

**EXPLORING THE EFFECTS OF DYNAMIC VISUAL CUES DURING CONTINUOUS
SUPPORT SURFACE TRANSLATIONS ON PERCEIVED MOVEMENT AND
POSTURAL RESPONSES**

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Abstract

Maintaining upright stance is essential for humans to explore their environment and complete tasks necessary for survival. To maintain balance, there are complex interactions that take place between one's environment and their sensory systems which enables the appropriate motor response dependent on the demands of the task. Perception is a key aspect in this as correctly perceiving one's own movement may dictate the strategy one uses to maintain upright. While perceived movement has been studied, there is a lack of research on how one perceives their self-motion when visually perturbed during a dynamic balance task.

This study aimed to explore the effects of transient visual stimuli during continuous support surface translations on perceived movement and actual postural responses. Virtual reality (VR) was used to elicit visual perturbations with velocities of 0.5 m/s, 1 m/s or 1.5 m/s while the support surface was translating +/- 5cm at 0.1 Hz, 0.4 Hz and 0.9 Hz. Ground reaction forces were measured using a force plate on the translating platform and kinematics were collected using 3D motion capture. Perceived sway amplitude was tracked through a controller compatible with the VR head mounted display (HMD).

Postural responses, measured through amplitude of centre of pressure (COP) and trunk displacement, were significantly greater in anterior conditions. However, quotient amplitude measures increased in posterior conditions. Biomechanical constraints, threat-modulated behaviour and an increased conscious control of movement may explain these findings. Future work exploring the neural networks involved in perceived movement during dynamic balance with visual perturbations is needed.

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List of Abbreviations

AP – Anterior-Posterior

ANOVA – Analysis of Variance

ASIS - Anterior Superior Iliac Spine

BOS – Base of Support

C7 – Seventh Cervical Vertebra

CNS – Central Nervous System

COM – Centre of Mass

COP – Centre of Pressure

HMD – Head Mounted Display

LOS – Limit of Stability

ML – Medio-Lateral

MP – Mean Position

PSIS - Posterior Superior Iliac Spine

PL – Path Length

QMP – Quotient Mean Position

QPL – Quotient Path Length

QRMS – Quotient Root Mean Square

RDK – Random Dot Kinematogram

RMS - Root Mean Square

S1 – First Sacral Vertebra

T10 – Tenth Thoracic Vertebra

VEPR – Visually Evoked Postural Response

VR – Virtual Reality

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Chapter 1: Introduction

Maintaining upright stance is multifaceted and requires the integration of the environment and one's sensory systems. As well, the perception of one's self-motion is essential for choosing the correct postural strategy to maintain upright stance. The relationship between one's perception of their self-motion and their actual postural responses during a dynamic balance task while manipulating vision is currently unexplored. Exploring these mechanisms is crucial to understand the strategies one uses if their perceived movement and postural responses are incongruent when exposed to visual and mechanical perturbations. Chapter 1 of this thesis will provide a literature review of balance, the role of vision during dynamic balance, and perception. Chapter 2 will outline the methodology utilized to examine perceived movement and postural responses while being exposed to transient visual perturbations during a dynamic balance task. Chapter 3 outlines the findings of this study and Chapter 4 discussed the implications of these findings.

1.1 Balance

Maintaining balance is necessary for interacting with one's environment through routine behaviours that are essential for everyday life. Balance in humans can be defined functionally as a task-specific ability to maintain static or dynamic equilibrium (Knudson, 2007). In a static state, the centre of mass (COM) of the person must be within their base of support (BOS). COM can be defined as the weighted average of the body in space where the mass is equal in all directions and the BOS can be defined as the area of contact the person makes with the surface (Winter, 1995).

1.1.2 Maintaining Balance

Maintaining balance during a static task can be defined as the ability to maintain upright stance while the COM remains inside the BOS, while in a dynamic task, it can be defined as the ability to maintain upright stance while the BOS may change while weight is being shifted (Dunsky et al., 2017). In order to maintain balance, the centre of pressure (COP), defined as the net neuromuscular force that one generates, must work in accordance with the COM. This is represented in the inverted pendulum model, where COP acts as a controlling variable to COM. This can be expressed mathematically as the difference between the COP and COM signals are proportional to the horizontal acceleration of the COM (Winter, 1998). This model has been validated in various studies, such as Masani et al. (2007), which found that the difference between COP and COM was proportional to the horizontal acceleration of the COM in a quiet standing task in both young and elderly age groups, where the relationship was stronger in elderly age groups.

While the inverted pendulum model outlines the mechanics for maintaining balance, one must also adopt broader strategies in order to stay upright. These strategies can be classified under the term postural control, where there are compensatory responses, anticipatory responses, or a combination of both during either a fixed support or change-in-support response to reduce instability (Maki & McIlroy, 1997). A compensatory response can be described as a reactive postural response to an unpredicted perturbation while an anticipatory response is a planned postural response to a predicted perturbation (Pollock et al., 2000). A fixed support response can be understood as when the feet are in place and the BOS does not change, whereas a change-in-support response is when the BOS is altered through a movement such as a step or a grasp.

1.2 Dynamic Balance

Due to the complexity involved in maintaining balance, including change in support strategies and nonlinear multibody dynamics, defining dynamic balance is challenging (Neptune & Vistamehr, 2018). A commonly used definition of dynamic balance is the ability to maintain balance while the base of support is moving and weight is being shifted (Karimi & Solomondis, 2011). However, a more comprehensive definition may encompass any type of external perturbation that could potentially elicit instability, whether or not the BOS is moving, such as upper body or seated perturbations (McCrum et al., 2022). Various tilting and translating platforms have been used to study postural responses during dynamic balance tasks. Continuous support surface translations have been used to examine dynamic postural control, where postural responses can be reactive or anticipatory (Van Ootegham et al., 2008). It has been shown that a pseudorandom ternary sequence perturbation for the platform is more effective at inducing postural threat as the random perturbations prevent adaptations seen in continuous, sinusoidal perturbations (Peterka, 2002; Jilk et al., 2015). It has also been shown that postural responses may be affected by the type of perturbation, where postural responses to transient perturbations are greater in nonlinearity compared to continuous perturbations. (Maki & Ostrovski, 1993). Nonlinear postural responses are more complex and contribute to variability and adaptability of one's balance response (Kędziorek & Błażkiewicz, 2020). Potential causes of nonlinearity may be amplitude-related changes in postural strategy, such as the adoption of the hip strategy at greater perturbation amplitudes (Maki & Ostrovski, 1992). This highlights the potential differences between the postural responses to transient and continuous perturbations, where complex and detailed analyses are crucial for understanding its mechanisms and applications.

During dynamic balance tasks, two well-documented strategies include the ankle strategy and the hip strategy. The ankle strategy uses a distal to proximal pattern of activation where there is increased joint rotation around the ankles while the hip strategy shows a proximal to distal pattern of activation with increased rotation around the hip (Nashner & McCollum, 1985; Runge et al., 1999). Studies have shown that the strategies implemented by an individual change during dynamic balance tasks, where they start to introduce the “hip strategy” during unexpected perturbations while the “ankle strategy” is more prevalent during an unperturbed task (Blenkinsop et al., 2017). However, during different dynamic tasks, such as when the velocity of the perturbations is slower, there is evidence of a mixed strategy where both the ankle and the hip are utilized to maintain upright posture (Runge et al., 1999; Colobert et al., 2006). Accordingly, the literature suggests that during some perturbations within dynamic balance tasks, there is evidence of ankle or hip activation being more prominent, but they work cohesively to maintain upright posture depending on the task.

1.3 Visual, Vestibular and Somatosensory Systems

The visual, vestibular and somatosensory systems work together by creating a feedback system that allows one to maintain balance (Fitzpatrick & McCloskey, 1994). Within the visual system, photoreceptors convert light into a sensory input through a reaction in the retina that is carried to the optic nerve, a part of the central nervous system (CNS) that connects the eye to the brain (Stangor & Walinga, 2014). The vestibular system has two main sensory receptors: otolith organs and semicircular canals, where the otolith organs detect linear motion and semicircular canals detect angular motion (MacNeilage et al., 2010). It has been shown that the otolith organs operate in low frequencies (less than 0.5 Hz) to change head position during a postural

perturbation (Borger et al., 1999). Semicircular canals transfer limited information at low frequencies but encode angular head acceleration more efficiently between 0.5-1 Hz (Jamali et al., 2014). The somatosensory system has various receptors that sense stimuli, including cutaneous receptors, muscle spindles, mechanoreceptors and golgi tendon organs (Calvert et al., 2004). Cutaneous receptors detect touch, pressure, temperature or pain and send information through the spinothalamic tract and posterior column-medial lemniscus pathway to the somatosensory cortex where it can be processed (Daly et al., 2012). There are various types of mechanoreceptors which all transmit mechanical information to the CNS; to maintain balance, mechanoreceptors in the joint detect changes in joint rotation (Ergen & Ulkar, 2007). Muscle spindles are peripheral stretch receptors that detect changes in muscle length, where golgi tendon organs detect changes in muscle tension (Stein, 2017). When analyzing the sensory systems with respect to the frequency of a COP signal, it has been found that the visual system dominated frequencies of 0.01-0.1 Hz and the somatosensory system has been shown to operate at higher frequencies, around 0.5-1 Hz (Salsabili et al., 2013).

1.4 Role of Vision in Dynamic Balance

Within dynamic balance tasks, the visual system plays an important role in the maintenance of upright stance (Collings et al., 2015). When exposed to two dynamic balance tasks, the tandem walk and step up/over tests, it has been found that individuals with subnormal vision, either congenital or acquired, had significantly greater sway than individuals with normal vision (Tomomitsu et al., 2013). Jilk et al. (2015) have shown that when vision is removed while being exposed to a pseudorandom sequence of continuous support surface translations, maintaining postural control requires an increase in the magnitude of their postural responses.

Quantitatively, the root mean square (RMS) of the hip displacement and velocity significantly increased when vision was removed compared to the RMS of ankle displacement and velocity, suggesting the use of the hip strategy when vision is removed during dynamic balance (Jilk et al., 2015). This finding exemplifies that in the absence of vision, an individual's postural strategy may change in order to maintain upright stance in a dynamic balance task.

1.4.1 Optic Flow

Optic flow is defined as the pattern of motion that is generated from the objects and surfaces that project onto the retina and changes as the individual moves through their environment (Niehorster, 2021). Optic flow is essential for individuals to perceive their environment as well as their physical space in the environment, where one can use optic flow cues to estimate their direction of self-motion (heading) quickly and accurately (Lappe et al., 1999). This efficiency in perceiving direction of self-motion has been shown even when an individual experiences visual perturbations (Riddell et al., 2019).

1.5 Visual Perception

Perception can be defined as the processing of sensory information that begins as a physical or chemical stimulus which gets converted into a neural signal (Montemayor & Haladjian, 2017). Visual perception is the brain's ability to process a visual stimulus; the signal gets transformed within the retina, area V1 and extra-striate cortex among other cortical regions which creates an activation pattern (Braddick, 2001). Visual perception involves the collaboration of various cortical and subcortical regions to transform visual stimuli into meaningful representations. These representations influence behavior by integrating visual

information with other sensory inputs and cognitive processes, enabling appropriate motor responses relative to the environment. The ventral stream, extending from the primary visual cortex to the temporal lobe, is responsible for object recognition and categorization (Braddick, 2001). Along with the ventral pathway, the dorsal pathway is hypothesized to be important for spatial information and executing movements based on visual information (Goodale & Milner, 1992). Visual awareness tasks have shown that the dorsal pathway is less active than the ventral pathway in consciously perceiving visual stimuli (Zhan et al., 2018).

Studies suggest that visual perceptual abilities decline with age, specifically the ability to retain spatial frequency information, as well as size, motion, and symmetry processing (Faubert, 2002). To further understand how a lack of perceptual ability affects one's ability to maintain upright, visual perception can be manipulated in a lab-based setting, such as through virtual reality (VR).

1.6 Virtual Reality

VR has been used as a tool to create a virtual environment that can be manipulated in order to examine various types of research and clinical implications. It allows the researcher to create a standardized environment that is easily reproducible which promotes greater accuracy when examining the effects between subjects (Morel et al., 2015). A head-mounted display (HMD) allows the subject to become immersed in the virtual environment, where they perceive being physically present in a virtual world (Radianti et al., 2020). The implementation of VR for balance research and training has been validated in various studies ranging from healthy populations to clinical populations, such as those with Parkinson's Disease and Multiple

Sclerosis (Wang et al., 2019; Eftekharsadat et al., 2015). VR is useful for balance research in particular as it allows the researcher to manipulate the virtual environment to induce postural threat due to visual perturbations or sensory conflict (Morel et al., 2015).

1.7 Vection and Visually Evoked Postural Responses (VEPRs)

Vection can be defined as the illusion of self-motion when no actual movement has occurred where it can either be circular or linear. Circular vection can be defined as rotations within the pitch, yaw and roll plane and linear vection can be defined as translations away or towards the individual either in the anterior-posterior (AP) or mediolateral (ML) directions (Palmisano et al., 2015). Vection can create a sensory conflict between the systems where these conflicts, specifically within visual-vestibular interactions, can lead to visually induced motion sickness (Wright, 2009; Bos et al., 2008).

The intensity of vection has also been positively correlated with velocity, where higher velocities lead to stronger vection intensity (Brandt et al., 1973). Moreover, increased velocity increases the onset of perceived vection and perception of one's self-motion velocity (Riecke, 2010). While it has been shown that a visual stimulus angle as little as 7.5° induces vection; increasing the size of the stimulus also increases the intensity of the vection (Andersen & Braunstein, 1985; Berthoz et al., 1975).

When vection leads to a quantifiable movement, it is known as a visually evoked postural response (VEPR) (Meyer et al., 2013). It has been shown that VEPRs can occur around 600ms after the vection onset and the first postural response is in the same direction as the visual

stimulus followed by a corrective response in the opposite direction (Bronstein, 1986). When exposed to an unexpected visual stimulus, the onset for a head sway response was found to be around 300-400ms (Guerraz et al., 2001).

1.7.1 Vection Perception and VEPRs

It has been shown that VEPRs can occur within 1 second, while the perception of vection comes after (Berthoz et al., 1979). Tanahashi et al. (2007) proposed the hypothesis that while the mechanisms required for the processing of VEPRs and vection perception use the same signal, vection and VEPRs occur at different thresholds. Guerraz & Bronstein (2008) suggest that there is a complex interaction between vection and VEPRs where there are two different types of VEPRs that can occur: firstly, the short latency VEPR which is automatic and preconscious, and secondly, a long latency VEPR that occurs after the conscious perception of vection. It is suggested that transient visual stimuli promote the short latency VEPR mechanism (Guerraz & Bronstein, 2008). Research on the mechanisms of vection perception is significant, as depending on the type of visual stimuli, the postural responses may change, and thus different strategies may be adopted to maintain upright stance.

1.8 Perceived Movement

While the sensory systems work together to provide information used to perceive the environment, one also has to perceive their own movement to maintain stability (Britton & Arshad, 2019). The underlying mechanisms of one's perception of their own self-motion has proven to be complex and multifaceted, as corrective balance responses can occur at a

subconscious level (Luu et al., 2012). Perception of self-motion has been previously studied both on a neural and behavioural level.

1.8.1 Neural Contributions

During reactive tasks, the conscious perception of self-motion becomes imperative to maintain upright stance as the demands of the task are greater. Perception of self-motion has been shown to be variable across individuals (Punkattalee et al., 2016). This may be modulated by negative event-related potential (N1), a neural response that takes place 100-200ms after a perturbation localized in the supplementary motor area (SMA), possibly associated with the anterior cingulate cortex (ACC) activity (Marlin et al., 2014; Solis-Escalante et al., 2021). N1 responses have been shown to decrease with sensory stimulation, prior experience, and anticipation of a perturbation, possibly essential for the multisensory integration required in reactive balance control (Staines et al., 2001; Adkin et al., 2006; Payne & Ting, 2020). It is suggested that changes in N1 reflect flexibility in sensorimotor responses, specifically in preparation for perception and movement (Mirdamadi et al., 2023).

1.8.2 Postural Responses

A study encoded perturbations that were aimed to be indistinguishable from one's corrective balance responses, as the perturbations operated at amplitudes and velocities within the normal range of quiet standing, and participants were told to perceive any external perturbations they felt (Tisserand et al., 2022). This study found that after being exposed to some of these perturbations, the participants began to perceive their own corrective responses as external perturbations, suggesting that corrective balance responses occur at a subconscious

level, and one's perception of them can be manipulated (Tisserand et al., 2022). This is significant as the perception of self-motion may affect the characteristics of the corrective response an individual undergoes when perturbed.

At the conscious level, studies examining the effects of postural threat, induced by height, on perceived movement have shown that there is a disconnect between the amount that one perceives they are swaying compared to their objective sway amplitude (Cleworth & Carpenter, 2016). As well, when exposed to continuous, pseudo-random support surface translations at height, the amplitude of perceived sway significantly increases (Cleworth et al., 2019). However, the research in this area is limited to inducing postural threat by height and must be expanded to understand the effects of a dynamic balance task on perceived movement within various types of tasks.

1.9 Current Research Gap and Significance:

Postural responses have been assessed within a wide range of dynamic balance tasks. The relationship between perceived movement and postural responses has been explored previously. However, it has primarily been studied under static conditions or while inducing postural threat through height. There is limited research examining how an individual perceives their sway response during a dynamic balance task. Furthermore, there is a need to examine how the relationship between one's perceived movement and their actual movement is affected by transient visual perturbations within a dynamic balance task. It is important to develop the mechanistic knowledge of perception during dynamic balance as misperception of body position may lead to an increased fall risk.

1.10 Purpose

The purpose of this study was to assess the ability of an individual to perceive their sway during a dynamic balance task and to quantify their postural responses. Specifically, this study aimed to examine the effects of transient visual perturbations during continuous support surface translations on an individual's perceived movement and their postural responses. This will give us insight into how one perceives their own movement during a multisensory dynamic balance task and the relationship between their perception and their actual sway response.

1.11 Hypothesis

It is hypothesized that postural responses will increase as the velocity of the visual stimuli increases (Dokka et al., 2009). It is unclear how the participants will perceive this increase in postural response due to the interaction ofvection-related perceived movement and perceived movement to actual body displacement.

Chapter 2: Methods

2.1 Participants

Thirty healthy young adults between the ages of 18 and 40 (Mean age = 23.5 ± 1.76 years; 21 males, 9 females) were recruited from York University and the surrounding community. Four subjects were excluded due to technical issues during the collection. The exclusion criteria were any known balance, neurological, or musculoskeletal impairments that may have affected their ability to complete the tasks. All participants provided written informed consent approved by the York University Research Ethics Board.

2.2 Experimental Design

The VIVE Pro 2 (HTC Canada) HMD was used to display the virtual environment, which was developed using the program, Vizard (Worldviz, USA). A VIVE controller (HTC Canada) was used to track the participant's subjective body position in space. Forty reflective markers were placed on the subject to track objective movement where it was visualized and processed in the VICON Nexus 2 software (VICON, USA). Eight cameras were placed around the room where they captured motion from the reflective light of the markers. Participants stood on a force plate (AMTI, USA) which measured the ground reaction forces on the translating platform with their feet shoulder-width apart and hands by their side. Their foot placement was marked with tape on the force plate to ensure consistency across the trials. Continuous support surface translations were elicited using a translating platform (H2W Technologies, USA) (Figure 1).

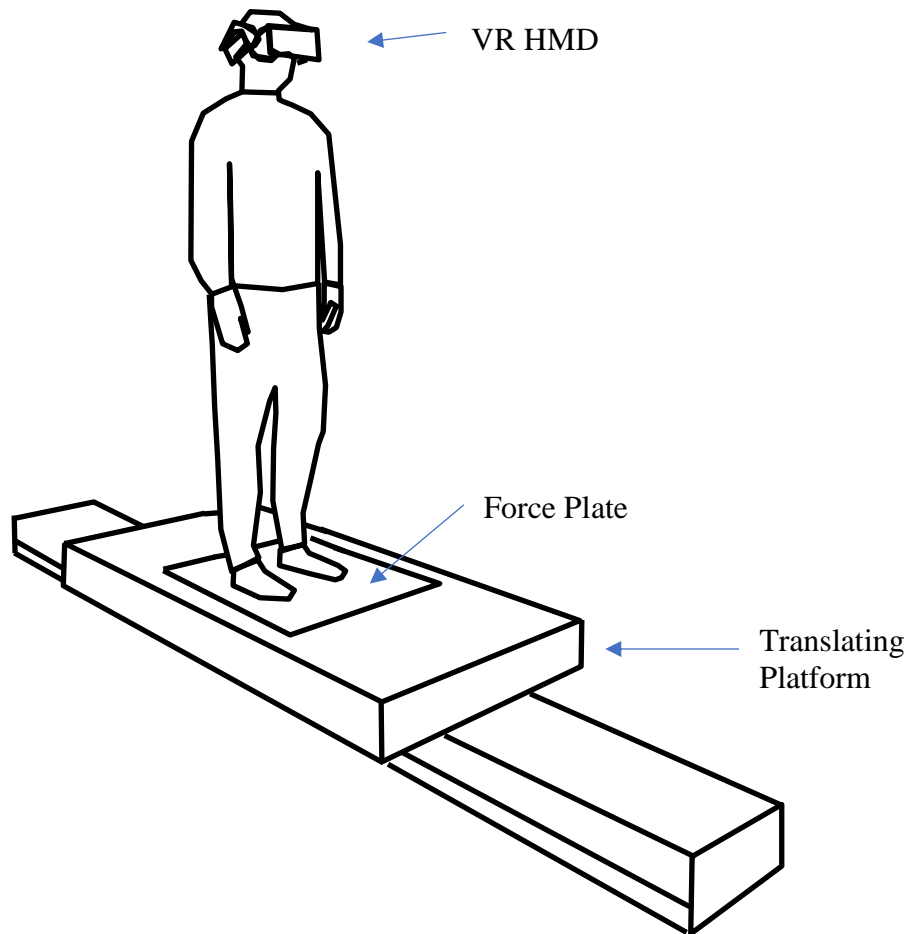


Figure 1: Experimental Setup. This figure shows the participant standing on a force plate mounted into a translating platform while wearing the VR HMD.

2.3 Visual Stimuli

The visual stimuli presented to the subject were transient linear perturbations of different velocities (Figure 2). The scene was a random dot kinematogram (RDK) which has been suggested to be a more comprehensive scene for motion perception (Bae & Luck, 2022). The randomly generated spheres had a radius of 0.1m and the perturbations were 1 second long. The velocities were either 0.5 m/s, 1 m/s or 1.5 m/s or a sham condition with a velocity of 0 m/s. The

perturbations were either in the anterior (away from subject) or posterior (towards the subject) direction for a total of 7 possible conditions. The conditions were randomly shuffled with a random delay of 4-6 seconds between each condition.

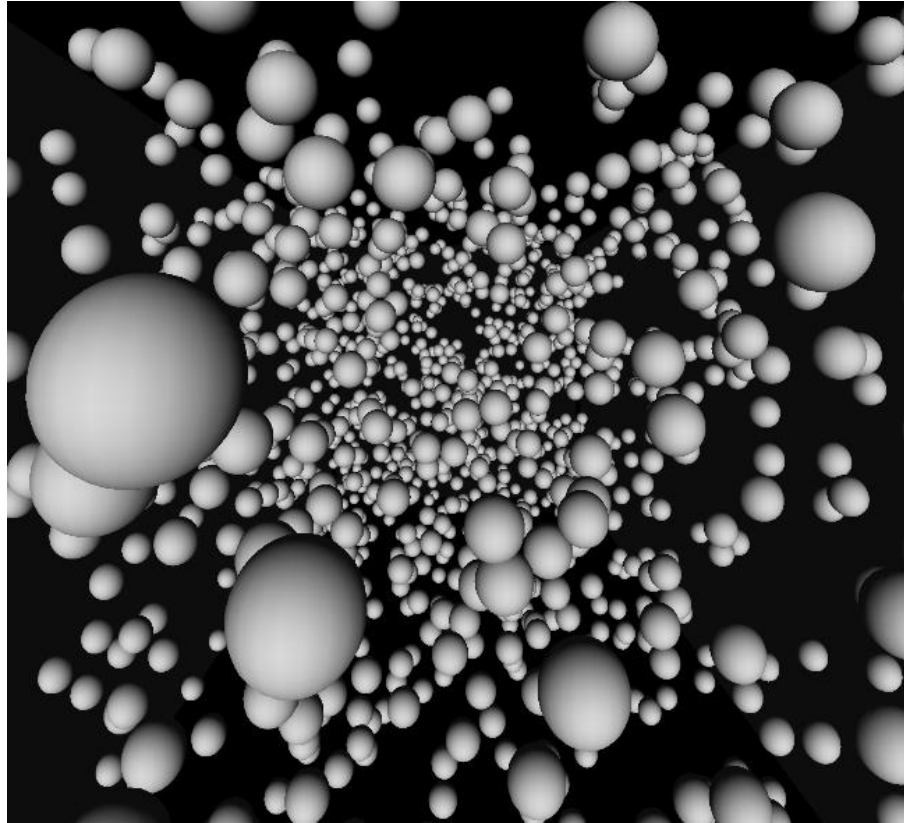


Figure 2: Participants' view inside the HMD; the random dot kinematogram (RDK) used as the visual scene. Transient linear perturbations were performed in the anterior and posterior directions.

2.4 Translating Platform Perturbation

The participants were exposed to continuous support surface translations on a translating platform. The perturbation was extrapolated from a signal generated in MATLAB that operates between frequencies: 0.1 Hz, 0.4 Hz and 0.9 Hz (Figure 3) (MathWorks, USA). After

extrapolating the peaks and troughs of the signal, it was programmed in Galil to create the support surface translations (Galil, USA). The perturbation was randomly generated to account for potential feedforward adaptations that occur during sinusoidal perturbations (Jilk et al., 2014). The platform translated continuously ± 5 cm from the centre of the platform.

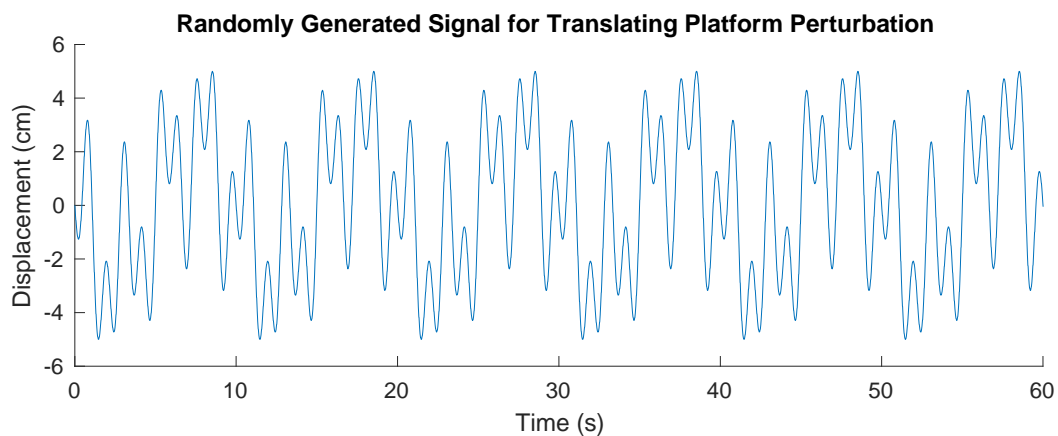


Figure 3: A random signal generated in MATLAB across the 0.1, 0.4 and 0.9 Hz frequencies showing the perturbation of the translating platform.

2.5 Perceived Movement

Perceived movement was collected using the VIVE controller, where the participant started with their thumb in the centre of the track pad. Their trunk movement was tracked relative to their sway, where they move it up when they feel their trunk position sway forward in space and move it down when they feel their trunk position sway backwards in space. The data were recorded in Vizard, outputted to VICON Nexus 2 through LabJack, a data acquisition system, and processed in MATLAB. The amplitude of perceived movement was recorded in

volts (V), bias removed, and normalized to maximum lean values to convert the units to a percentage of maximum lean.

2.6 Procedure

The subjects were first exposed to 3 practice trials. In the first practice trial, the participant watched the translating platform move without standing on it for 20 seconds. Next, they were put into a passive safety harness which was used to provide safety in case of a fall, but without giving feedback that could interfere with the balance task. The participants were then placed onto the translating platform without shoes while a spotter was beside them at all times. The subject was instructed to face forward, stand quietly and keep their hands by their side while tracking their trunk sway using the controller. The participant was asked to sway maximally forwards and backwards while moving the tracker; this familiarized the participant with their maximum sway amplitudes. In the second practice trial, the participant stood on the translating platform as it moved for 20 seconds with no HMD while tracking their trunk sway. In the third practice trial, the participant stood on the translating platform for 20 seconds while tracking their trunk sway and wearing the HMD with the visual scene with no perturbations. Once the practice trials were completed, there were 7 blocks collected that could be used for the analysis. Each block consisted of a 90-second translating platform cycle of perturbations while each of the 7 visual conditions, including the sham condition, were randomly shuffled with a delay of 4-6 seconds between each and then repeated. In total, the subject was exposed to 12 visual perturbations in one block with 2 sham conditions. There were 5 blocks where they were tracking their perceived sway, and a pre- and post-block where they were not tracking. After each block, the participant took a mandatory rest of 5 minutes. In total, the participant was exposed to 84 visual perturbations, 14 per each visual stimulus, during the data collection.

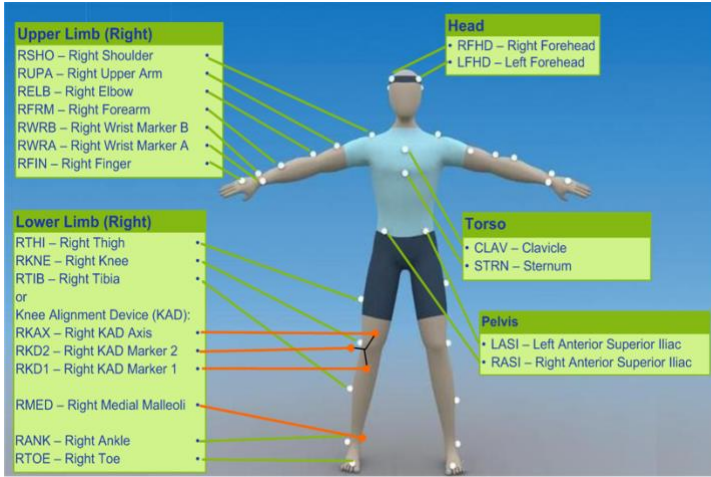
2.7 Kinetics

Ground reaction forces and moments were recorded from the force plate, sampled at 1000 Hz, recorded through VICON Nexus 2, and used to calculate COP displacements in order to quantify postural responses. The COP data were low pass filtered using a 5 Hz dual pass Butterworth filter and bias removed in MATLAB. This data were used to calculate COP displacements in the AP and ML direction.

2.8 Kinematics

Kinematic data were calculated using a full body, 40 reflective marker set up placed on various anatomical landmarks on the subject (Figure 4) and 4 markers placed on the translating platform. The markers were placed bilaterally on the following anatomical landmarks: the head (on the zygomatic bone and back of the head), the glenohumeral joint, the upper arm, the lateral epicondyle, the forearm, the radial and ulnar styloid, the third metacarpal, the anterior superior iliac spine (ASIS), the posterior superior iliac spine (PSIS), the upper thigh, the tibiofemoral joint, the tibialis anterior, the lateral malleolus, the third metatarsal and the calcaneus. As well, markers were placed on the clavicle, the sternum, the seventh cervical vertebra (C7), the tenth thoracic vertebra (T10), the first sacral vertebra (S1) and a tracking marker on the right upper back. The data were recorded in VICON Nexus 2 and processed in MATLAB, where it was bias removed to become a relative displacement with the platform and normalized to maximum lean trials to convert the units from millimetres (mm) to a percentage of maximum lean. Individual marker displacement, particularly focusing on the trunk (sternum), was recorded, analyzed and correlated with the perceived data.

A)



B)

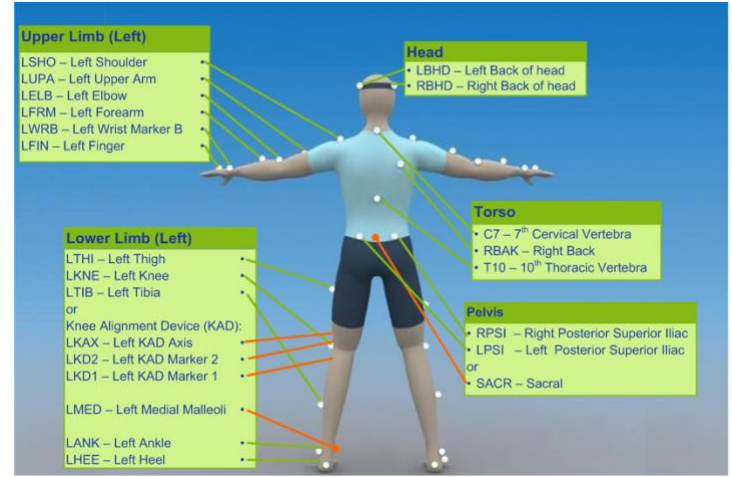


Figure 4: 40 marker kinematic model based on the full body Plug-in Gait Dynamic Model from VICON (VICON, USA). **A** shows the view of the participant from the front; **B** shows the view of the participant from the back.

2.9 Outcome Measures

Root mean square (RMS) was calculated for COP, trunk and perceived data using the following equation:

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^n x_i^2}$$

where x is the data sample and n is the number of data points. Path length (PL) and Mean Position (MP) were also calculated for COP, trunk, and perceived data. Quotient measures were also used to assess the changes in perceived movement with respect to actual postural responses (Cleworth et al., 2019). These quotients were calculated by dividing perceived displacement by trunk displacement for RMS (QRMS), PL (QPL) and MP (QMP). These calculations were made from the normalized signal. All outcome measures were analyzed using a windowed analysis,

where the data were analyzed for 2.5 seconds after the onset of each stimulus. All trunk and tracked displacement measures were converted into a maximum lean percentage, where the amplitude of their displacement was relative to a maximum lean the participants executed before the trials. All COP displacement measures were converted into mm.

2.10 Data Processing

All data were analyzed for 2.5 seconds after the onset of each stimulus. Postural responses, measured through trunk and COP displacement, and perceived movement, measured through tracked displacement, were used for all outcome measures. Cross correlations were done between the tracked movement data and trunk displacement data as well as the trunk displacement and platform displacement data. This was done using the *xcorr* function in MATLAB, which looks at the strength of correlation and lag of the signal (MathWorks, USA). The correlation will be on a scale of -1 to 1, where 1 represents a perfect positive correlation, -1 represents a perfect negative correlation and 0 represents no correlation between the two signals.

2.11 Statistical Analysis

A 2x3 repeated measures Analysis of Variance (ANOVA), where the 2 levels represent the anterior and posterior direction and the 3 levels represent the different velocities, was conducted to test the effect of direction and velocity of visual perturbations for RMS, PL, MP and the quotient measures. As well, the 2x3 repeated measures ANOVA was conducted on maximum correlation and lag at maximum correlation between perceived and trunk displacement were extracted from cross correlations. The Shapiro-Wilks test and Mauchely's Test of Sphericity were used to evaluate normality and sphericity. Greenhouse-Geisser corrections were

used to adjust the sphericity of the data if needed. Outliers were defined as a value greater than two standard deviations above the mean (Field, 2009). Time-series plots were viewed in MATLAB to see if there were technical issues in potential outliers. If no technical issues were present, the outliers were replaced with a value equal to two standard deviations above the mean (Field, 2009). The α -level was set at 0.05 and Šídák corrections were utilized for multiple comparisons. Paired t-tests were conducted between the sham condition and the other conditions, with a corrected α -level of 0.0083 (dividing 0.05 by the 6 comparisons).

Chapter 3: Results

3.1 General Results

A directional effect was found in the amplitude of postural responses with no changes found with velocity. The amplitude of perceived movement was unchanged with direction, but differences were found in velocity. Quotient measures showed an effect of direction, but not velocity. No changes were found in the correlations between the perceived and trunk displacement. Mean displacement for COP, trunk and tracked displacement is shown in Figure 5.

3.2 Postural Responses

A main effect of direction was found for RMS of trunk displacement ($p=0.002$; Table 1; Figure 6A) and COP displacement ($p=0.005$; Table 1; Figure 6B), where anterior visual perturbations elicited a greater postural response compared to posterior visual perturbations. Paired t-tests showed a significant difference in the anterior conditions with velocities of 1 m/s and 1.5 m/s compared to the sham condition ($p<0.001$; Table 2). Mean trunk position ($p<0.001$; Table 1; Figure 8A) and mean COP position ($p<0.001$; Table 1; Figure 8B) also showed this main effect of direction. PL of trunk displacement also showed this directional effect ($p < 0.001$; Table 1; Figure 7A). Significant differences were found between the posterior condition of 1 m/s and anterior conditions of 1 m/s and 1.5 m/s compared to the sham condition in trunk MP (Table 2). There was a significant difference between the anterior condition with a velocity of 1.5m/s compared to the sham ($p<0.001$; Table 2). No main effect of velocity was found, as well as no interaction effect between direction and velocity for all outcome measures (Table 1).

3.3 Perceived Movement

No main effect of direction was found in the RMS (Figure 6C), PL (Figure 7B) or MP (Figure 8C) of the tracked displacement (Table 1). A main effect of velocity was found for tracked displacement of PL ($p=0.037$; Table 1). Post-hoc analyses showed that the difference in velocity was between the velocity of 0.5m/s and 1.5m/s ($p=0.028$). Paired t-tests also showed a difference between the posterior condition with a velocity of 1.5m/s and the sham condition ($p=0.008$, Table 2). No interaction effect was found between direction and velocity for all variables (Table 1).

3.4 Perceived Movement and Postural Responses

A main effect of direction was found in QRMS (Figure 6D) ($p=0.002$; Table 1) and QPL (Figure 7C) ($p<0.001$; Table 1), where posterior perturbations had a greater quotient amplitude compared to anterior perturbations. Paired t-tests showed a significant difference in the anterior conditions with velocities of 1 m/s ($p=0.002$) and 1.5 m/s ($p=0.005$) compared to the sham condition (Table 2). No main effect was found in velocity and no interaction effect was found between direction and velocity (Table 1). QMP (Figure 8D) showed no changes (Table 1).

Cross correlations were done between trunk and tracked displacement (Figure 9). No main effect was found in direction or velocity and no interaction was found between direction and velocity for maximum correlation (Figure 9A) and lag at maximum correlation (Figure 9B) (Table 1).

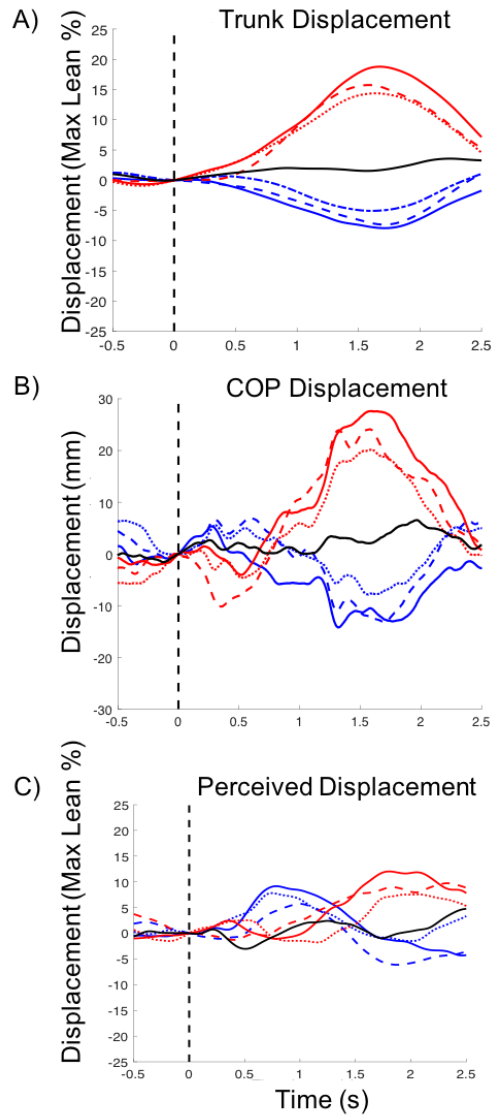


Figure 5: Mean Displacement Across Conditions. This figure shows the trunk displacement (max lean %) (A), COP displacement (mm) (B), and perceived displacement (max lean %) (C). The anterior conditions (red), the posterior conditions (blue) and the sham trial (black) across time (seconds) are plotted for each displacement. The dotted line represents the 0.5 m/s velocity, the dashed line represents the 1 m/s velocity, and the solid line represents the 1.5 m/s velocity. The black dashed line at time (0 s) represents the onset of the stimulus. A positive displacement value is towards the anterior direction and a negative displacement value is towards the posterior direction.

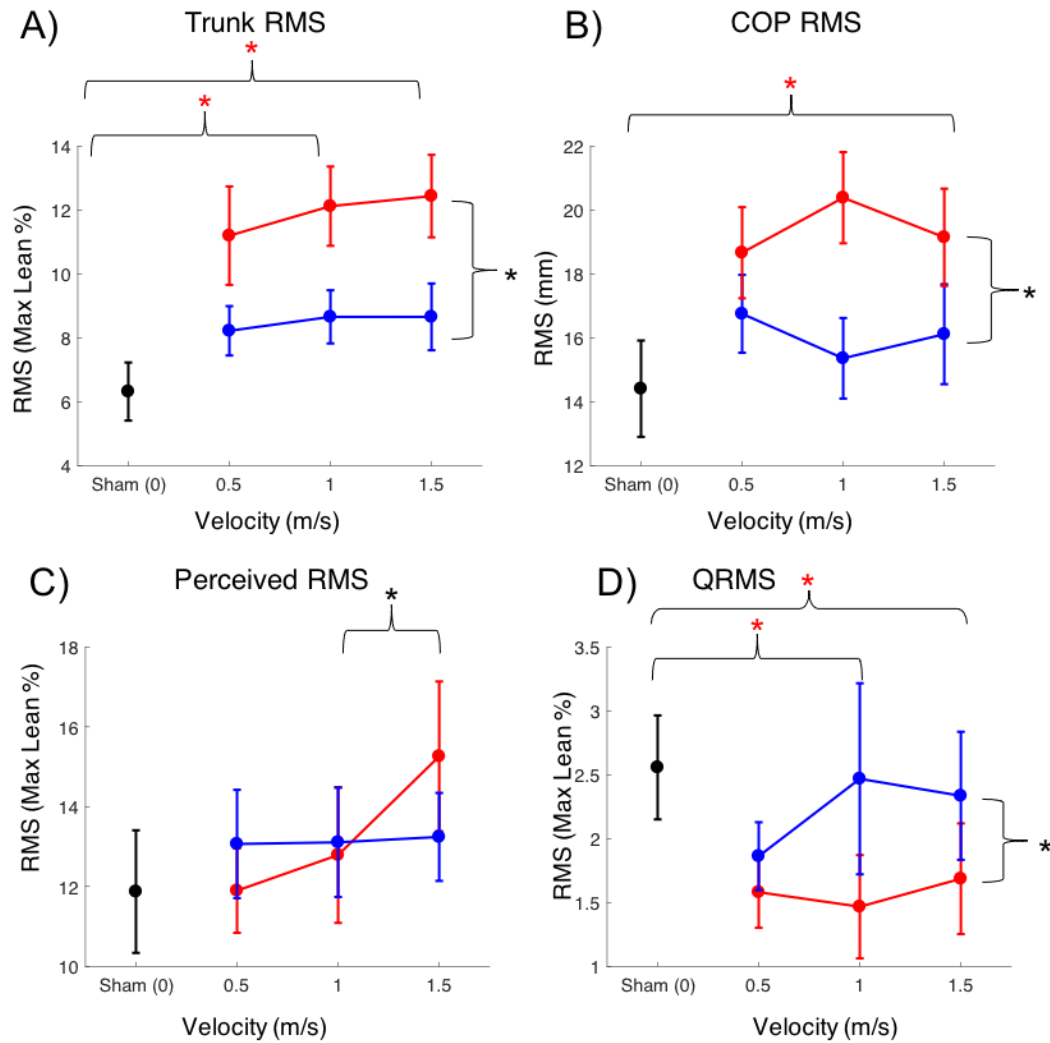


Figure 6: RMS Across Conditions. This figure shows the trunk RMS (max lean %) (A), COP RMS (mm) (B), perceived RMS (max lean %) (C) and quotient RMS (QRMS) (max lean %) (D). The anterior conditions (red), the posterior conditions (blue) and the sham condition (black) is across time (seconds). The error bars represent the standard error of the mean (SEM). The (*) indicates significance between anterior and posterior conditions and the red (*) represents significance between anterior conditions and the sham condition.

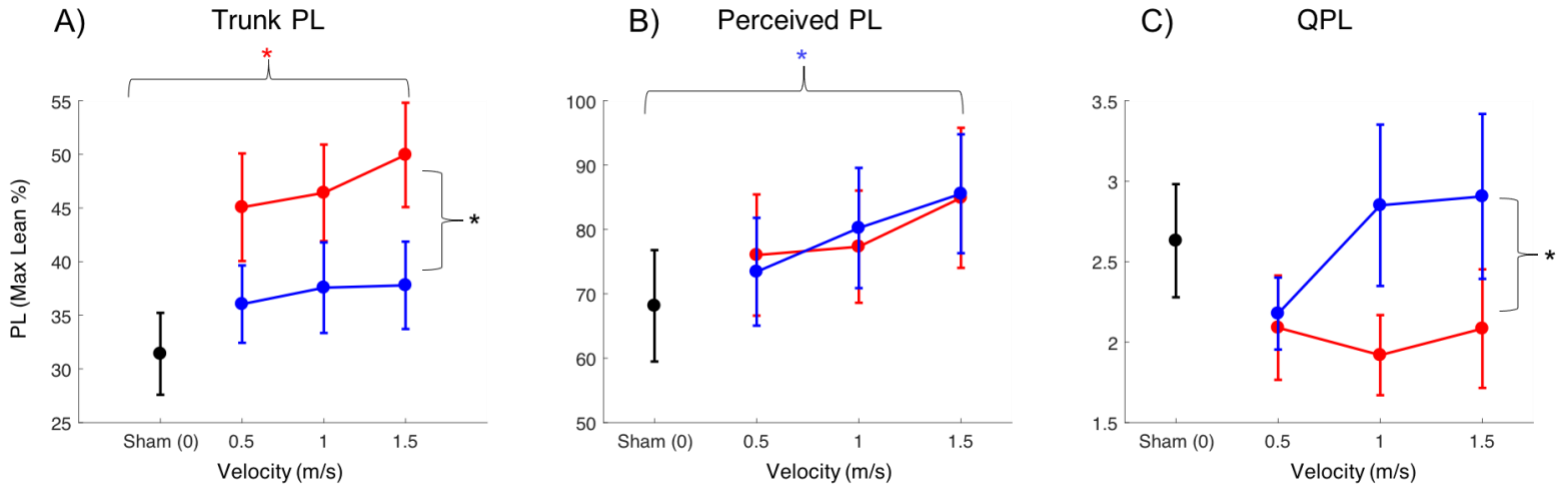


Figure 7: PL Across Conditions. This figure shows the trunk PL (A), perceived PL (B), and quotient (QPL) (C). Max lean % of the anterior conditions (red), the posterior conditions (blue) and the sham condition (black) is across time (seconds). The error bars represent the standard error of the mean (SEM). The (*) indicates significance between anterior and posterior conditions, the red (*) represents significance between anterior conditions and the sham condition, and the blue (*) represents significance between posterior conditions and the sham condition

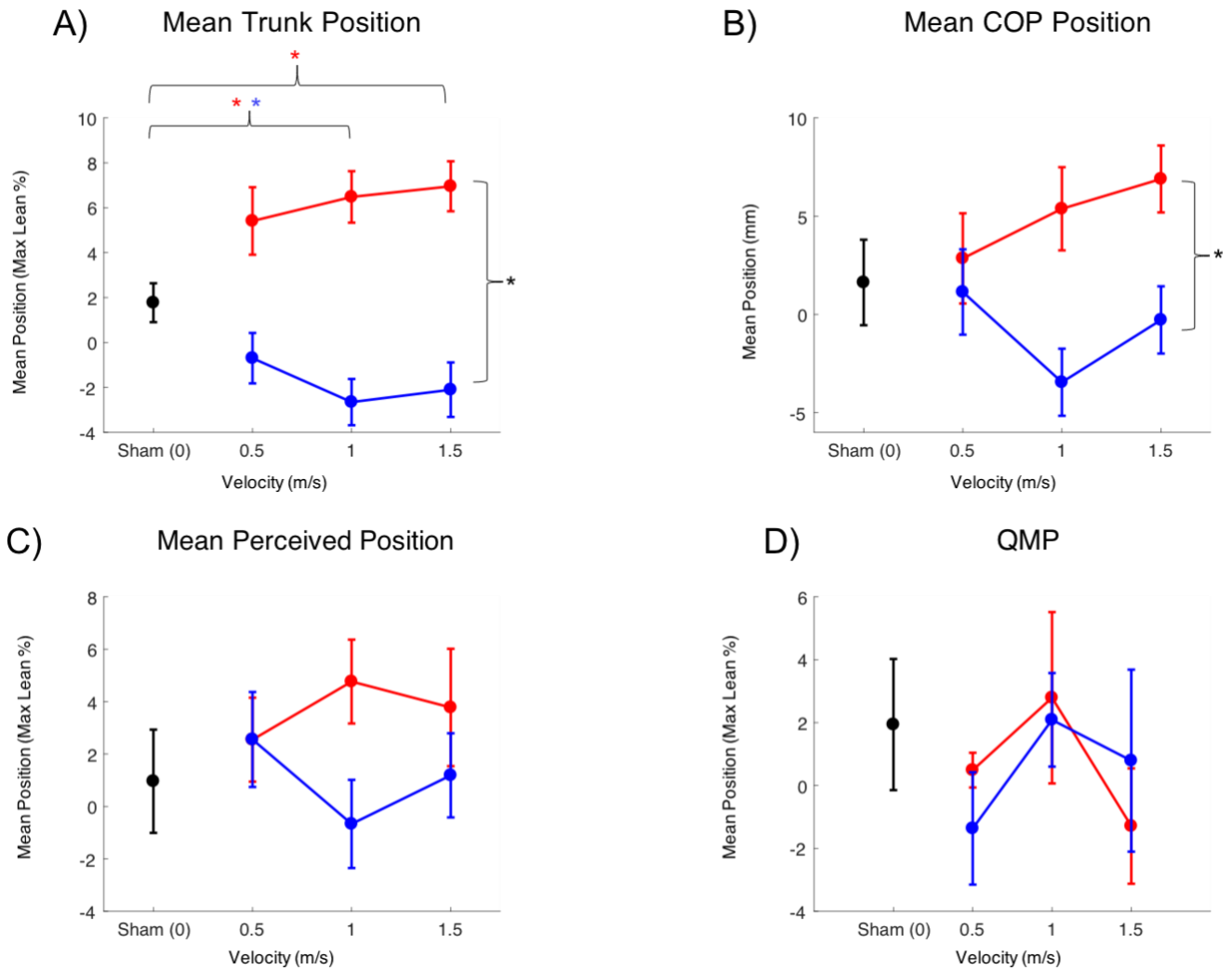


Figure 8: MP Across Conditions. This figure shows the trunk MP (max lean %) (A), COP MP (mm) (B), perceived MP (max lean %) (C) and quotient MP (QMP) (max lean %) (D). The anterior conditions (red), the posterior conditions (blue) and the sham condition (black) is across time (seconds). The error bars represent the standard error of the mean (SEM). The (*) indicates significance between anterior and posterior conditions, the red (*) represents significance between anterior conditions and the sham condition, and the blue (*) represents significance between posterior conditions and the sham condition.

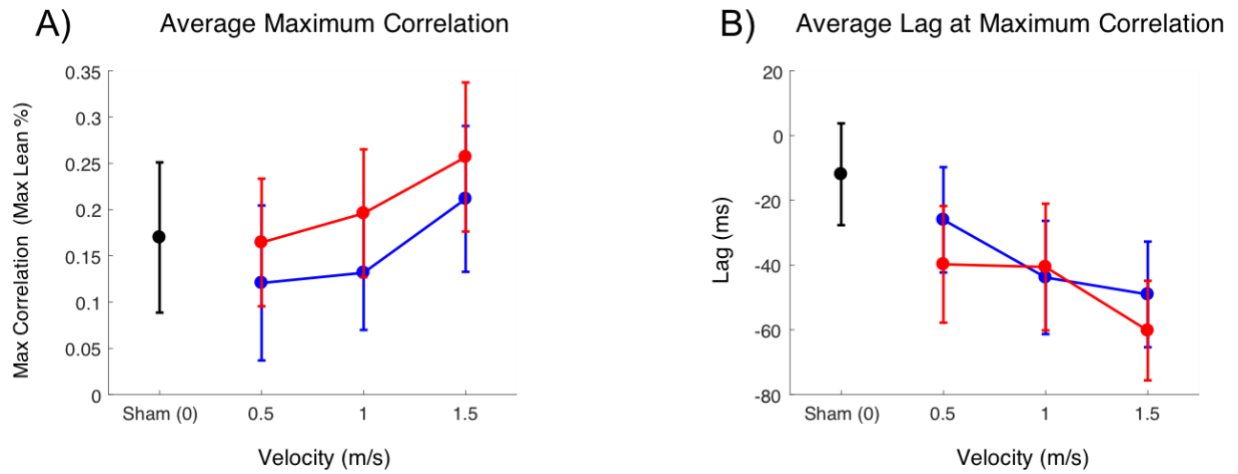


Figure 9: Average Maximum and Lag at Maximum Correlation Across Conditions. This figure shows the average maximum correlation (max lean %) (A) and the average lag at maximum correlation (B) across conditions. The anterior conditions (red), the posterior conditions (blue) and the sham condition (black) is across time (seconds). The error bars represent the standard error of the mean (SEM).

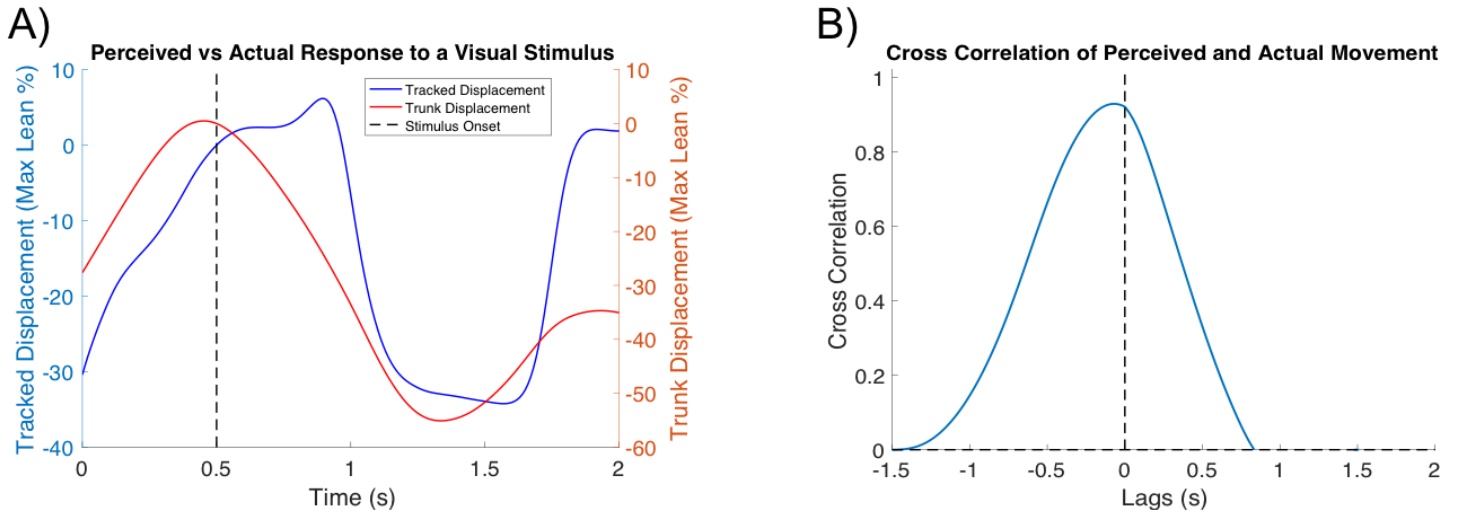


Figure 10: Representative Subject's Perceived and Actual Response to an Anterior 1.5m/s Visual Perturbation (A) and its Cross Correlation (B). In Figure 10A, the blue line represents tracked displacement, the red line represents trunk displacement, and the dashed black line represents the onset of the stimulus. In Figure 10B, the dashed line represents where the peak of the signal would be if the signal was unshifted, where left of the line represents the actual response leading the perceived, and the right of the line represents the perceived response leading the actual.

Table 1: Outcome measures of trunk, COP and tracked displacement are displayed in the first column. Main effects of direction, velocity and the interaction effect of direction*velocity from the RM-ANOVA are displayed in the subsequent columns. F values, and p-values are displayed in the columns below the main effects. Significant results are highlighted in bold font.

Outcome Measure	Direction		Velocity		Direction*Velocity	
	F	p-value	F	p-value	F	p-value
Trunk RMS	12.678	0.002	0.585	0.561	0.306	0.738
COP RMS	9.612	0.005	0.329	0.722	0.456	0.637
Tracked RMS	0.048	0.829	1.953	0.155	1.499	0.235
QRMS	12.437	0.002	1.441	0.249	0.311	0.734
Trunk PL	15.288	<0.001	0.721	0.492	0.180	0.836
Tracked PL	0.603	0.445	3.527	0.037	0.222	0.801
QPL	20.665	<0.001	0.769	0.469	1.974	0.151
Trunk MP	82.847	<0.001	0.122	0.886	1.487	0.235
COP MP	20.682	<0.001	0.596	0.554	2.463	0.095
Tracked MP	3.348	0.078	0.049	0.952	1.324	0.275
QMP	0.143	0.708	0.160	0.853	0.160	0.853
Max Corr	2.708	0.112	2.142	0.128	0.024	0.977
Lag at Max Corr	0.551	0.465	1.919	0.157	0.142	0.868

Table 2: Paired t-test results for all outcome measures. All conditions are compared to the sham condition, where the A corresponds to anterior, P corresponds to posterior and 0.5, 1 and 1.5 correspond to the velocity. t-scores and p-values are displayed in the subsequent columns. Significant results are highlighted in bold font, with an adjusted α -level of 0.0083.

Outcome Measure	Pair	t-score	p-value	Outcome Measure	Pair	t-score	p-value	Outcome Measure	Pair	t-score	p-value
Trunk RMS	P (0.5)	1.696	0.103	QRMS	P (0.5)	-1.664	0.110	QPL	P (0.5)	-1.483	0.152
	P (1)	2.139	0.043		P (1)	-1.374	0.183		P (1)	-0.197	0.845
	P (1.5)	2.155	0.042		P (1.5)	-0.960	0.347		P (1.5)	-0.011	0.991
	A (0.5)	2.723	0.012		A (0.5)	-2.695	0.013		A (0.5)	-2.172	0.040
	A (1)	4.027	<0.001		A (1)	-3.565	0.002		A (1)	-2.451	0.022
	A (1.5)	4.184	<0.001		A (1.5)	-3.126	0.005		A (1.5)	-2.623	0.015
COP RMS	P (0.5)	1.353	0.188	Trunk PL	P (0.5)	1.422	0.168	COP MP	P (0.5)	-0.038	0.970
	P (1)	0.922	0.365		P (1)	1.477	0.153		P (1)	-2.124	0.043
	P (1.5)	0.966	0.343		P (1.5)	1.533	0.139		P (1.5)	-0.640	0.528
	A (0.5)	2.381	0.025		A (0.5)	2.637	0.015		A (0.5)	0.636	0.530
	A (1)	4.115	<0.001		A (1)	3.352	0.003		A (1)	1.637	0.113
	A (1.5)	2.917	0.007		A (1.5)	4.245	<0.001		A (1.5)	1.983	0.058
Perceived RMS	P (0.5)	0.951	0.351	Perceived PL	P (0.5)	1.240	0.227	Trunk MP	P (0.5)	-1.929	0.064
	P (1)	0.592	0.560		P (1)	2.042	0.052		P (1)	-3.288	0.003
	P (1.5)	0.751	0.460		P (1.5)	2.895	0.008		P (1.5)	-2.364	0.026
	A (0.5)	-0.079	0.938		A (0.5)	1.022	0.317		A (0.5)	2.150	0.041
	A (1)	0.149	0.883		A (1)	1.451	0.159		A (1)	3.140	0.004
	A (1.5)	2.257	0.033		A (1.5)	2.100	0.046		A (1.5)	3.646	0.001
Max Correlation	P (0.5)	-0.713	0.482	Lag at Max Correlation	P (0.5)	-0.760	0.454				
	P (1)	-0.606	0.550		P (1)	-1.764	0.089				
	P (1.5)	0.478	0.637		P (1.5)	-1.839	0.077				
	A (0.5)	-0.057	0.955		A (0.5)	-1.443	0.161				
	A (1)	0.418	0.680		A (1)	-1.365	0.184				
	A (1.5)	1.186	0.247		A (1.5)	-2.715	0.011				

4. Discussion

4.1 Overview

This study was the first to examine the effect of visual perturbations during a dynamic balance task on perceived movement and postural responses. Previous work has shown the effect of dynamic visual cues on postural responses (Bronstien, 1986; Guerraz & Bronstein, 2008) and the effect of support surface translations on postural responses (Van Ootegham et al., 2008; Maki & Ostrovski, 1993). Further understanding the effect of simultaneous mechanical and visual perturbations on postural responses is important as the postural control system must adapt when sensory systems become unreliable. These combined perturbations increase the ecological validity of the study, as real-world perturbations are complex and require sensorimotor integration of the postural control system (Peterka, 2002). As well, the relationship between perceived movement and postural responses has been explored (Cleworth et al., 2019; Cleworth & Carpenter, 2016; Luu et al., 2012). This relationship is important in further understanding postural control as balance responses can be misperceived, potentially leading to maladaptive balance strategies (Tissereand et al., 2022). Altogether, this study aimed to examine the effects of visual perturbations during a dynamic balance task on postural responses, perceived movement and the relationship between the two.

This study found that amplitude of postural responses increased in the anterior direction compared to the posterior direction (Figures 6-8). Specifically, RMS of COP and trunk displacement as well as PL of trunk displacement increased in anterior conditions. There was an increase in perceived displacement when exposed to the highest velocity (1.5 m/s) (Figure 6C).

As well, there was a disconnect in the amplitude of the perceived movement compared to the actual postural responses when comparing anterior and posterior conditions, where the posterior conditions had a significantly greater quotient amplitude despite smaller postural responses (Figures 6D & 7C).

4.2 Postural Responses

During this study, participants exhibited significantly greater postural responses to anterior compared to posterior visual perturbations (Figures 6-8). The participants swayed in the direction of the stimulus (Figure 5). This is in accordance with the literature on linearvection stimuli, where postural responses can occur in the same direction as the visual perturbation (Guerraz & Bronstein, 2008; Bronstein & Buckwell, 1997). However, this seems to be dependent on visual context, where postural responses move in the opposite direction of the visual stimuli when focusing on a stationary object in the foreground, known as the motion parallax (Guerraz & Bronstein, 2008; Bronstein & Buckwell, 1997). The virtual environment used in this study was an RDK with high coherence (all the dots moving in the same direction simultaneously). Previous studies have demonstrated an effect of high coherence RDKs on postural responses, where there are stronger and more consistent responses as coherence increases (Wei et al., 2010). This suggests that the coherence of the visual stimulus chosen may have influenced the postural response moving in the direction of the visual stimulus.

An explanation for greater postural responses in the anterior direction is found within the literature on biomechanical constraints, where anterior limits of stability (LOS) relative to their BOS are 78.12% and 18.01% for the posterior LOS relative to their BOS (Huo, 2000). When

exposed to AP support surface translations, it has been found that posterior (toe-down) perturbations, causing a posterior displacement of the COM, resulting in earlier activation of various extensor muscles, larger angular displacement in the trunk and hip and faster horizontal COM displacements (Chen et al., 2014). Likewise, posterior visual perturbations may cause the COM to shift in the posterior direction and due the biomechanical constraints of the LOS, the postural responses are significantly smaller than the anterior visual perturbations.

It was hypothesized that the amplitude of postural responses would increase with the increase in velocity (Dokka et al., 2009; Hanssens et al., 2013). However, no effect of velocity on postural responses was observed (Figures 8-12). It is possible that the threshold to elicit a maximum postural response to a linear visual perturbation is lower than the velocities chosen in the study. This saturation of VEPRs has been explored in other studies, where maximal saturation thresholds for postural responses are 0.13 degrees/s in the AP direction and 0.21 degrees/s in the ML direction for circular vection stimuli (Hanssens et al, 2013). MacNeilage et al. (2010) found that linear vection could be perceived at a velocity of as little as 0.0316 m/s. In this study, we used velocities of 0.5 m/s, 1 m/s and 1.5 m/s which was used in previous literature, as well as being chosen based on piloting (Palmisano et al., 2016). During continuous support surface translations, it is possible that the threshold to elicit a maximum postural response is significantly lower than the velocities chosen, complying with our finding that there was no effect of velocity on the amplitude of the postural response.

4.3 Perceived Movement

The amplitude of perceived movement did not have a clear main effect of direction like the postural responses (Figures 6-8). However, there was a velocity effect, where the highest velocity elicited the greatest amplitude of perceived movement (Figure 6C). This follows some of the previous work on perceived movement, where an increase in velocity of circular vection stimuli lead to an increased perceived hand movement (Blanchard et al., 2013). However, this was the first study to demonstrate this in a linear vection task, suggesting that there may be a disconnect in the perceived movement and postural responses, where this velocity effect was not present. Cross correlations showed no significant differences across direction or velocity between perceived and trunk displacement (Figure 9). The maximum correlation of the various conditions was not significantly different from the sham, with a value of 0.1698 (Figure 9A). This normalized cross correlation was utilized to prevent amplitude dependence of the signals in the analysis, which is a limitation in unnormalized covariant analyses (Kaso, 2018). Correlation values closer to 0 suggest a weaker correlation and values closer to 1 suggest a higher correlation, suggesting that the perceived movement and postural responses exhibited a weak correlation in this study. Lag at max correlation values were also not significantly different across velocities or direction.

This observed disconnect between the participants' perceived movement and their postural responses was shown in Figures 6D & 7D, where they perceived a greater amount of movement relative to their actual movement in the posterior direction, despite their postural responses actually increased significantly in the anterior direction. This finding was documented previously, where the amplitude of perceived movement increased at height despite the

amplitude of postural responses remaining the same (Cleworth et al., 2019). As well, the gain, defined as the ratio of the amplitude across multiple frequencies, for perceived movement compared to trunk movement was increased at height (Cleworth et al., 2019). Instead of eliciting threat through height, participants in this study may have experienced threat to their postural control when visually perturbed in the posterior direction, causing them to feel more unstable (Colebatch & Govender, 2019; Chen et al., 2014). The threat to their postural control associated with posterior visual perturbations in a dynamic balance task may have led to a stiffening strategy. This strategy is identified by an increase in muscle coactivation and a decreased range of motion and velocity in the lower limb in order to minimize COM displacement (Nagai et al., 2012; Brown et al., 2002; Carpenter et al., 2001). This adopted stiffening strategy may explain why there are significantly higher values in quotient amplitude measures in the posterior direction, as the threat of a posterior perturbation causes an increased amplitude of perceived sway while the stiffening strategy reduces the postural response. However, future work using electromyography (EMG), or other measures to quantify stiffening during a tracking task with AP translations is needed to observe this potential effect.

4.4 Age-related Changes & Perceptual Deficits

The findings of this study may be accentuated in an older population due to age-related changes and declines. LOS relative to the BOS in the anterior and posterior direction were significantly reduced in an older population (Huo, 2000). As well, cognitive, perceptual and sensory abilities have been shown to decline with age (Harada et al., 2013; Yan et al., 2023; Zalewski, 2015). Specifically, perceived self-motion thresholds continuously increase with age and when manipulating different stimulus parameters (presentation time, number of dots, motion

coherence and stereoscopic stimulation), there was a significant decrease with age in each parameter (Lich & Bremmer, 2014). Older adults also exhibit an increased fear of falling, which affects balance control and increases fall risk (Jung, 2008; MacKay et al., 2021). As well, postural control strategies change, including different muscle recruitment and trying to reduce the amplitude of compensatory postural adjustments (Kanekar & Aruin, 2014). This study demonstrated that in a population of young adults, the relationship between perceived and actual displacement was disconnected. With a decrease in perceptual ability and changes in biomechanical constraints and psychosocial behaviour, these findings may be stronger in an older population. This has been documented in previous work, where older adults perceivevection to be stronger and longer in duration compared to younger adults (Murovc et al., 2022). However, in another study, older adults perceived lessvection than younger adults despite having greater postural responses (Haibach et al., 2009). The relationship betweenvection perception and postural responses with aging factors is multifaceted and not fully understood. Future studies should examine the effects of visual and mechanical perturbations on perceived movement in an older population with the understanding that age-related changes that may affect the relationship between perceived movement and postural responses.

Another population of interest is those with perceptual deficits, such as persistent postural-perceptual dizziness (PPPD), a vestibular disorder where an individual is subjected to persistent dizziness, unsteadiness and/or vertigo lasting for more than three months (Staab et al., 2017). Some individuals with PPPD have impaired postural control which affects their ability to maintain balance (Schmid et al., 2018). Those with PPPD have also been found to have a dysregulated perception of their own movement during balance tasks (San Pedro et al., 2023).

This interaction between their postural misperception and susceptibility to impaired postural control leads to potential balance deficits and increased fall risk. One factor suggested to contribute to the pathophysiology of PPPD is an increased perception of self-motion, potentially caused by a disconnect between actual and expected signals (Brandt 1996; Wuehr et al., 2013). Replicating this study in a population of PPPD patients may be insightful to how an altered perceptual system affects one's postural strategies when exposed to visual and mechanical perturbations.

4.5 Limitations

To prevent feedforward adaptations, a pseudorandom sequence for the support surface translations was combined with a random delay between each visual perturbation. Due to the embedding of the two perturbations, the perceived and actual response to each visual perturbation took place at different cycles of the support surface translation. Accordingly, this may be a limitation as the responses associated with each visual stimulus cannot be fully attributed tovection alone, rather an interaction between various visual perturbations with a translating platform. This created limitations in the analyses, where the unpredictability and short window between each visual perturbation prevented us from using coherence and frequency measures.

Another limitation is that the group of subjects were young, healthy and recruited from York University and the surrounding community. The lack of older adults, or those suffering from specific deficits, may create a misrepresentative sample of the population. Future studies examining perceived movement and postural responses in a dynamic balance task with dynamic

visual cues on an older population or a population with perceptual deficits is key for growing this field of research.

4.6 Future Work

This study exclusively uses linear measures to quantify balance and perceptual behaviour. Due to the multisensory integration required to maintain balance as well as the variability in vection responses, non-linear measures may quantify balance and perceptual behaviour more comprehensively. For instance, recurrence quantification analysis (RQA), an analysis based on quantifying the number of recurrences in a dynamic system that has been used previously to quantify fluctuations in COP data (Ramdani et al., 2013). In a study examining the effectiveness of RQA in seated vection compared to linear measures, they suggested that linear measures became more unreliable as the complexity of the vection increased (contracting flow and jittering flow) (Apthorp et al., 2014). Due to the complexity of the tasks in this study, implementing a non-linear analysis, such as RQA, may allow us to comprehensively assess postural responses where linear measures are limited

As well, future work aiming to understand the neural networks involved in perceived self-motion during visual and mechanical perturbations is necessary to understand the complex mechanisms of sensorimotor control during dynamic balance tasks. Previous work has shown that vection perception involves the vestibular cortical network through the deactivation of vestibular cortical regions in the parieto-insular vestibular cortex (PIVC) (Becker-Bense et al., 2012). Correlation analyses revealed that stimulus detection processing was associated with the ventral stream and the intensity of perceived vection was associated with the dorsal stream

(Becker-Bense et al., 2012). However, these findings are limited to circularvection and exploring the cortical contributions during a linearvection task would expand the knowledge in this area.

As perceived movement may be influenced by threat detection and conscious control, the amygdala, thalamus, brainstem and vestibular cortices, may be essential for the integration of sensory and cognitive processes (Staab et al., 2013; Babalan, 2004; Dietrich & Brandt, 2008). For reactive balance control, it has been shown that the N1 response and beta activity are scaled with the magnitude of the perturbation and may be helpful in understanding the sensorimotor state during a balance task, specifically error detection, movement initiation and adjustment (Boebinger et al., 2024). Future studies focusing on these cortical contributions and neural networks will yield valuable insight to the underlying mechanisms of perceived movement when exposed to visual and mechanical perturbations.

4.7 Conclusion

The goal of this study was to explore the relationship between perceived movement and postural responses in the presence of dynamic visual cues with continuous support surface translations. The amplitude of COP and trunk displacement was significantly greater in anterior conditions compared to posterior conditions, potentially due to the biomechanical constraints of the BOS. However, quotient amplitude measures showed a greater disconnect in posterior conditions compared to anterior conditions, suggesting a greater perceived movement compared to actual movement in posterior conditions. This misperception of sway amplitude may be partially attributed to threat detection and an increased conscious control of movement due to the

intensity of the perturbation. However, future work examining neural networks and cortical contributions on perceived movement during visual and mechanical perturbations is needed. Applying these findings to populations of interest including older adults and those with perceptual deficits may be beneficial in the development of rehabilitation strategies.

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