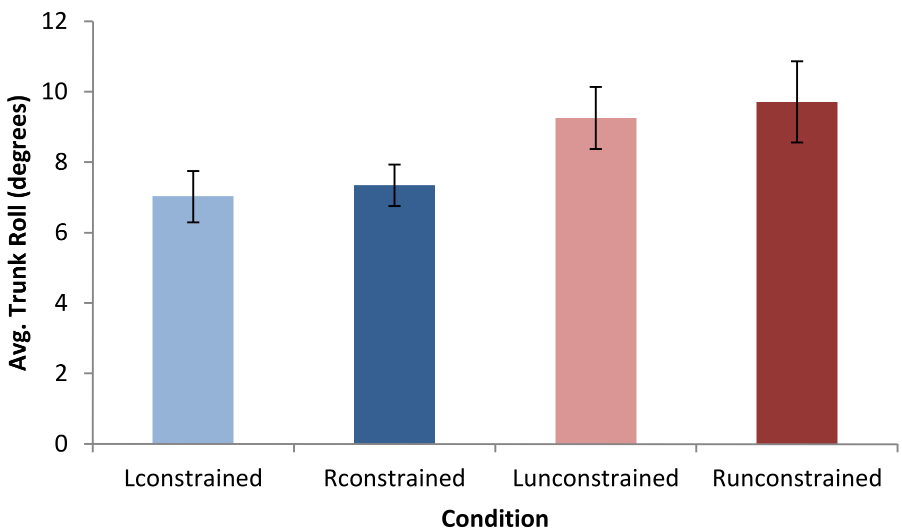


Figure 16- The results revealed that mean trunk roll angle was significantly affected by condition ($F_{(3,21)}$=4.84; p=0.01; d=.45), such that the constrained trials (left and right start) were significantly greater than the unconstrained trials.

3.2.4 Trunk Pitch (degrees)

The analysis of the trunk pitch was calculated to determine whether or not the walking conditions produced different levels of frontal angular trunk control. A paired-samples t test was performed to determine whether mean trunk pitch was significantly different between the two conditions; we fail to reject the null ($t_{(constrained)}$=0.73; p=0.24) and conclude that mean trunk pitch during constrained trials ($\bar{x}_{constrained}$=-28.77°) was not significantly different than the mean trunk roll of the unconstrained trials ($\bar{x}_{unconstrained}$=-29.16°).

RMS of trunk roll was analyzed to assess trunk variability about the mean. There were no significant interactions: there was no significant interaction of segment and condition ($F_{(3,18)}$=.88;

p= .47; d=.13); there was no significant interaction of condition and time ($F_{(6,36)}$=1.13; p= .37; d=.16); there was no significant interaction of segment and time ($F_{(2,12)}$=.81; p= .47; d=.120); and no significant interaction condition and segment and time ($F_{(6,36)}$=1.45; p= .22; d=.20).

Additionally, trunk pitch angles were not significantly affected by condition ($F_{(3,18)}$=.94; p= .44; d=.14); time ($F_{(2,12)}$=1.49; p= .27; d=.20); nor segment number ($F_{(1,6)}$=2.26; p= .18; d=.27).

3.2.5 Trunk-Head Control

The analysis of trunk-head pitch was calculated to determine if the head and trunk were independently controlled. The results did not reveal a significant interactions of condition and segment ($F_{(3,24)}$=0.95; p= .43; d=.11); condition and time ($F_{(6,48)}$=1.65; p= .15; d=.17); nor segment and time ($F_{(2,16)}$=.81; p=0.46; d=.09). As well, there was no significant interaction effect of condition and time and segment ($F_{(6,48)}$=.90; p= .50; d=.10).

Additionally, there was no main effect of trunk-head pitch to report. Trunk-head pitch was not affected by segment number ($F_{(1,8)}$=1.55; p= .25; d=.16); nor did it change from the first trial to the last ($F_{(2,16)}$=.42; p= .66; d=.05). As well, the trunk-head pitch was not different between the constrained and unconstrained trials ($F_{(3,24)}$=.18; p= .91; d=.02).

3.2.6 Dynamic Stability Margin minimum (cm)

The analysis of the DSMmin is an indication of one's stability during single support. The results did not reveal any significant interactions, such that stability during left single support and right single support were not affected by condition ($F_{(3,24)}$=1.15; p= .35; d=.14) nor trial number (i.e., foot by time) ($F_{(2,14)}$=.68; p= .52; d=.09). Also, the type of condition was not affected by trial number (condition by time) ($F_{(6,42)}$=2.01; p= .09; d=.22). No significant interaction was observed between condition and foot in single support and trial number ($F_{(6,42)}$=.63; p= .71; d=.08).

However, DSMmin was affected solely by the type of condition ($F_{(3,21)}$=4.89; p= .01; d=.41). Post hoc analysis revealed that the mean DSMmin of both the right and left foot starts during the unconstrained trials ($\bar{x}_{Runconstrained}$=9.67cm, SD=.44; $\bar{x}_{Lunconstrained}$=9.40cm, SD=.59) was greater than that of the DSMmin of right and left foot starts for constrained trials ($\bar{x}_{Rconstrained}$=6.30cm, SD=.53; $\bar{x}_{Lconstrained}$=6.09cm, SD=.49) (refer to Figure 17).

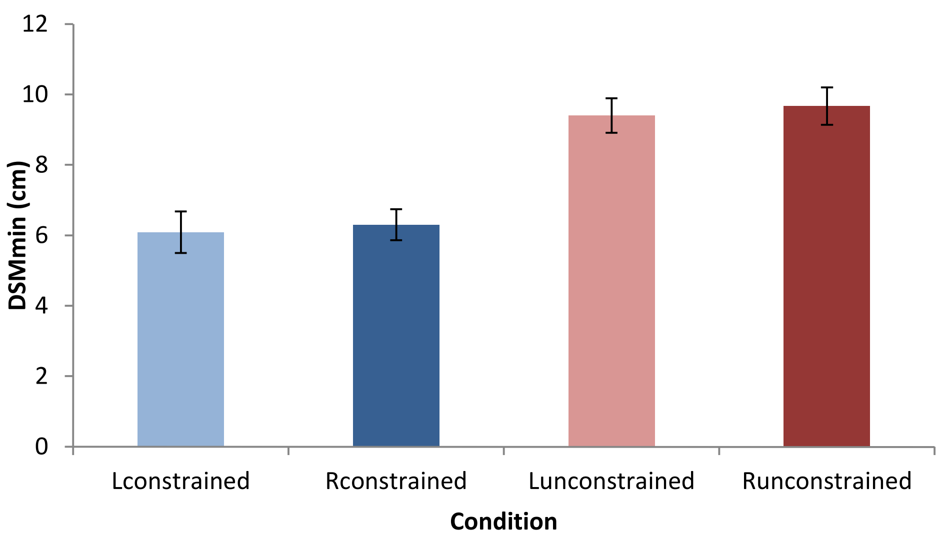


Figure 17- The results revealed that mean DSMmin during the constrained conditions (left and right foot starts) were significantly greater than the unconstrained conditions ($F_{(3,21)}$=4.885; p= .01; d=.411).

Additionally, there was a main effect of trial number ($F_{(2,14)}$=7.85; p= .01; d=.53). Post hoc analysis revealed that the first trial ($\bar{x}_{time1}$=10.31cm, SD=.74) was significantly greater than the last trial completed ($\bar{x}_{time3}$=5.69cm, SD=1.16). However, the DSMmin for the middle trial completed ($\bar{x}_{time2}$=7.97cm, SD=.36) was not significantly different than that of the DSMmin of the first trial (refer to Figure 18).

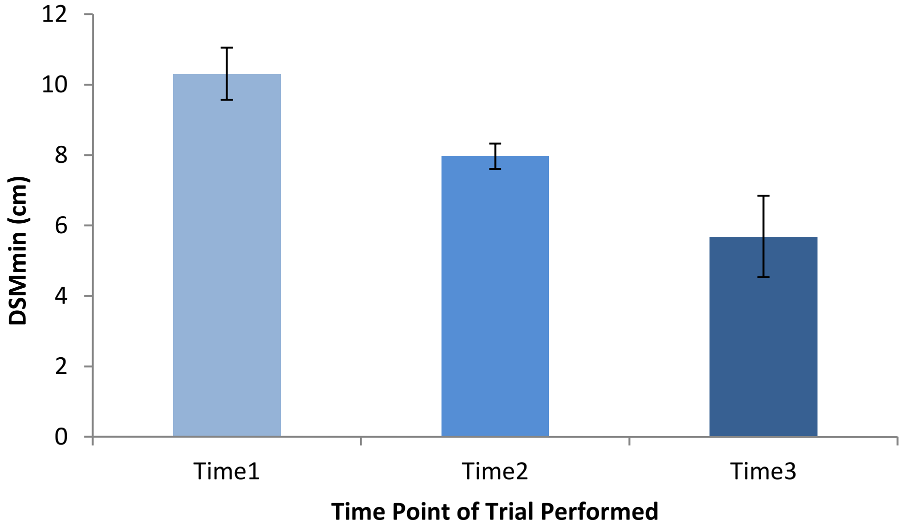


Figure 18- The DSMmin was significantly affected by trial number ($F_{(2,14)}$=7.85; p= .005; d=.53), such that the first trial (Time1) ($\bar{x}_{time1}$=10.31, SD=.74) was significantly greater than that of the mean DSMmin of the last trial ($\bar{x}_{time3}$=5.69, SD=1.16). The DSMmin of the middle trial (time point two) ($\bar{x}_{time2}$=7.97, SD=.36) did not significantly differ from either the DSMmin of the first of last trials.

And furthermore, there was a main effect of foot in single support ($F_{(1,7)}$=6.22; p= .04; d=.47), such that when the left foot was in single support the average DSMmin ($\bar{x}_{Lfoot}$=9.09, SD=.61) was greater than when the right foot was in single support ($\bar{x}_{Lfoot}$=6.89, SD=.68) (refer to Figure 19).

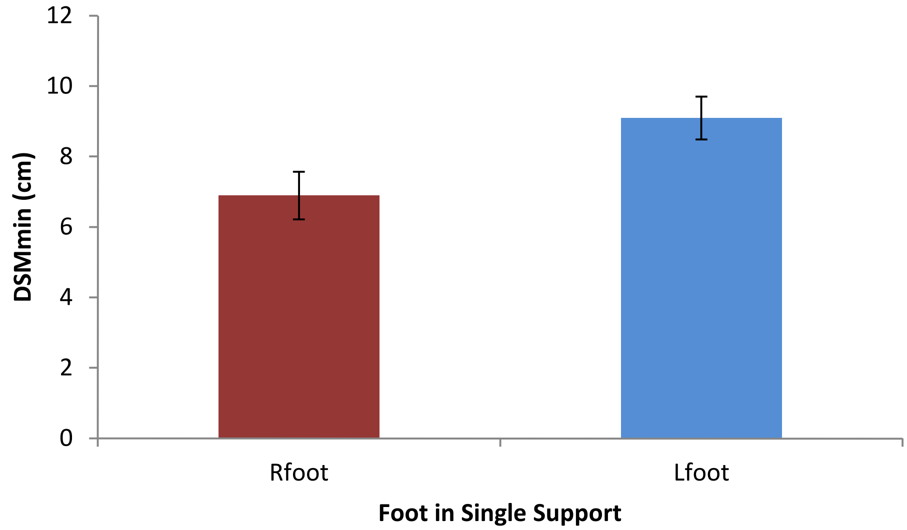


Figure 19- The DSMmin when the left foot ($\bar{x}_{Lfoot}$=9.09, SD=.61) was in single support during the first set of predetermined foot positions was significantly greater than when the right foot ($\bar{x}_{Lfoot}$=6.89, SD=.68) was in single support ($F_{(1,7)}$=6.22; p= .041; d=.471).

4.0 DISCUSSION

The purpose of this study was to examine the effect of a complex navigational stone stepping task on HAT segment control. It was hypothesized that the conditional demands of the task would produce gaze and kinematic behaviours which were dependent on whether or not the participants' path was constrained or not and these differences in behaviours would be the result of a means to maintain upright postural control. In order to determine whether this was true or not, the primary objective of the current study was to understand possible relationships between gaze and kinematic behaviours across all participants.

The visual system is the only sensory system which is capable of gathering information at a distance while integrating information from other sensory systems to coordinate whole-body movements. Thus, researchers measure behaviours produced and strategies exhibited to begin to understand the role that the visual system has on the control of locomotion. In the current study, gaze behaviours were separated into vertical and horizontal pupil movements to quantitatively analyze observable real-time strategies.

4.1. Visual Control of Whole-Body Kinematics

Results from the current study did not show any differences in gaze fixation duration and frequency, meaning that the two conditions did not require individuals to perform different gaze behaviours with respect to the number of fixations and the duration of fixations. From a quiet eye perspective, Vickers (2007) suggests that the quiet eye (i.e. final fixation prior to action) stems from processing abilities of the individual such that an inverse relationship between number of fixations and duration of fixations forms: as processing abilities increase, so too does the duration of fixations while the number of fixations decrease. However, the results indicate no such differences are present, which may suggest that the two conditions of individuals navigated essentially placed the same cognitive load on the individuals. One proposed theory is that with no difference in the number of fixations or duration of fixations between conditions, it is possible that both had equal number of task relevant items [Vickers, 1992]. However, it is possible that the participants gathered visual information differently between the two conditions.

As an insight into where individuals were gathering information about task relevant items during both tasks, a representative participant was selected to understand where participants were looking and gathering information about the environment. In order to do so, a frame-by-frame analysis was performed to begin to understand where fixations were located with respect to the participant's location. As the results demonstrate, there were differences in the general location of fixation between the two conditions, suggesting that during unconstrained trials more fixations were approximately two steps ahead whereas during constrained trials the fixation location was roughly split between one and two steps ahead. If this was the case, a difference in fixation location would make sense as the two conditions require the individual to perform two different gaze behaviours—scanning versus sampling. During scanning, the individual looks ahead to predetermined footholds as a means of planning and scans back to guide foot placement. Conversely, during sampling, the individual is searching for the ideal foothold. These two proposed gaze behaviours are possible if in fact fixation location is a factor, providing some insight in where the approximate fixation location may be. Moving forward, research should direct attention to pinpoint the exact location of gaze to fully understand how individuals are using pertinent information.

In order to be able to characterize observable eye movements, it is suggested to separate pupil/eye movements into vertical and horizontal components to gain an understanding of how eye/pupil movements influence the rest of the body [Rottach *et al*, 1996]. This type of analysis is possible through an Eye-Head Integration (EHI) technique that combines visual data from the Eye Tracker program and kinematic data with respect to head and body movements in space. However, EHI could not be setup and calibrated properly for the current study and so the discussion will focus on visual control strategies of the one representative participant and how fixations relate to whole-body control. The first fixation behaviour was characterized within the vertical plane. During real-time gaze behaviour analysis, an observable gaze strategy borrowed elements of travel fixation and footprint fixation strategies, specifically during constrained navigation trials. As indicated, fixation appeared to be approximately one or two footholds away from the individual before shifting gaze to a more imminent foothold, guiding foot placement; then, gaze was redirected back to predetermined footholds that were approximately two steps away. As demonstrated in the Figure 13, fixation location was roughly even between one and two steps away; fixations two steps away were greater in proportion to scan upcoming footholds.

One possible suggestion for this particular fixation location behaviour could be to scan future footholds, quickly gather information about the foothold and return gaze to more local footholds in order to accurately guide foot placement. This scanning type of gaze behaviour was similar to that observed in a study by Hollands et al. (1995) in which participants were asked to step on specific footholds and occurred predominantly in the vertical (with respect to the scene) direction. And by doing so, it could be argued that the reason why there is almost an even split in the proportion of fixations two steps away versus one step away could be this alternation between future footholds and local footholds. By scanning ahead two steps and returning back to a foothold that is one step away, environmental cues can be assessed and taken into account when following the predetermined path (i.e. constrained condition). However, with that said, it should be noted that fixations two steps away were slightly more predominant than fixations one step away. This could be as a result of scanning further ahead to plan and prepare for upcoming foot placements in addition to controlling trunk rotations.

As a means to quantify these visual control strategy observations in the vertical direction, the root mean square (RMS) of vertical pupil velocity was analyzed. As the results indicate, there was a greater mean vertical velocity RMS of both right and left foot starts for constrained trials in comparison to unconstrained trials (Figure 13). The greater vertical velocity RMS is consistent with the sampling behaviours observed from the one participant and is in line with the conditional demands of navigating a predetermined pathway, stepping only on the superior surfaces of indicated stones in succession.

When the stability of the individual was not challenged, as in previous flat ground target stepping (Hollands et al., 1995; Patla & Vickers, 2003), gaze behaviours would quickly move from one foothold to the next to control foot placement in an online fashion. However, when stability was challenged—as in the current study—it seemed as though possible observable gaze strategies emerged as a way to ensure stability, guiding foot placement. In order to do so, participants from the current study tended to fixate to the next immediate foothold before moving fixation to future footholds on the path. It is possible that alternating between immediate and further footholds (i.e., scanning) was performed to ensure greater trunk control in an anticipatory manner. Anticipatory postural adjustments (APAs) have been documented as a term to describe postural changes associated with shifts in COP that are observed prior to the initiation of voluntary movement [Massion, 1992]. APAs are strategies used to counteract perturbations that affect balance and stability, typically associated with the goal to minimize displacement of COP [Bouisset & Zattara, 1987].

One suggestion as to why individuals performed a scanning strategy was to plan and prepare the body for upcoming anticipated perturbations. By doing so, the individual can scan two steps ahead while returning fixation in order to modulate foot placement at more immediate footholds based on dynamic stability at that instant. This particular strategy is demonstrated as a means to maintain upright postural control during locomotion. Moreover, Winter (1991; 1995) suggested that movements about the hip are the predominant control mechanism to counteract perturbations. And with the HAT segment comprising approximately 70% of total body mass, it can be argued that trunk control is the main mechanism of postural control.

As the results from the current study demonstrate, trunk roll RMS revealed a significant, but moderate difference in magnitude of roll between the conditions. Trunk roll was greater during the unconstrained trials than during the constrained trials (refer to Figure 16). One proposed theory is that that the vertical scanning behaviours of the participants between one and two steps away—primarily during the constrained trials—provides insights into the manner in which participants used vision to assist in controlling trunk rotations better (i.e., lower trunk roll). This theory arises from work conducted by MacLellan and Patla (2006) who suggested that a tighter regulation (e.g. less movement about the hips) in the trunk could argue better trunk control. This moderate difference in trunk roll between the two conditions could be the result of the participants having to step on predetermined footholds along the pathway versus choosing where to place their feet. Future foot placement selection is based on arriving at one's desired location and one's current state of stability (Warren, 2007). Therefore, participants in the current study most likely had larger trunk roll angles during the unconstrained pathway because they had the freedom to select where to place their feet and foot placement was in response to this increased trunk rotation, whereas during the constrained pathway foot placement was predetermined and therefore participants had to control trunk rotations in order to accomplish proper foot placements. Similarly, Patla and colleagues (1999) suggested that this whole body stabilization formulates in a top-down fashion, stabilizing the head to stabilize gaze; the trunk is free move about the hips. This demonstrates the role of head stabilization and trunk movement as a means to stabilize gaze while propelling the body forward.

With this idea of head stabilization and free trunk movement, the current study assessed head and trunk movements to determine if similar segmental control strategies were present. Head and trunk control were assessed by subtracted head pitch (RMS angle) from trunk roll (RMS angle) to provide further insight into identifying which segment had great movement within the sagittal plane. Values greater than zero indicated that the level of segmental control was predominantly controlled via the trunk; any values less than zero indicated that the level of segmental control was predominantly controlled via the head. The results of this study did not reveal any significant differences in trunk-head values between conditions, segments, or time points. However, all reported mean values were greater than zero, suggesting that there were greater amounts of movement within the trunk. This finding could be attributed to the possible stabilization of the head and gaze in space in order to better select appropriate footholds. By stabilizing the head and gaze, it can be suggested that the individual is able to accurately fixate on possible foothold locations and guide foot placement more successfully.

The inverted pendulum model is important to discuss as the HAT segment is a large mass that sits atop a balance point (e.g. the hips), rotating about that point. Winter (1995) suggested that the trunk fluctuated ±1° over the course of a stride. However, due to the complex nature and uneven terrain of the current paradigm, it was observed that the trunk tended to rotate more than 7° across all conditions (refer to Figure 15). Moreover, Mathis and colleagues (2015; 2014;

2013) suggested that during a foot placement task similar to the current study, individuals gather visual information at a distance in order to exploit the biomechanical properties of this inverted pendulum. Thus, providing reasoning as to why individuals tend to perform certain visual control strategies. For instance, in a simple six-target navigation task, as in previous studies, travel fixation behaviour (i.e., gathering information two steps ahead) was the dominant gaze behaviour performed. Therefore, as a result of a need to step on particular footholds during constrained trials, individuals need to tightly regulate postural control of the trunk in order to conform to the unnatural footfalls of the predetermined path. By doing so, angular trunk movements in the AP direction were reduced as the individual needed to scan ahead in order to prepare for future footholds.

And this makes sense when looking at the average walking speed. The results show that there was a conditional effect of walking speed, suggesting that individuals tended to walk faster during the constrained condition opposed to the unconstrained condition. From the previous findings we see that individuals tend to fixate roughly two steps ahead roughly and scan back while preparing their trunk for the next preplanned step. In order to do so, it is suggested that individuals typically walk at a greater speed to successfully place their foot on the targeted foothold. However, previous research suggests that walking speed is not a controlling factor rather than a supporting one in the sense of controlling whole-body stability [Mohler, Thompson, & Warren, 2007].

The second fixation behaviour was characterized within the horizontal plane. During real-time gaze behaviour analysis, an observable gaze strategy borrowed some elements of travel fixation at approximately two steps away. However, this particular strategy was observed predominantly during the unconstrained conditions where the individual had the freedom to choose her own path. As the individual traversed the pathway, the gaze tended to shift horizontally, from one stone to the next as if the individual was sampling possible footholds. As the results indicate, there was an overall greater mean horizontal velocity RMS across all participants for unconstrained trials in comparison to constrained trials. The difference in RMS velocity in the horizontal direction along with the individual participant's frame by frame analysis provides some evidence that during the unconstrained conditions individuals were more likely to adopt a visual sampling strategy to locate possible footholds.

Travel fixation and footprint fixation strategies are considered visual control strategies for locomotion, however visual sampling is not thought to provide the same amount of control as evidenced in greater trunk roll RMS during the unconstrained condition (Figure 13) [Hollands, Patla & Vickers, 2002; Patla, 1997; Patla & Vickers, 2003]. In fact, it seemed as though (from the one participant's frame by frame analysis) visual sampling was used not to fixate on successive future footholds, but rather more immediate potential footholds as a collective. One possible reason as to why individuals typically performed this scanning behaviour during the unconstrained conditions was to quickly assess their options of potential footholds to gauge their upcoming step under a possible hierarchical scheme. For instance, if an individual is on stone A and about to step on stone B—while sampling the stones around stone B- he or she could determine other possible options in the event the individual needs to opt-out of stepping on stone B during mid-swing in order to regain balance and step on another nearby stone that would increase his or her stability. To regain stability, the individual could do one of two things: 1) step long as a means to increase their BOS, placing their foot along the plane of progression [Moraes, Allard, & Patla, 2007]; or 2) step laterally to widen BOS to regain stability more effectively [Hak et al., 2012]. Therefore, unlike the constrained trials, it seems as though sampling behaviour promotes more of a local, step-by-step scene survey, performing online adjustments according to each step rather than using vision to plan and coordinate body movements ahead of time.

One proposed theory for this visual control strategy could be based upon the current state of stability. Since the sampling behaviour could be more of a ‘step-by-step’ control strategy, it makes sense that this is performed more often during unconstrained trials (i.e. participants choose their own path). As the results show, RMS trunk roll is significantly greater during unconstrained conditions (with a moderate effect size; Figure 16). This finding suggests that ML movement of the trunk was much more variable about the mean trunk position during the unconstrained trials where the individual was free to choose their own path. Thus, two arguments could be made with respect to greater trunk roll and foot placement: 1) individuals were able to choose their foot positions and in doing so they could have selected footholds to regain stability; 2) individuals could have chosen footholds that they thought would have been ideal but actually resulted in less stability which forced them to find a foothold to regain stability. On the other hand, there was no significant difference with respect to average trunk pitch and RMS trunk pitch between conditions. A possible reason as to why there was no difference in trunk pitch RMS between conditions could be that the participants tried to maintain similar trunk pitch movements between the two conditions in order to ensure overall stability. This is similar to findings by VanOoteghem and colleagues (2008), who found that during platform perturbations individuals try to minimize trunk movements in order to possibly stabilize gaze and maintain stability. The desire to control trunk pitch similarly across conditions is further supported through the analysis of walking velocities across the two conditions; average walking velocity was influenced by conditional demands yet trunk pitch was not. During the constrained trials, individuals were confined to a predetermined pathway where each step was critical with respect to the proper foot placement on each stone along the predetermined path. As a result, individuals walked at a much faster speed in order to place each foot on the predetermined stone and spend as little time on each of these footholds because they were not necessarily located ideally for proper control of stability. Therefore, better active regulation of the trunk in the AP direction, the body—specifically the trunk—is able to move freely while the head stabilizes in space [Winter, 1991]. This strategy becomes important when considering the visual control strategy used to sample the terrain and locate ideal footholds.

Furthermore, when assessing the control of the trunk from another perspective, the results showed that DSMmin significantly differed between conditions. During unconstrained trials, the DSMmin was greater than during the constrained trials; a greater DSMmin (i.e., COM is further from BOS outer limits) value suggests a greater measure of stability. This finding further supports the ideal that when free to choose, individuals will carefully select footholds that promote dynamic stability. Unfortunately, it is difficult to determine if this was the case for every step along the path because DSMmin was only calculated during the predetermined foot placements. Originally, the idea of two sets of predetermined foot placements offered a level of control to each trial as each participant was instructed to incorporate and step on the two sets of predetermined foot placements. With a condition that centralized around freedom of path selection, the predetermined foot placements were important to estimate the individual's DSMmin halfway through the path and at the end of the pathway for every trial. However, there were two main issues with regards to the setup/layout of the predetermined foot placements: 1) the length of the pathway inhibited data collection of foot markers near the second set of predetermined stones. With the path being 7.2m long and the Optotrak cameras only being able to accurately record marker information up to 6m away, the foot markers were not always visible by all cameras. That made it difficult to calculate the DSMmin at that end of the pathway; and 2) the first set of predetermined foot placements acted almost as a reset for any instabilities incurred during the first half of the pathway. This was demonstrated by Figure 19 which showed that the first step (e.g. right foot) had a significantly lower DMSmin than the second step (e.g. left foot), which suggests that the individual's margin of stability was increased over that second step. However, it is believed that the first step did serve as a good indication of the participants' dynamic stability prior to that point in time. Thus, similar to the findings of Glize and Laurent (1997), any cumulative instability accumulated during the first part of the trial was observed in the first step (i.e., right foot) but reset by the second predetermined step (i.e., left foot).

Even though this study did shed light into some interesting findings, given the chance to redesign/make modifications to the paradigm, the first aspect to alter would be the predetermined foot placements; more specifically, the location and the options around the predetermined foot placements. The current paradigm arranged the predetermined foot placements to be at an average step length and width (e.g. 60cm long and 10cm wide) with no other options/distractors. Each participant was given the instructions to always incorporate those stones into their pathway, stepping with the right foot first followed by the left. The purpose of the DSMmin measurement was to assess each participant's margin of stability during each trial and determine how conditions may influence the DSMmin of the individual. For this study, the analysis time window for DSM was measured at the first set of predetermined footholds as means to consistently estimate each participant's DSM every trial—during unconstrained trials, the participant was free to choose their own path which would make it difficult to assess DSM at a certain point for every trial, across every participant.

However, an improvement to this design would incorporate the predetermined foot placements into the path without necessarily pointing out key footholds so that all participants would approach each potential footfall location as the same. The constrained pathway would be easy to modify—more rock climbing holds would have to be fastened down and the pathway would incorporate the two predetermined foot placements. The issue arises when looking at the unconstrained condition: with the freedom to choose any sequence, it may be difficult to find a particular foothold that is consistent across all trials. As their current state of stability may change from one foothold to the next, participants may select various pathways, making it difficult to compare their DSMmin at particular location on the pathway.

5.0 CONCLUSION

The current experiment combined visual and kinematic data to determine the effects of a complex navigational task on the segmental control of the HAT segment. The results demonstrated a conditional effect across most variables, suggesting that individuals treated the two types of conditions differently.

During the constrained trials, observable gaze behaviour was decipherable as eye movements seemed to concentrate on vertical movement more than horizontal. It was found that there was a greater vertical velocity during constrained trials, leading to the classification of eye movements to be referred to a scanning behaviour. Scanning promoted fixating on the pathway two steps ahead, gathering visual information, and returning gaze fixation to more immediate footholds before fixating ahead once again. This strategy was performed during the constrained trials as the pathway was already determined: all the individual had to do was locate future footholds and use visual information to guide successful foot placement.

Furthermore, it was discussed that scanning behaviour was a byproduct of trunk control during the constrained pathway trials. Using visual information from two steps ahead, the individual would have time to plan and prepare the body for upcoming footholds. As a result, there was dampened angular movement about the trunk in the AP direction when compared to unconstrained trials. This was in effort to tightly regulate postural control of the trunk as a means stabilize head/gaze.

During unconstrained trials, observable gaze behaviour was decipherable as eye movements seemed to concentrate on horizontal movement more than vertical. It was found that there was a greater horizontal velocity during unconstrained trials, leading to the classification of eye movements to be referred to a sampling behaviour. Sampling promoted the surveying of the environment over a cluster of possible footholds, rather than a specific one. While sampling, it could be suggested that the individual was able to quickly distinguish desirable from undesirable footholds, taking into account the physical features and location of the stone. However, it could be argued that the current state of postural control was held as a higher priority. This was supported by the findings of greater angular trunk movement in the AP direction—during unconstrained trials—that suggests that the freedom of path selection enabled individuals to navigate on a step-by-step basis.

Therefore, with conditional demands influencing whole-body kinematics and visual behaviours, the argument for what individuals do and why can synthesize down to a need versus a want. During constrained trials, individuals need to step on a particular stone in sequence and in order to do so, they need to regulate trunk movement and control their stability to a greater degree. On the contrary, during unconstrained trials, individuals step to the location where they want to, based on their current state of postural control.

The current study provided insight into the segmental postural control during a complex target-foot placement task. This project provides some understanding of what people are doing to control their body during a complex task and sheds some light onto some visual control strategies used to navigate a complex terrain. By assessing whole-body kinematics and visual control, we get some insight into how the CNS organizes and coordinates movements to maintain postural control. Future studies could examine muscle activity of the lower limb and trunk to provide further insight into the regulation of control. More specifically, this would provide a further understanding of postural control as the trunk moves about the hips and the muscles involved with maintaining upright locomotion during a complex navigational task. Furthermore, this design could be applied to examine the importance of other sensory systems and how they contribute to whole-body movement control. Such methods could include removal of a particular sensory system or the manipulation of that particular system (e.g. affecting somatosensory information in the feet), as well as assessing the effects of age-related degenerative changes.

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