THE EFFECT OF OPTIC FLOW DURING ATTENTION RELATED TASKS AND QUIET STANCE

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Abstract

Vision plays a significant role in balance as it provides visual cues to help maintain balance. Increasing visual information during upright stance leads to tighter regulation of upright stance. Cognitive related tasks and postural control share capacities and compete for cognitive resources which may cause interference on one or both tasks. There is limited work on the impact of visual gain manipulation on dual tasks that include attention tasks that require visual information while maintaining an upright stance. While previous studies have explored how dual tasks and modified visual feedback influence balance separately, there is limited work on the impact of visual feedback during dual tasks that require visual information.

This study explored how visual cues affect balance when combining effects of visual conditions and different cognitive attention tasks. Optic flow was amplified or reduced to 4 gain conditions (0.25x,1x,4x,16x) within virtual reality (VR) relative to the head position while participants stood quietly on a force plate that measure ground reaction forces and completed 12 randomized trials across 3 conditions. Kinematics were collected through 8 markers placed on different parts using motion capture. Muscle activity was also collected by placing EMG on 3 lower leg muscles during the trials. MSRS questionnaire was completed after each trial to assess movement consciousness. Root mean square (RMS), and the mean power frequency (MPF) of Centre of Pressure (COP) and head position (HeadPos) were used to quantify balance. The mean angle RMS of relative angular displacement of the hip, knee and ankle was calculated, and the mean angle RMS of absolute angular displacement of the trunk, thigh, shank, foot was calculated to quantify balance. Developing a greater understanding of complex dynamics of visual feedback on cognitive task that requires vision while quiet standing, may enhance our understanding of how visual information aids postural control during dual tasks.

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Abbreviations

The table below highlights the scientific significant and the short forms for the thesis proposal. The items marked as (A) indicate bony anatomical landmarks.

Abbreviation	Description
AC	Acromion
AP	Anteroposterior
ANOVA	Analysis of variance
BOS	Base of support
CLC	Calcaneus (A)
CNS	Central nervous system
COM	Center of Mass
COP	Center of Pressure
COG	Center of gravity
EMG	Electromyography
FthMT	Base of 5^{th} metatarsal (A)
FOG	Force of gravity
Gast	Gastrocnemius
GT	Greater trochanter of femur (A)
HP	Head position
Hz	Hertz
HMD	Head-mounted display
LE	lateral epicondyle of humerus (A)
LM	lateral condyle of femur (A)
LMF	Lateral malleolus of ankle (A)
MedGas	Medial head of gastrocnemius
ML	Mediolateral
MP	Mastoid process
MPF	Mean power frequency
MVC	Maximal voluntary contraction
mVel	Mean velocity
RMANOVA	Repeated measures analysis of variance
RMS	Root mean square
Sol	Soleus
TibAnt	Tibialis anterior
VR	Virtual reality
VE	Virtual environment
ZY	Zygomatic arch

Overview of thesis

It is important for individuals to maintain balance to move effectively in their environment to avoid falls. Individuals rely on different senses, as well as attention, to maintain balance especially when performing two tasks at the same time. Previous studies have explored the effects of performing secondary tasks that require attention, as well as have explored the effects of augmented visual motion on balance. However, the impact of augmented visual motion on attention related cognitive tasks, particularly one that relies on visual information during upright stance have not been explored. The aim of this study was to deepen our understanding of how augmented visual motion affect balance by studying the combined effects of visual conditions and different attention tasks. Chapter 1 of this thesis reviews the existing literature on how senses contribute to balance, the effect of performing two tasks on balance, and the impact of visual information when manipulated within virtual environments. Chapter 2 explains the methods used to study the impact of augmented visual motion on cognitive task that particularly relies on visual information during upright stance. Chapter 3 presents the study's results, while Chapter 4 offers an in-depth discussion and interpretation of the findings, addressing the research question and exploring how joint mechanics, muscle activity, and conscious behaviour influence balance. Lastly, the thesis concludes with the study's future implications, significance and the overall conclusion.

Chapter 1: Literature review on sensory contributions to balance and dual tasks

1.1 Balance

Balance is often associated with postural control and is achieved when the body's Center of Mass (COM), also referred to center of gravity (COG), remains within the Base of Support (BOS). During upright stance, when COG is outside the BOS, one loses balance (Pollock et al, 2000). To maintain balance, interactions between sensory inputs, cognitive processes and motor responses are required (Horak & Macpherson, 1996; Peterka, 2002; Woollacott & Shumway-Cook, 2002). Different forms of balance exist, including static and dynamic. Static can be defined as evaluating balance in an undisturbed stance, focusing on subject's ability to maintain equilibrium without external perturbations (Visser et al., 2008). In contrast, dynamic evaluates balance during conditions where body experiences external or internal perturbations, providing insight into the subject's ability to adapt and maintain balance when perturbed (Campolettano et al., 2018). These forms of balance show postural control complexity, requiring contributions from the motor and sensory systems to manage both stable and dynamic scenarios (Visser et al., 2008; Peterka, 2002; Woollacott & Shumway-Cook, 2002).

To maintain upright stance, the individuals rely on vestibular, somatosensory and visual systems, as well as the alterations and the reliance of these systems (Fitzpatrick & McCloskey, 1994). The following section will briefly describe contributions from vestibular and somatosensory and will provide a more detailed and in-depth view on the contributions that vision makes to balance.

1.2 Sensory contributions to balance

The vestibular system, situated in the inner ear, plays a crucial role in detecting head movements and orientation, providing the brain with information about the body's position and movement in three-dimensional space, enabling a sense of spatial positioning necessary for balance maintenance (Augustine et al, 2001; Jones et al., 2009; Calvert et al, 2012; Angelaki & Cullen, 2008; Lopez, 2015). Through mechanisms such as the vestibulo-occular reflex and the vestibulospinal reflex, the vestibular system aids in gaze stabilization and posture adjustments by coordinating eye movements with head motions (Ramos de Miguel et al, 2020; Casale & Gupta, 2020; Massion, 1994; Cenciarini & Peterka, 2006; Van Kordelaar et al, 2018). The somatosensory system complements this by providing critical feedback on body positioning and external forces, integrating touch, temperature, and pain information. Proprioceptive receptors such as the muscle spindles, detect changes in muscle length and movement, and the proprioceptive receptors such as the Golgi tendon organs are responsible for monitoring muscle tension. This proprioceptive information is essential to the central nervous system, facilitating the coordination of muscle activities important for maintaining balance (Tsunozaki & Bautista, 2009; Shaffer & Harrison, 2007; Hayes, 1982). The visual system is also vital for providing feedback to coordinate appropriate postural responses during balance tasks, with the eyes capturing external information, undergoing phototransduction in the retina, and then transmitting the data-to the brain for processing (Bronstein, 2019; Lord & Dayhew, 2001). The visual data referring to the sensory information from the environment, such as spatial cues, light patterns and motions, travels through the thalamus and occipital lobe, along with other pathways, to inform motor reactions that help maintain balance (Redfern et al., 2001; Kandel et al., 2013; Schiller & Tehovnik, 2015; Yoo & Mihaila, 2022; Kandel et al., 2013).

Sensory reweighting

The vestibular, somatosensory and the visual systems work together, continuously re-weighting sensory information from each system to provide relative inputs that shape motor responses to help maintain balance (Shaffer & Harrison, 2007; Visser et al., 2008). However, when the integration of these sensory systems is disrupted, or if one system becomes more dominant due to reduced reliability of another, postural control may be compromised (Stergiou & Decker, 2011). This occurs because the ability of the nervous system to prioritize and appropriately respond to most relevant sensory input can become less effective, and this leads to inadequate feedback to the motor system. For example, when there is absence of accurate proprioceptive information and over reliance on visual cues, it can result in difficulty in maintaining balance when there is unavailable or altered visual feedback.

Tools like the Sensory Organization Test (SOT) assess how these systems integrate to maintain balance, especially under challenging conditions such as reducing visual or proprioceptive feedback (Grove et al., 2021; Visser et al., 2008). Proprioceptive information from the ankle and feet are a primary source for maintaining balance; when this input becomes less reliable, the body depends more on visual and vestibular cues (Bergin et al., 1995; Peterka & Benolken, 1995; Hamid et al., 1991). This sensory re-weighting is crucial for individuals with balance impairments, such as those with Parkinson's disease or peripheral neuropathy, emphasizing the role of sensory integration in adapting to environmental changes (Evans & Krebs, 1999).

The dynamic reliance on different sensory cues reveals the adaptability of the balance system, adjusting based on the context and the state of the body. Understanding the multisensory contributions to maintain balance establishes the groundwork for exploring the role of visual feedback in maintaining balance. The next section delves deeper into how visual information, through optic flow, contributes to postural control and influences movement.

1.3 Visual contributions to postural control

Optic flow and visual contributions to balance

The visual system interprets patterns and motion in our environment as optic flow, which is essential for perceiving self-motion and navigating through space. This process involves the detection of changes in light patterns, creating an optical array that helps individuals infer movement relative to their surroundings (Ludwig et al., 2018; Royden et al., 1992; Harris et al., 2000). Optic flow may significantly influence the perception of self-motion, with alteration in retinal motion patterns affecting strength of this perception (Royden et al., 1992; Harris et al., 2000). The natural positioning of the eyes allows for depth perception through differences in image localization on each retina, enhancing the ability to perceive spatial details and depth (Howard & Rogers, 2008).

Studies have shown that standing with eyes closed increases sway by 40-50% compared to standing with eyes open, highlighting the importance of visual feedback in detecting objects, assessing distances, and coordinating responses to maintain upright stance (Diener et al., 1984; Bronstein, 2019; Lord & Dayhew, 2001; Stoffregen et al., 2000). For instance, a study showed poor depth perception in individuals (using the Howard- Dohlman Depth Perception test) and predicted that these individuals were at higher risk of falling multiple times throughout their lives (Lord & Dayhew, 2001). While vision is crucial for achieving postural control, the involvement of vision during balance tasks is not always consistent. Some studies suggests that vision is engaged even at low sway frequencies (0.1Hz) (Salsabili et al., 2013). On the other hand, other studies found no correlation between gaze shifts or visual fixation and step placements during rapid stepping reactions, suggesting that vision might not be quick enough to influence the faster responses (McIlroy, & Maki, 2005; Diener et al., 1984; Redfern et al., 2001; Zettel et al., 2008). Lastly, postural responses are influenced by the structural characteristics of optic flow, including expansion, shear, rotation, and texture. Although texture can influence balance in both real and virtual environments, virtual reality (VR) allows controlled manipulation of texture characteristics to study the effects of postural control (Koenderink & VanDoorn, 1976; VanAsten et al., 1988b). These insights regarding the functions of optic flow and visual feedback in balance underscore the importance of regulated visual input and open the door for further investigation into the ways in which manipulating optic flow gain can enhance postural control mechanisms.

Optic flow gain manipulation using virtual reality

VR, through head mounted displays (HMDs), offers a unique platform for studying perception and behaviour by replicating real-world experiences and aligning with the user's head position and orientation (Asslander & Streuber, 2020a; Robert et al, 2016; Slater & Wilbur, 1997). Virtual environments (VE) provide spatial references and depth cues, enhancing the perception of self-motion (Riecke et al., 2006). Studies indicate that realistic VR scenes do not significantly differ from real-world settings in terms of their impact on body sway, suggesting VR's potential in balance research (Asslander & Streuber, 2020a; Robert et al., 2016; Slater & Wilbur, 1997; Pine et al., 2002; Streuber et.al, 2012; Sherman & Craig, 2018; Riecke et al., 2006).

The role of visual information in maintaining balance during quiet stance can be revealed by understanding how optic flow gain affects postural control under different gain values. For example, a study explored the effects of different optic flow gains (0.25, 2, 4, and 16) on center of pressure (COP) and head position (HeadPos). It was discovered that as optic flow gain increased, particularly to a gain of 16, the amplitude of COP decreased, while the frequency increased (Lavalle & Cleworth, 2023). Interestingly, a gain of 4 was identified as sufficient for sway reduction, as an increase to gain of 16 did not significantly impact COP amplitude further, indicating a plateau in the effectiveness of higher optic flow gain on postural control. Furthermore, it was indicated that the higher the optic flow gain, the more visual information and, with more visual feedback, smaller deviations of sway were detected, indicating tighter regulation of upright stance (Lavalle & Cleworth, 2023). This finding suggested that increased visual feedback, while beneficial to a point, does not necessarily enhance postural control. Amplified optic flow requires individuals to exert more stabilizing force to control their center of mass (COM), which can place more demands on the body's balance mechanisms rather than improve balance (Lavalle & Cleworth, 2023). Reduced optic flow is associated with poorer postural control, underscoring the importance of visual information in maintaining balance (Bronstein, 2019; Jilk et al, 2014; Horak et al., 1989; Lavalle & Cleworth, 2023). The study also found that head position was more sensitive to changes in optic flow than COP, with the amplitude decreasing as optic flow increased, suggesting that there may have been an adaptive head stabilization strategy to minimize eye movement and enhance postural control, despite no significant changes in frequency (Lavalle & Cleworth, 2023). This research highlighted the complex relationship between optic flow gain and postural control, showing that although more visual feedback can initially aid in postural control, an over-reliance on it may compromise stability rather than improve it.

Optic flow when manipulated through VR has provided valuable knowledge into the role of visual feedback and its contributions to balance. While increased visual feedback decreases movement while quiet standing, over reliance on it may introduce additional attentional demands on the postural control system (Stoffregen et al., 2000; Lavalle & Cleworth, 2023). The nuanced relationship highlights the need to further explore how other factors such as the attentional demands may have an influence on balance and comprehending how sensory feedback adjusts to various task demands. The following section focuses its shift to investigating the effects of cognitive tasks on postural control during quiet standing and will provide a more detail into the dynamic interaction between attention and postural control.

1.4 Effect of Attention Related Tasks on Balance During Quiet Standing

Dual task paradigms

Dual tasks can be defined as performing two tasks at the same time, such as cognitive and postural tasks, where each task is measured independently, and performance depends on resource allocation and processing capacities (Bayot et al., 2018; Woollacott & Shumway-Cook, 2002; McIsaac et al., 2015). This dual-task framework highlights how engaging in both tasks can either delay or enhance performance, depending on resource allocation and shared processing capacities (Bayot et al., 2018; Woollacott & Shumway-Cook, 2002). Although we perceive postural control as automatic, it competes for cognitive resources with other tasks, potentially leading to interference (McIsaac et al., 2015; Woollacott & Shumway-Cook, 2002; Bayot et al., 2018). This competition can cause a bottleneck effect, where the tasks are processing serially, and so the concurrent demands delay information processing, affecting performance on one or both tasks (Ward et al., 2022; Bayot et al., 2018). Some researchers indicate that cognitive tasks can significantly impact postural control, diverting attention and competing for the neural resources necessary for maintaining balance (Kang & Lipsitz, 2010; Donker et al., 2007).

The capacity- Sharing Model provides deeper insight into the dual-task interferences, suggesting that posture and cognitive task interference arises because of limited attentional resources that must be distributed across both tasks (Bayot et al., 2018). When maintaining balance and performing a cognitive task are performed simultaneously, the supply of attention is divided between them, leading to reduced efficiency in one or both tasks (Bayot et al., 2018). The dividing of resources explains why higher cognitive load may lead to increased postural sway, since fewer resources are available for maintaining balance (Lanzarin et al., 2015). However, when the cognitive demands are low, balance may improve or remain stable as automatic postural control mechanisms take over (Prado et al., 2007; Donker et al., 2007).
Furthermore, the complexity of cognitive and postural tasks play an important role in determining the mechanisms of postural control, in which an increase in the difficulty of the task increases the competition for resources (Prado et al., 2007; Donker et al., 2007). These interactions between cognitive demands and postural control reveal the potential interference, which lays the foundation to further investigate how attention related cognitive tasks specifically affect the ability to maintain balance.

Attention related cognitive task effects on balance

Differences in dual-task performance are notable, with some healthy individuals maintaining posture with minimal sway during cognitive tasks (Donker et al, 2007; Prado et al, 2007). However, tasks that heavily engage working memory such as numeric tasks or those that require external focus, can increase postural sway, highlighting the complex role of attention in postural control (Woollacott & VanderVelde, 2008). For instance, research has shown that when performing mental tasks, it typically leads to an increase in sway amplitude, as cognitive resources divert from maintaining balance (Lanzarin et al., 2015).

Cognitive stress from tasks like arithmetic (subtracting by 3's) can particularly affect sway in the medio-lateral (ML) direction, reflecting shifts in postural stiffness and control strategy (Kang & Lipsitz, 2010). This variation in sway suggests a prioritization mechanism within the central nervous system (CNS), as it adjusts postural responses differently across AP and ML directions based on task demands (Kang & Lipsitz, 2010). Interestingly, increased sway is not always disadvantageous; in some contexts, it can be beneficial and sometimes necessary to be able to explore the surroundings and gather relevant sensory information. Through subtle movements, individuals can gather cues from the environment and assess external conditions to make adaptive postural adjustments to be able to maintain upright stance (Riley et al., 1997).

Visual attention may also play a crucial role in postural control. For example, optic flow can help reduce sway, but cognitive distractions can disrupt this balance (Stoffregen et al, 2000). The type and difficulty of visual tasks significantly influence postural sway, suggesting that the demands of visual attention, rather than just the act of looking, are essential in determining postural control dynamics. With visual search tasks, participants aimed to strengthen postural control, explaining reduced sway (Stoffregen et al, 2000). This understanding of dual-task interactions emphasizes the relationship between cognitive load, visual attention, and postural control, and it highlights the need for further research into the different conditions that affect postural control.

Automatic and conscious postural control during dual tasks

The complexity of dual-task scenarios that involve cognitive and postural demands affect performance, depending on whether individuals manage the tasks automatically or consciously (Nafati & Vuillerme, 2011). Directing attentional resources toward balance often leads to more conscious control, which can interfere with the automatic processes to maintain upright stance

(Roerdink et al., 2011; Wulf et al., 2001). When trying to remain upright becomes a conscious role, the body becomes less adaptable, tightened and controlled, resulting in small, more frequent adjustments that make it difficult to maintain balance (Cavanaugh et al., 2007; Stergiou & Decker, 2011). This aligns with the Constraint Action Hypothesis (CAH), which suggests that consciously trying to control movement can create interference with the natural, automatic adjustments required to maintain balance (Wulf et al., 2001). When the postural control is automatic, the body can make small, flexible movements to help balance efficiently. However, when the individuals overthink their movements, it leads to a more rigid, constrained control system, leading to reduced adaptive control (Masters & Maxwell 2008). SampEn findings support this, indicating that a more automatic control system means low constraint, allowing for random sway adjustments, while a constrained control system may lead to stiff inefficients movements, making balance more difficult to maintain (Cavanaugh et al., 2007; Stergio & Decker, 2011).

In some cases, engaging in a cognitive task can enhance automatic postural control by diverting attention away from controlling upright stance, leading to more automatic adjustments. However, consciously focusing on decreasing sway impacts postural control, leading to an increase in postural sway (Nafati & Vuillerme, 2011). When attention is towards performing a cognitive task, postural adjustments may become more relaxed and flexible, reducing pressure on postural control system (Cavanaugh et al., 2007).

Cognitive task difficulty also plays a role in balance. As cognitive load increases, individuals may have difficulty in maintaining focus on both the cognitive and postural tasks, resulting in inconsistent shifts between the cognitive task and maintaining balance (Lajoie et al, 2016; Potvin-Desrochers et al., 2017). Cognitive tasks that require minimal visual information may shift the individual's focus towards consciously controlling their posture, and with less visual cues, they may need to enhance other sensory inputs such as proprioception to maintain balance (Lajoie et al, 2016). In such situations, the body compensates by re-weighting sensory information from the remaining systems, such as somatosensory and vestibular systems, to maintain balance. Even though the body is trying to adjust, it is more difficult because fewer senses are involved (Peterka, 2018; Shumway-Cook & Horak, 1986).

The Movement Specific Reinvestment scale (MSRS) may provide an insight into this dynamic by assessing the tendency to focus on the mechanics of one's movement. Compromised of 20 items across scales for self- consciousness, emotional control, and cognitive failure, high scores on the MSRS are linked to disrupted motor performance, especially under stress, highlighting the influence of cognitive load on motor control (Masters &Maxwell, 2008). Notably, studies have shown that during cognitive tasks, MSRS are often lower, and it could be that as attention shifts towards performing a cognitive task, automatic postural control becomes prominent, supporting the ability to maintain balance (Huffman et al., 2009; Zaback et al., 2015). The complex interplay between cognitive demands and postural control underscores the necessity of good outcomes measures to capture the subtle balance changes that take place during quiet standing, providing a foundation for quantifying balance responses.

1.5 Quantifying balance and its outcome measures in upright stance

Posturography is how we measure postural control. Through posturography, we can gain both objective and subjective insights into quantifying upright stance (Visser et al., 2008). To fully understand and identify postural responses during balance control, variables such as the kinetic, kinematic, and electromyography (EMG) are used to derive outcome measures such as Root mean Square (RMS) and Mean Power Frequency (MPF) (Carpenter et al., 2010). As well, temporal measures have been used to further assess postural responses. These include analyses based on the onset response time and time to peak response, which is quantified as when the response reaches its maximum intensity, and stabilization time, which is the duration required for the body to regain equilibrium after a response (Horak & Nashner, 1986; Macpherson & Inglis, 1993). Faster onset time and time to peak response indicate a more responsive and well-coordinated postural control system (Horak & Nashner, 1986). Additionally, when there is a shorter stabilization time, this suggests more effective balance control (Macpherson & Inglis, 1993). Altogether, these outcome measures that are extracted from kinetic, kinematic, and EMG data comprehensively assess balance behaviour, allowing us to analyze postural control across multiple domains.

Kinetic and Kinematic measures

Kinetic analyses include observing changes in COP displacements via collecting ground reaction forces and moments (Carpenter et al., 2010; Agostini et al., 2020). Kinematic analyses include three-dimensional markers associated with bony landmarks using motion capture. Outcome measures such as amplitude and frequency of displacement to identify postural responses during balance control tasks can be extracted from these kinetic, kinematic (Carpenter et al., 2010).

The outcome measures that help movement during upright stance across time domain and frequency domain include root mean square (RMS) and mean power frequency (MPF). RMS, a form of standard deviation, can summarize COP, HeadPos, or other kinematic data, indicating postural sway amplitude (Bendo et al., 2013). RMS has been frequently used to assess balance behaviours related to changes in visual information availability (Kapteyn et al., 2008). An increased RMS suggests greater displacement and potentially reduced postural control (poorer

COM regulation within BOS) (Kapteyn et al., 2008; Carpenter et al., 2010). MPF is a frequency domain analysis that represents the average power of the harmonic components in the signal's power spectrum, with higher values indicating poorer postural control and increased fall risk (Phinyomark et al., 2012; Visser et al., 2008). Slower rate of body sway may decrease MPF leading to better control intake of sensory information, which allows for better postural control (Visser et al., 2008; Zaback et al., 2019).

To control quiet standing, specific frequency ranges have been linked with different sensory systems (Salsabili et al., 2013). The visual system correlates with slower frequencies of COP displacements, which are usually below 0.1 Hz. The vestibular system works at frequencies under 0.5 Hz, and the somatosensory system correlates with COP displacements along at frequencies around 1 Hz (Salsabili et al., 2013; Taguchi, 1978).

Electromyography (EMG)

Electromyography (EMG) complements the kinetic and kinematic analysis by recording muscle activity, indicating muscular adjustments in response to balance challenges (Carpenter et al., 2010; Agostini et al., 2020). Outcome measures can also be extracted from EMG analyses (Carpenter et al., 2010). EMG, particularly surface EMG (sEMG), offers a non-invasive method to explore muscular contributions to balance-related muscle activity. EMG may show how lower leg muscles, such as the tibialis anterior (TibAnt), medial gastrocnemius (MedGas), and soleus (Sol), coordinate to manage postural sway (Merletti et al., 2001; Disselhorst-K et al., 2009; Allum & Pfalts, 1985). These muscles may play a pivotal role in postural control by adjusting the body's BOS in relation to the ankle joint to maintain balance (Agostini et al., 2020; Merletti et al., 2001; Disselhorst-K et al., 2009; Allum & Pfalts, 1985). Sol and MedGas work synergistically to control plantar flexion TibAnt are responsible for dorsiflexion of the foot (Fok et al., 2021). The activity of these muscles may increase when under postural threat, correlating with increased ankle stiffness (Fok et al., 2021). The muscular coordination and its strategies emphasize the body's adaptive responses to maintain upright stance (Maki & McIlroy, 1997; Zettel et al., 2008; Ting et al., 2009; Keshner et al., 1987). Overall, these outcome measures provide a framework for assessing postural control, laying the groundwork to explore the effects of optic flow gain on attention-related tasks and quiet stance.

1.6 Current Research Gap

Despite existing research on optic flow gain and dual task balance effects, the interplay between optic flow gain adjustments and attention- demanding tasks involving visual cues while maintaining balance remains unexplored. Therefore, the aim of this study was to address a critical gap by examining how changes in optic flow can have an impact on balance while performing cognitive demanding tasks. This research is important because it addresses real-world challenges of maintaining balance while performing tasks that depend on vision- which are common in daily activities, rehabilitation situations and virtual environments. By examining the effects of optic flow on postural control during tasks that depend on vision, this study aims to improve our understanding of the interplay between sensory and attentional demands, with potential implications for fall prevention and rehabilitation.

1.7 Purpose and hypotheses

The objective of this thesis was to investigate the impact of different visual gain scenarios on postural control while engaging in cognitive tasks that require attention, with a particular focus on replicating and extending findings from previous studies. The research question probed how balance is affected across visual optic flow gain conditions and different cognitive attention related tasks, especially one that involves vision.

The three hypotheses that guided this study were:

1- Optic flow gain manipulation in VR would influence balance. As visual gain increases, movement amplitude decreases while frequency increases, indicating a tighter regulation of upright stance (Lavalle & Cleworth, 2023).

2- Cognitive tasks that demand attention during quiet standing will affect balance. Specifically, movement amplitude will decrease in the anterior- posterior direction while increasing in the medial-lateral as shown in prior research (Kang & Lipsitz, 2010; Stoffregen et al., 2000).

3- Optic flow manipulation during dual tasks that require visual information will affect balance. As visual gain increases during a dual task that requires visual information, movement amplitude decreases while frequency increases, indicating tighter regulation of upright stance.

Chapter 2: Methodology

2.1 Participant characteristics

Thirty-one young healthy participants (aged 19-40) were recruited from York University and nearby areas. To be included in the study, participants had to have normal or corrected- to-normal vision and no neurological, vestibular, or musculoskeletal issues affecting balance. The 31 participants were not on any balance impacting medications and completed a written informed consent. Ethical approval was granted by York University's Human Participant's Review Sub-Committee (*Certificate #:* e2019-367), ensuring adherence to the Canadian Tri-Council Research Ethics guidelines.

2.2 Procedure of experiment

The experimental paradigm involved having participants perform tasks in an immersive virtual reality (VR) environment, through HMD (VIVE Pro 2, HTC corporation). This HMD was used to replicate a real- world environment and to create a simulated setting 3.87meters from a virtual target wall (Figure 1B, C). Participants were instructed to stand barefoot on a force plate that captured kinetic data in the form of ground reaction forces and moments, maintaining a posture with arms crossed facing the wall, head forward, and feet width equal to foot length, as illustrated in Figure 1. The procedure was standardized across participants, ensuring uniformity in data collection, and had a spotter present nearby the participants for safety.

The experiment consisted of 15 one-minute standing trials, including 3 practise trials conducted at a standard optic flow gain of 1. Following this, 12 randomized trials were conducted, incorporating three cognitive tasks; control task (stood while looking at the wall in front), arithmetic task (stood while counting backwards by three, starting at a 3-digit number), and visual search task (stood while identifying specific letters in a text block), as illustrated in Figure 1A, B and C. Vizard Python programming (WorldViz) was used to apply optic flow gains of 0.25, 1, 4 and, 16 across conditions which would either reduce or amplify participant's optic flow relative to their head displacement, within the VR. The optic flow gains were selected based on previous literature indicating their effectiveness in modulating postural sway (Lavalle & Cleworth, 2023). Participants sat and rested for 1 minute between trials, during which they completed a self- rated questionnaire known as the Movement Specific Reinvestment Scale, adapted to assess movement consciousness (Appendix-A).

The visual search task involved 4 white boards of each 2.2m x 1.2m in size with randomized set of letters. For each white board, the order of the letters was different and had a letter assigned to it (N, A, S, or P), where participants were asked to count the number of times they saw the specific letter assigned on the white board until their 60-second trial ended. They had to start their letter search starting from the top left to top right of the white board and keep counting all the way to the end of the last row. If they reached the end of the letters, they were instructed to go back up to the first row and continue counting until their 60 second trial ended. The total frequency count of the specific letter and the location of where the participant stopped counting was reported at the end of the 60 second trial to count for accuracy and the number of errors for each trial.

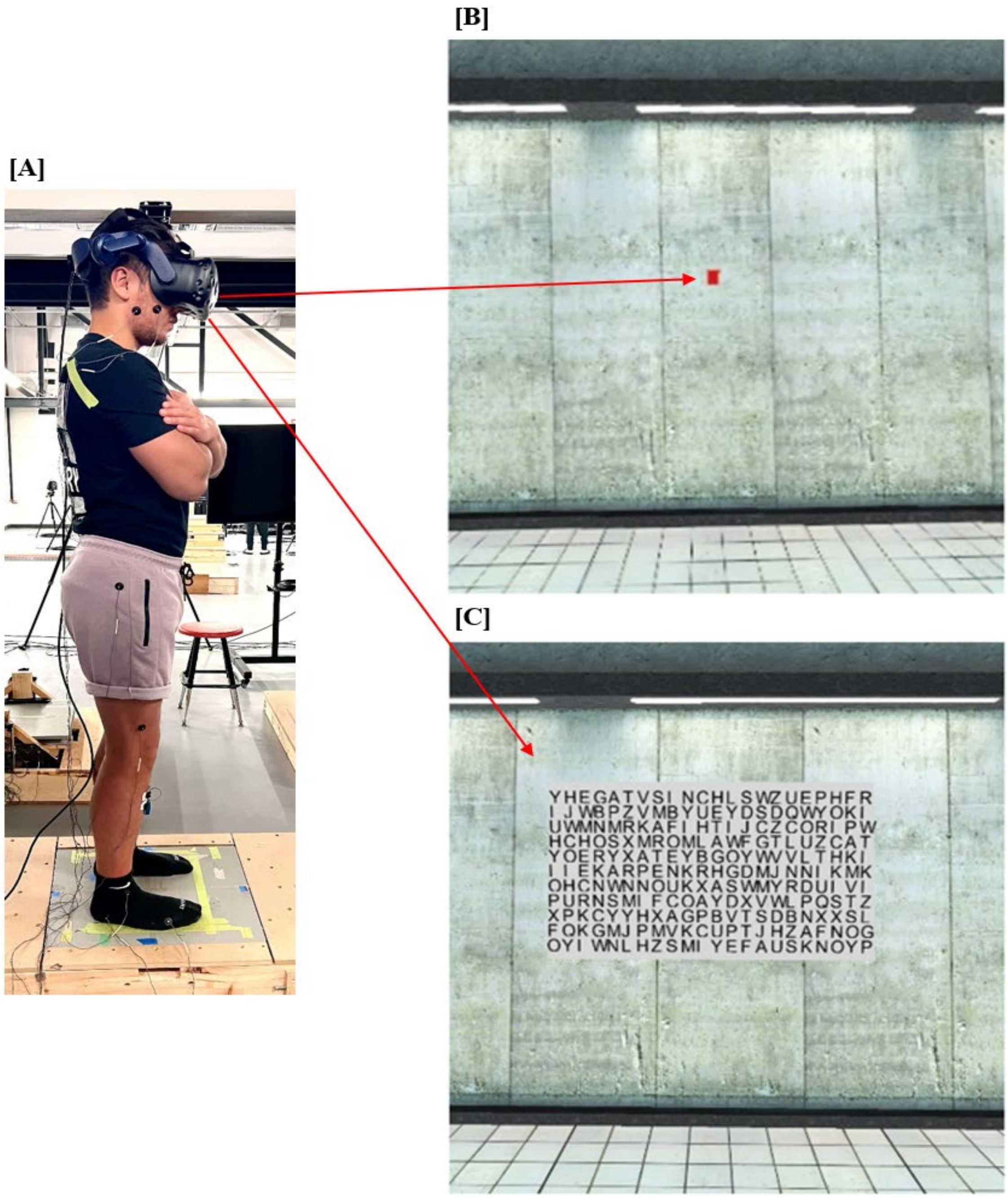

Figure 1. Experimental set up of kinematic model showing the 8 kinematic markers placed on the body segments; Calcaneus (CLC), Base of 5th metatarsal (FthMT),Greater trochanter of femur (GT), Lateral epicondyle of humerus (LE), Lateral condyle of femur (LM), Lateral malleolus of ankle (LMF), Mastoid process (MP), Zygomatic arch (ZY), [B] scene during control and arithmetic task, and [C] scene during visual search.

2.3 Data collection and analysis

EMG, kinetic and kinematic data were recorded through NDI First Principles software (Northern Digital Inc, Waterloo, Ontario, Canada). Following the data collection, the data was processed in MATLAB software (MATLAB R2022b, MathWorks Inc.) and later, along with the MSRS scores were processed in IBM SPSS Statistics 27 (IBM Corporation, Armonk, New York, USA) for data analysis.

Mechanical forces were applied to the force plate, which contained transducers converting the forces into analog voltage signals, to start the data gathering process. Analog signals representing forces and moments were produced by this conversion process, which converted mechanical energy into electrical energy. The Optotrak Data Acquisition Unit (ODAU), which transformed the analog signals into digital data for processing, received these signals together with EMG and kinematic marker position data. The forces (Fx, Fy, Fz) and moments (Mx, My, Mz) data from the force plate, initially collected in voltage units were sampled at 100Hz, the kinematic marker data, measured in millimeters inside the 3D space was also sampled at 100 Hz, and the electromyography data which recorded using the Noraxon Ultium EMG device was recorded at a sampling rate of 2000 Hz. The synchronized forces and moments from the force plate, the kinematic data and the electromyography data were sent to the Optotrak computer, which was running the NDI software. After, all the data was collected and saved by the NDI software in standardized units: meters for displacement and Newtons and Newton- meters for forces and moments.

Movement Specific Reinvestment Scale (MSRS)

In the study, the MSRS contained two subscales; movement self-conscious (MSC) and conscious motor processing (CMP) (10 item questionnaire scored on a 6-point scale; strongly disagree to strongly agree). CMP was the amount of conscious monitoring which was the contemplation of process of movement consistent with reinvestment theory and the MSC was the concern of style related to movement.

Electromyography (EMG)

To track the activity of the Medial Gastrocnemius (Med Gast), Soleus (Sol), and Tibialis Anterior (TA) muscles, electrodes were positioned on the right side of the body. By following recommendations from earlier studies, electrode placement was consistent for every participant during the trials to ensure that they were able to be compared between individuals and trials (Hermens et al., 2000). For TA, electrodes were placed parallel one-third of the way down the line between the medial malleolus and the tibial tuberosity on the surface of the skin, the Med Gast electrodes were placed parallel on the medial of the gastrocnemius, and Sol was placed parallel 2-3 cm below the gastrocnemius (Hermens et al., 2000). Prior to placement of the EMG, the hair of the electrode sites was shaved carefully with razor, cleaned with alcohol wipes, and a gentle abrasive gel was performed to remove dead skin cells to improve signal conductivity prior to the electrodes being applied (Hermens et al., 2000).

Before the main experimental trials, three trials for each muscle were collected from the participant to measure the Maximum Voluntary Contractions (MVC) of every muscle. The signals from all the trials were concatenated to create a single dataset for each muscle. Signals were processed using MATLAB software to determine peak MVC, filter, rectify, and create linear envelopes. To eliminate noise outside of the EMG frequency range characteristic of muscle activity, a dual-pass Butterworth bandpass filter was used, with a high pass at 30 Hz and low pass at 500 Hz (Winter, 2009). The total muscle activity was calculated by rectifying the filtered EMG signal by converting it to absolute values. To capture general trends in muscle activity, the rectified signal was smoothed using a 5th-pass Butterworth low-pass filter set to 3 Hz, resulting in a linear envelope (Zaback et al., 2021; De Luca, 1997). The linear envelope's peak value from the concatenated MVC trials was used to determine the MVC for each of the muscles. The identified peak value of the MVC was used to normalize the EMG signals from each of the experimental (Zaback et al., 2021).

For the experimental trials, EMG data were collected from the same muscles across 12 trials. The EMG signals from these trials were handled in a similar manner like those of the MVC trials, including filtering, rectification, and creating linear envelope. Co-contraction indices (CCI) were calculated for each trial to assess muscular co-activation between TA and SOL, and between TA and Gast, standardizing against MVC (Rudolph et al., 2000; Winter, 2009).

Kinetics

Following data collection with the Optotrak system, MATLAB was used to process the data. A CSV file with the data organized by participant, condition, and gain value was imported. Each force and moment signal were subjected to a dual-pass, 5 Hz low-pass Butterworth filter for signal filtering to preserve frequencies common to COP data. Phase shifts were avoided using a dual-pass technique, and high-frequency noise was removed by using the Butterworth filter to smooth frequency responses inside the passband. Following filtering, calibration matrices and amplifier gain values were used to convert the signals from volts to Newtons and Newton-meters. After that, COP was computed in both AP and ML directions. Bias removal was performed by subtracting the mean from the COP data to allow the data to oscillate around zero.

Kinematics

An optical measurement device known as the Optotrak Certus system was used to track positions and motions of infrared lights emitting diodes known as markers. For kinematic analysis, participants were equipped with the infrared emitting markers which were used to collect their 3D motion capture for kinematic analysis (Optotrak, NDI). Eight markers were placed on the participant's right side of the body at different anatomical landmarks. The locations of the landmarks were calcaneus, base of 5^{th} metatarsal (FthMT), greater trochanter of femur (GT), acromion (AC), lateral condyle of femur (LFC), lateral malleolus of ankle (LM), mastoid process (MP) and, zygomatic arch (ZY) to measure the movements during the task, as illustrated in Figure 1, A.

MATLAB software (MATLAB R2022b, MathWorks Inc.) was used to process the kinematic data after collection. The data was then configured to reflect each participant, task, and gain condition. Each marker's time-series data was imported. Signal processing was performed on the kinematic signals. To smooth the data and eliminate high-frequency noise while preserving the associated frequencies, low pass filter was conducted at 5 Hz using a dual-pass Butterworth filter (Winter, 1980). The mean data from the time series data was used to remove bias. To maintain a realistic movement trajectory, data interpolation was carried out using MATLAB's piecewise cubic Hermite interpolation (pchip) method if any of the infrared markers that were placed on the anatomical landmarks were out of view of the motion capture camera (Optotrak) for shorter than 0.5 seconds. Every marker data position in MATLAB was linked to a distinct anatomical site. To enable direction-specific movement, their coordinated data were divided into y (AP), x (ML), and z (vertical) directions. Each marker's linear movement in the x (ML), y (AP) and z (vertical) planes was measured. Joint angles in the sagittal plane were calculated using angular computations, which created a vector from 2D components. The head, trunk, and thigh's absolute angles with respect to the horizontal were determined using

MATLAB's "atan2d" function. The law of cosine was used to compute the angles of the hip, knee, and ankle joints.

2.4 Quantifying Behaviour

Root Mean Square (RMS) of COP, HeadPos displacement and joint angle was calculated to find the magnitude of fluctuating signals, specifically to quantify movement (Winter, 1990).

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

where n represents the number of data points in the sample, x_i^2 represents each data sample. By squaring each data point, averaging the squares, and then taking the square root of the result, the RMS captures how much movement displacement occurred (Winter, 1990). Mean Power Frequency (MPF) of COP and HeadPos was calculated to find the average frequency of the signal power, specifically to capture the characteristic of the frequency movements (Winter, 1990).

$$\textbf{MPF} = \frac{\sum f \times P(f)}{\sum P(f)}$$

Where $P(f)$ representing the power at each of frequency f, and p represents the power amplitude at frequency. The single value of the MPF represents the average frequency of movement displacement (Winter, 1990). For kinematic variables, absolute and relative joint angles were calculated to find movement displacement. Absolute joint angles were applied to find the orientation of body segment as it rotates around the joint (Winter, 2009).

$$\textbf{Absolute Angle} = \arctan\left(\frac{\Delta y}{\Delta z}\right)$$

Where y and z are the displacements in AP and vertical directions between two points of each segment for the head, trunk, and thigh, reflecting each segment's angle relative to the ground. Relative joint angles were applied to find the angle between two adjacent segments, providing a dynamic view of joint movement during quiet stance (Winter, 2009).

$$\mathbf{Cos}(\boldsymbol{\theta}) = (\frac{a^2 + b^2 - c\hat{}2}{2ab})$$

The law of cosine finds the internal joint angle, where a and b represent the length of the adjacent segments, and c is the distance between the end points of the segments (Winter, 2009). By calculating the absolute and relative joint angles, we can understand the changes in the joint behavior better. Co-contraction Index (CCI) was evaluated between TibAnt and MedGas and between TibAnt and Sol muscle to compare to each of the MVC muscle (Rudolph et al, 2000). EMG_{ANT} is antagonist muscle magnitude activation. EMG_{AG} is agonist muscle magnitude activation.

Formula: $$\mathbf{CCI}\ (\%) = \frac{\mathbf{EMG_{ANT}}}{\mathbf{EMG_{AG}}}\ (\mathbf{EMG_{ANT}} + \mathbf{EMG_{AG}})$$

2.5 Statistical Analysis

After data processing and calculating the outcome measures (RMS, MPF, CCI) in MATLAB, the data was then checked for outliers in Excel using a threshold of the mean plus or minus 2 times the standard deviation, where data points that fell outside this range were flagged as potential outliers. Following the outlier check, the data was imported into IBM SPSS Statistics 27 (IBM Corporation, Armonk, New York, USA) for statistical analysis.

For examining the main effects of conditions (control, arithmetic, and visual search tasks), gain, values (0.25, 1, 4, 16), and the interaction effects of conditions and gains on COP, kinematic, EMG and MSRS variables, a 3x4 repeated measured analysis of variance (RM-ANOVA) was conducted. Despite some deviations from normality in certain datasets, parametric test RM-ANOVA was applied based on its robustness to violations of normality assumptions (Field, 2009).

Assumptions of sphericity for the RM-ANOVA were assessed using the Mauchley's sphericity test. For any violations of sphericity, Greenhouse-Geisser corrections were applied to adjust the degrees of freedom, maintaining the validity of the analysis. Statistical significance was set at $p < 0.05$.

Post hoc analysis with Sidak corrections were performed to address multiple comparisons within the main effects of gain and condition. If the main effects were significant ($p<0.05$), Sidak-corrected post hoc comparisons were conducted to know the specific gain and condition differences.

In case of significant interaction effects between cognitive task and gain, a one-way ANOVA for each factor was conducted independently. Specifically, a 1x3 one-way ANOVA was conducted across cognitive tasks for each gain condition, and a 1x4 one-way ANOVA conducted across gain conditions for each cognitive task. These interaction effects were explored with post hoc tests and Sidak corrections, to locate where the significant differences within each main effect were. Furthermore, two 1x4 one-way ANOVAs were conducted across gain conditions to assess the number of errors that the participants made for the arithmetic task and visual search task. A summary of the statistical analyses for each of the outcome measures are reported in Tables 1, 2, 3, 4 and 5.

Chapter 3: Results

A total of thirty-one participants were included in the analysis for kinetics and HeadPos data. Two participants were excluded from the EMG analysis, as well as from kinematic measures of shoulder, trunk and hip data, resulting in a final sample of 29 participants for those analyses. Additionally, one participant was excluded from the ankle analysis, leaving a final sample of 30 participants.

3.1 Kinetics

COP AP RMS

For COP AP RMS, a significant main effect of gain was observed (p<0.001; Table 1), where post hoc results showed a decrease when gain was set at 16 compared to 0.25 (p<0.001) and 1 (p=0.008), and 4 compared to 0.25 (p=0.002) (Figure 2A). An interaction effect between gain and conditions observed (p=0.019; Table 1) (Figure 2C). There was a significant main effect of condition when gain was set at 0.25 (p=0.030; Table 2A) and 4 (p<0.014; Table 2A). When the gain was set at 0.25, the amplitude was smaller during the control task compared to the arithmetic task conditions (p=0.021) (Figure 3C). When the gain was set at 4, the amplitude was smaller during the control task compared to visual search task conditions (p=0.015) (Figure 3C). There was a significant main effect of gain during arithmetic task (p<0.001; Table 2B), and visual task (p<0.001; Table 2B). During arithmetic task, the amplitude was smaller at gains of 16 compared to 0.25 (p<0.007). During visual search task, the amplitude was smaller at the gains of 16 compared to gain of 0.25 (p<0.001) and 1 (p=0.0100), and 4 compared to 0.25 (p=0.002) and 1 (p=0.001) (Figure 3C). However, there was no significant main effect of condition (p=0.152; Table 1) (Figure 2B).

COP ML RMS

For COP ML RMS, a significant main effect of gain was observed (p<0.001; Table 1), where post hoc results showed a decrease when gain was set at 16 compared to 0.25 (p=0.005) and 1 (p<0.001) (Figure 3A). Significant main effects of condition were observed (p=0.006; Table 1), where post hoc results showed that the amplitude was larger during arithmetic task conditions compared to control conditions (p=0.012) and was larger during visual search task conditions compared to control conditions (p=0.021; Table 1) (Figure 3B). An interaction between condition and gain was observed (p=0<0.007; Table 1). There was a significant main effect of condition when gain was set at 0.25 (p<0.001; Table 2A) and 1(p<0.004; Table 2A). When the gain was set at 0.25, the amplitude was smaller during the control task compared to the visual search task conditions (p=0.001), and arithmetic task conditions (p=0.004; Table 2A) (Figure 3C). When the gain was set at 1, the amplitude was smaller during the control task compared to visual search task conditions (p=0.003), and arithmetic task conditions (p=0.010; Table 2A) (Figure 3C). There was a significant main effect of gain during visual search task (p<0.001; Table 2B). During visual search task, the amplitude was smaller at the gains of 4 compared to gain of 1(p=0.001), and 16 compared to 0.25 (p=0.003) and 1 (p=0.002) (Figure 3C). There was a significant main effect of gain during arithmetic task (p<0.020; Table 2B). During arithmetic task, the amplitude was smaller at the gains of 16 compared to gain of 1(p=0.030), and 16 compared to 0.25 (p=0.001) (Figure 3C).

COP AP MPF

For COP MPF AP, a significant main effect of gain was observed (p=0.009; Table 1), where post hoc results showed an increase in frequency when gain was set at 16 compared to 0.25 (p=0.005), when gain was set at 4 compared to 0.25 (p=0.013), and when gain was set at 1 compared to 0.25 (p=0.044)(Figure 4A). Significant main effect of condition was found

($p<0.001$; Table 1), where post hoc results showed that the frequency was lower during visual search task compared to arithmetic task conditions ($p<0.004$) and was larger during arithmetic task compared to control task conditions ($p<0.001$), and lower during control task compared to visual search task conditions ($p=0.001$) (Figure 4B). An interaction between condition and gain was observed ($p=0<0.023$; Table 1). There was a significant main effect of condition when gain was set at 1 ($p<0.001$; Table 2A), 4 ($p=0.047$), and 16 ($p<0.001$). When the gain was set at 1, the amplitude was smaller during the control task compared to the visual search task conditions ($p<0.001$), and arithmetic task conditions ($p<0.001$; Table 2A) (Figure 3C). When the gain was set at 4, the interaction effects did not show where the comparisons existed. When the gain was set at 16, the amplitude was smaller during the control task compared to arithmetic task conditions ($p<0.001$; Table 2A) (Figure 4C). There was a significant main effect of gain during arithmetic task ($p=0.011$; Table 2B), and visual search task ($p=0.014$; Table 2B). During arithmetic task, the amplitude was smaller at the gains of 0.25 compared to gain of 16 ($p=0.007$). During visual search task, the amplitude was smaller at the gain of 0.25 compared to gain of 1($p=0.002$) (Figure 4C).

COP ML MPF

For COP ML MPF, a significant main effect of condition was found ($p=0.033$; Table 1), where post hoc results showed an increase in frequency during arithmetic task compared to control task conditions ($p=0.041$) (Figure 5B). An interaction between condition and gain was observed ($p=0<0.038$; Table 1). There was a significant main effect of gain during control task ($p=0.047$), however, the pairwise comparison did not show where the difference existed. There was a significant main effect of condition when gain was set at 16 ($p=0.003$; Table 2A). The amplitude was smaller during the control task compared to the arithmetic task conditions (p<0.001; Table 2A) (Figure 5C). No significant main effect of gain (p=0.082; Table 1) (Figure 5A).

3.2 Kinematics

For the shoulder RMS, trunk RMS, and hip RMS, the results were analysed from 29 participants. Ankle RMS results were calculated from 30 participants. Knee RMS and thigh RMS were analyzed from 31 participants.

HeadPos AP RMS

For Head AP RMS, a significant main effect of gain was observed (p<0.001; Table 1), where post hoc results showed a decrease when gain was set at 16 compared to 0.25 (p<0.001) and 1 (p=0.003), and when gain was set at 4 compared to 0.25 (p=0.001) and 1 (p=0.029) (Figure 6A). An interaction effect between condition and gain was significant (p=0.005; Table 1).

There was a significant main effect of condition when gain was set 0.25 (p<0.002; Table 2A) and 1 (p<0.016; Table 2A). When the gain was set at 0.25, the amplitude was smaller during the control task compared to the visual search task conditions (p<0.009) (Figure 6C), and the amplitude was smaller during the arithmetic task compared to visual search task (p=0.036) (Figure 6C). When the gain was set at 1, the amplitude was smaller during the control task compared to the visual search task conditions (p<0.016) (Figure 6C). There was a significant main effect of gain during the arithmetic task (p=0.003; Table 2B) and the visual search task (p<0.001; Table 2B) (Figure 6C). During the arithmetic task, the amplitude was smaller at the gain of 16 compared to 0.25 (p=0.010). During the visual search task, the amplitude was smaller at the gains of 16 compared to 0.25 (p<0.001) and 1 (p=0.007), and at gains of 4 compared to 0.25 (p<0.001) and 1 (p<0.006) (Figure 6C). There was significant main effect of condition for the amplitude of HeadPos in the AP direction, but it did not show where the significance exists (p=0.020; Table 1) (Figure 6B).

HeadPos ML RMS

For HeadPos ML RMS, a significant main effect of gain was observed (p<0.001; Table 1), where post hoc results showed a decrease when gain was set at 16 compared to 0.25 (p<0.001) and 1 (p<0.001), and 4 (p=0.048) (Figure 7A). Significant main effect of condition was observed (p=0.001: Table 1), where post hoc results showed that the amplitude was larger during visual search task compared to control conditions (p<0.001) (Figure 7B). An interaction effect between condition and gain was observed (p=0<001; Table 1). There was significant main effect of condition when gain was set at 0.25 (p<0.001; Table 2A) and 1(p<0.001; Table 2A). When gain was set at 0.25, the amplitude was smaller during the control task compared to the visual search conditions (p<0.001) (Figure 7C). When the gain was set at 1, the amplitude was smaller during the control task compared to visual search task conditions (p<0.001) (Figure 7C). There was a significant main effect of gain during arithmetic conditions (p<0.001, Table 2B) and visual search task conditions (p<0.001; Table 2B). During arithmetic task, the amplitude was smaller at the gains of 16 compared to 0.25 (p=0.006) and 1 (p= 0.001). During visual search task, the amplitude was smaller at the gains of 16 compared to gains of 0.25 (p<0.001) and 1 (p<0.001), and at the gains of 4 compared to 1 (p=0.013) (Figure 7C).

HeadPos AP MPF

For HeadPos AP MPF, significant main effect of condition was observed (p<0.001; Table 1), where post hoc results showed an increase in frequency during the visual search task compared to the control task conditions (p<0.001) and was larger during the arithmetic task compared to the control task conditions (p<0.001) (Figure 8B). There was no significant main effect of gain observed (p=0.438; Table 1) (Figure 8A) and no interaction effect was observed between condition and gain (p=0.324; Table 1) (Figure 8C).

HeadPos ML MPF

For the MPF of HeadPos ML, a significant main effect of condition was observed (p<0.001; Table 1). The differences were noticed between the control and the visual search task conditions (p<0.001), and between the control and arithmetic condition (p<0.001), with the visual condition having the greater frequency compared to the control condition, and it was lowest in the control condition compared to both the arithmetic and visual conditions (Figure 9B). There was no significant main effect of gain observed (p=0.105; Table 1) (Figure 9A), and no interaction effect observed between condition and gain (p=0.460; Table 1) (Figure 9C).

Shoulder AP RMS

For linear displacement of Shoulder AP, a significant main effect of gain was observed (p<0.001; Table 1), where post hoc results showed a decrease in amplitude when gain was set at 16 compared to 0.25 (p<0.001) and 1 (p=0.001), and when gain was set at 4 compared to 0.25 (p=0.002) and 1 (p=0.037) (Figure 10A). There were no significant main effects of condition (p=0.167; Table 1) (Figure 10B), and no interaction effects were observed between condition and gain (p=0.169; Table 1) (Figure 10 C).

Shoulder ML RMS

For linear displacement of Shoulder ML, a significant main effect of gain was observed (p<0.001; Table 1), where post hoc results showed a decrease when gain was set at 16 compared to 0.25(p<0.001), 1 (p<0.001) (Figure 11A). An interaction effect between condition and gain was observed (p=0.005; Table 1). There was a significant main effect of condition when gain was set at 0.25 (p=0.017; Table 2A) and 1 (p=0.005; Table 2A) (Figure 11C). When gain was set at 0.25, the amplitude was smaller during the control task compared to the visual search task conditions ($p=0.002$) (Figure 11C). When gain was set at 1, the amplitude was smaller during the control task compared to the visual search task conditions ($p=0.003$) (Figure 11C). There was significant main effect of gain during arithmetic task ($p<0.001$; Table 2B) and visual search task conditions ($p<0.001$; Table 2B). During arithmetic task, the amplitude was smaller at the gains of 16 compared to 0.25 ($p=0.018$) and 1 ($p=0.003$) (Figure 11C). During visual search task, the amplitude was smaller at the gains of 16 compared to gains of 0.25 ($p=0.001$) and 1 ($p<0.001$), and smaller at the gains of 4 compared to 0.25 ($p=0.027$) and 1 ($p=0.020$) (Figure 11C). There was no significant main effect of condition observed ($p=0.210$; Table 1) (Figure 11B).

Trunk Angle RMS

For mean of angular displacement of Trunk segment, a significant main effect of gain observed ($p<0.001$; Table 1), where post hoc results showed a decrease in amplitude when gain was set at 16 compared to 0.25 ($p=0.002$) and 1 ($p<0.001$), and when gain was set at 4 compared to 1 ($p=0.041$) (Figure 12A). A significant main effect of condition was observed ($p=0.050$; Table 1) (Figure 12B), where post hoc results showed a decreased in amplitude during control task compared to visual search task ($p=0.045$) (Figure 12B). There was no interaction effects observed between condition and gain ($p=0.255$; Table 1) (Figure 12C).

Hip Angle RMS

For mean of angular displacement of Hip joint, a significant main effect of gain was observed ($p=0.002$; Table 1), where post hoc results showed a decrease in amplitude when gain was set at 16 compared to 0.25 ($p=0.002$), 1 ($p=0.020$), and when at 4 compared to 1 ($p=0.017$) and 4 ($p=0.035$) (Figure 13A). A significant main effect of condition was observed ($p=0.030$;

Table 1) however, the post hoc results did not indicate significance (Figure 13B). There was an interaction effects observed between condition and gain (p=0.040; Table 1) (Figure 13C).

Thigh Angle RMS

For mean of angular displacement of Thigh segment, a significant main effect of gain was observed (p<0.001; Table 1), where post hoc results showed a decrease in amplitude when gain was set at 16 compared to 0.25 (p<0.001) and 1 (p=0.005), and when gain was set at 4 compared to 0.25 (P=0.024) (Figure 14A). There was an interaction effects observed between condition and gain (p=0.006; Table 1) (Figure 14C). There was a significant main effect of condition when gain was set at 0.25 (p=0.026; Table 2A) (Figure 14C). However, the post hoc results did not indicate significance. There was significant main effect of gain during arithmetic task (p=0.001; Table 2B) and visual search task conditions (p<0.001; Table 2B). During arithmetic task, the amplitude was smaller at the gains of 16 compared to 0.25 (p=0.002) and 1 (p=0.038), and at gain of 4 compared to 1 (p=0.012) (Figure 14C). During visual search task, the amplitude was smaller at the gains of 16 compared to gains of 0.25 (p=0.001) and 1 (p=0.003), and smaller at the gains of 4 compared to 0.25 (p=0.005) and 1 (p=0.035) (Figure 14C). No significant main effects of condition (p=0.598; Table 1) (Figure 14B).

Knee Angle RMS

For mean of angular displacement of the Knee joint, a significant main effect of gain was observed ((p<0.001; Table 1), where post hoc results showed a decrease in amplitude when gain was set at 16 compared to 0.25 (p<0.001) and 1 (p<0.001) (Figure 15A). No significant main effects of condition (p=0.304; Table 1) (Figure 15B), or interaction effects were observed between condition and gain (p=0.214; Table 1) (Figure 15C).

Ankle Angle RMS

For mean of angular displacement of Ankle joint, a significant main effect of gain was ($p<0.001$; Table 1), where post hoc results showed a decrease in amplitude when gain was set at 16 compared to 0.25 ($p=0.001$) and 1 ($p=0.011$) (Figure 16A). A significant main effect of condition was observed ($p=0.029$; Table 1) however, the post hoc results did not indicate significance (Figure 16B). An interaction effect between condition and gain was significant ($p<0.001$; Table 1). There was a significant main effect of condition when the gain was set at 0.25 ($p=0.007$; Table 2A) and 4 ($p=0.004$; Table 2A) (Figure 16C). When gain was set at 0.25, the amplitude was smaller during control task compared to arithmetic task conditions ($p=0.026$) and visual search task ($p=0.040$) (Figure 16C). When the gain was set at 4, the amplitude was smaller during the visual search task compared to the control task conditions ($p=0.025$) and the arithmetic task conditions ($p=0.003$) (Figure 16C). There was significant main effect of gain observed during the arithmetic task ($p=0.004$; Table 2B) and the visual search task conditions ($p<0.001$; Table 2B). During arithmetic task, the amplitude was smaller at the gains of 16 compared to 0.25 ($p=0.003$) and 4 ($p=0.040$) (Figure 16C). During visual search task, the amplitude was smaller at the gains of 16 compared to 0.25 ($p=0.023$), and when gain was at 4 compared to 0.25 ($p=0.003$) and 1 ($p=0.002$) (Figure 16C).

3.3 Muscle Activity

For TA-GAST Co-contraction Index (CCI), a significant main effect of gain was observed ($p=0.032$; Table 1), however, the post hoc results did not indicate significance. No significant main effects of condition ($p=0.537$; Table 1), or interaction effects were observed between condition and gain ($p=0.706$; Table 1) (Figure 17A). For TA-SOL, no significant main effects of gain ($p=0.158$; Table 1) or condition ($p=0.467$; Table 1), and no interaction effects were observed between condition and gain ($p=0.193$; Table 1) (Figure 17B). There were no significant main effects or interactions for gain and/or condition for other EMG variables (Table 1) (Figure 18).

3.4 Movement Specific Re-investment Scale (MSRS)

For MSRS mean scale scores, an interaction effect between condition and gain were observed ($p<0.001$; Table 3). Post-hoc results showed that for all the gain values (0.25, 1, 4 and 16), significant differences were between the control and visual task conditions, and between the control and arithmetic conditions (Figure 19). During controlled conditions, there was greater MSRS mean values compared to arithmetic and visual conditions (Figure 19). When gain was at 0.25, the mean score was higher during control tasks compared to arithmetic task ($p=0.002$) and visual search task conditions ($p=0.003$). When gain was at 1, the mean score was higher during control tasks compared to arithmetic task ($p=0.005$) and visual search task conditions ($p=0.004$). When gain was at 4, the mean score was higher during control tasks compared to arithmetic task ($p=0.005$) and visual search task conditions ($p<0.001$). When gain was at 16, the mean score was higher during control tasks compared to arithmetic task ($p=0.005$) and visual search task conditions ($p=0.016$) (Figure 19).

3.5 The accuracy- error during the arithmetic and visual search task

During the arithmetic task, there were no significant main effects of gain observed ($p=0.472$; Table 5) (Figure 20). During the visual search task, there was a significant main effect of gain observed ($p=0.039$, Table 5), however the post-hoc results did not indicate significances(p's>0.05) (Figure 21).

The RMS across experimental trials (AP)

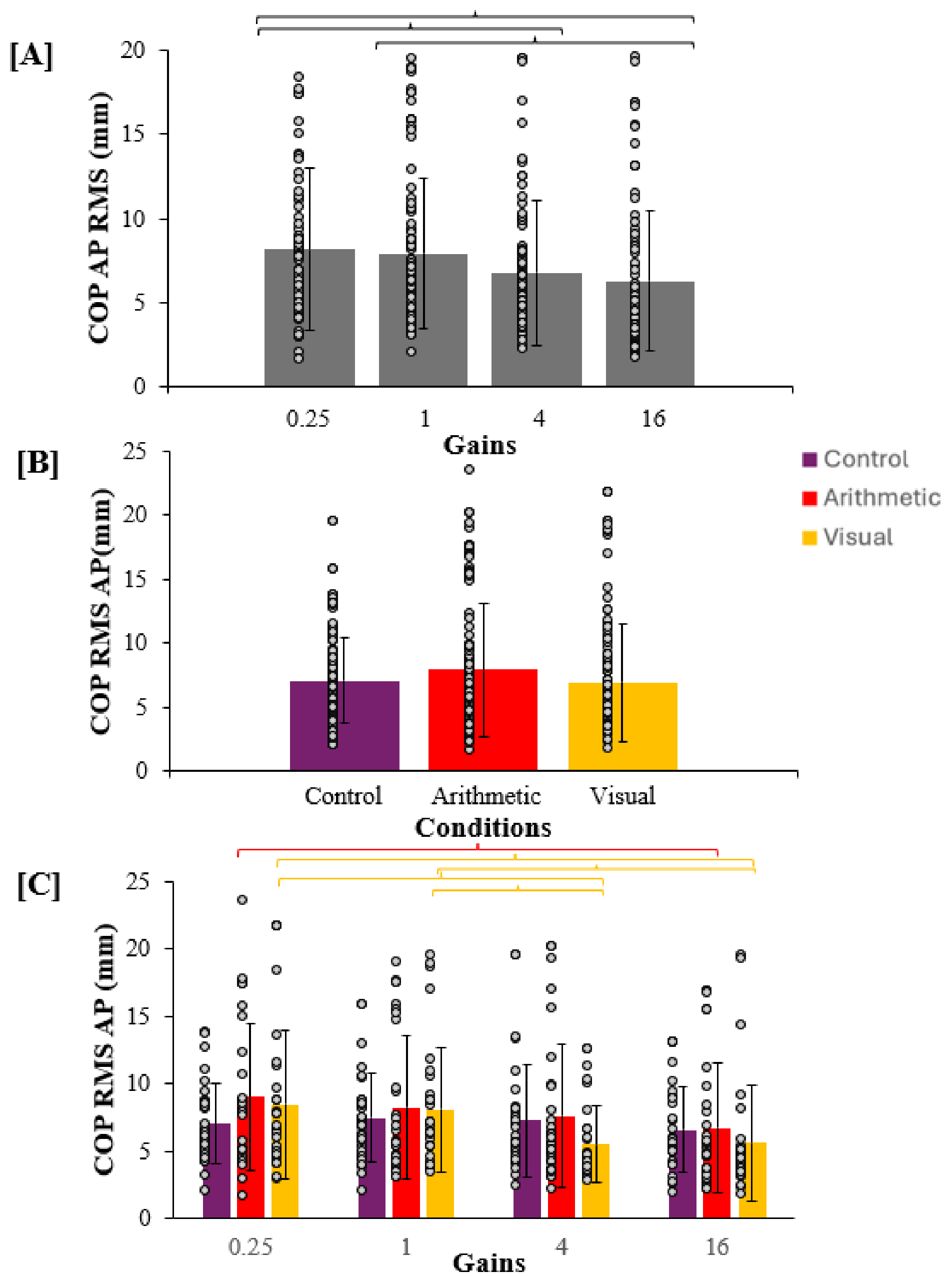

Figure 2. COP RMS in the AP direction. Figure A illustrates main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

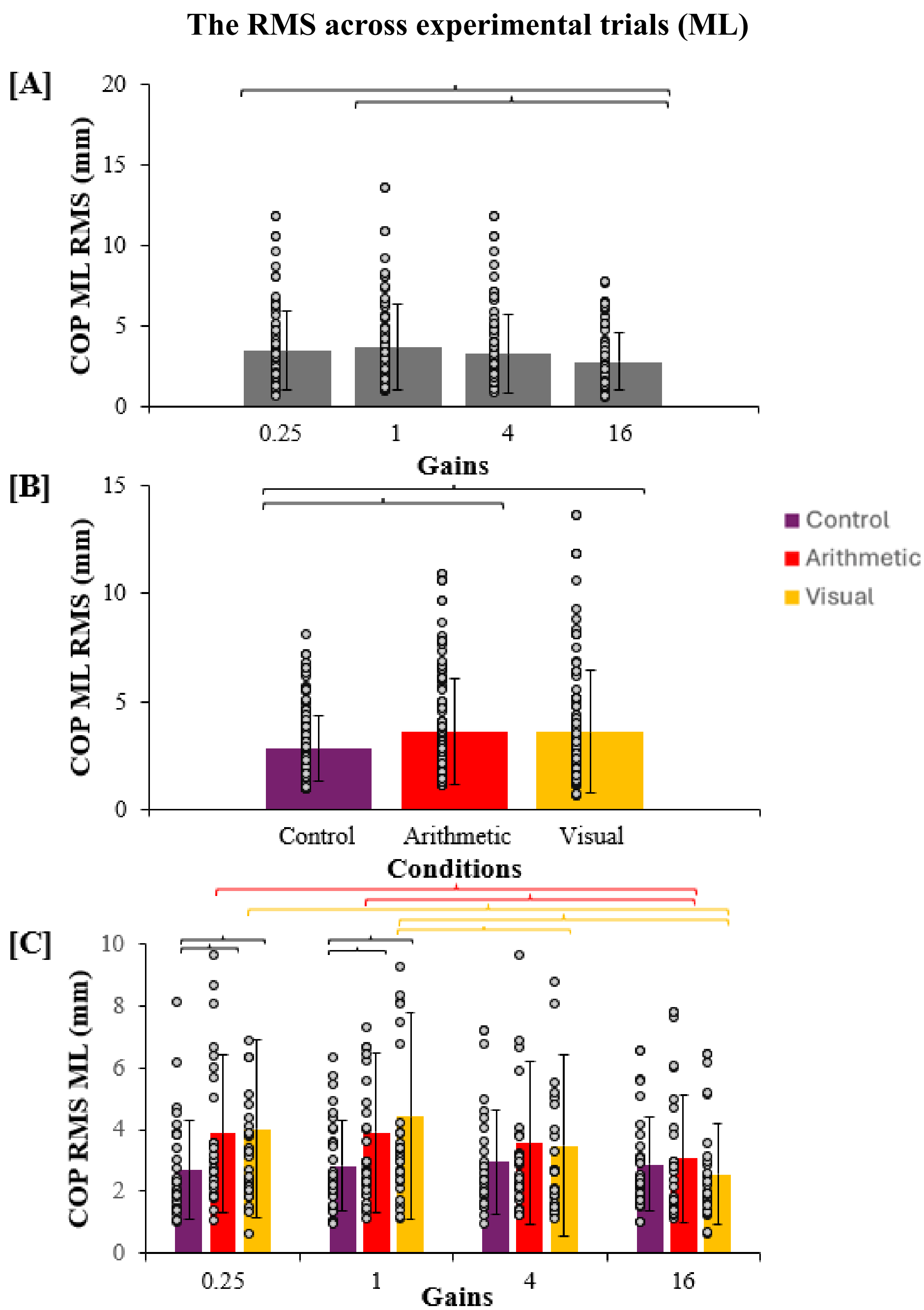

Figure 3. COP RMS in the ML direction is observed. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Figure C illustrates interaction effects between the gain values and task conditions. Yellow lines indicate effects between gain values within visual search task, and black lines indicate effects between conditions within gain values ($p < 0.05$, ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

The MPF across experimental trials (AP)

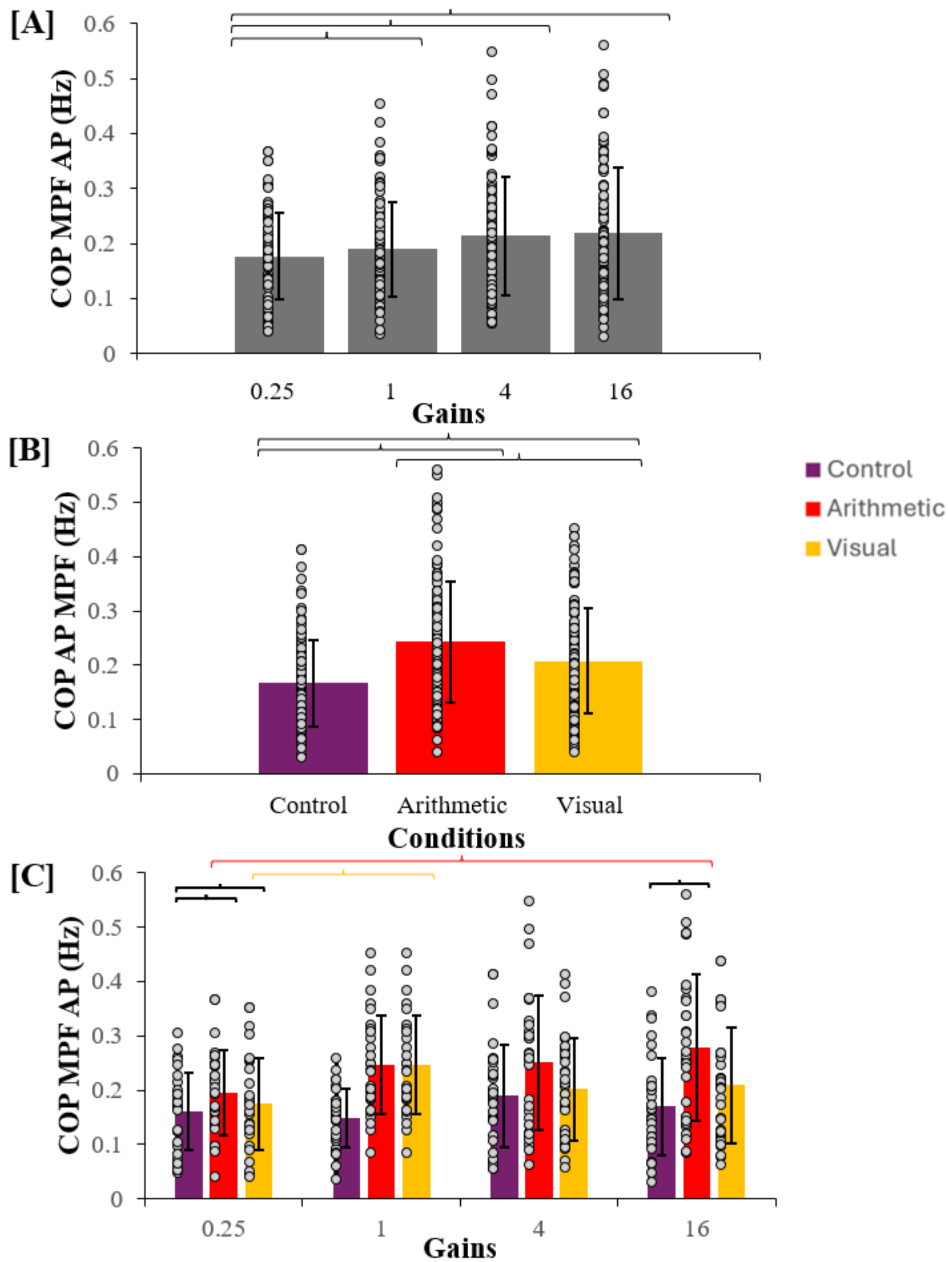

Figure 4. COP MPF in the AP direction. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

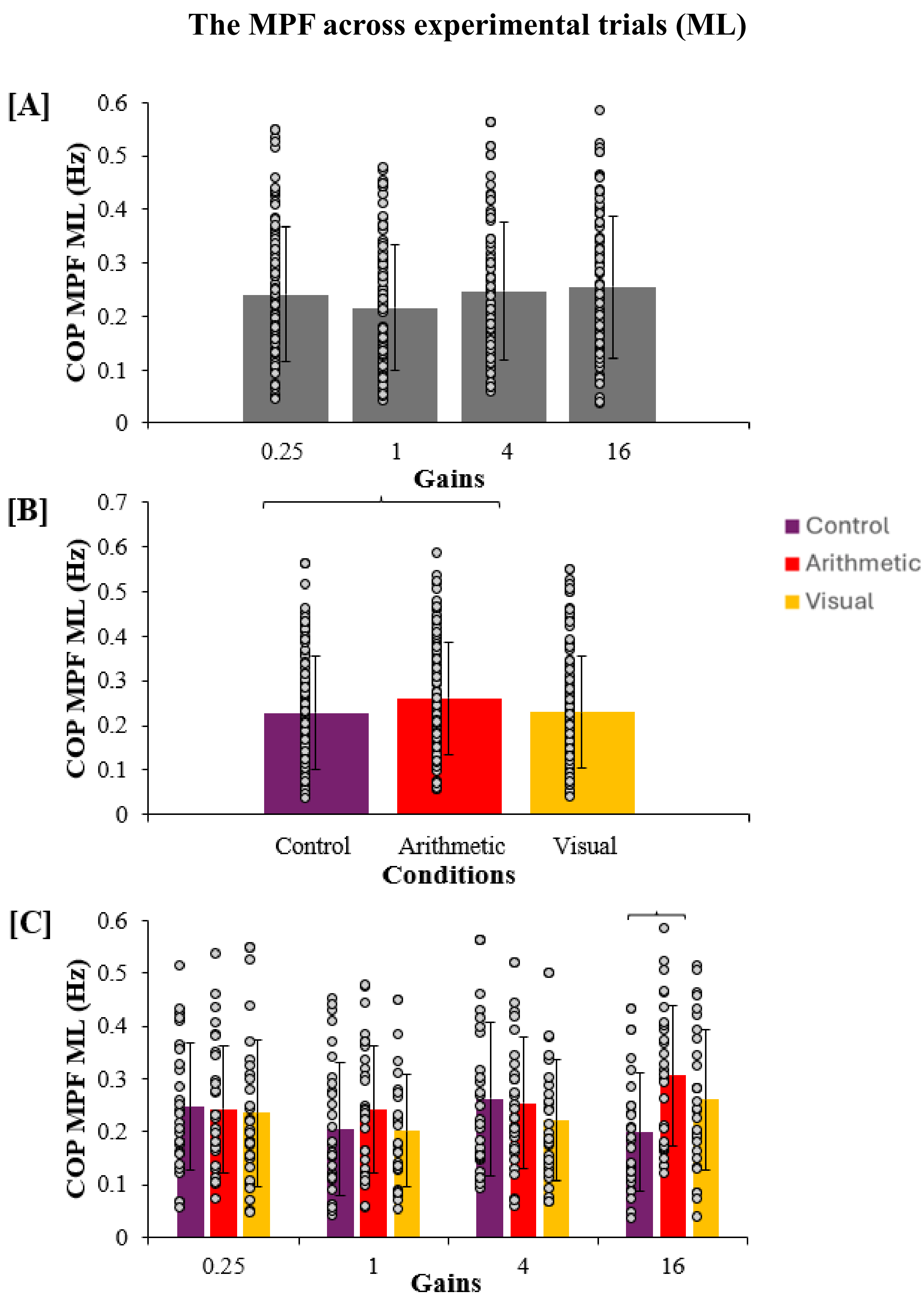

Figure 5. COP MPF in the ML direction. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

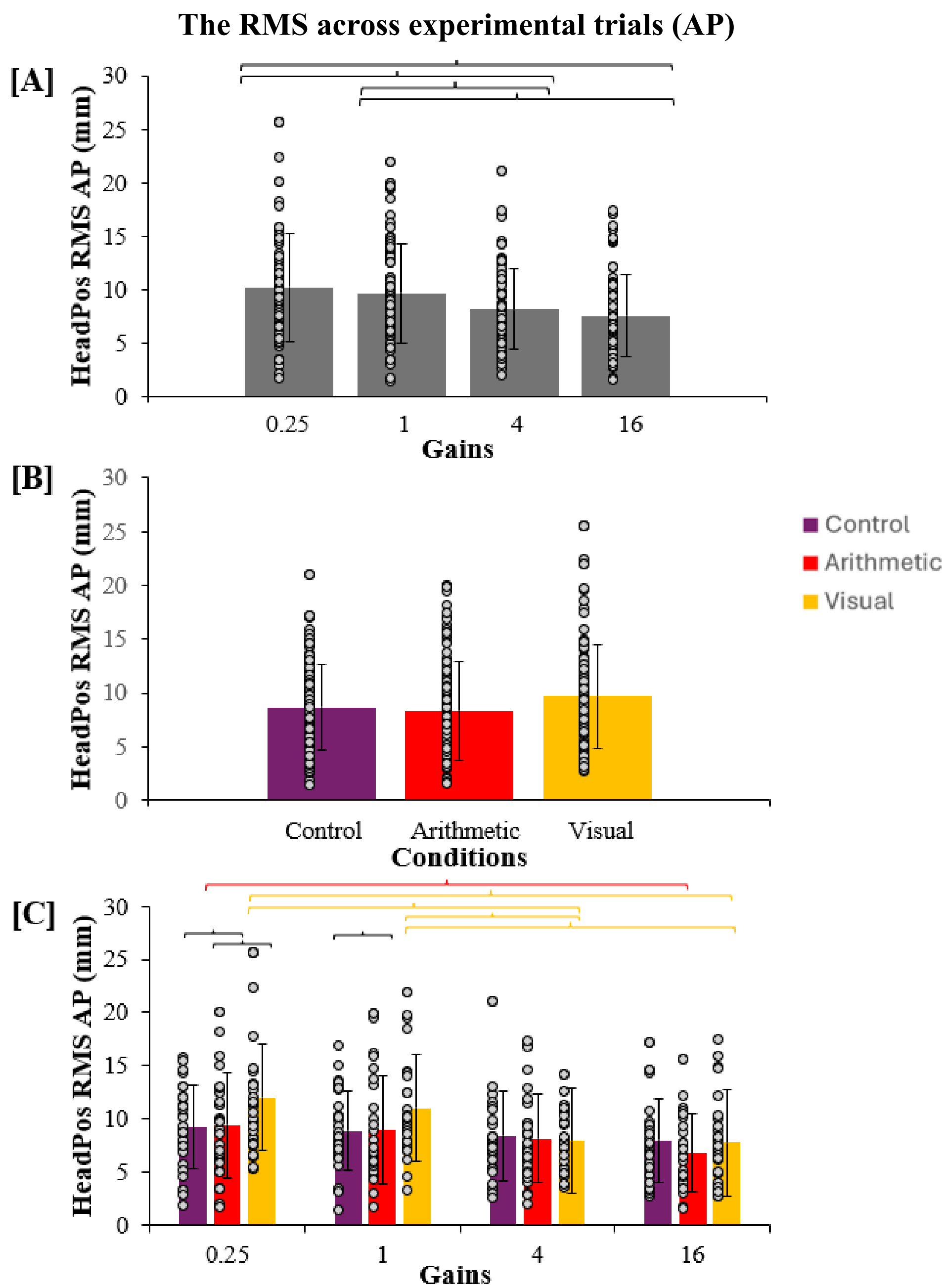

Figure 6. HeadPos RMS in the AP direction. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Figure C illustrates interaction effects between the gain values and task conditions. Yellow lines indicate effects between gain values within visual search task, and red line indicate effects between gain values within arithmetic task, and black lines indicate effects between conditions within gain values ($p < 0.05$, ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

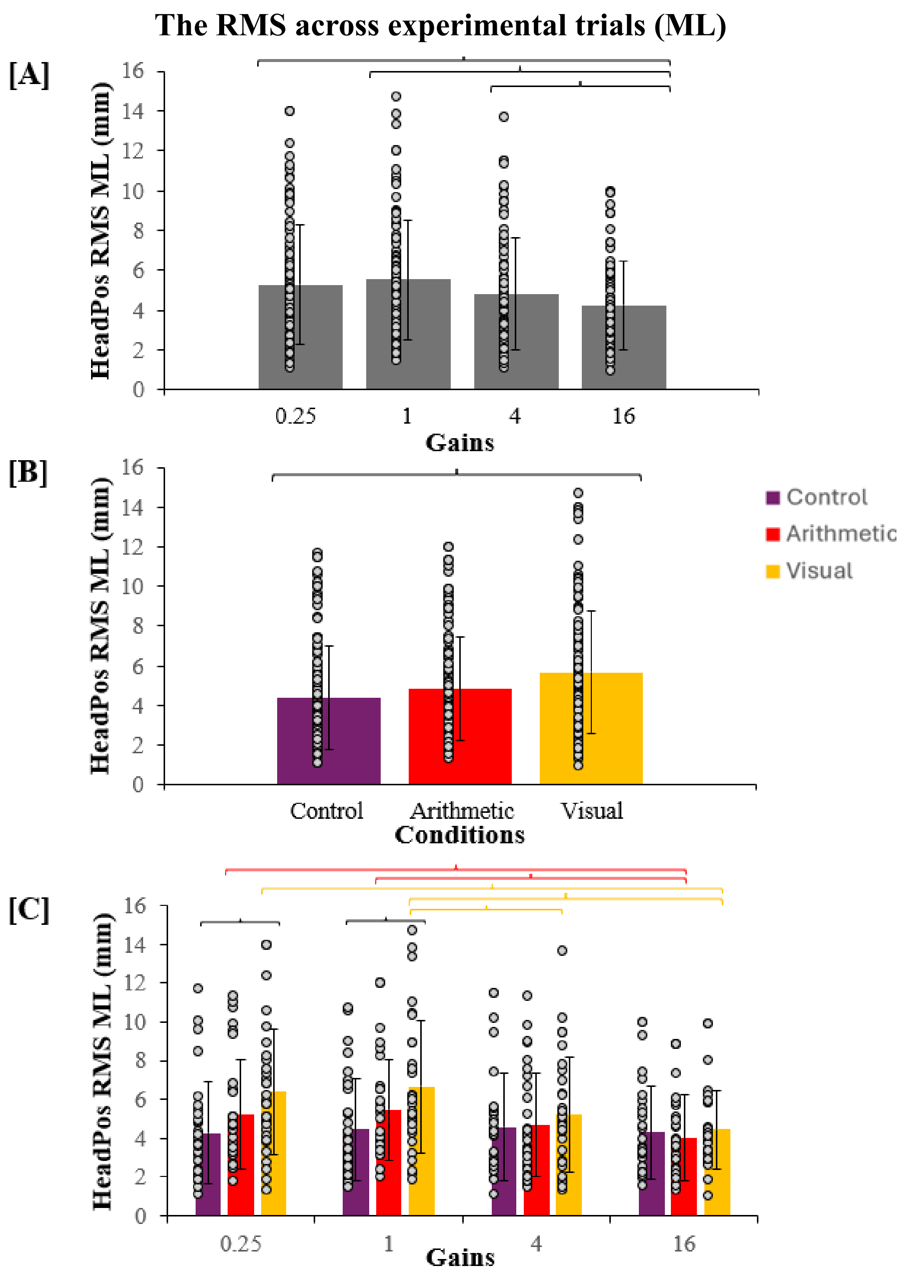

Figure 7. HeadPos RMS in the ML direction. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Figure C illustrates interaction effects between the gain values and task conditions. Yellow lines indicate effects between gain values within visual search task, and red lines indicate effects between gain values within arithmetic task, and black lines indicate effects between conditions within gain values ($p < 0.05$, ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

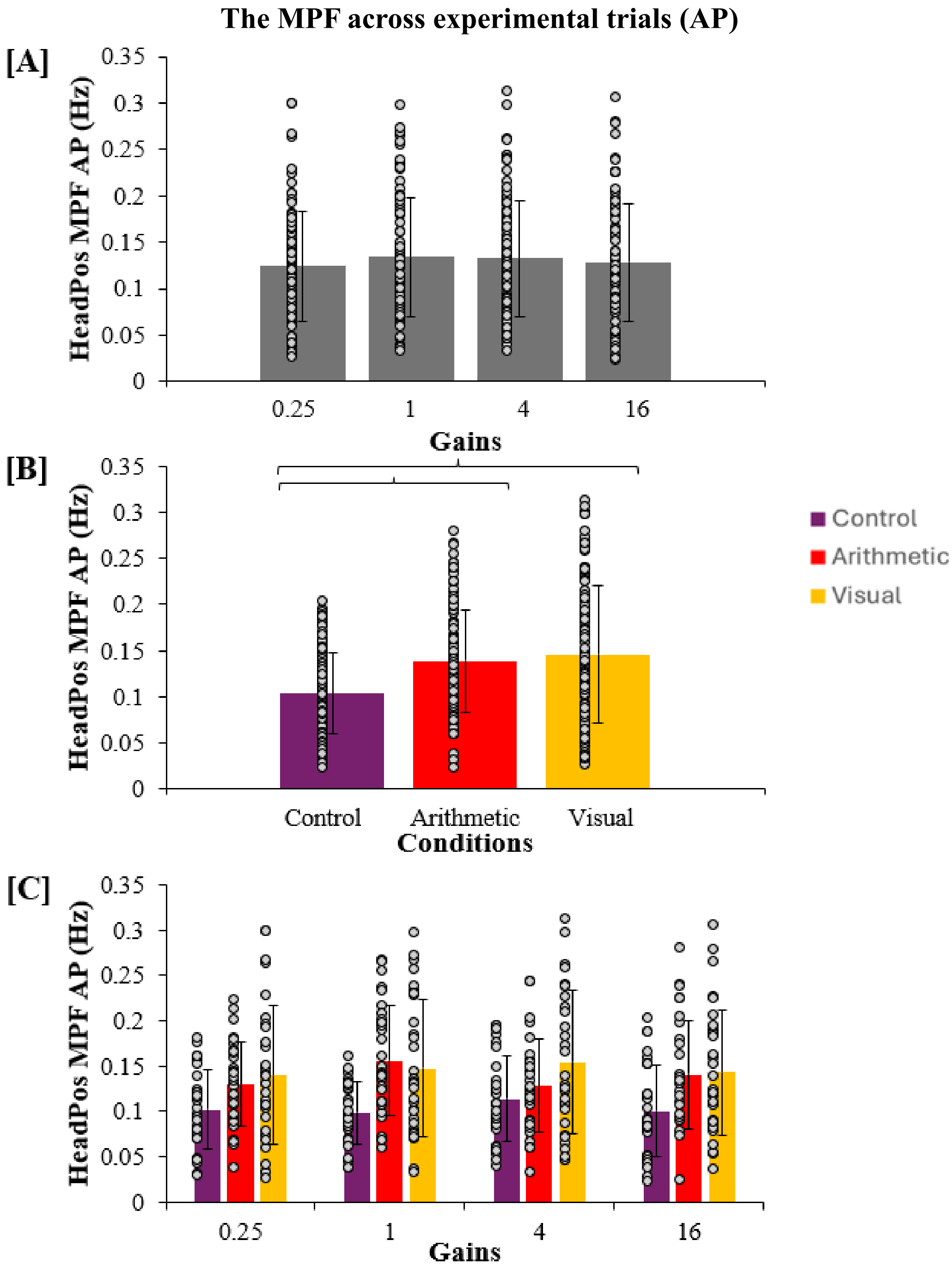

Figure 8. Head MPF in the AP direction. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

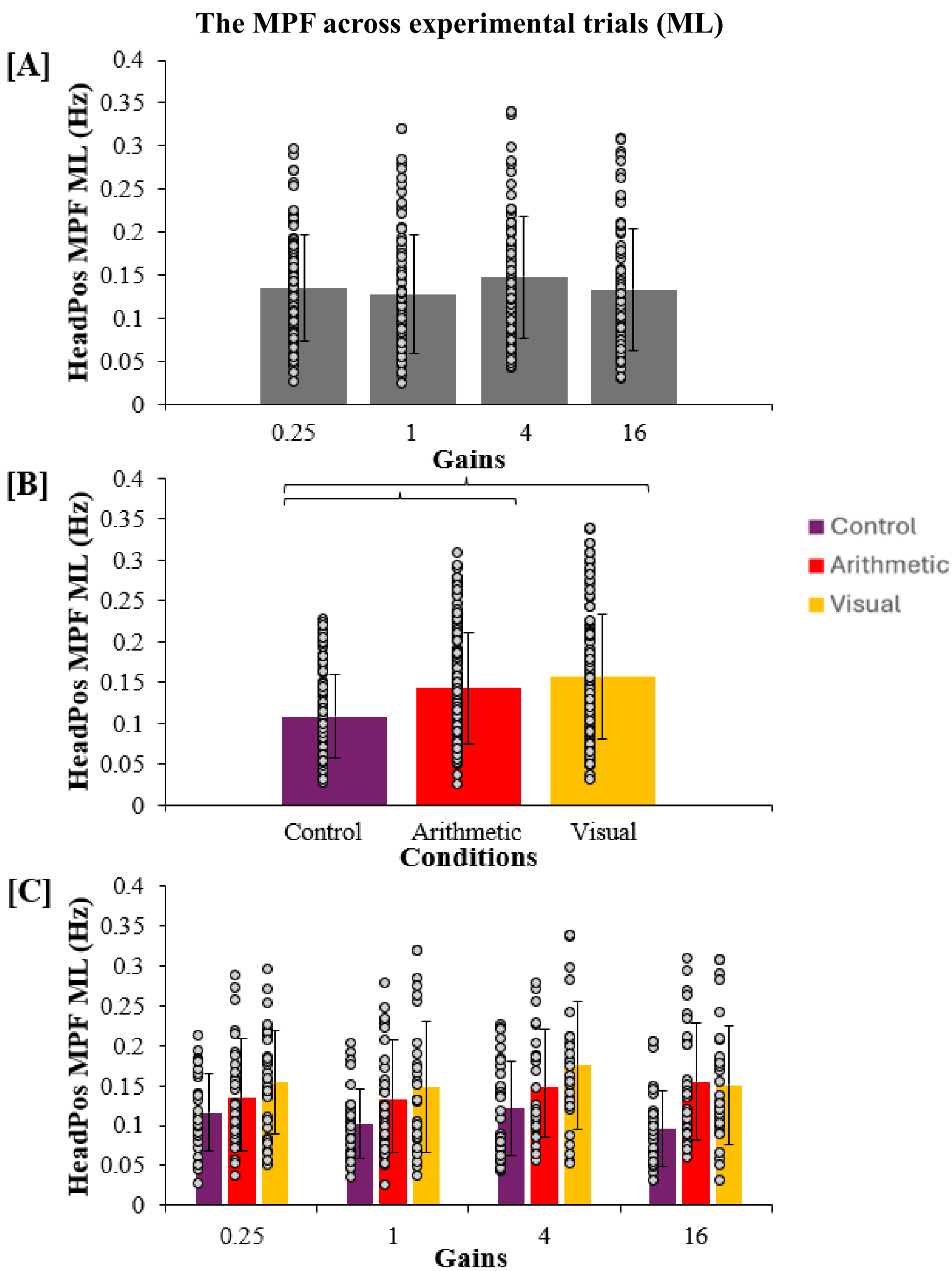

Figure 9. Head MPF in the ML direction. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

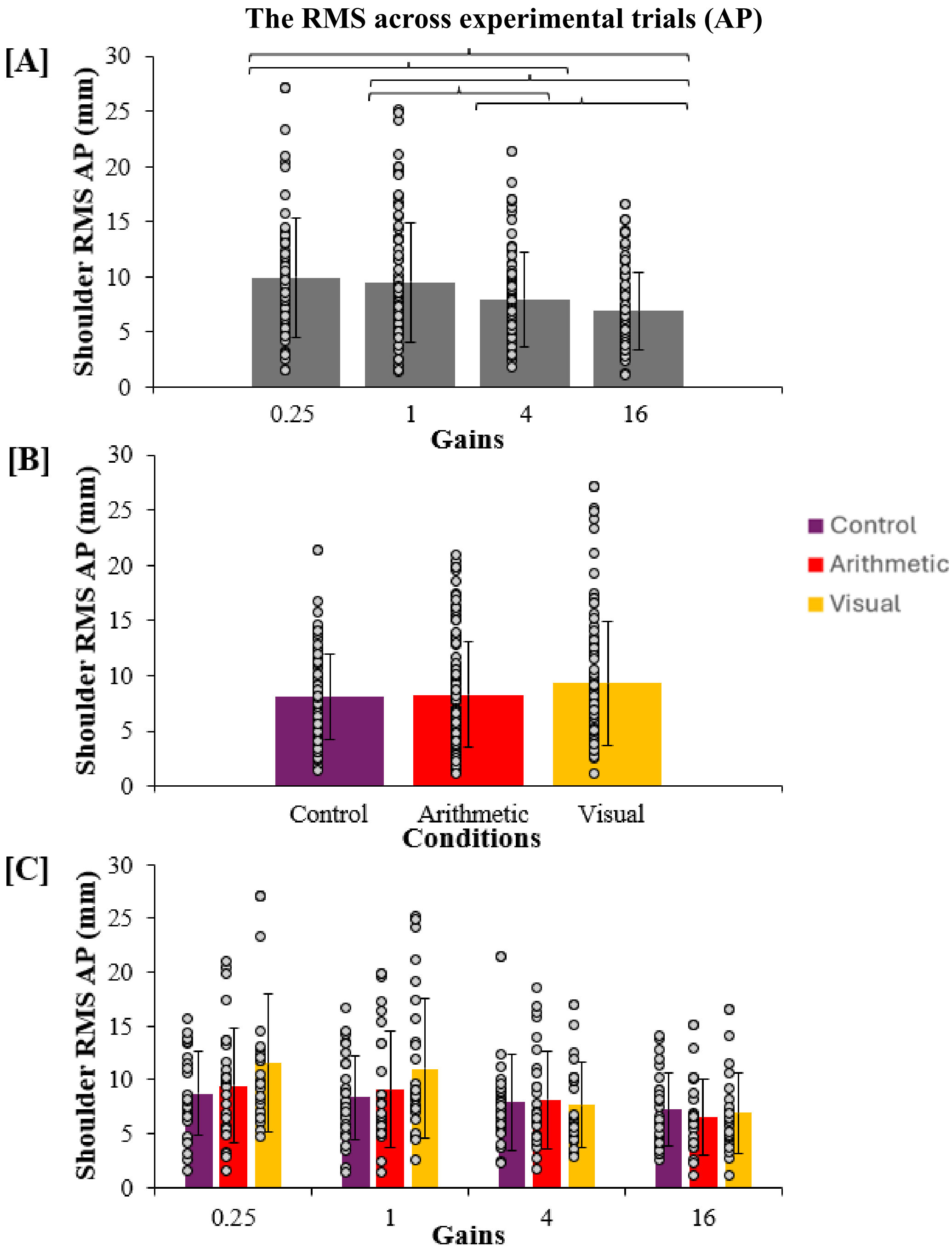

Figure 10. The mean of linear Shoulder RMS in the AP direction is observed. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

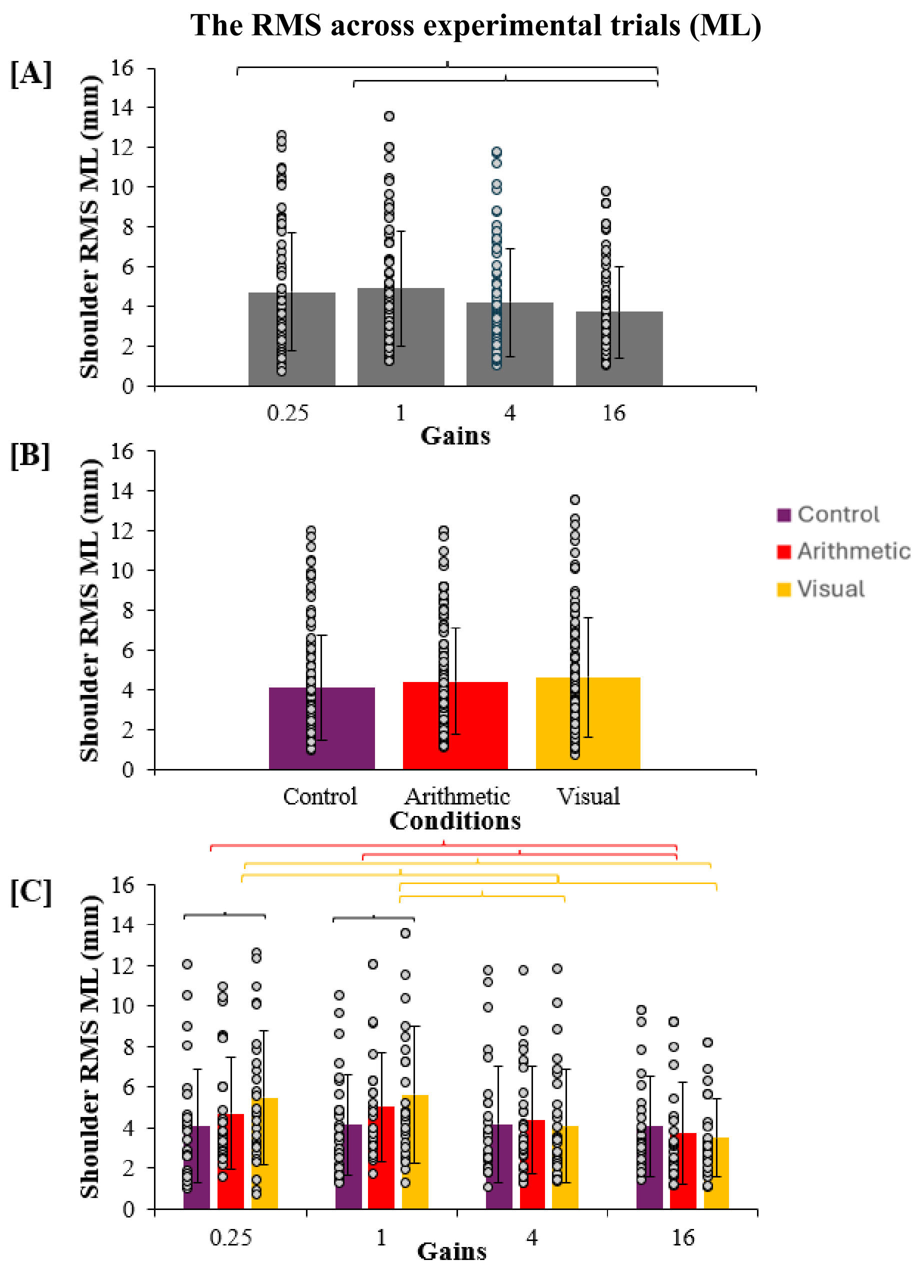

Figure 11. Linear Shoulder RMS in the ML. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Figure C illustrates interaction effects between the gain values and task conditions. Yellow lines indicate effects between gain values within visual search task, and red lines indicate effects between gain values within arithmetic task, and black lines indicates effects between conditions within gain values ($p < 0.05$, ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

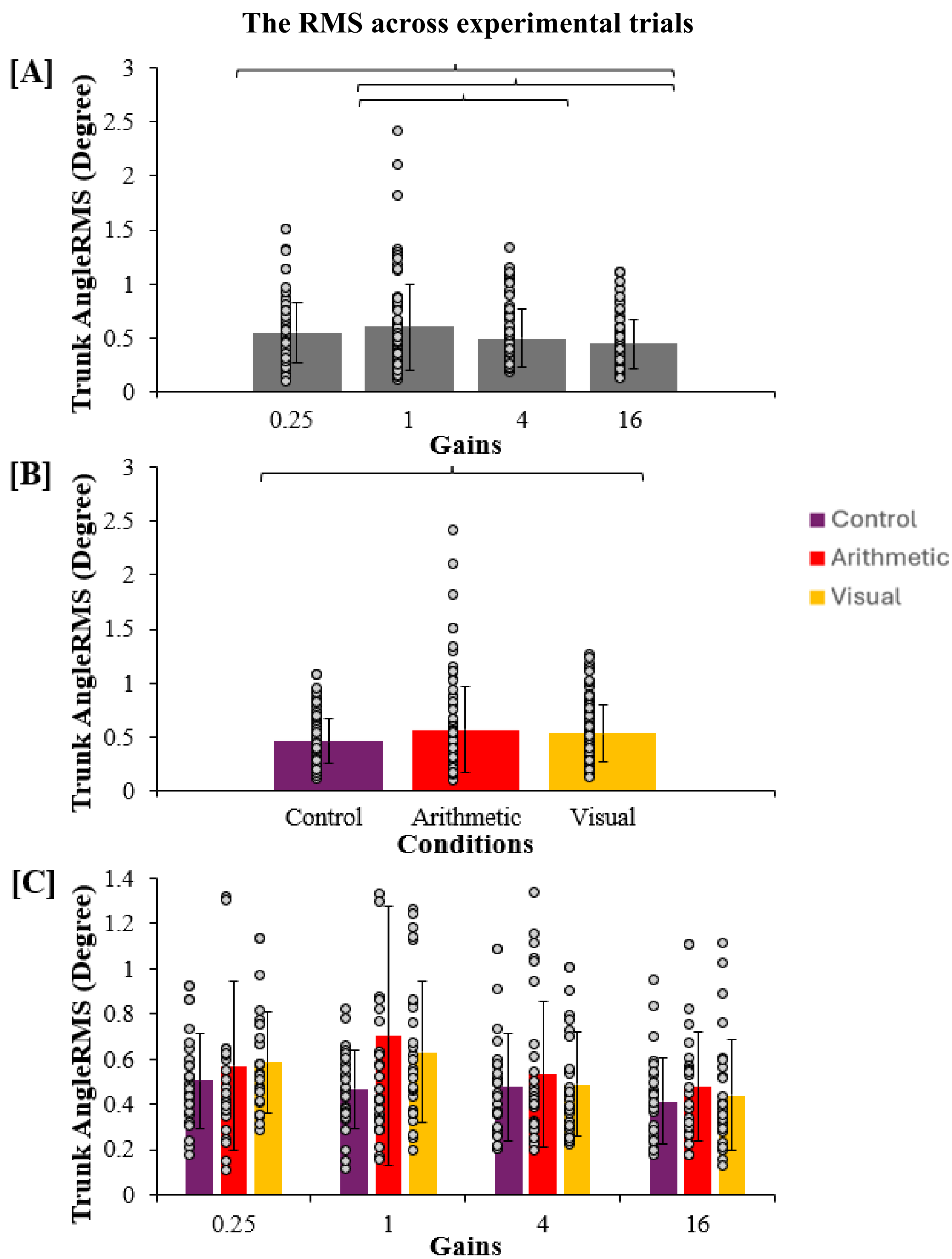

Figure 12. Absolute Trunk angle RMS. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

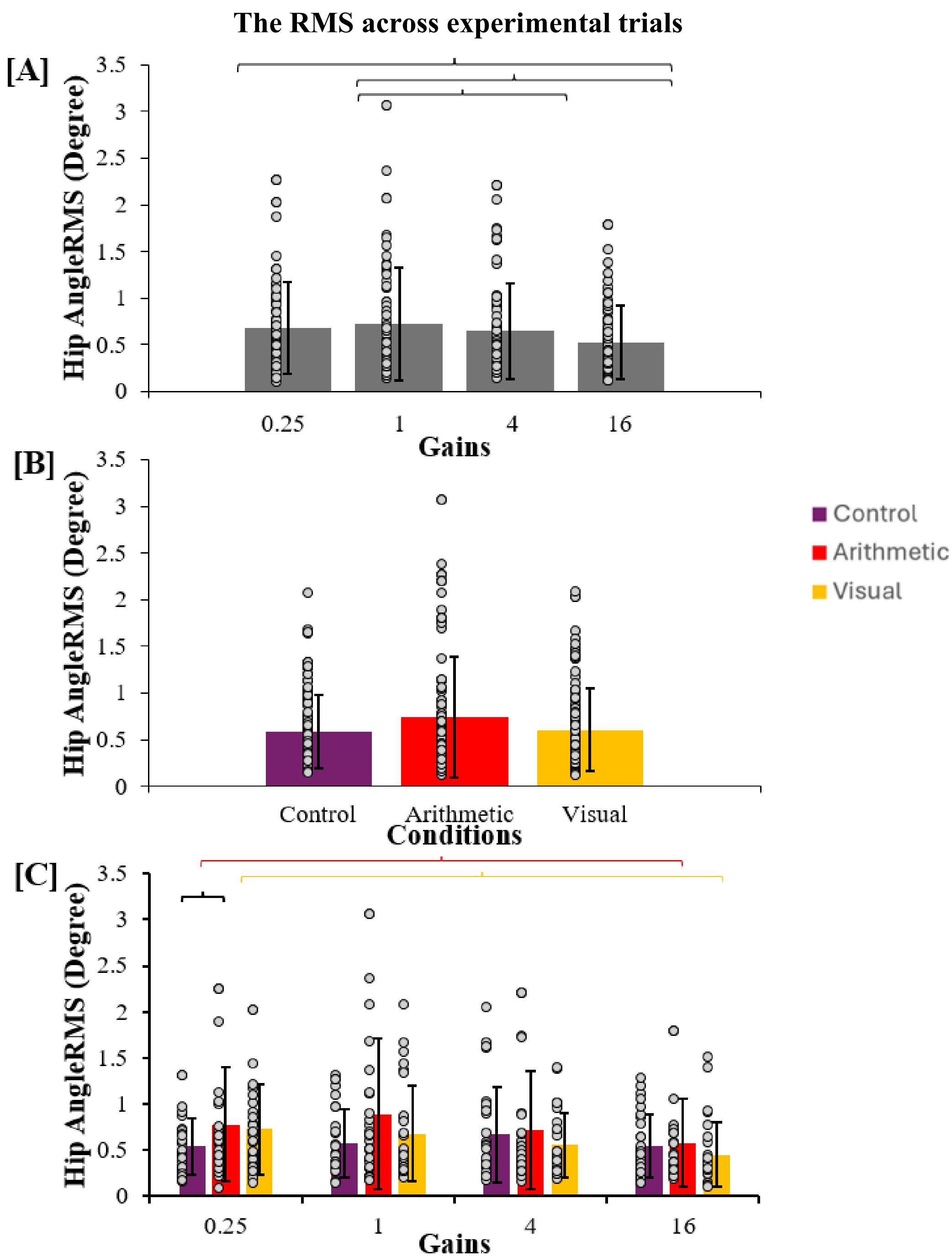

Figure 13. Relative Hip angle RMS. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

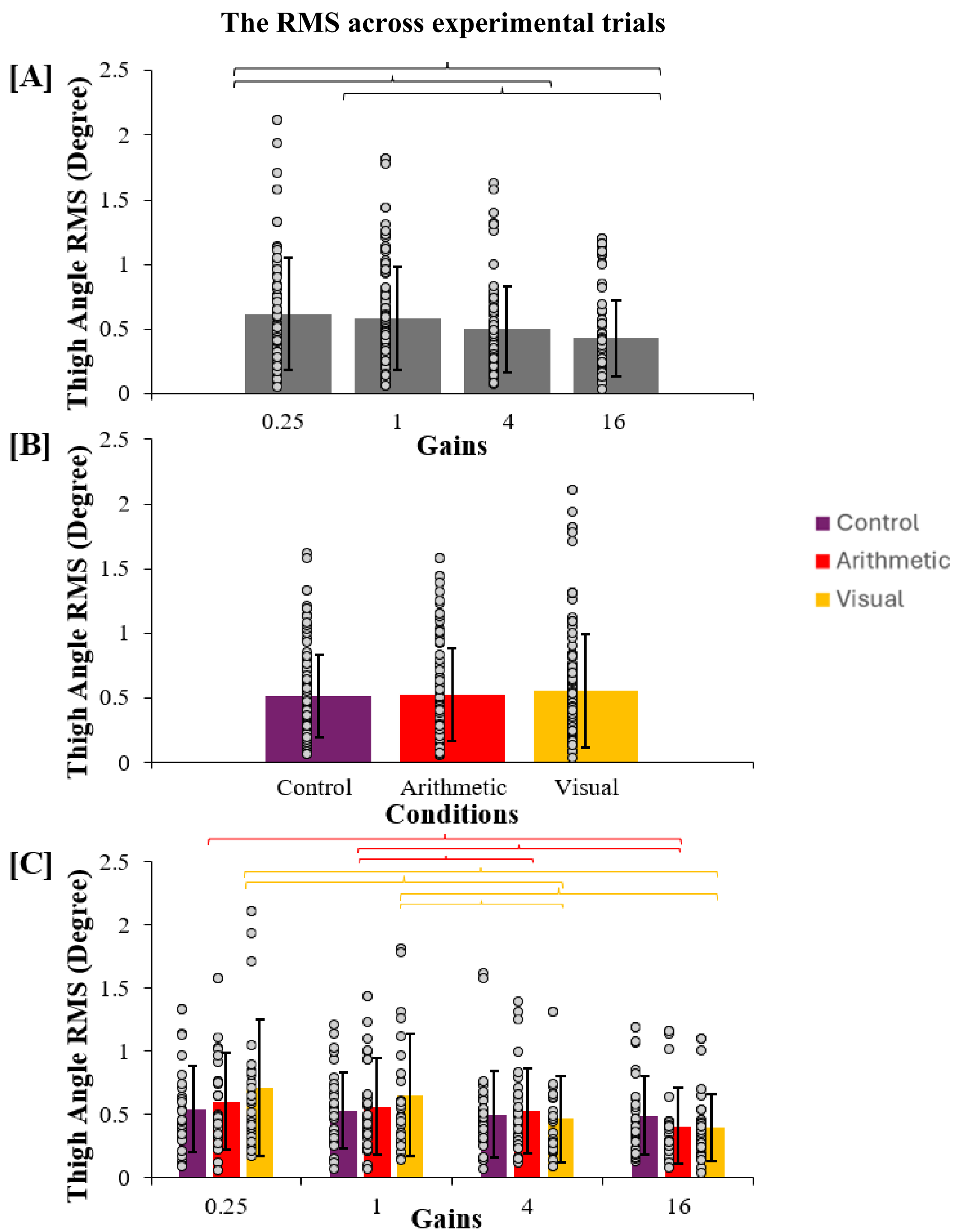

Figure 14. Absolute Thigh angle RMS. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

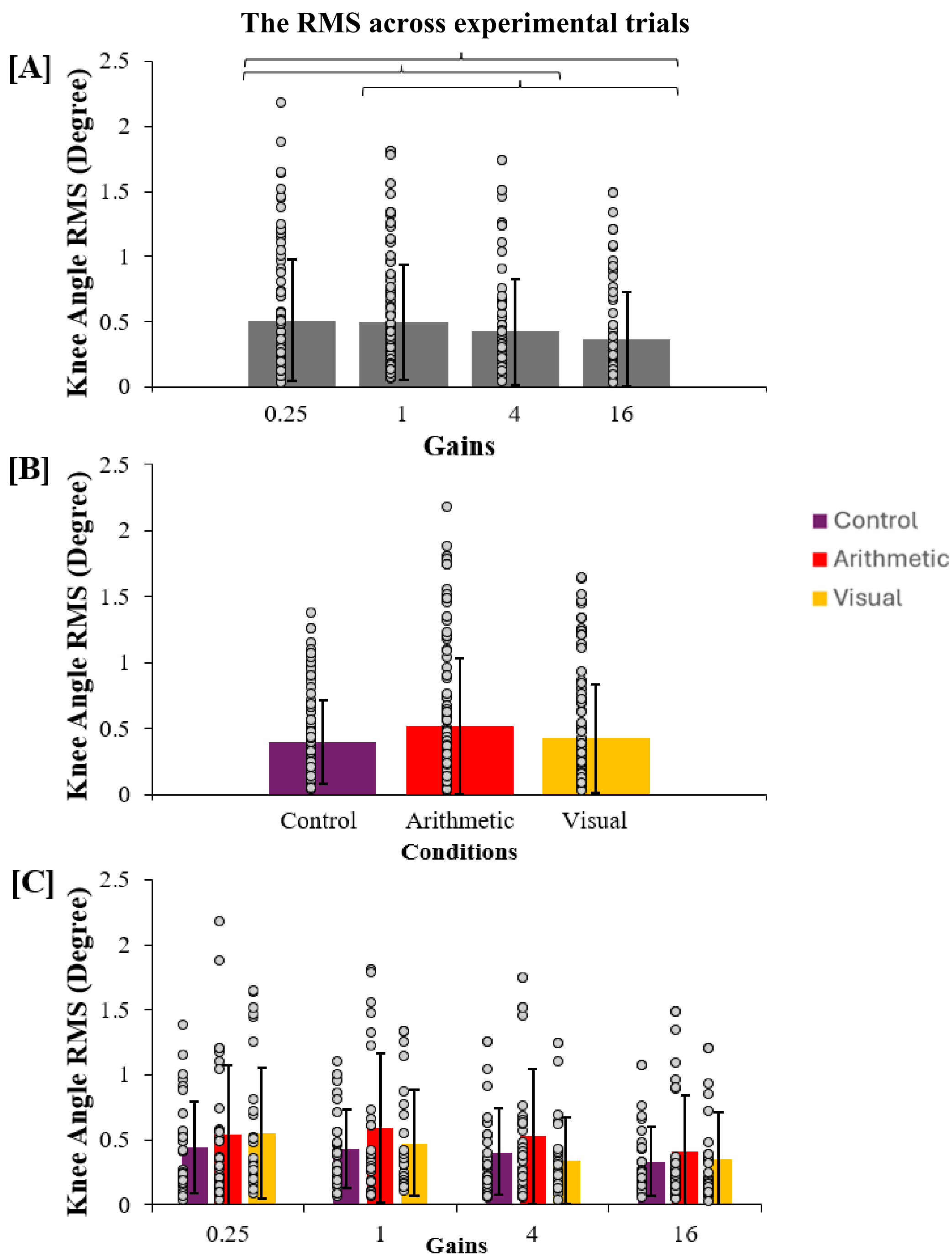

Figure 15. Relative Knee angle RMS. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Figure C illustrates interaction effects between the gain values and task conditions. Horizontal black lines indicate significant differences at $p < 0.05$ (ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

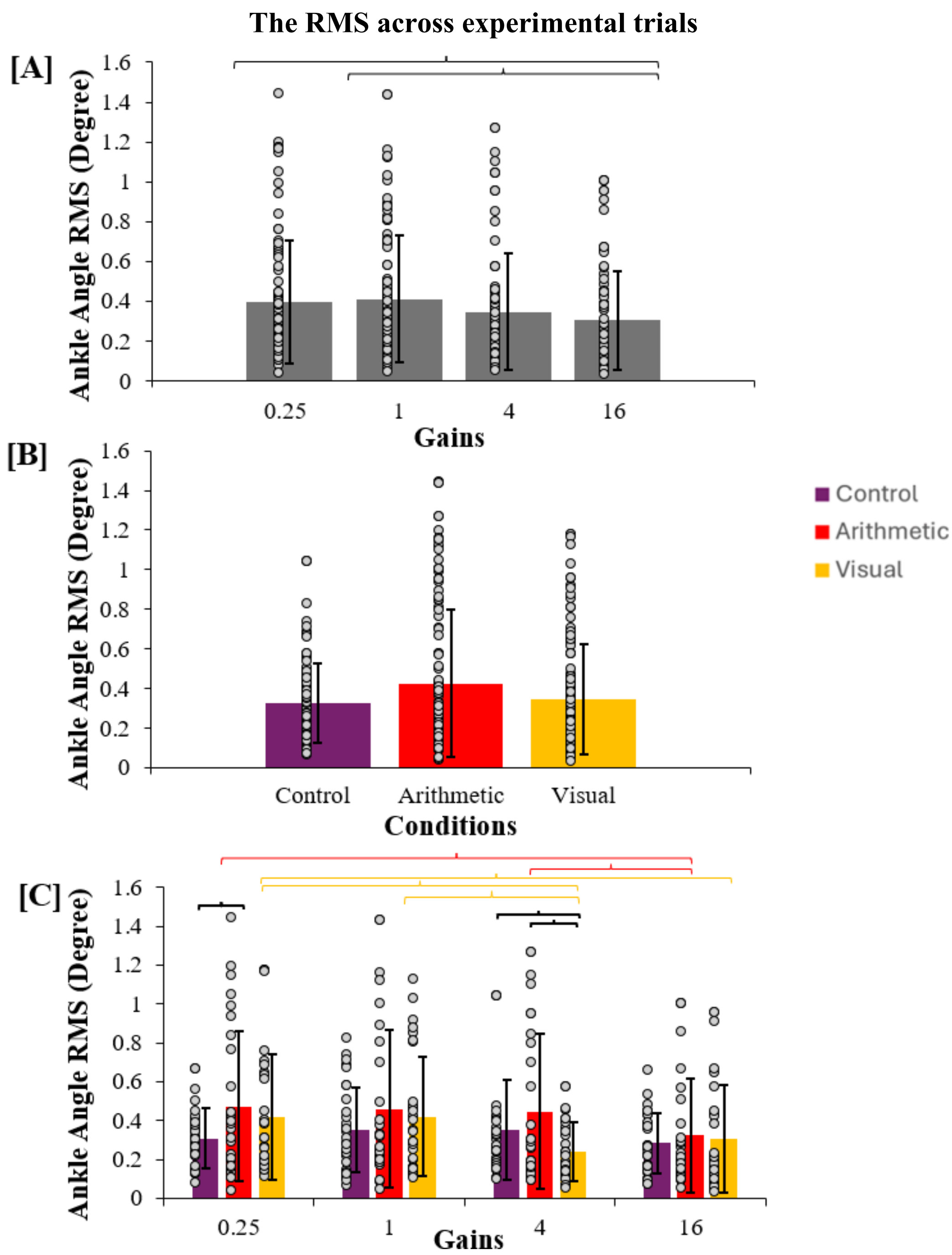

Figure 16. Relative Ankle angle RMS. Figure A shows the main effects of optic flow gain (0.25, 1, 4, 16). Figure B compares the task conditions (Control, Arithmetic, Visual). Horizontal black lines indicate significant differences at $p<0.05$(ANOVA pairwise comparisons). Figure C illustrates interaction effects between the gain values and task conditions. Yellow lines indicate effects between gain values within visual search task, and red lines indicate effects between gain values within arithmetic task, and black lines indicates effects between conditions within gain values ($p<0.05$, ANOVA pairwise comparisons). Individual data points are displayed as dots. Coloured bars represent means with error bars representing ± standard deviations.

The Co-contraction Index across experimental trials

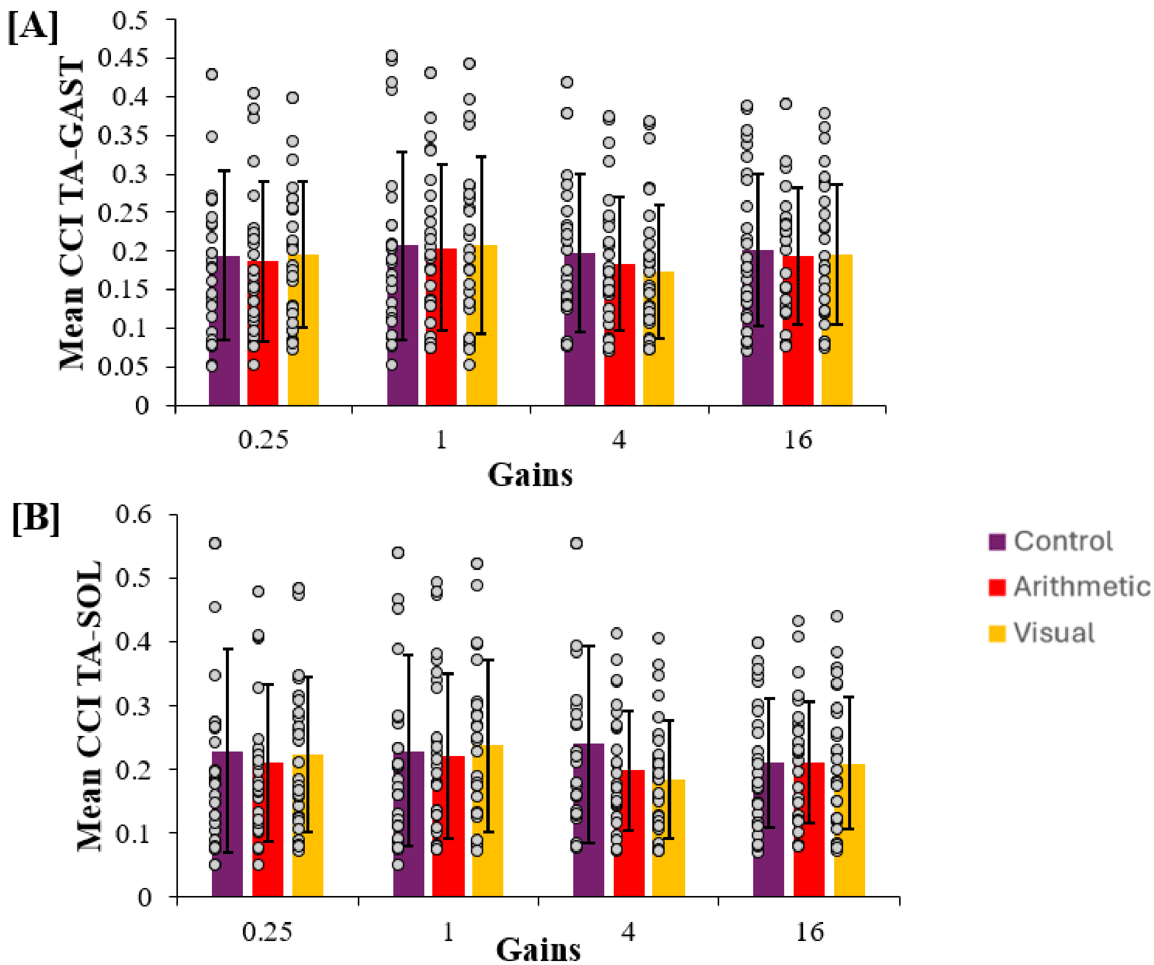

Figure 17. Co-contraction (CCI) value. The figures illustrate interaction effects, with no significant differences between conditions within gain values. Data points are shown as dots, with error bars representing ± standard deviations.

The mean normalization of each muscle across experimental trials

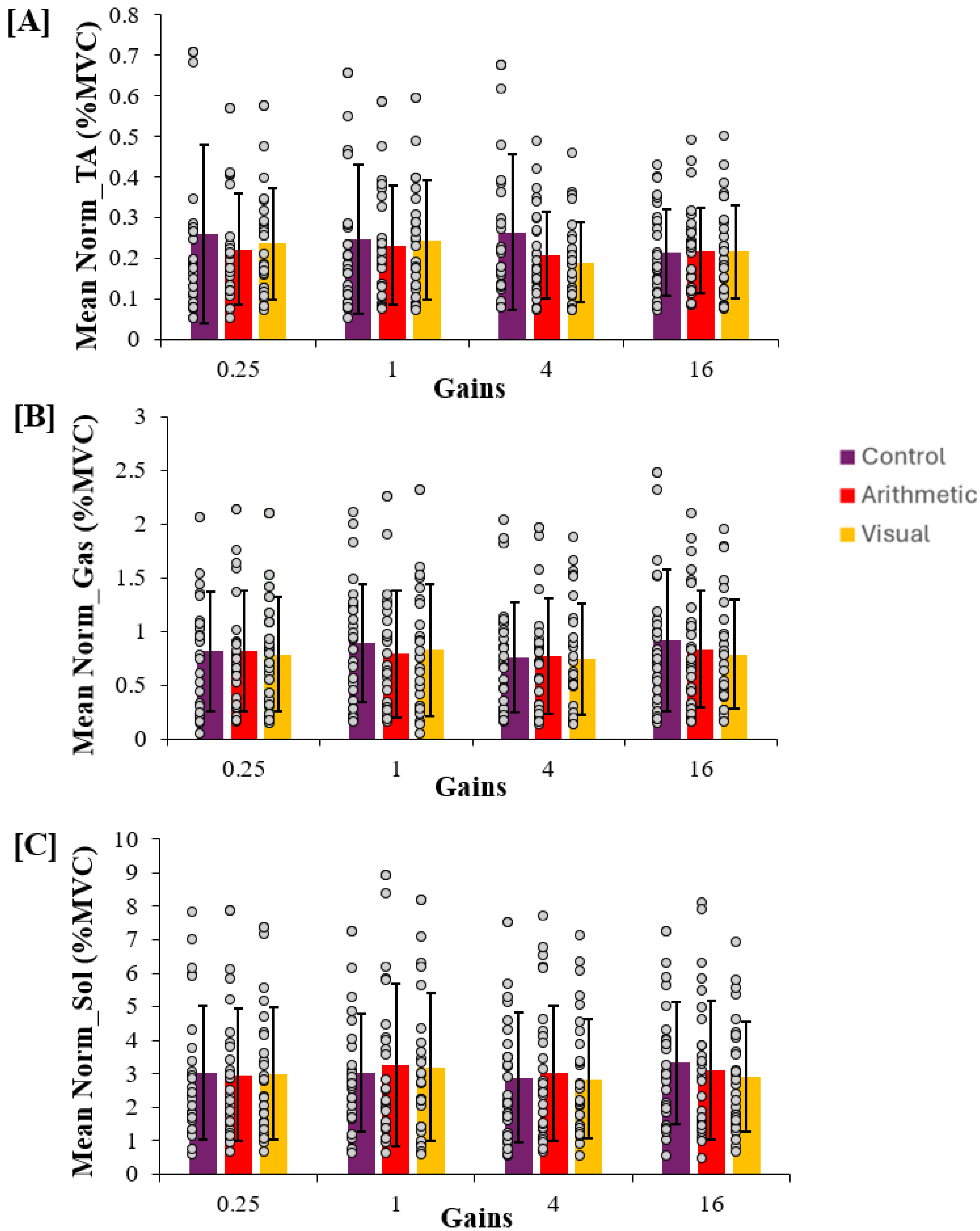

Figure 18. % MVC normalized from the MVC values, illustrating interaction effects, with no significant differences between conditions within gain values. Data points are shown as dots, with error bars representing ± standard deviations.

The Movement Specific Re-Investment Scale Questionnaire

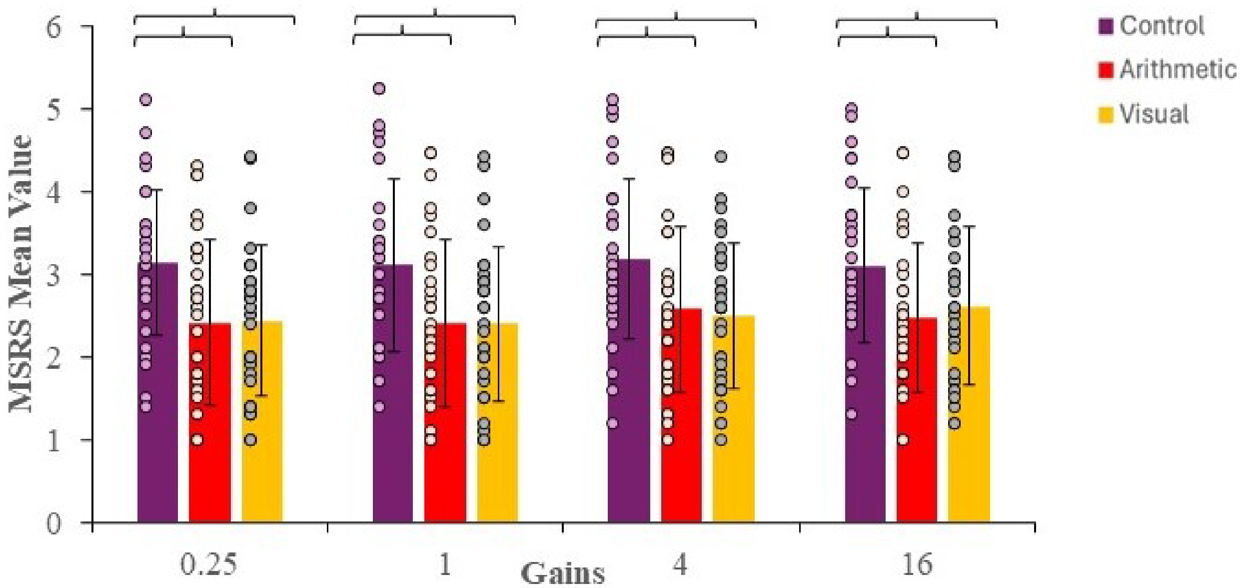

Figure 19. Mean MSRS value. The figure illustrates interaction effects, with significant differences between conditions within gain values shown by black lines ($p < 0.05$, ANOVA pairwise comparisons). Data points are shown as dots, with error bars representing ± standard deviations.

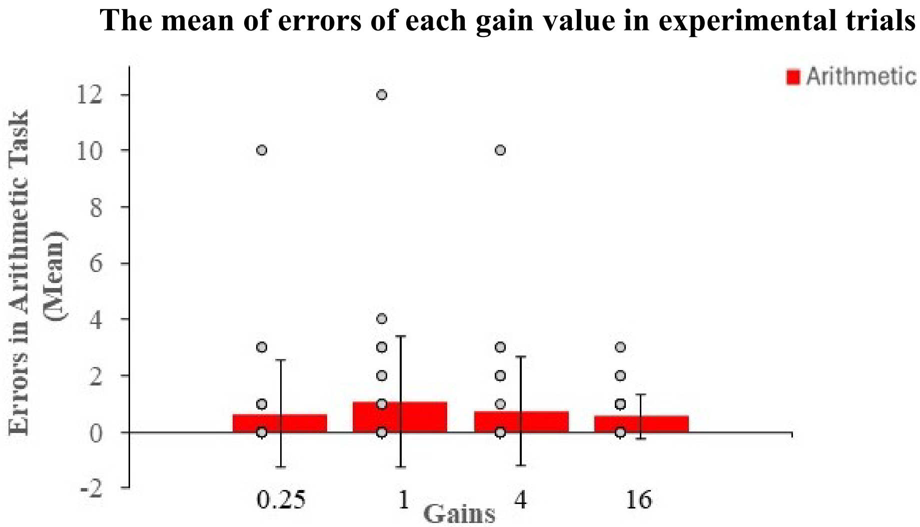

Figure 20. Number of errors made during the arithmetic task across each gain value (0.25,1, 4, 16). Each bar graph corresponds to a specific optic flow gain to show the analysis of the effect of gain on task accuracy. A one-way ANOVA showed no significant main effect on errors ($p>0.05$). Error bars represent the ± standard deviations, and data points are shown individually.

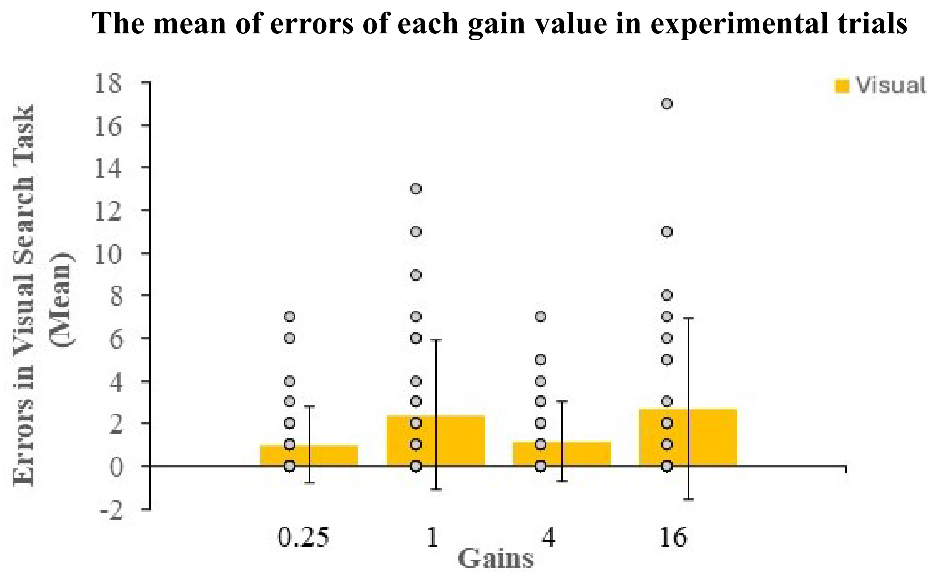

Figure 21. Number of errors made during the visual search task across each gain value (0.25,1, 4, 16). Each bar graph corresponds to a specific optic flow gain to show the analysis of the effect of gain on task accuracy. A one-way ANOVA showed no significant main effect on errors ($p>0.05$). Error bars represent the ± standard deviations, and data points are shown individually.

Table 1- Summary of 3x4 repeated measures ANOVA results for experimental trials

Results shown for RMS (mm), MPF (Hz), and Angle (Degree) Bolded p-values denote statistical significance. 29 participants for EMG, shoulder, trunk, and hip data analysis; 30 participants for ankle data analysis.

	Conditions			**Gains**			**Conditions*Gains**		
	F	**df**	**p-value**	**F**	**df**	**p-value**	**F**	**df**	**p-value**
COP AP RMS	2.048	1.4522, 45.647	0.151	11.662	1.522, 45.647	**<0.001**	2.997	4.242.12, 7.255	0.019
COP ML RMS	5.624	2, 60	**0.006**	10.056	2.276,68.267	**<0.001**	4.008	3.362,100.846	**P<0.007**
HeadPos AP RMS	4.190	2, 60	0.020	14.606	2.123,63.702	**<0.001**	3.265	6,180	**0.005**
HeadPos ML RMS	7.622	2, 60	**0.001**	11.233	3, 90	**<0.001**	4.160	6, 180	**<0.001**
COP AP MPF	24.751	2, 60	**<0.001**	4.138	3, 90	**0.009**	2.931	4.024, 120.706	**0.023**
COP ML MPF	3.606	2, 60	**0.033**	2.307	3, 90	0.082	2.276	6,180	**0.038**
HeadPos AP MPF	11.863	1.57,46.992	**<0.001**	0.858	3, 90	0.466	1.268	6,180	0.274
HeadPos ML MPF	13.663	2,60	**<0.001**	2.103	3, 90	0.105	0.951	6, 180	0.460
Shoulder AP RMS	1.3.067	2, 56	0.054	16.402	2.170,60.748	**<0.001**	2.917	6, 168	0.169
Shoulder ML RMS	1.604	2, 56	0.210	10.882	3, 84	**<0.001**	4.019	3.836, 107.418	**0.005**
Trunk Angle RMS	3.508	1.53,42.936	0.050	10.390	3, 84	**<0.001**	1.813	3.416, 95.653	0.142
Hip Angle RMS	3.733	2, 56	**0.030**	6.367	2.230,62.426	**0.002**	2.789	3.304,92.507	**0.040**
Thigh Angle RMS	0.519	2, 60	0.598	10.335	2.23,67.004	**<0.001**	3.706	4.236, 127.065	**0.006**
Knee Angle RMS	2.195	1.314,39.416	0.141	9.842	3,90	**<.001**	1.879	4.159,124.779	0.115
Ankle Angle RMS	3.774	1.29, 37.342	**0.029**	8.261	2.31, 66.958	**<.001**	4.079	6,174	**<0.001**
CCI TA-GAST	0.485	1.28, 35.911	0.537	3.527	2.196, 61.487	**0.032**	0.513	3.568, 99.895	0.706
CCI TA-SOL	0.771	2, 56	0.467	1.87	2.262, 63.332	0.158	1.572	3.579, 100.202	0.193
MEAN GAST	0.942	2, 56	0.396	1.975	2.383, 66.722	0.139	0.592	3.903, 109.276	0.665
MEAN SOL	1.018	2,56	0.368	3.487	3, 84	**0.019**	1.981	3.984, 111.564	0.102
MEAN TA	0.929	1.41, 39.354	0.373	1.684	2.146, 60.088	0.192	1.598	3.888, 108.867	0.182

Table 2- Summary of 1x3(A)(Conditions) and 1x4(B)(Gain) one-way ANOVA results after finding interaction effects in the experimental trials

Results shown for RMS (mm), Bolded p-values denote statistical significance.

	[A]	Conditions			[B]	Gains		
		F	Df	p-value		F	df	p-value
COP AP RMS	0.25	**3.737**	**2,60**	**0.030**	Control	**1.028**	**3,90**	**0.384**
	1	0.554	1.58, 47.2888	0.538	Arithmetic	**3.763**	**3,90**	**0.014**
	4	**4.615**	**2,60**	**0.014**	Visual	**12.322**	**2.451,73.530**	**<0.001**
	16	1.427	1.627,48.822	0.249				
COPML RMS								
	0.25	**8.718**	**2, 60**	**<0.001**	Control	0.402	2.312, 69.352	0.700
	1	**6.840**	**1.61, 48.239**	**<0.004**	Arithmetic	**3.859**	**2.352, 70.557**	**0.020**
	4	1.525	2, 60	0.226	Visual	**9.429**	**2.225, 66.754**	**<0.001**
	16	1.210	2, 60	0.305				
COP AP MPF								
	0.25	2.134	2,60	0.127	Control	1.908	3,90	0.134
	1	**39.260**	**2,60**	**<0.001**	Arithmetic	**3.934**	**3,90**	**0.011**
	4	**3.214**	**2,60**	**0.047**	Visual	**3.732**	**3,90**	**0.014**
	16	**9.497**	**2,60**	**<0.001**				
COP ML MPF								
	0.25	0.118	2,60	0.889	Control	2.762	3,90	0.047
	1	1.357	2,60	0.265	Arithmetic	2.339	3,90	0.079
	4	1.126	2,60	0.331	Visual	1.752	3,90	0.162
	16	**7.367**	**1.59, 47.804**	**0.003**				
HeadPos AP RMS								
	0.25	**6.795**	**2, 60**	**0.002**	Control	1.439	3, 90	0.237
	1	**4.699**	**2, 60**	**0.013**	Arithmetic	**5.420**	**2.50, 74.104**	**0.003**
	4	0.175	2, 60	0.840	Visual	**13.563**	**2.180,65.389**	**<0.001**
	16	1.653	2, 60	0.200				
HeadPos ML RMS								
	0.25	**10.604**	**2, 60**	**<0.001**	Control	0.324	2.327,69.806	0.808
	1	**11.100**	**2, 60**	**<0.001**	Arithmetic	**7.514**	**3, 90**	**<0.001**
	4	0.847	2, 60	0.434	Visual	**11.141**	**3, 90**	**<0.001**
	16	0.646	2, 60	0.528				

Shoulder ML RMS								
	0.25	**4.385**	**2, 56**	**<0.017**	Control	0.036	3, 84	0.991
	1	**45.729**	**2, 56**	**<0.005**	Arithmetic	**5.790**	**3, 84**	**0.001**
	4	0.173	2, 56	0.841	Visual	**11.680**	**3, 84**	**<0.001**
	16	1.105	2, 56	0.338				
Hip RMS								
	0.25	**4.537**	**2,56**	**0.015**	Control	1.609	3,84	0.193
	1	**4.082**	**1.34,37.494**	**0.039**	Arithmetic	**4.499**	**1.870,52.364**	**0.039**
	4	2.075	2,56	0.135	Visual	**5.794**	**2.096, 58.687**	**0.004**
	16	1.513	2,56	0.229				
Thigh RMS								
	0.25	3.870	2,60	**0.026**	Control	0.403	3,90	0.751
	1	1.989	2,60	0.146	Arithmetic	5.569	3,90	**0.001**
	4	1.002	2,60	0.373	Visual	12.060	2.02,60.616	**<0.001**
	16	1.651	2,60	0.201				
Ankle RMS								
	0.25	**5.465**	**2, 58**	**0.007**	Control	1.943	3,87	0.129
	1	1.981	1.47, 42.663	0.160	Arithmetic	**4.688**	**3, 87**	**0.004**
	4	**7.103**	**1.54, 44.582**	**0.004**	Visual	**9.682**	**2.259,65.519**	**<0.001**
	16	0.369	2, 58	0.693				

Table 3- Summary of 3x4 repeated measures ANOVA results for experimental trials for the movement specific re-investment scale (MSRS) and Cognitive Task Accuracy- Error Test

Bolded p-values denote statistical significance

		Conditions			Gains			Condition*Gain	
	F	df	p-value	F	df	p-value	F	df	p-value
MSRS Mean Scale Score	1.884	2, 60	0.167	0.585	3, 90	0.626	11.553	2.16	**<0.001**

Table 4- Summary of 1x3(A)(Conditions) and 1x4(B)(Gain) one-way ANOVA results after finding interaction effects in the experimental trials

Bolded p-values denote statistical significance

A	Conditions			B	Gains		
MSRS	**F**	**df**	**p-value**	MSRS	**F**	**df**	**p-value**
0.25	11.327	1.45, 43.486	**<0.001**	Control	0.199	3,90	0.897
1	10.624	1.478, 44.343	**<0.001**	Arithmetic	0.904	2.348, 70.454	0.424
4	11.689	1.656, 49.670	**<0.001**	Visual	0.623	2, 60	0.54
16	9.21	1.56, 46.804	**0.001**				

Table 5- Summary of 1x4 (Gain) one-way ANOVA results for the number of errors while performing the cognitive task experimental trials

Bolded p-values denote statistical significance

		Gains	
	F	df	p-value
Arithmetic Accuracy-Error	0.751	1.927, 57.824	0.427
Visual Accuracy-Error	3.327	2.149, 64.483	**0.039**

Chapter 4: Discussion

4.1 Discussion Summary

Visual cues, especially optic flow, have a significant impact on postural control, whether an individual is quietly standing or performing an attention-demanding task while quiet standing. This study aimed to understand how changes in optic flow can influence balance, showing the effect of these changes both in quiet stance and during dual-task conditions.

The study found that there was an effect of optic flow during attention related tasks and quiet stance. Independent of dual tasks, it was observed that as optic flow-related visual feedback increased, the amplitude of COP and HeadPos displacement in both the AP and ML directions decreased. In addition, there was an increase in the frequency of postural movement, but only in the AP direction.

Independent from the effects of optic flow, dual tasks that demanded attention also had an impact on balance, especially in the ML direction for both COP and HeadPos. When participants were performing the visual search task while standing quietly, the amplitude for both the COP and HeadPos was higher compared to quiet stance alone. Similarly, when performing the arithmetic task during quiet stance, the amplitude of COP increased compared to the standing quietly without a secondary task.

Novel results were observed when looking at how the interplay between optic flow and attention demanding tasks, especially those involving vision, affected balance. Dual task effects were observed when the optic flow gain was low (0.25 or 1). However, as the optic flow gain increased, the dual task effects disappeared, with movement amplitudes decreasing and becoming similar across conditions. Since there were no differences in the MSRS across the gain conditions (only observed across dual task conditions), it is unlikely that these changes were caused by a shift in attention. Visual information plays an important role to balance as it provides crucial sensory information and aid in supporting attention to maintain balance. During the visual search task, the amplitude of COP, HeadPos and Shoulder in the ML direction, and the HeadPos in the AP direction decreased as visual feedback increased. A similar trend was seen with the arithmetic task, but it was only observed in the amplitude of HeadPos for both AP and ML directions, and for the amplitude of Shoulder in the ML directions. At lower gains, when participants were performing the cognitive tasks, the amplitude of the COP in the ML direction was higher than during quiet stance alone. Furthermore, during the visual search task, there was even a greater amplitude for the HeadPos in both the AP and ML directions compared to just quiet stance alone. While previous studies highlighted the impact of cognitive demands on balance, the standout in this study is that the ML direction seemed to show the most effects when looking at the interplay between optic flow manipulation and dual tasks, especially one that requires a visual search task.

4.1.1 The effects of optic flow on postural control

The study outcomes supported the first hypothesis. It confirmed that an increased optic flow in the VR increases the ability to maintain postural control. The COP and HeadPos RMS significantly decreased, and the COP MPF increased in the AP directions (with no significant changes in the HeadPos MPF in the AP direction, and the COP and HeadPos MPF in the ML direction), indicating that the CNS effectively uses visual information to help maintain balance. This highlights the important role of visual feedback in helping to regulate balance and emphasizes the robustness of such mechanics under different conditions.

In both AP and ML directions, there were differences in the RMS values of COP and HeadPos. The amplitude of COP and HeadPos decreased in both directions as visual feedback increased, implying less movement during a balance task (Cawsey et al., 2009; Lavalle & Cleworth, 2023). Aligned with previous studies, clear vision is maintained by retinal image movement of less than 2-4 degrees per second, which helps with decreasing the amplitude of postural control (Crane & Demer, 1998; Engel et al., 2020; Bles et al., 1980). According to Lavalle and Cleworth (2023), increased visual feedback reduces movement amplitude (RMS), resulting in less sway deviation and tighter regulation for maintaining upright (Lavalle & Cleworth, 2023). In the AP direction, where an increase in visual feedback led to reduced movement or decrease in amplitude, the CNS played an important role in using the visual information to better control HeadPos (Stoffregen & Riccio, 1991). Similarly, in the ML direction, more visual feedback resulted in lower COP amplitude, which as suggested, may have improved spatial accuracy and reduced lateral sway, leading to a better ability to maintain balance (Horak et al., 2002; Keshner et al., 1999). Furthermore, some studies also suggested that higher visual feedback during complex tasks plays an important role in the decrease of HeadPos RMS in the ML direction because sensory reweighting during tasks allows for visual feedback to be more prominent and reduces the reliance on other and less precise inputs like proprioception, resulting in better ability to maintain the HeadPos upright (Asslander & Peterka, 2014). In addition, when participants need to visually focus on tasks that require head movement, visual feedback allows for more controlled adjustments because the CNS provides more accurate information to process and respond to any disturbances (Stoffregen et al., 2006)

In prior studies, during quiet standing, it has been mentioned that the visual system typically operates at lower frequencies, and it is usually below 0.1 Hz (Lin et al., 2019; Salsabili et al., 2013). An increase in the MPF may indicate that there are more frequent adjustments, with an increase in nervous system activity and greater difficulty in maintaining balance (Rougier et al., 2004; Woollacot & Shumway-Cook, 2002; Stoffregen & Riccio, 1991). Higher MPF values were observed in the COP, especially in the AP direction as visual feedback increased. Nonetheless, like earlier research, HeadPos in the AP direction remained relatively consistent with gain variations during quiet stance, which indicated fewer modifications were necessary (Stoffregen et al., 2000). Both the COP and HeadPos frequencies showed no main effects of gain in the ML direction. This could be that when there is lower MPF values, the postural control system increases its sensory intake, resulting in minor oscillation or adjustments to be made to control posture (Winter et al., 1998; Visser et al., 2008; Zaback et al., 2019). Furthermore, proprioception and vestibular inputs could have been more crucial than visual feedback in maintaining balance with lower MPF values in the HeadPos, suggesting that frequent head movements or minor adjustments may not have been necessary (Keshner & Kenyon, 1999; Lavalle & Cleworth, 2023).

As visual feedback increased, COP amplitude in the AP direction decreased, reflecting smaller, more controlled movements due to more visual input being processed by the CNS, enhancing postural regulation and reduced sway (Rougier et al., 2004). Visual cues help the nervous system to better control head position, reducing movement displacement (Asslander & Peterka, 2014). This is why at a gain of 16, head movement in both directions was lower during both arithmetic and visual search tasks than at gain of 0.25.

4.1.2 The effects of attention related tasks on postural control

The second hypothesis, which proposed that attention-demanding cognitive tasks during quiet stance would increase sway in the ML direction, was validated. Even though the visual feedback resulted in a decrease in COP amplitude in the AP direction, the cognitive tasks did lead to increased sway in the ML direction compared to no cognitive tasks. The increased displacement in the ML direction highlights the effect of cognitive load on postural control. Thus, the findings highlight that cognitive tasks that require attention can have an impact on balance.

Furthermore, with no significant effects of conditions in the COP RMS in the AP direction, it is possible that the visual feedback may have been a dominant factor in balance regulation in these circumstances, aligning with earlier studies that visual feedback is still the primary mechanism in maintaining balance even though cognitive load can also affect postural control (Swan et al., 2007; Lavalle & Cleworth, 2023; Stoffregen et al., 2000). However, dual tasks that increased cognitive load such as visual search task and arithmetic task led to greater ML displacements compared to controlled task in both COP and HeadPos, suggesting diverting attention from maintaining balance to performing memory arithmetic task or, scanning and counting targets that added visual processing demands (Woollacott & Shumway-Cook, 2002). Despite better ability to maintain balance from visual feedback, the cognitive load still resulted in increased ML displacement. While increased visual feedback provided more accurate spatial information and helped reduce sway and improve balance, the cognitive demands of the dual tasks still resulted in greater COP and HeadPos displacement in the ML direction.

Cognitive tasks that require attention can cause distractions, making it necessary to make more frequent adjustments to maintain balance (Andersson & Yardley, 2001). A study indicated that when there is visual feedback involved while standing quietly, there may be lower MPF but if tasks become more difficult like adding cognitive demand, then the MPF for both COP and HeadPos may increase (Shumway-Cook & Woollacott, 2007). Aligned with previous research, cognitive tasks like arithmetic and the visual search task, increased the frequency of HeadPos in the AP direction, leading to more frequent head adjustments. And, in the ML direction, COP and HeadPos frequency was higher in arithmetic compared to control task. This may have been because the participants had to concentrate more in performing the task as there was fewer visual cues, causing distractions that interfered with maintaining balance (Kang & Lipsitz, 2010; Swan et al., 2004; Kang & Lipsitz, 2010). The frequency of the HeadPos in the ML direction also increased in visual search task compared to the control task. When comparing the visual search task to the control conditions, the frequency of the HeadPos in the ML direction was higher in the visual search task. The reason could be that they had to move their heads from left to right within the virtual environment to count the letters on the white board, highlighting the difficulty to stay balanced when performing a task that requires visual engagement and cognitive focus. The results may suggest that during the cognitive tasks, individuals had to work harder to make frequent head adjustments to maintain balance, especially in the ML direction (Stoffregen et al., 2000; Stoffregen & Riccio, 1991).

To explain further, movement during quiet standing is concentrated in the lower frequencies, usually oscillating below 1Hz, reflecting slow, subtle corrections to maintain upright stance (Winter et al., 1998; Lafond et al., 2004. With attentional- demanding cognitive tasks during quiet stance, there was an increase in the MPF of both COP and HeadPos, though their frequency values remained within the lower frequency range (<0.1Hz). This conveys that while the participants were making frequent adjustments, these adjustments were relatively minimal and controlled, indicating that the postural control system was actively controlling posture even under cognitive demands (Prieto et al., 1996; Duarte & Freitas, 2010).

4.1.3 The effects of optic on dual tasks that require visual information and while quiet stance

The third hypothesis, examining the effects of optic flow manipulation during dual tasks, especially one that requires visual information was supported by the findings. The results showed that as visual feedback increased, particularly to a gain of 16, there was an increased ability to maintain balance, as demonstrated by the decrease in COP and HeadPos RMS, and an increase in COP and HeadPos MPF. Tasks that require visual attention and are cognitively demanding like the visual search task, introduced challenges in maintaining balance, especially in the ML direction. The overview of the key findings in the study lays a framework for a more thorough examination to show how these findings support the research hypothesis and help address the main central question: how is balance affected across visual gain conditions and different cognitive attention related tasks, especially one that involves vision?

Examining the impact of optic flow manipulation during dual tasks that require visual information has been assessed in previous studies (Lavalle & Cleworth, 2023). Increased visual feedback, particularly at a gain of 16, resulted in smaller COP and HeadPos deviations in the AP direction. The result of this may have allowed the nervous system to fine-tune postural adjustments by integrating sensory information. Previous work on sensorimotor integration highlights how the CNS uses available sensory feedback to make adjustments, supporting postural control (Peterka, 2002). While cognitive tasks like arithmetic and visual search task pose challenges for HeadPos, an increase in visual feedback provided spatial information, which in term led to a decrease in amplitude (Berencsi et al., 2005). Particularly during visual search task, the amplitude of the HeadPos in the AP direction was lowest at a gain of 16 and highest at gains of 0.25 and 1, indicating that significant changes typically occur when there are changes at these gains and that the changes are mostly observed in both HeadPos and COP (Lavalle & Cleworth, 2023). During the arithmetic task, HeadPos and COP amplitude in the AP direction decreased as visual feedback increased but were less noticeable than visual search task. This was likely because the arithmetic task required less head movement performing the mental counting task, unlike the visual search task, which involved head movement making visual surrounding appear more natural and clearer to read. As mentioned earlier, the differences in the type of tasks highlight the importance of visual feedback in postural control, specifically in tasks that require head movement.

As previously discussed in the introduction, maintaining balance in the ML direction is naturally aided by a wider BOS in a bipedal stance, providing greater lateral ability, minimizing ML sway (Kang & Lipsitz, 2010). However, this does not mean that one cannot stand with a narrower BOS or cannot support balance in the ML direction; rather, a narrower BOS increases the challenge of maintaining balance since it reduces the allowance for lateral sway. When performing dual task conditions, the CNS reallocates neural resources, including attentional focus to be able to maintain an upright stance (Woollacott & Shumway, 2002; Lajoie et al., 1993). In situations that require simultaneous cognitive control and postural control, the CNS prioritizes resources to be able to manage balance efficiently. This adaptive response emphasizes how the CNS actively engages attention to maintain postural control, especially in situations where there is little external visual feedback. Since the CNS does not provide additional support by activating muscles for the ML direction, it prioritizes muscles that help maintain balance in the AP direction (Kang & Lipsitz, 2010).

The theory that while cognitive tasks can disrupt balance, visual information makes up for the difficulty of maintaining balance (Shumway-Cook & Woollacott, 2007; Woollacott &

Shumway, 2002; Stoffregen et al., 2006). This is supported by the findings in this study that an increase in visual feedback minimizes movement displacement. For both COP and HeadPos RMS in the ML direction, at lower gains, there were dual task effects. The amplitude of the visual search task was larger than that of the control task when the gain was set at 0.25 and 1. This could be because at lower gains there was less visual information being processed to perform the visual task, causing the attention to be allocated into performing the task than trying to control posture. Similarly, the amplitude increased at lower gains such as 0.25 and 1 during arithmetic task when compared to control task in COP RMS in the ML direction and HeadPos RMS in the AP direction. This was likely because the participants only had to think of maintaining upright and they were more aware of their balance, and more self-conscious about their balance (Masters &Maxwell, 2008). The dual task effects and the type of the task itself, highlights the impact of task- specific demands on balance.

As visual feedback increased, there was higher frequency of COP in the AP direction during arithmetic task. And, at gain of 0.25 and 16, dual task effects existed, with tasks having higher frequencies compared to control task. Higher MPF indicates more active balance strategies as the nervous system responds dynamically to stabilize the body against disturbances that occur within the virtual environment (Rougier et al., 2004). Lower frequency of COP AP in the control condition may mean less cognitive demand. However, cognitive tasks like the arithmetic task and visual search task challenge the body's postural system, resulting in higher frequency of COP AP. The lack of visual assistance performing the arithmetic task (memory task) required the postural control system to compensate, leading to the frequency of COP AP being higher than when performing the visual search task. In addition, during the visual search task, participants shifted their head displacement in the AP direction more frequently than during the control task, suggesting they probably had to adjust their eyes to the field of view to count the letters. This result is consistent with other studies and supports prior statement that demands for cognitive function and visual feedback increase the necessity for head adjustments to maintain an upright (Shumway-Cook & Woollacott, 2007).

Interestingly, like COP and HeadPos, with cognitive load, there was an increase in the amplitude of linear shoulder displacement in the ML direction, particularly at lower gains. With lower visual feedback, participants received less visual cues regarding how their body was positioned in relation to their surroundings, and with reduced visual feedback and cognitive load, participants may have had to rely more on internal cues like vestibular and proprioceptive inputs, which tend to be less precise than visual feedback in maintaining upright posture in the ML direction, leading to an increased shoulder displacement, as the body made larger compensatory adjustments to maintain balance (Winter, 1995; Peterka, 2002; Horak et al., 2002; Stoffregen & Riccio, 1991; Shumway-Cook & Woollacott, 2007). On the other hand, shoulder displacement decreased across all conditions as visual gain increased to 16. This supports previous research that mentions as visual feedback increases, the brain receives more accurate information that enables finer, more precise postural adjustments. This causes shoulder movements and RMS values to go down (Winter, 1995; Peterka, 2002).

This study also looked at how visual feedback and cognitive demanding tasks like the math and visual search tasks influence the amplitude of linear shoulder displacement. Interesting patterns were found, especially in the ML direction during the cognitive task trials compared to controlled trials. During the arithmetic task, shoulder RMS increased at lower visual gains (0.25 and 1) compared to a gain of 16, suggesting that the combination of minimal visual feedback and cognitive load made the ability to maintain balance more challenging (Lajoie et al., 1993). The dual task interference theory says that the brain must divide its attention between doing the cognitive task and keeping its balance. This makes postural control less accurate, as shown by the fact that shoulder RMS increased in the ML direction in this study (Lajoie et al., 1993; Shumway-Cook & Woollacott, 2007; Kang & Lipsitz, 2010). During the visual search task, participants used visual information, which probably enhanced the visual feedback given at higher gains. In other words, the visual search task and the feedback system, when combined with visual information at higher visual gains of 4 and 16, aided in maintaining postural control, potentially leading to the lowest shoulder RMS values (Swan et al., 2004; Andersson & Yardley, 2001). It has been shown in other studies that the tasks that require side-to side- head movement, including visual search tasks, increase sway amplitude and make it more difficult to maintain ML balance (Assländer & Peterka, 2014; Stoffregen et al., 2006). Also, research demonstrated that the narrow base of support makes it more challenging to control ML displacement, particularly when the feet are placed closely together (Winter et al., 1998; Peterka, 2002). By lowering the upper body's moment of inertia, the effect of crossed arms during quiet stance also contributed to these results. With a lower moment of inertia, it was easier for the body to control posture. However, under conditions of low visual feedback and high cognitive load, the reduced inertia was not sufficient to prevent the increase in shoulder movement, resulting in higher RMS values (Winter, 1995).

To go back into addressing the main research question; based on the findings, the third hypothesis is well-supported. It shows that by enhancing visual feedback, particularly at higher gains, results in significantly improving balance during dual tasks that require visual information. However, the study also demonstrates that maintaining balance becomes difficult due to cognitive demands of the tasks, particularly ones like visual search that call for focused visual attention, especially in the ML direction. This suggests that even though visual feedback is important for postural control, it also raises neuromuscular effort to maintain it in situations that require cognitive function. These insights emphasize how postural control strike a strong balance between sensory input and cognitive load. Moreover, understanding the difficulty in maintain balance and the mental involvement during visual feedback creates a framework to investigate how these conditions influence muscle activity and the interaction between them.

4.4 Muscle Activity and Co-Contraction Index (CCI)

A deeper understanding of the effects of optic flow manipulation on cognitive task and quiet standing is evaluated using the EMG to measure muscle activity. There was lack of significance differences across all gain and conditions in all muscle activity variables, including CCI of TA-GAS and TA-SOL, suggesting a more intricate relationship between cognitive load and visual feedback.

The TA controls the dorsiflexion of the foot and plays an important role in stabilizing the ankle while one is maintaining upright stance. Previous studies have mentioned that TA activity increases when there are greater postural demands (Di Giulio et al., 2009). The gastrocnemius and the soleus work together to control plantar flexion and help to stabilize the joint of the ankle. Increased activity in these two muscles means that there has been greater postural demand, leading to counterbalance and greater demand in maintaining balance (Fok et al., 2021). Furthermore, the TA-GAS and TA-SOL CCI indexes show how the muscles work together to maintain balance. An increase in CCI indicates greater co-contraction (Rudolph et al., 2000). The increase of CCI is a strategy used to improve the ability to maintain upright and to increase joint stiffness (Rudolph et al., 2000). Although there were differences in the movements of COP and HeadPos in the ML direction, there were no significant differences observed in the three muscles measured. According to previous research, the primary muscle controlling postural control in the ML direction are located around the hip (Winter, 2009). The hip abductors and adductors are usually the muscle groups that manage the balance in the ML direction, and the three muscles measured in this study are primarily involved for AP adjustments as per previous research (Winter, 2009, Fok et al., 2021). Therefore, this may explain why there were no effects observed in the muscle activities. It would be better to look at the hip muscles that are for ML movements rather than the lower leg muscles that were for AP adjustments.

Furthermore, the lack of significant differences in this study could indicate that the visual feedback that was stimulated by the environment within the VR may have been adequate to help in postural control, eliminating the need for increased co-contraction or muscular adjustments (Fok et al., 2021). As visual feedback increased, the amplitude of movement decreased. The effect of visual feedback provided precise spatial information, reducing the need for muscular adjustments. In other words, visual feedback allowed for participants to maintain balance without the increase in muscle activation. This aligns with a previous study done by Horak et al. (2002), who found that visual feedback can minimize movement displacement, resulting in better ability to maintain balance. The findings of this study, however, matched even more with Shumway-Cook and Woollacott (2007), who showed that even though cognitive tasks can cause disruption in one's posture, visual feedback may lessen the difficulty in the ability to maintain balance. Moreover, it is possible that the visual feedback that the VR environment provided helped control posture, which lessened the extra necessity for the TA, GAS, and SOL muscles to be activated to the extent to show significance (Fok et al., 2021; Horak et al., 2002). Additional variables, such as angular displacements under comparable scenarios of cognitive load and visual feedback, may help further clarify the connection between muscular activity and visual feedback to maintain balance.

4.5 Angular displacement

As visual feedback increased, the amplitude of the angular displacements of the hip, knee and, the ankle decreased, suggesting that with more visual information from the CNS provide accurate and detailed information about where the body is positioned in the environment, reducing the need to increase corrective movements at the hip, knee and the ankle joints (Peterka, 2002; Winter, 1995). Furthermore, increased visual feedback allows the participants to rely more on automatic postural control rather than conscious postural control (Lajoie et al., 1993; Peterka, 2002). At lower gains, the body relies more on proprioceptive and vestibular inputs, and postural control shifts to larger conscious corrective movements as there is limited visual information (Peterka, 2002, Shumway-Cook & Woollacot, 2007).

When participants made minor forward and backward movements, the ankle joint acted as a pivot point. The gastrocnemius and soleus muscles-controlled sway by exerting forces against the ground through the foot, creating torque at the ankle joint to help maintain the center of mass (COM) over the base of support (BOS) (Winter, 1995). When cognitive tasks are introduced, the brain divides attentional resources to perform the cognitive task and maintain balance. And because there is a cognitive load, the body tends to allocate fewer resources from the brain to actively adjust for postural control and relies more on automatic, unconscious adjustments, leading to decreased postural adjustments (Lajoie et al., 1993). This was particularly shown during arithmetic task, where the ankle joint displacement was larger when compared to performing controlled task and visual search task, especially when gain was set at 0.25 and 4. During the visual search task, ankle joint displacement was lower than in control trials and arithmetic trials when the visual gain was set at 4. This implies that the visual information from reading the letters on the board helped visual search tasks conditions, making it easier for the body to rely on automation postural control. Nevertheless, in controlled trials without cognitive tasks, the ankle and other joints showed insignificant involvement, suggesting that the ankle made subtle changes to maintain the COM within the BOS (Winter, 1995). In these trials, the brain focused fully on maintaining balance (Winter, 1995; Shumway-Cook & Woollacott, 2007). As visual feedback increased, ankle displacement decreased, indicating that at lower visual gains (especially at 0.25), with reduced visual input, the postural control system shifted toward conscious control mechanisms. In this case, more conscious cognitive involvement was necessary, indicating that the brain actively adjusted body movements in response to sensory feedback, such as visual and proprioceptive inputs (Stoffregen & Riccio, 1991). But it is possible that cognitive tasks may have engaged automatic control mechanisms, leading to smaller, more subtle corrections, particularly as visual feedback increased.

The results underscore the significance of visual information in enhancing postural control, particularly when cognitive tasks are involved, and underscore the need to consider both sensory feedback and cognitive demands when understanding angular displacements. Because visual feedback, cognitive load, and movement displacements all affect each other in complex ways, the impact of them on conscious postural control, especially when measured by the Movement Specific Reinvestment Scale (MSRS) is also important to be investigated.

4.6 MSRS Mean Value

As previously indicated, higher scores on the MSRS are linked to disrupted motor performance, highlighting the influence of the cognitive load on motor control (Masters &Maxwell, 2008). In this study, control task conditions across all gain values had the highest mean scores compared to the arithmetic and visual search task. This suggests that when a person is performing dual task, they may have to shift their attention from maintaining balance to trying to perform the cognitive task, indicating that there is an influence of cognitive load on the ability to control posture (Donker et al., 2007; Masters &Maxwell, 2008). The result of this study aligns well with previous research, which indicates that while performing a task that only involves quiet standing, participants switch their attention by consciously maintaining balance, resulting in more frequent adjustments that make it difficult to maintain balance (Cavanaugh et al., 2007; Stergiou & Decker, 2011; Nafati & Vuillerme, 2011). To broaden our understanding with regards to these findings, it is important to learn how it can impact future research and its implications.

4.7 Implications of the Study

This study's focus was to have an impact on the field of biomechanics and neuroscience through knowledge enhancement of the topic of optic flow manipulation during cognitive tasks specifically one that require vision and quiet stance. The findings have potential applications in various areas, including the training programs involving balance and integrating visual feedback to enhance postural control, particularly in populations at risk of balance impairments (Shumway- Cook & Woollacott, 2007). Like previous study's practical applications like the VR rehabilitation programs and assistive technologies where there is simulation of different visual feedback conditions within a realistic virtual environment can effectively help in improving balance function (Sloot et al. 2014). Like previous studies that revealed cognitive demands can have impact on postural control, this research may be important for interventions where multitasking is necessary, especially ones that involve visual attention during dual tasks to improve physical performance along with cognitive abilities (Cavanaugh et al., 2007; Li et al.2012). This study provided evidence on the influence of optic flow on cognitive tasks during quiet stance, aiming to fill a literature gap. The study's contribution is crucial to advance research that involves theory within the field of neuromechanics.

4.8 Limitations

With valuable insights about this study, there are still limitations that need to be noted. Restricting the sample size to 31 participants, might have limited the generalizability of the findings. Even though there was an advantage in terms of experimental purposes, the conditions (controlled task, arithmetic task, visual search tasks) did not exactly replicate or fully capture the real-world dual tasks. Also, being in a controlled environment may have limited validity of the findings. The participants reaction to each trial that included visual feedback may have been influenced by the VR's virtual scene which was an imperfect portrayal of a real-world environment even though there was an attempt to mimic it. Potential fatigue and the repetitiveness of the trials, despite its randomization, may have introduced a variability due to the learning effects across repeated trials. Additionally, individual differences in factors like attention span, prior VR experience, and visual acuity may have influenced participant's performances. Lastly, it is important to note that factors such as IQ, cognitive ability, and the years of education were not assessed in participant selection. With cognitive tasks involved in the study, individual differences in cognitive capacity may have influenced task performance and postural control responses. With these limitations mentioned, several avenues for future research can be built upon this study's findings and address the constraints identified.

4.9 Future Work

A broader population would have been advantageous since postural control mechanisms differ with age especially ones that have difficulty in maintaining. Including more complex tasks that replicate realistic daily activities can help improve our understanding of the relationship between visual feedback while there are tasks that involve cognitive demands while standing. Longitudinal experiments may be good to understand how individuals react to dual tasks with visual input involved in the long run and find whether consistent exposure leads to improvements of if these improvements plateau. Furthermore, combining visual feedback with other sensory feedback methods like vestibular and proprioceptive inputs, may expand our knowledge on how the nervous systems maintain balance while dual tasking. In the future, these suggested gaps within the field of study may emphasize the continuous need for research.

4.10 Conclusion

These findings directly addressed the gap concerning the effects of optic flow manipulation on cognitive related tasks, especially one that involves vision while maintaining upright stance. While it has been shown that visual feedback enhances postural control, the interaction between visual demands and cognitive loads presents unique challenges, especially in the ML direction. The CNS prioritizes maintaining balance in the AP direction, while the ML direction is more prone to disruptions due to the task's specific cognitive and visual demands. The study not only fills the important gap in research but also provides new important insights in the complex balance regulation under conditions that manipulate cognitive demands and visual feedback, leading to enhancing our understanding of balance maintenance in challenging environments.

References

Agostini, V., Ghislieri, M., Rosati, S., Balestra, G., & Knaflitz, M. (2020). Surface Electromyography Applied to Gait Analysis: How to improve its Impact in Clinics? Frontiers in Neurology, 11.

Augustine, G. J., Fitzpatrick, D., & Purves, D. (2001). *Neuroscience* (2nd ed.). Sinauer Associates

Allum, J. H., & Pfaltz, C. R. (1985). Visual and vestibular contributions to pitch sway stabilization in the ankle muscles of normals and patients with bilateral peripheral vestibular deficits. Experimental Brain Research, 58(1), 82–94.

Andersson, G., & Yardley, L. (2001). Cognitive-behavioral interventions for chronic dizziness: A controlled trial. Journal of Psychosomatic Research, 50(2), 113-120.

Angelaki, D. E., & Cullen, K. E. (2008). Vestibular system: the many facets of a multimodal sense. Annual Review of Neuroscience, 31, 125–150.

Assländer, L., & Peterka, R. J. (2014). Sensory reweighting dynamics in human postural control. Journal of Neurophysiology, 111(9), 1684-1696

Assländer, L., & Streuber, S. (2020a). Virtual reality as a tool for balance research: Eyes open body sway is reproduced in photo-realistic, but not in abstract virtual scenes. PLoS One, 15(10), e0241479.

Bayot, M., Dujardin, K., Tard, C., Defebvre, L., Bonnet, C. T., Allart, E., & Delval, A. (2018). The interaction between cognition and motor control: A theoretical framework for dual-task interference effects on posture, gait initiation, gait and turning. Neurophysiologie Clinique, 48(6), 361–375.

Bendo, A., Kuvarati, S., Skënderi, D., & Veveçka, A. (2013). A theoretical study on the evaluation of stability and postural sway, based on the results of the confidence ellipse. International Journal of Scientific Research, 4, 2319–7064.

Berencsi, A., Ishihara, M., & Takagi, A. (2005). The influence of visual feedback on head movement during upright stance. Neuroscience Research, 52(1), 68-72.

Bergin, P. S., Bronstein, A. M., Murray, N. M. F., Sancovic, S., & Zeppenfeld, K. (1995). Body sway and vibration perception thresholds in normal aging and in patients with polyneuropathy. Journal of Neurology, Neurosurgery and Psychiatry, 58, 335-340.

Bles, W., Kapteyn, T. S., Brandt, T., & Arnold, F. (1980). The mechanism of physiological height vertigo: II, Posturography. Acta Otolaryngologica, 89, 534–540.

Bronstein, A. M. (2019). A conceptual model of the visual control of posture. Progress in Brain Research, 248, 285–302.

Calvert, G., Charles, S., & Stein, B. E. (2012). The new handbook of multisensory processes. Cambridge, Mass: MIT Press.

Campolettano, E. T., Gellner, R. A., & Rowson, S. (2018). Assessing static and dynamic postural control in a healthy population. Biomedical Sciences Instrumentation, 54(1), 24–31.

Carpenter, M. G., Murnaghan, C. D., & Inglis, J. T. (2010). Shifting the balance: Evidence of an exploratory role for postural sway. Neuroscience, 171(1), 196–204.

Casale, J., & Gupta, G. (2020). Physiology, Vestibular System. PubMed; StatPearls Publishing.

Cavanaugh, J. T., Guskiewicz, K. M., Giuliani, C., Marshall, S., Mercer, V. S., & Stergiou, N. (2007). Recovery of postural control after cerebral concussion: New insights using approximate entropy. *Journal of Athletic Training*, 41(3), 305-313

Cawsey, R. P., Chua, R., Carpenter, M., & Sanderson, D. J. (2009). To what extent can increasing the magnification of visual feedback of the centre of pressure position change the control of quiet standing balance? *Gait & Posture*, *29*, 280–284.

Cenciarini, M., & Peterka, R. J. (2006). Stimulus-dependent changes in the vestibular contribution to human postural control. Journal of Neurophysiology, 95(5), 2733–2750.

Crane, B. T., & Demer, J. L. (1998). Gaze stabilization during dynamic posturography in normal and vestibulopathic humans. Experimental Brain Research, 122(2), 235–246.

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics, 13*(2), 135-163.

Diener, H. C., Dichgans, J., Bruzek, W., & Selinka, H. (1984). Stabilization of human posture during induced oscillations of the body. *Experimental Brain Research*, 45(1-2), 126–132

Disselhorst-Klug, C., Schmitz-Rode, T., & Rau, G. (2009). Surface electromyography and muscle force: Limits in sEMG-force relationship and new approaches for applications. Clinical Biomechanics, 24(3), 225–235.

Donker, S. F., Roerdink, M., Greven, A. J., & Beek, P. J. (2007). Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. Experimental Brain Research, 181(1), 1–11.

Duarte, M., & Freitas, S. M. (2010). Revision of posturography based on force plate for balance evaluation. *Brazilian Journal of Physical Therapy*, 14(3), 183-192

Engel, D., Schütz, A., Krala, M., Schwenk, J. C. B., Morris, A. P., & Bremmer, F. (2020). Inter-trial phase coherence of visually evoked postural responses in virtual reality. Experimental Brain Research, 238, 1177–1189.

Evans, M. K., & Krebs, D. E. (1999). Posturography does not test vestibulospinal function. Otolaryngology--Head and Neck Surgery: Official Journal of American Academy of Otolaryngology-Head and Neck Surgery, 120(2), 164–173.

Field, A. (2009). *Discovering statistics using SPSS* (3rd ed.). SAGE Publications.

Fitzpatrick, R. C., & Gandevia, S. C. (2005). Paradoxical muscle contractions and the neural control of movement and balance. The Journal of Physiology, 564(Pt 1), 2.

Fitzpatrick, R. C., & McCloskey, D. I. (1994). Proprioceptive, visual and vestibular thresholds for the perception of sway during standing in humans. *The Journal of Physiology*, 478(1), 173–186

Fok, K. L., Lee, J. W., Unger, J., Chan, K., Musselman, K. E., & Masani, K. (2021). Co-contraction of ankle muscle activity during quiet standing in individuals with incomplete spinal cord injury is associated with postural instability. Scientific Reports, 11.

Grove, C. R., Whitney, S. L., Hetzel, S. J., Heiderscheit, B. C., & Pyle, G. M. (2021). Validation of a next-generation sensory organization test in adults with and without vestibular dysfunction. Journal of Vestibular Research: Equilibrium & Orientation, 31(1), 33–45.

Haddad, J. M., Rietdyk, S., Claxton, L. J., & Huber, J. (2013). Task-dependent postural control throughout the lifespan. *Exercise and Sport Sciences Reviews*, 41(2), 123-132

Hamid, M., Hughes, G., & Kinney, S. (1991). Specificity and sensitivity of dynamic posturography. Acta Otolaryngological (Stockholm), 481(Suppl.), 596-600.

Harris, L. R., Jenkin, M., & Zikovitz, D. C. (2000). Visual and non-visual cues in the perception of linear self-motion. *Experimental Brain Research*, 135(1), 12–21

Hayes, K. C. (1982). Biomechanics of postural control. Exercise and Sport Sciences Reviews, 10, 363–391.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, 10(5), 361–374

Horak, F. B., & Nashner, L. M. (1986). Central programming of postural movements: Adaptation to altered support-surface configurations. *Journal of Neurophysiology, 55*(6), 1369–1381.

Horak, F. B., Diener, H. C., & Nashner, L. M. (1989). Influence of central set on human postural responses. Journal of Neurophysiology, 62(4), 841–853.

Horak, F. B., & Macpherson, J. M. (2002). Postural orientation and equilibrium. In J. H. Kandel, E. R. Schwartz, & T. M. Jessell (Eds.), Principles of Neural Science (pp. 801-814). McGraw-Hill.

Horak, F. B., & Nashner, L. M. (1986). Central programming of postural movements: Adaptation to altered support-surface configurations. *Journal of Neurophysiology, 55*(6), 1369-1381.

Howard, I. P., & Rogers, B. J. (2008). Binocular vision and stereopsis. In Oxford Scholarship Online.

Howarth, S. J., & Callaghan, J. P. (2010). Quantitative assessment of the accuracy for three interpolation techniques in kinematic analysis of human movement. Computer Methods in Biomechanics and Biomedical Engineering, 13(6), 847–855.

Huffman, J. L., Horslen, B. C., Carpenter, M. G., & Adkin, A. L. (2009). Does increased postural threat lead to more conscious control of posture? *Journal of Motor Behavior*, *41*(4), 535–543.

Jones, S. M., Jones, T. A., Mills, K. N., & Gaines, G. C. (2009). Anatomical and physiological considerations in vestibular dysfunction and compensation. Seminars in Hearing, 30(4), 231–241.

Joseph Jilk, D., Safavynia, S. A., & Ting, L. H. (2014). Contribution of vision to postural behaviors during continuous support-surface translations. Experimental Brain Research, 232(1), 169–180.

Kapteyn, T. S., Kuiper, J. I., de Graaf, B., & Lugtigheid, J. (2008). The reliability of RMS as a measure of postural stability. *Gait & Posture*, 28(2), 257–262

Kandel, E. R., Schwartz, J. H., Jessell, T. M., Siegelbaum, S. A., & Hudspeth, A. J. (2013). Principles of Neural Science (5th ed.). McGraw Hill Medical.

Kang, H. G., & Lipsitz, L. A. (2010). Stiffness control of balance during quiet standing and dual task in older adults: The MOBILIZE Boston Study. Journal of Neurophysiology, 104(6), 3510–3517.

Keshner, E. A., & Kenyon, R. V. (1999). Postural and spatial orientation influenced by vestibular and cognitive processing. Annals of the New York Academy of Sciences, 871(1), 386-399.

Keshner, E. A., Allum, J. H., & Pfaltz, C. R. (1987). Postural coactivation and adaptation in the sway stabilizing responses of normals and patients with bilateral vestibular deficit. Experimental Brain Research, 69(1), 77–92.

Kibler, W. B. (1998). The role of the scapula in athletic shoulder function. *The American Journal of Sports Medicine*, 26(2), 325-337

Koenderink, J. J., & van Doorn, A. J. (1976). Local structure of movement parallax of the plane. Journal of the Optical Society of America, 66, 717–723.

Lavalle, L. K., & Cleworth, T. W. (2023). The effect of modified optic flow gain on quiet stance. Neuroscience Letters, 797, 137068.

Lafond, D., Duarte, M., & Prince, F. (2004). Postural control during quiet standing in athletes and non-athletes. *Clinical Biomechanics*, 19(5), 465-472

Lin, I. S., Lai, D. M., Ding, J. J., Chien, A., Cheng, C. H., Wang, S. F., Wang, J. L., Kuo, C. L., & Hsu, W. L. (2019). Reweighting of the sensory inputs for postural control in patients with cervical spondylotic myelopathy after surgery. Journal of Neuroengineering and Rehabilitation, 16(1), 96.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research*, 97(1), 139-144

Lajoie, Y., Richer, N., Jehu, D. A., & Tran, Y. (2016). Continuous cognitive tasks improve postural control compared to discrete cognitive tasks. *Journal of Motor Behavior*, *48*(3), 264–269.

Lopez, C. (2015). Making sense of the body: The role of vestibular signals. Multisensory Research, 28(5-6), 525–557.

Lord, S. R., & Dayhew, J. (2001). Visual risk factors for falls in older people. Journal of the American Geriatrics Society, 49(5), 508–515.

Ludwig, C. J. H., Alexander, N., Howard, K. L., Jedrzejewska, A. A., Mundkur, I., & Redmill, D. (2018). The influence of visual flow and perceptual load on locomotion speed. Attention, Perception & Psychophysics, 80(1), 69–81.

Macpherson, J. M., & Inglis, J. T. (1993). Stance and balance in health and disease. *Physiological Reviews, 73*(1), 623-649.

McIlroy, W. E., & Maki, B. E. (2005). Visual influences on rapid motor responses in relation to falls in older adults: A review. *Age and Ageing*, 34(3), 205–212

Masters, R., & Maxwell, J. (2008). The theory of reinvestment. International Review of Sport and Exercise Psychology, 1(2), 160–183.

McIsaac, T. L., Lamberg, E. M., & Muratori, L. M. (2015). Building a framework for a dual task taxonomy. BioMed Research International, 2015, 1–10.

Merletti, R., Rainoldi, A., & Farina, D. (2001). Surface electromyography for noninvasive characterization of muscle. Exercise and Sport Sciences Reviews, 29(1), 20–25.

Nafati, G., & Vuillerme, N. (2011). Decreasing internal focus of attention improves postural control during quiet standing in young healthy adults. Research Quarterly for Exercise and Sport, 82(4), 634–643.

Paillard, T., & Noé, F. (2015). Techniques and methods for testing the postural function in healthy and pathological subjects. BioMed Research International, 2015, 891390.

Pavão, S. L., Lima, C. R. G., & Rocha, N. A. C. F. (2021). Effects of motor and cognitive manipulation on the dual-task costs of center of pressure displacement in children, adolescents and young adults: A cross-sectional study. Clinical Biomechanics, 84, 105344.

Peterka, R. J., & Benolken, M. S. (1995). Role of somatosensory and vestibular cues in attenuating visually induced human postural sway. Experimental Brain Research, 105(1), 101–110.

Peterka, R. J. (2002). Sensorimotor integration in human postural control. Journal of Neurophysiology, 88(3), 1097-1118.

Peterka, R. J. (2018). Sensory integration for human balance control. *Handbook of Clinical Neurology*, *159*(3), 27–42.

Phinyomark, A., Thongpanja, S., Hu, H., Phukpattaranont, P., & Limsakul, C. (2012). The usefulness of mean and median frequencies in electromyography analysis.

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., & Myklebust, B. M. (1996). Measures of postural steadiness: Differences between healthy young and elderly adults. *IEEE Transactions on Biomedical Engineering*, 43(9), 956-966

Pollock, A. S., Durward, B. R., Rowe, P. J., & Paul, J. P. (2000). What is balance? Clinical Rehabilitation, 14(4), 402–406.

Potvin-Desrochers, A., Richer, N., & Lajoie, Y. (2017). Cognitive tasks promote automatization of postural control in young and older adults. *Gait and Posture*, *57*, 40–45

Prado, J. M., Stoffregen, T. A., & Duarte, M. (2007). Postural sway during dual tasks in young and elderly adults. Gerontology, 53(5), 274–281.

Ramos de Miguel, A., Zarowski, A., Sluydts, M., Ramos Macias, A., & Wuyts, F. L. (2020). The superiority of the otolith system. Audiology & Neuro-Otology, 25(1-2), 35–41.

Redfern, M. S., Yardley, L., & Bronstein, A. M. (2001). Visual influences on balance. Journal of Anxiety Disorders, 15(1-2), 81–94.

Riecke, B. E., Schulte-Pelkum, J., Bülthoff, H. H., & der Heyde, M. von. (2006). Cognitive factors can influence self-motion perception (vection) in virtual reality. ACM Transactions on Applied Perception (TAP), 3(3), 194–216.

Robert, M. T., Ballaz, L., & Lemay, M. (2016). The effect of viewing a virtual environment through a head-mounted display on balance. Gait & Posture, 48, 261–266.

Roerdink, M., De Haart, M., Daffertshofer, A., Donker, S. F., Geurts, A. C. H., & Beek, P. J. (2006). Dynamical structure of center-of-pressure trajectories in patients recovering from stroke. Experimental Brain Research, 174(2), 256–269.

Roerdink, M., De Haart, M., Daffertshofer, A., Donker, S. F., Geurts, A. C. H., & Beek, P. J. (2011). Influence of consciously and unconsciously available visual information on postural control. *Gait & Posture*, 33(2), 175–180

Rougier, P., Garin, M., & Lelong, C. (2004). The effect of visual feedback on the control of body sway. Acta Oto-Laryngologica, 124(7), 706-712

Royden, C. S., Banks, M. S., & Crowell, J. A. (1992). The perception of heading during eye movements. Nature, 360(6404), 583–585.

Rudolph, K. S., Axe, M. J., & Snyder-Mackler, L. (2000). Dynamic stability after ACL injury: Who can hop? Knee Surgery, Sports Traumatology, Arthroscopy, 8(5), 262–269.

Salsabili, H., Bahrpeyma, F., Esteki, A., Karimzadeh, M., & Ghomashchi, H. (2013). Spectral characteristics of postural sway in diabetic neuropathy patients participating in balance training. Journal of Diabetes and Metabolic Disorders, 12, 29.

Shaffer, S. W., & Harrison, A. L. (2007). Aging of the somatosensory system: A translational perspective. Physical Therapy, 87(2), 193–207.

Sherman, W. R., & Craig, A. B. (2018). Understanding virtual reality: Interface, application, and design. Morgan Kaufmann.

Shumway-Cook, A., & Horak, F. B. (1986). Assessing the influence of sensory interaction on balance. *Physical Therapy*, *66*(10), 1548–1550.

Shumway-Cook, A., & Woollacott, M. H. (2007). Motor Control: Translating Research into Clinical Practice. Lippincott Williams & Wilkins

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. Presence: Teleoperators & Virtual Environments, 6, 603-616.

Sloot, L. H., van der Krogt, M. M., & Harlaar, J. (2014). Effects of adding a virtual reality environment to different modes of treadmill walking. Gait & Posture, 39(3), 939-945.

Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Human Movement Science*, 30(5), 869-888

Stoffregen, T. A., & Riccio, G. E. (1991). An ecological theory of orientation and the vestibular system. Psychological Review, 98(2), 171-206

Stoffregen, T. A., Hove, P., Schmit, J., & Bardy, B. G. (2000). Voluntary head movements and postural control. Experimental Brain Research, 132(4), 377-392.

Stoffregen, T. A., Pagulayan, R. J., Bardy, B. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. Human Movement Science, 19(2), 203–220.

Stoffregen, T. A., Riccio, G. E. (1991). An ecological theory of orientation and the vestibular system. Psychological Review, 98(2), 171-206.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (2006). Postural stabilization of visually guided eye movements. Ecological Psychology, 8(3), 197-229.

Streuber, S., Mohler, B. J., Bülthoff, H. H., & de la Rosa, S. (2012). The influence of visual information on the motor control of table tennis strokes. *Presence: Teleoperators and Virtual Environments*, 21(3), 281–294

Swan, L., Otani, H., & Loubert, P. V. (2004). Reducing postural sway by manipulating the difficulty levels of a cognitive task and a balance task. Gait & Posture, 20(3), 212-216.

Swan, L., Otani, H., & Loubert, P. V. (2007). Reducing postural sway by manipulating the difficulty levels of a cognitive task and a balance task. Gait & Posture, 26(3), 390-394.

Taguchi, K. (1978). Spectral analysis of the movement of the center of gravity in vertiginous and ataxic patients. Agressologie, 19(B), 69–70.

Thompson, L. A., Badache, M., Cale, S., Behera, L., & Zhang, N. (2017). Balance performance as observed by center-of-pressure parameter characteristics in male soccer athletes and non-athletes. Sports, 5(4), 86.

Ting, L. H., van Antwerp, K. W., Scrivens, J. E., McKay, J. L., Welch, T. D., Bingham, J. T., & DeWeerth, S. P. (2009). Neuromechanical tuning of nonlinear postural control dynamics. Chaos, 19(2), 026111.

Tsunozaki, M., & Bautista, D. M. (2009). Mammalian somatosensory mechanotransduction. Current Opinion in Neurobiology, 19(4), 362–379.

Van Asten, W. N., Gielen, C. C., & Denier van der Gon, J. J. (1988). Postural adjustments induced by simulated motion of differently structured environments. Experimental Brain Research, 73(2), 371–383.

Van Asten, W. N., Gielen, C. C., & Denier van der Gon, J. J. (1988b). Postural adjustments induced by simulated motion of differently structured environments. *Experimental brain research*, *73*(2), 371–383.

Van Kordelaar, J., Pasma, J. H., Cenciarini, M., Schouten, A. C., van der Kooij, H., & Maurer, C. (2018). The reliance on vestibular information during standing balance control decreases with severity of vestibular dysfunction. Frontiers in Neurology, 9, 371.

Visser, J. E., Carpenter, M. G., van der Kooij, H., & Bloem, B. R. (2008). The clinical utility of posturography. Clinical Neurophysiology, 119(11), 2424–2436.

Ward, N., Menta, A., Ulichney, V., Raileanu, C., Wooten, T., Hussey, E. K., & Marfeo, E. (2022). The specificity of cognitive-motor dual-task interference on balance in young and older adults. Frontiers in Aging Neuroscience, 13.

Winter, D. A. (1995). Human balance and posture control during standing and walking. Gait & Posture, 3(4), 193-214.

Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement* (4th ed.). Wiley

Winter, D. A., Patla, A. E., Prince, F., Ishac, M., & Gielo-Perczak, K. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology, 80*(3), 1211-1221.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. Gait & Posture, 16(1), 1–14.

Woollacott, M., & VanderVelde, T. (2008). Non-visual influences on postural control: Mechanisms and implications. *Advances in Experimental Medicine and Biology*, 629, 144–158

Wulf, G., McNevin, N., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology A*, *54*(4), 1143–1154.

Yoo, H., & Mihaila, D. M. (2022). Neuroanatomy, Vestibular Pathways. In: StatPearls. StatPearls Publishing, Treasure Island (FL); PMID: 32491312.

Yu, H., & Huang, H. H. (2017). Biofeedback and virtual reality technologies in balance training for stroke rehabilitation: A systematic review and meta-analysis. *Journal of NeuroEngineering and Rehabilitation*, 14(1), 34

Zaback, M., Cleworth, T. W., Carpenter, M. G., & Adkin, A. L. (2015). Personality traits and individual differences predict threat-induced changes in postural control. *Human Movement Science*, *40*, 393–409.

Zaback, M., Adkin, A. L., & Carpenter, M. G. (2019). Adaptation of emotional state and standing balance parameters following repeated exposure to height-induced postural threat. Scientific Reports, 9(1), 12449.

Zaback, M., Brown, S. H., & Kuhl, S. A. (2021). The effects of task difficulty on muscle synergies during isometric force production. Journal of Electromyography and Kinesiology, 57, 102519

Zettel, J. L., McIlroy, W. E., & Maki, B. E. (2008). Effect of competing attentional demands on perturbation-evoked stepping reactions and associated gaze behavior in young and older adults. The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 63(12), 1370–1379

Appendix A- Movement re-investment questionnaire used across all trials with all participants

The Movement Specific Reinvestment Scale (MSRS)

Conscious Motor Processing

I am always trying to think about my movements when I carry them out.

I reflect about my movement a lot.

I am always trying to figure out why my actions failed.

I am aware of the way my body works when I am carrying out a movement.

I rarely forget the times when my movements have failed me.

Movement Self-Consciousness

I am concerned about my style of moving.

I am self conscious about the way I look when I am moving.

If I see my reflection in a shop window, I will examine my movements.

I sometimes have the feeling that I am watching myself move.

I am concerned about what people think about me when I am moving.

Rating scale for each statement:

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6