LOCOMOTOR RESPONSES TO GALVANIC STIMULATION OF THE VESTIBULAR SYSTEM IN HUMANS

by

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Balance is controlled through the integration of vestibular, visual and proprioceptive senses; however, the impact of each during walking is not fully understood. The primary aim of this thesis is to understand the impact of vestibular signals in the maintenance of balance during walking. Galvanic vestibular stimulation (GVS) was used to evoke internal perturbations of the human balance system. Subjects were exposed to binaural-bipolar GVS during gait and body movements were obtained using VICON motion capture. GVS induced a lateral deviation of whole-body movements towards the anodal side during gait. Head rotation was small compared to the thorax or pelvis throughout gait irrespective of the presence of vision or GVS. The pelvis and thorax experienced significant tilting due to GVS; however, a counter rotation of the head compensated for this tilt. Vision had a significant effect on the GVS response. When walking with eyes open, GVS had a minimal effect on the gait trajectory, spatial foot placement, or tilt angle of the head, thorax, and pelvis. During eyes closed, foot placement and pelvis displacement were significantly affected by GVS. GVS induced shorter steps, lateral displacement of the body, and tilt rotations of the pelvis and thorax. The presence of GVS also affected the temporal ordering of which the maximum tilt angle of the head, thorax, and pelvis were observed depending upon fall direction. Falls towards the stance limb appear to be driven by the head as lower-body segments deviate in an attempt to regain balance and avoid a fall. Falls away from the stance limb appear to be driven by the pelvis and lower-body. This study

indicated that there is an intricate interaction of body segments in response to GVS that is dependent upon other sensory information available.

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NOMENCLATURE

AP	Anterior-posterior
ASIS	Anterior superior iliac spine
BOS	Base of support
COM	Center of mass
EC	Eyes closed
EO	Eyes open
FT	Feet together
G	Gait
GCS	Global coordinate system
GVS	Galvanic vestibular stimulus
HC	Heel contact
LCS	Local coordinate system
ML	Mediolateral
MS	Mid-stance
NI	National Instruments Corporation
PSIS	Posterior superior iliac spine
R^+	Anode right first, anode left second
R^-	Anode left first, anode right second
T	Tandem stance

PREFACE

Subjects were screened for vestibular deficiencies at the Eye and Ear Institute, University of Pittsburgh Medical Center by Kara McMongale and Susan Strelinski. Partial funding was provided by Robert Bosch LLC. Three-dimensional schematics of the plug-in gait marker set were supplied with the kind permission of Vicon, Los Angeles.

1.0 INTRODUCTION

Falls are a leading cause of injury in the developed world. Older adults are particularly at risk, with 62% of injuries (Dellinger et al., 2006) and 40% of injury-related deaths (Finkelstein et al., 2006) in the elderly being due to falls. Not only are falls a significant problem for older adults, but associated injuries and the fear of falling both affect the quality of life of some older adults. The future of fall prevention may depend on technological advances in fall prediction and the development of fall interventions. An introduction to said research using anthropometric test dummies has been previously presented (Steed et al., 2008). The primary aim of this current work is to study human responses to internal vestibular perturbations in hopes of gaining further understanding of the key characteristics of the postural control during walking.

In this study, a loss of balance was induced using galvanic vestibular stimulation (GVS). Research pioneers have been using GVS to stimulate the vestibular system for over a century in hopes to gain insight into postural control (Breuer, 1889, described by Kayan et al., 1974). A small electrical current was applied to the vestibular system via surface electrodes placed over the mastoid processes. This trans-mastoid current changes the firing rate of the vestibular nerve resulting in involuntary corrective movements of the body. The movement response to these stimuli were measured and analyzed in this experiment to gain a better understanding of how vestibular inputs are utilized during walking to maintain balance.

2.0 SIGNIFICANCE

The long term goal of this project is to reduce the number of falls experienced by the elderly and patients with vestibular disorders. The sensory integration process for balance during locomotion is not fully understood. The experiments conducted increased our understanding of the postural control system during walking by examining the kinematic responses to internally produced vestibular perturbations through the use of an externally supplied GVS. The knowledge gained can be applied to identification and rehabilitation of balance disorders. Furthermore, the information gained in this study may aid in improving of the quality of life of those with balance disorders. Aggressive diagnosis and treatment of balance disorders will lead to more timely treatment of those who suffer from such a disease. The rehabilitation of those with balance disorders will likely reduce the frequency of falls and fall related injuries as well as the fear of falling.

3.0 SPECIFIC AIMS

The goal of this study is to gain better understanding of the factors that affect balance while people walk and how people recover from perturbations of balance that may lead to falls. More specifically, because GVS affects information coming from the vestibular system, we can consider this type of perturbation as internal, as opposed to external perturbations such as trips and slips. In the long term, we hope to determine the biomechanical process of falls and fall onset using GVS. A perturbation approach using GVS was used to induce trajectory deviations during gait, in the mediolateral (ML) direction of human subjects. The response to such a perturbation was evaluated using a motion analysis system and footswitches to aid in the deciphering of the specific phases of the gait cycle.

The specific aim of this study is to examine the specific kinematic responses of the body segments in response to GVS during locomotion. Head movements were examined to determine stability during gait perturbations. Foot placement as well as upper body (head, torso, and pelvis) movement was examined to enhance current literature that debates an inverted pendulum model as opposed to segmental tilting during a balance loss. Temporal parameters aided in the determination of sequential segmental tilting. Lastly, the coordination of joint responses was investigated, such as the interaction of head and torso as well as the interaction of the torso and pelvis.

4.0 BACKGROUND

To fully understand whole-body biomechanical responses to external and internal perturbations, one must first understand how the vestibular system functions and how the body maintains balance. This chapter provides a review of published literature detailing the anatomy and function of the vestibular system as well as research performed using GVS.

4.1 THE VESTIBULAR SYSTEM

The human vestibular system contributes to the perception of gravity and movement of the body. The vestibular system consists of the peripheral vestibular apparatus and the central neural structures that integrate the signals from the peripheral apparatus with other sensory signals concerning balance (Figure 1). The vestibular apparatus itself is located in the bony labyrinth of the ear and includes primary afferent neurons (Germann et al., 2005; Gray, 1969; Sherwood, 2004). These neurons spontaneously discharge at a constant rate when at rest, but alter their discharge rate when experiencing a stimulus. Head movements are detected by specialized hair cells in the two primary components of the vestibular system: semicircular canals and otolith organs (Germann et al., 2005; Kandel et al., 2000; Sherwood, 2004). The semicircular canals sense angular acceleration that is then processed directly into estimates of angular velocity of the head. The otolith organs detect linear acceleration of the head induces by gravity and movement,

resulting in an estimate of a combined gravito-interial signal. Outputs from the vestibular apparatus cause changes in the firing rate of the vestibulocochlear nerve (cranial nerve VIII) (Kandel et al., 2000; Sherwood, 2004).

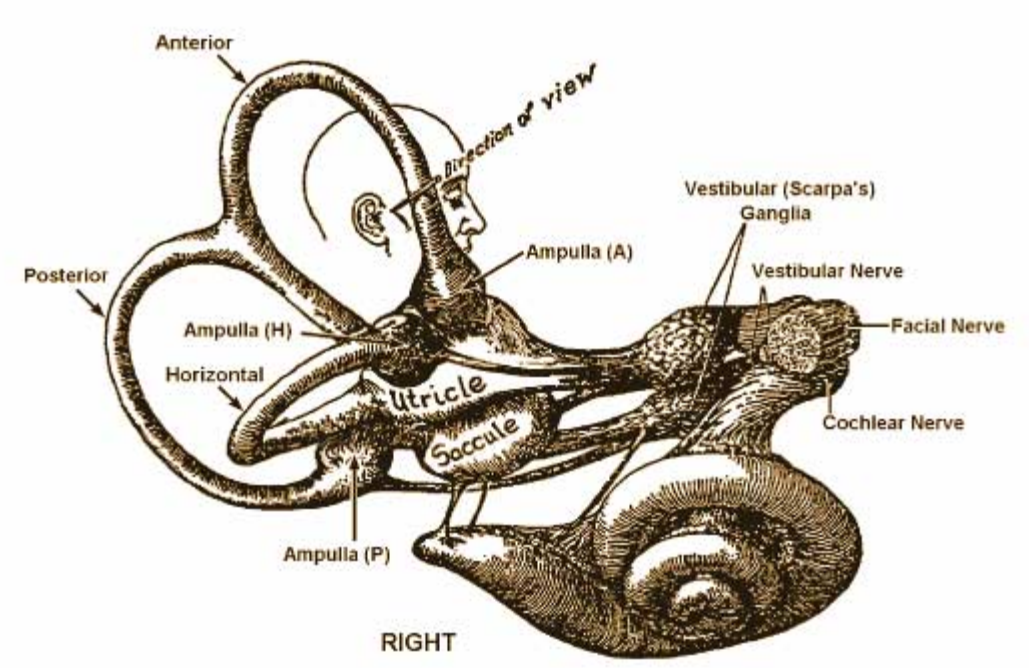

Figure 1. Schematic representation of the vestibular apparatus (Hardy et al., 1934)

4.1.1 The Semicircular Canals

Each side of the head contains one set of three semicircular canals that detect rotational accelerations. Each of the three semicircular canals is oriented in a nearly orthogonal arrangement allowing for detection of rotational acceleration in three planes (Gray, 1969; Germann et al., 2005; Kandel et al., 2000; Sherwood, 2004). Though the three semicircular canals are nearly orthogonal, they do not lie in a major anatomical plane (Kandel et al., 2000).

Thus, pure rotational accelerations about one anatomical axis are detected by two of the canals, but not the third (Kandel et al., 2000). There is then a transformation in the brain to resolve these signals into an estimate of head rotation. Such a system allows for increased reliability and accuracy. Likewise, the mirroring structures on each side of the head compare signals adding redundancy to the system.

The semicircular canals are filled with a gel-like solution, called perilymph (Gray, 1969; Germann et al., 2005; Kandel et al., 2000; Sherwood, 2004). Small hair cells, cilia, are embedded in the membrane of the canals. As a rotational acceleration is experienced in the head, the fluid within the canals remains relatively still as the rigid canals and hair cells pass around it, due to the properties of inertia. This difference in motion between the "flowing" gelatinous solution and the "stationary" hair cells creates a bend in the hair cells that alters the firing rates of the afferent fibers from that of tonic levels (Kandel et al., 2000). The longest of the patches of hair cells are called the kinocillium. The bending of the hair cells away from the kinocillium causes a decrease in the firing rate, while bending of the hair cells towards the kinocillium causes an increase in firing rate (Kandel et al., 2000) (Figure 2). Greater rotational accelerations yield greater differences in firing rate from the zero-acceleration constant discharge rate. Constant rotational velocities have no affect on primary afferent neuron firing rate once steady state rotation of the perilymph and labyrinth occurs.

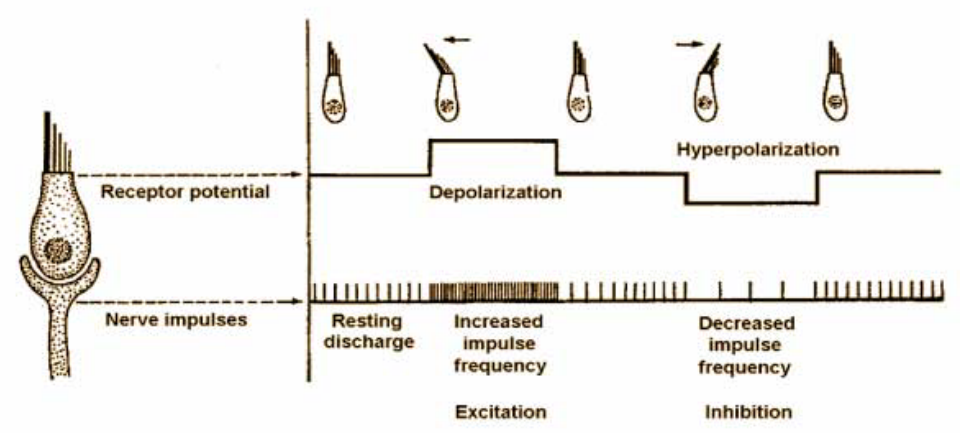

Figure 2. Schematic representation of the kinocilia and discharge rate (Kandel et al., 2000).

4.1.2 The Otolith Organs

Along with the three semicircular canals, each side of the head has a set of two otolith organs: the utricle and saccule (German et al., 2005; Gray, 1969; Kandel et al., 2000; Sherwood et al., 2004). These organs detect linear acceleration of the head (Germann et al., 2005; Kandel et al., 2000; Sherwood, 2004). Along with detecting vertical accelerations that may be experienced while riding in an elevator, or horizontal accelerations that may experienced during an automobile ride, the otolith organs detect the constant downward linear force of gravity. Similar to the semicircular canals, the otolith organs contain hair cells; however, the ends of the hair cells are embedded in a gelatinous sheet immersed in a gelatinous solution (Germann et al., 2005; Kandel et al., 2000; Sherwood, 2004). Again, any change in linear acceleration causes an increase or decrease in the firing rate of the afferent neurons. The utricle and saccule are approximately aligned with the semicircular canals. Unlike the semicircular canals that contain hair cells all aligned in the same direction, the utricle and saccule contain hair cells that point inward towards the a “centerline” called the striola that divides the pars lateralis and pars interna

(Germann et al., 2005; Kandel et al., 2000; Sherwood, 2004). Thus, for certain accelerations, one group of hair cells is maximally excited and another group of hair cells is maximally inhibited (Kandel et al., 2000; Sherwood, 2004). As the hair cells of the pars lateralis are bent and the firing rate is increased, the hair cells on the opposite side of the striola will decrease their firing rate.

A closer examination of a simple head movement will more clearly convey how the vestibular system operates. During one head movement consisting of a downward rotation from standard anatomical posture to chin-down, maintaining the posture, and then returning to standard anatomical posture for example, the afferents of the semicircular canals respond differently than those of the otolith organs. The afferents of the semicircular canals deviate from their typical tonic firing rate only during the movements themselves. During the time when the head is held downward towards the floor, the firing rate returns to the normal tonic firing rate because the head is not experiencing a rotational acceleration at this time. The afferents of the otolith organ however, responding to changes in linear accelerations, maintain an altered firing rate during the entire movement (Figure 3). The most significant difference in firing rate from the original posture from the otolith organs is observed when the head is held in the chin-down posture (Yates, 2008).

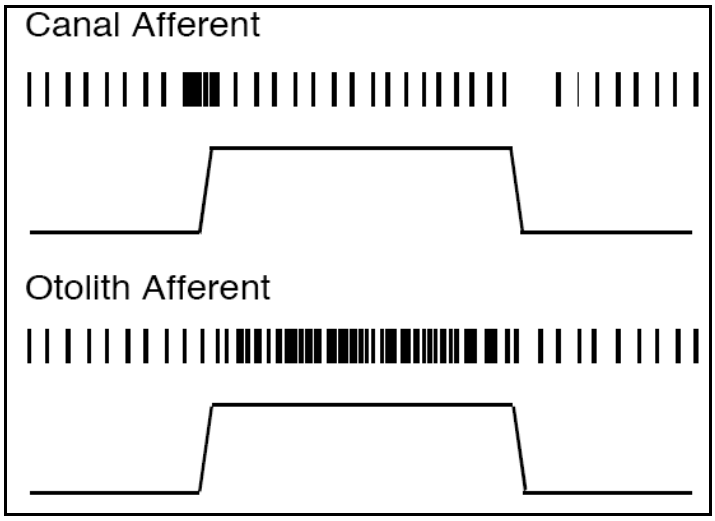

Figure 3. Vestibular afferent responses to prolonged tilts (Yates, 2008)

4.2 GALVANIC VESTIBULAR STIMULATION (GVS)

Galvanic Vestibular Stimulation is typically applied through stimulating electrodes that are adhered to the skin covering the mastoid processes. Exact details of skin preparation, equipment used, and the process of delivering the galvanic current may be found in the Methods section.

4.2.1 The Physiological Effects of GVS

The site of action of GVS has been well investigated and was determined to be the primary afferent neurons. The majority of the previous work has been performed using animal subjects. Thus, we must make the assumption that the vestibular system of animals, such as the thornback ray (Lowenstein, 1955) and squirrel monkey (Goldberg et al., 1984), function similarly to that of humans. Under this assumption, the physiological effects of GVS on the vestibular organs are

fairly well understood. Spiegel and Scala determined that severing the vestibulocochlear nerve eliminates typical responses to electrical stimulation. They concluded that "the [galvanic] current acts on the peripheral neuron of the vestibular nerve" (Spiegel et al., 1943). About a decade later, Lowenstein showed that the sensory end organs of the semicircular canals alter their discharge rates when exposed to galvanic currents (Lowenstein, 1955). This change in discharge rate, induced from the unnatural galvanic current, appeared to be the same as the response elicited by natural head rotations. More recent studies attempted to identify the mechanisms affected by the galvanic stimulus and explain the altered discharge rates of afferent nerves. Goldberg et al. provided clear evidence that the stimulus acts at the "spike trigger site" and alters the firing rate of the vestibular nerve by modifying the resting potential (Goldberg et al., 1984). In other words, the externally applied galvanic current acts directly "on the spike encoder in the axon terminal" (Goldberg et al., 1984; adapted from Goldberg, 2000).

4.2.2 The Effects of GVS on the Otolith Organs

As described above, the otolith organs are responsible for the detection of changes in linear acceleration as well as the detection of head tilt due to gravitational changes. The unique arrangement of the hair cells in the utricle allow for precise detection of linear accelerations in the lateral and sagittal directions. The hair cells of the saccule detect components of linear acceleration in the vertical and sagittal directions (German et al., 2005; Gray, 1969; Kandel et al., 2000; Sherwood et al., 2004). The duplicate structures on opposite sides of the head provide repeatability to the signals of the vestibular system and add significantly to the precision of the overall detection system.

During binaural-bipolar GVS, such as used in this experiment, a natural stimulus of a constant head tilt in the cathodal direction or linear acceleration in the anodal direction is perceived (Wardman et al., 2002). To avoid a fall, the body flexes in the direction of the perceived tilt. This flexing, or segmental roll always occurs towards the anodal side.

The effect of binaural-bipolar GVS in the coronal and sagittal planes is much less significant than it is in the frontal plane. The decreased effects in the coronal plane are explained by the functionality of the saccules. While the firing rates of the afferents in the saccule may be altered, the net effect would be an upward acceleration on one side of the head with a downward acceleration on the opposite side of the head. This would be perceived as a head roll without net vertical acceleration (Wardman et al., 2002). Similarly, the rather uniformly distributed hair cells of the saccule will experience equal changes in the anterior and posterior direction. Again, this balanced reading will result in an insignificantly small net acceleration. The differences in anterior and posterior directions on opposite sides of the head will be perceived as a yaw rotation without sagittal acceleration (Wardman et al., 2002).

4.2.3 The Effects of GVS on the Semicircular Canals

As previously stated, the semicircular canals of the inner ear detect angular accelerations in the head. Typically, specific firing rate patterns are produced for specific rotational motions of the head. During GVS however, the firing rates change in an unnatural fashion. Unlike natural stimuli, the galvanic current causes an increase in the firing rate of all afferents (Wardman et al., 2002). Though the horizontal canals experience a natural net yaw stimulus, the anterior and posterior canals experience contradicting stimuli which negate each other and sum to minimal yaw and pitch stimulus.

4.2.4 The Applications of GVS

Galvanic vestibular stimulus is typically generated on humans using small electrodes placed on the thin layer of skin behind the ears that covers the bony mastoid processes. GVS results in the perception of acceleration of the head, with the direction depending upon the polar orientation of the electrodes. This perception results in postural responses to counteract the perceived acceleration. The most common application of GVS is to cause postural deviations during standing to investigate the impact of the vestibular system on stance in healthy adults as well as in patients with balance disorders. Some studies have also applied GVS during walking to study the impact of vestibular inputs on gait.

Numerous studies have shown that a GVS current of 1mA or less is capable of creating noticeable vestibular disturbances resulting in postural responses (Bent et al., 2000; Bent et al., 2004; Cauquil et al., 2000; Day et al., 1997; Day et al., 1998; Fitzpatrick et al., 1999; Jahn et al., 2000; Latt et al., 2003; McFayden et al., 2006; Pavlik et al., 1999). The following sections describe some of the more important GVS studies in the literature.

4.2.4.1 GVS during Stance

The human balance system is responsible for creating the whole-body response to GVS during standing (Fitzpatrick et al., 2004). There is much debate, however, about how the body perceives the GVS and why the characteristic response is generated. Cauquil and others believe that the body is attempting to maintain balance during a perception of standing on an “inclined support surface” (Cauquil et al., 1998; Day et al., 1997). Others argue that the body is attempting to move towards an internal “perceived vertical” and in doing so, causes a loss of balance (Hlavacka et al., 1996). Others argue that the human body perceives a sway in a certain

direction and in order to maintain balance, the body sways in the opposite direction (Day et al., 1997; Fitzpatrick et al., 1999). Such a response would keep the center of mass (COM) within the base of support (BOS) and reduce the risk of a fall (Bent et al., 2005; Cauquil et al., 1998; Day et al., 1997). Previously, Day et al. (1997) had shown that differences in stance width and BOS greatly affect the biomechanical response to GVS. A smaller BOS generates larger sway responses during standing (Day et al., 1993). Later research by the same group showed segmental tilting of the body during stance and exposure to GVS where higher segments tilted to a greater degree than the segments below. Not only did the higher segments experience greater tilt angles, but markers placed on these higher segments experienced greater fluctuations in position and velocity than their lower counterparts. Segmental tilting in this manner summed to a bending towards the anodal ear and was maintained throughout the entire duration of the stimulus (Day et al., 1997). Consistent with their previous work, increasing the BOS lessened the visual biomechanical response and segmental tilting due to increased rigidity at the pelvis. It is this rigidity at the pelvis that mechanically limits the motion and tilting of the pelvis. Thus, the previously hypothesized "inverted pendulum" theory of human posture during standing is not fully accurate (Day et al., 1993) and needs to be refined. These findings led the group to insist that such responses do not act to stabilize the head in space, but rather stabilize the body as a whole (Day et al., 1997). More recent studies by Wardman et al. argue the opposite and believe the whole-body responses to GVS do in fact act to stabilize the head in space (Wardman et al., 2003b). The issue of stabilization is still a topic of debate.

4.2.4.2 GVS during Gait

Head and whole-body stabilization is also a crucial issue during gait. In an attempt to gain insight into the intricacies of the human balance system, researchers have used GVS to internally

perturb the vestibular system during gait. In some instances, one type of input to the nervous system, such as vision, is not present. In these types of situations, an increased contribution from a different sensory system is observed (Cenciarini et al., 2006). Additionally, it has been shown that vision dominates over other types of sensory information that dictate the control of movement, including the vestibular system (Bent et al., 2006; Kennedy et al., 2003; Deshpande et al., 2005; Deshpande et al., 2007). This phenomenon is even more clearly present when GVS is applied during step initiation and step execution, as opposed to during quiet stance (Bent et al., 2002). Consistent with the findings of Cenciarini et al., when the sense of vision is not available, the human body is forced to compensate for this loss by increasing the sensitivity of other sensory inputs. Thus, one would hypothesize that responses to a galvanic stimulus would increase with lack of vision. It follows that the opposite would be true when vision is present. Fitzpatrick et al., for one example, demonstrated that the whole-body sway response to GVS decreases when visual input is available (Fitzpatrick et al., 2004). When the eyes are open and the sense of vision is present, the nervous system receives vital information from both the visual and vestibular systems. In this case, one would presume that a diminished response to GVS would be present. Accordingly, Bent et al. showed that GVS is capable of producing minimal, yet "noticeable deviation" in gait while vision is available (Bent et al., 2000).

The effects of GVS on human gait have been previously investigated. During gait, increased amounts of galvanic current have been shown to cause increased amounts of movement and deviation from a straight trajectory (Bent et al., 2000). Multiple authors have reported that the effects of GVS during stance and gait are seen throughout the entire stimulus. In addition, there is no observed learning or adjusting to the galvanic stimulus. Furthermore, Bent, Wardman, and others report that there is no evidence of the gait trajectory returning back

towards the original target after initial deviation from the time of stimulus onset until stimulus termination (Bent et al., 2000; Wardman et al., 2003). Without voluntary control, subjects deviate laterally (when using a binaural-bilateral electrode configuration) away from their planned trajectory (Bent et al., 2000; Bent et al., 2002; Bent et al., 2003; Bent et al., 2004; Brandt et al., 2000; Deshpande et al., 2005; Deshpande et al., 2007; Fitzpatrick et al., 1999; Jahn et al., 2000; Kennedy et al., 2003; Kennedy et al., 2005; McFayden et al., 2006).

To further examine the effects of galvanic stimulation on the vestibular system and locomotion, GVS has been initiated during various parts of the gait cycle, with eyes open or closed, and even with a self-delivered stimulus. Cauquil et al. demonstrated that the tilt of the body in the frontal plane is greater when the cue to start moving coincides with the stimulus onset (Cauquil et al., 1998). In a relatively similar study, Bent et al. provided the stimulus onset at heel contact, mid-swing, and toe-off during gait. They determined that although no differences were present for the magnitude of ML deviation of the head, trunk or pelvis, the largest deviations in foot placement are observed when stimulus onset is at heel contact. Smaller foot placement deviations were observed when the galvanic stimulus was initiated during mid-swing (Bent et al., 2004).

The movement response to GVS during gait does not appear to be adaptive or affected be expectation or learning. Fitzpatrick et al. investigated the effects of learning on GVS by permitting the subject to self-deliver the stimulus. Even in this extreme situation, the sway response does not appear to lessen or adapt with time (Fitzpatrick et al., 2004). Lastly, differences in gait trajectory have been reported when stimulating human subjects toward their right versus their left sides (Bent et al., 2000). The origin of these differences is still unclear. They may, in part, be due to the innate differences of specific phases in gait, subject and side

specific sensitivity and resistance of one side of the head to galvanic stimulation, or to the physiological makeup of the dominant limb.

5.0 METHODS

The following study was approved by the Institutional Review Board of the University of Pittsburgh (IRB# PRO07010046).

5.1 SUBJECTS

Nine healthy young adults (2 females, 7 males; age range 21-33 years; mean 25±3.7 years) provided written informed consent to participate (Table 1). These subjects were previously screened to be free of neurological and vestibular disorders at the Eye and Ear Institute of the University of Pittsburgh as part of other studies. Subjects wore tight fitting clothing and standardized rubber-soled shoes. Subjects also wore a safety harness to protect from ground contact injuries that may result from a loss of balance. Before the start of the testing session, subjects were informed that they may or may not experience GVS during any trial.

Table 1. Subject population stratified by gender. Mean (standard deviation) reported.

	Female (N=2)	**Male (N=7)**
Age (yrs)	25 (1)	24 (4)
Height (cm)	171 (1)	183 (9)
Weight (kg)	83 (21)	78 (14)

5.2 EQUIPMENT

5.2.1 Testing Area

All of the data of the current study were collected in the Human Movement and Balance Laboratory at the University of Pittsburgh. Subjects walked through a predetermined calibration area approximately 4m (length) by 2.5m (width) by 2.5m (height), though the length of the entire walkway was approximately 8m in length (Figure 4).

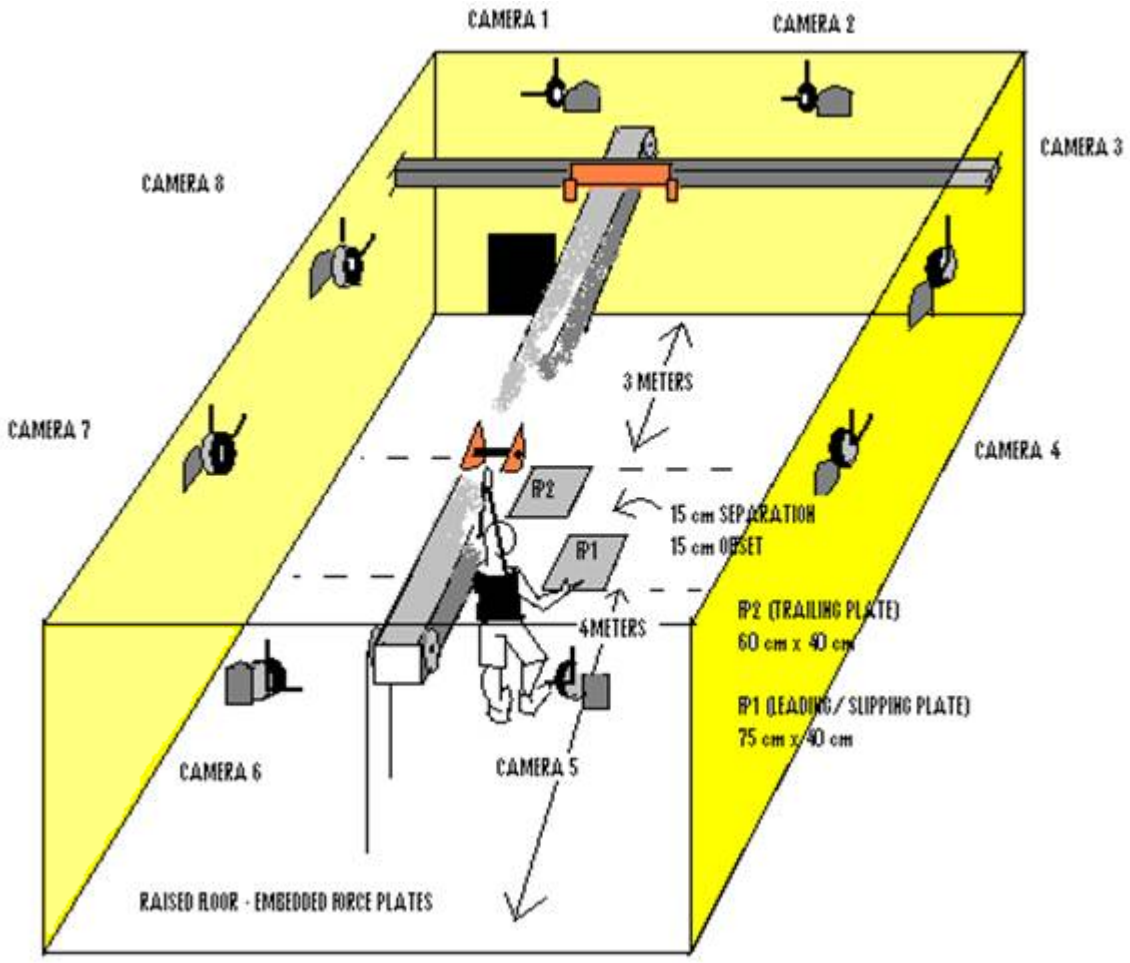

Figure 4. Schematic illustration of the testing area of the Human Movement and Balance Laboratory, University of Pittsburgh, showing eight motion tracking cameras and harness safety system (Moore, 2008)

5.2.2 Motion Tracking System

A Vicon 612 motion tracking system (8 cameras; 120Hz) was used to reconstruct 40 reflective markers into three dimensional trajectories using Vicon Workstation software. The full body modified Helen Hayes marker set was used with an additional reflective marker placed on top of the head accelerometer (Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, and Figure 10). During

post-hoc analysis, all segments were assumed to be rigid bodies. Data were collected with LabVIEW (National Instruments Corporation (NI)) using a custom graphical user interface.

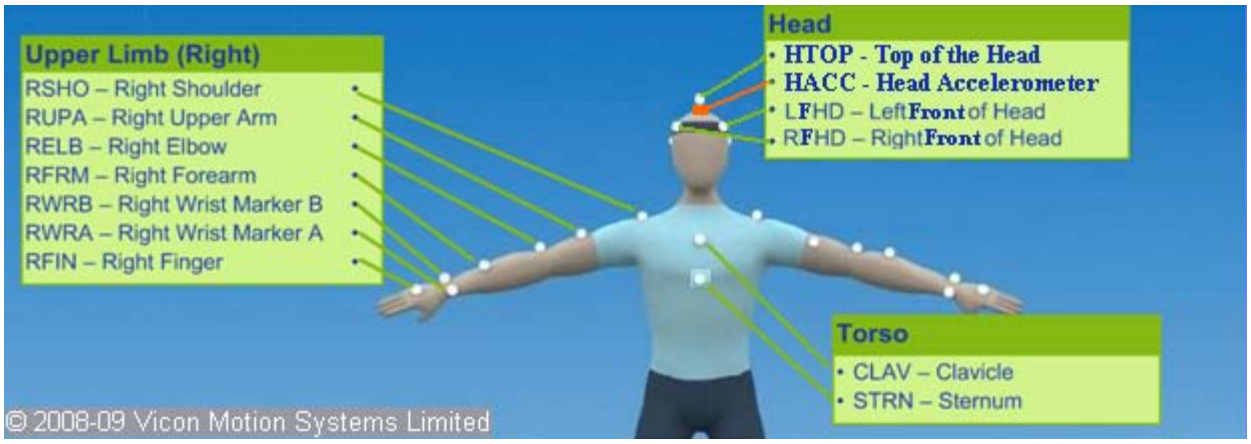

Figure 5. Schematic representation (frontal view) of the upper body modified Helen Hayes marker set, with additional marker attached to the top of the head accelerometer. Also displayed (orange) is the accelerometer attached to the top of the head. Modified from Vicon (Vicon 2008).

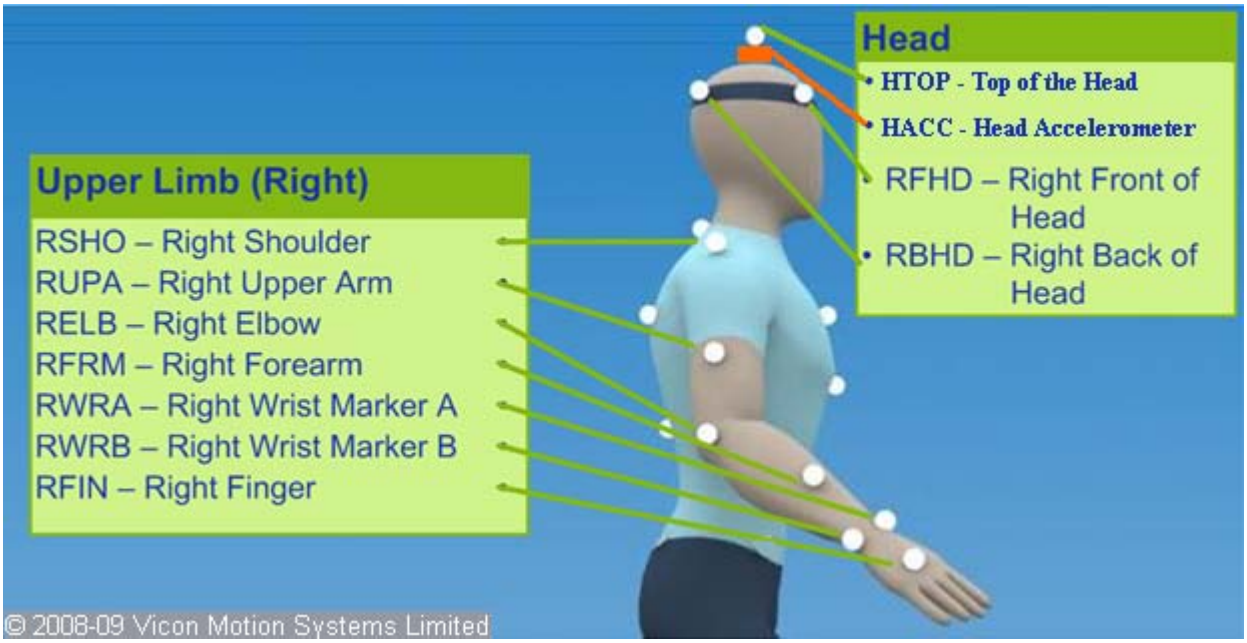

Figure 6. Schematic representation (sagittal view) of the upper body modified Helen Hayes marker set, with additional marker attached to the top of the head accelerometer. Also displayed (orange) is the accelerometer attached to the top of the head. Modified from Vicon (Vicon 2008).

Figure 7. Schematic representation (posterior view) of the lower body modified Helen Hayes marker set. Also displayed (orange) is the pelvic accelerometer. Modified from Vicon (Vicon 2008).

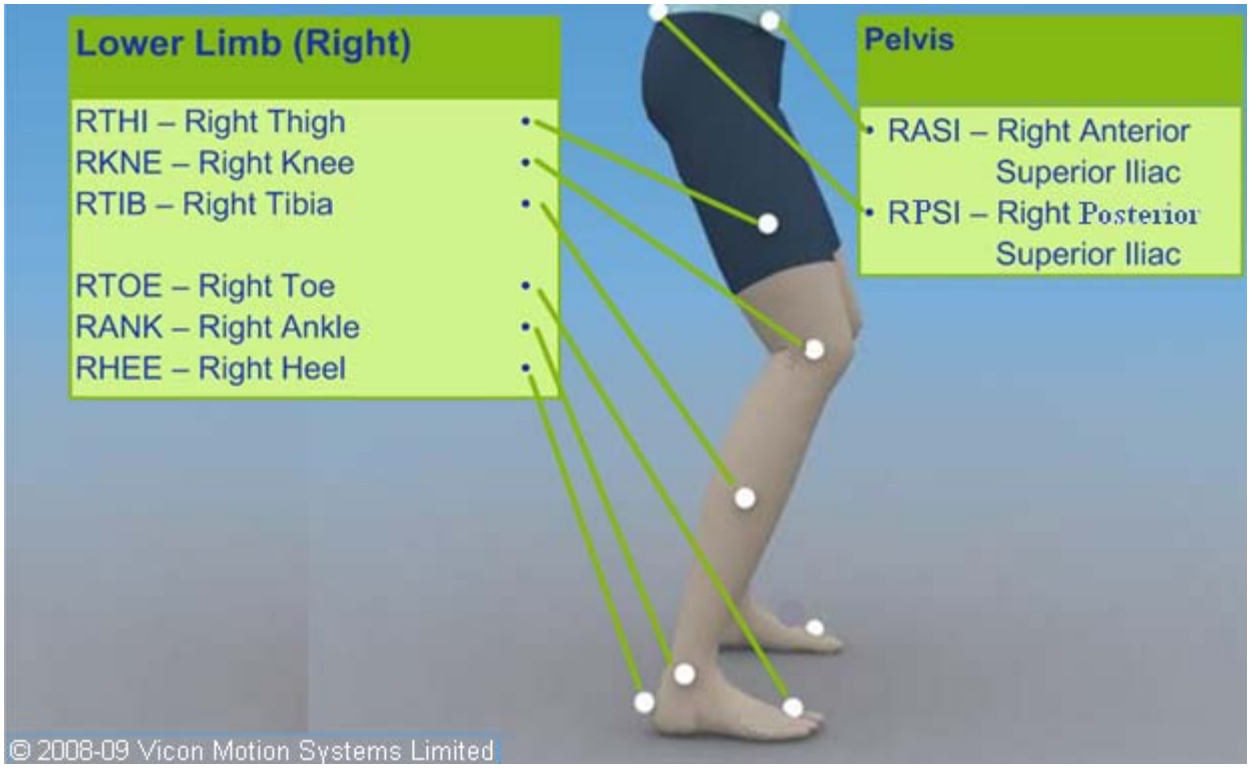

Figure 8. Schematic representation (sagittal view) of the lower body modified Helen Hayes marker set. Modified from Vicon (Vicon 2008).

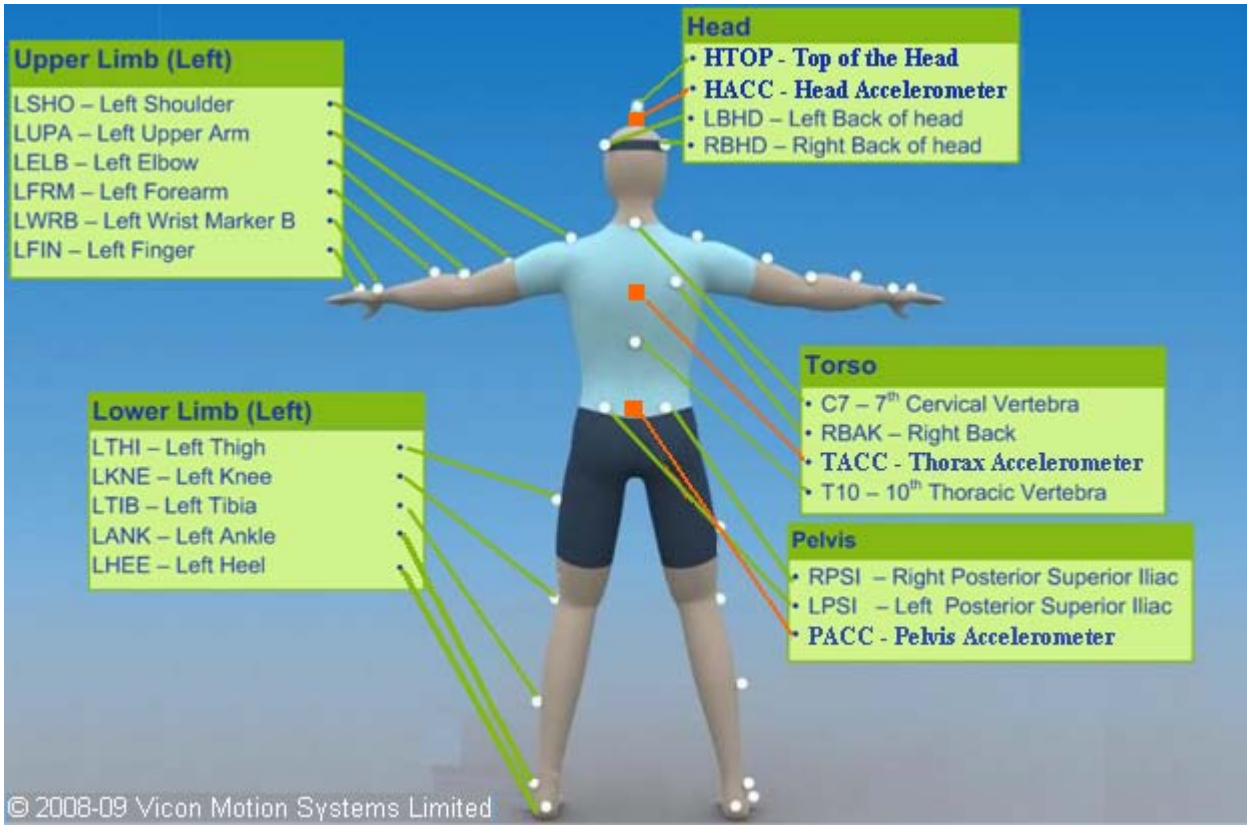

Figure 9. Schematic representation (posterioir view) of the full body modified Helen Hayes marker set. Also displayed (orange) are the head, thorax, and pelvic accelerometers. Modified from Vicon (Vicon 2008).

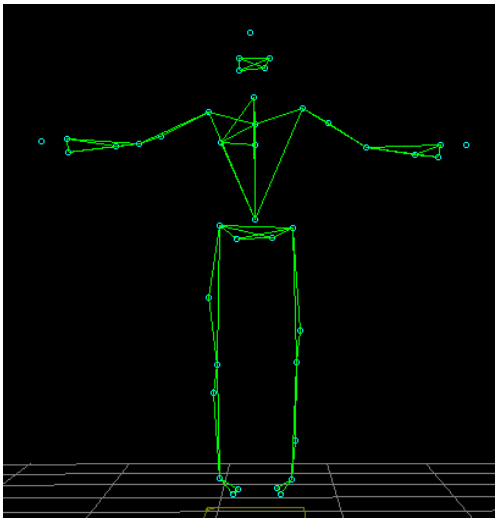

Figure 10. Full body modified Helen Hayes marker set, as viewed using Vicon Workstation software, with additional marker attached to the top of the head accelerometer.

5.2.3 Accelerometers

Three triaxial accelerometers (160Hz; SparkFun, Freescale MMA7260Q, ±6g) were adhered to the top of the head, back of the thorax between the scapula, and back of the pelvis between the right and left posterior superior iliac spines using double-sided toupee tape (Figure 11). Each accelerometer allowed for the collection of three dimensional accelerations in each segment up to six gravitational units (g) (typical sensitivity = 200mV/g; XY bandwidth response = 350 Hz; Z bandwidth response = 150Hz). Accelerometers were connected to the CPU via a NI USB-6211 data acquisition device, collected at 160Hz.

Figure 11. Photograph of one accelerometer, built in-house, to be placed on the head, thorax, or pelvis

5.2.4 Footswitches

Simple, on-off, membrane footswitches were adhered to the posteriolateral edge of the sole of the subjects' shoes (Figure 12). The switches allowed for precise temporal determination of heel contact for both the right and left foot. Each footswitch was rated for 5oz activation and external wires connected to the CPU via a NI USB-6211 data acquisition device, collected at 160Hz.

Figure 12. Photograph of standardized footwear and footswitches

5.2.5 Skin Preparation for Galvanic Stimulation

The skin over the subjects' mastoid processes was abraded using NuPrep™ skin prepping gel. The abraded area was then cleansed using an alcohol swab. TENS Clean-Cote® skin wipes were used to decrease skin resistance and aid electrode adherence. Self-adhering Superior Silver® TENS/NMES/FES stimulating electrodes (3.17cm diameter) were fixed over each mastoid process, in a binaural-bipolar configuration (Figure 13, Figure 14). A minimum of 20 minutes was allowed between adherence of the electrodes and the start of the testing session.

Figure 13. Photograph of Superior Silver® self-adhering, stimulating electrodes

Figure 14. Photograph of stimulating electrodes, head accelerometer, and reflective markers

5.2.6 Galvanic Stimulation Setup

During trials where the GVS was applied, the current duration was eleven seconds in total (linear stimulus isolator, model A395R-A, World Precision Instruments Inc., Sarasota FL, USA). Subjects were exposed to two separate five second mock-square waves of alternating polarity, separated by one second of rest within each GVS trial (Figure 15). Though the galvanic stimuli appear to be the square, they are not true square waves. The stimulus was incremented by 0.1 mA every 0.01 seconds from 0.0 mA to ±1.0 mA over the first 0.1 second of the stimulus. A similar trend was present at the termination of the stimulus from ±1.0 mA to 0.0 mA. The two distinct five second periods of GVS (featuring opposite current polarity) during the same trial were present to ensure that the vestibular system did not become improperly polarized.

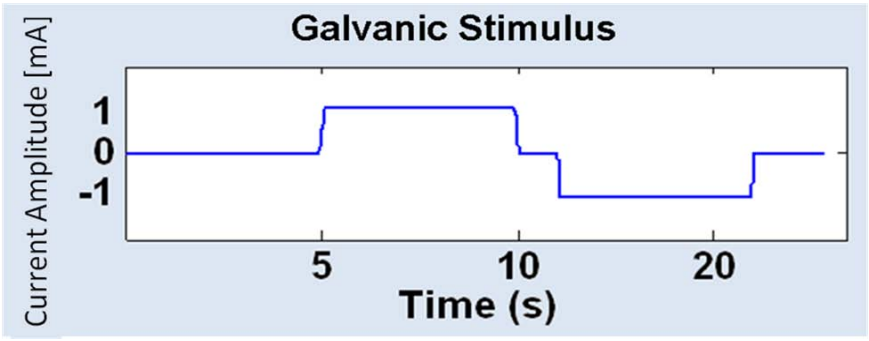

Figure 15. Schematic representation of the galvanic stimulus.

Trials with the anode toward the subjects' right first and anode left second are denoted 'R^+'. Trials with the anode toward the subjects' left first and anode right second are denoted 'R^-'. Subjects were exposed to the GVS in an increasing fashion (0.25mA, 0.5mA, 1.0mA) over six stance trials in order to allow subjects to acclimate to the cutaneous sensations of the galvanic stimulus. Said trials of increasing current ensure that any deviations during gait are from the vestibular effects of GVS and not due to the cutaneous sensations of the current application. More specifically, two trials were performed using 0.25mA (R^+ then R^-). Then, two trials were performed using 0.5mA (R^+ then R^-). Then finally, two trials were performed using the final testing current of 1mA (R^+ then R^-). For any trial where the GVS was applied, only the first five seconds of the current are analyzed in this experiment (Figure 16).

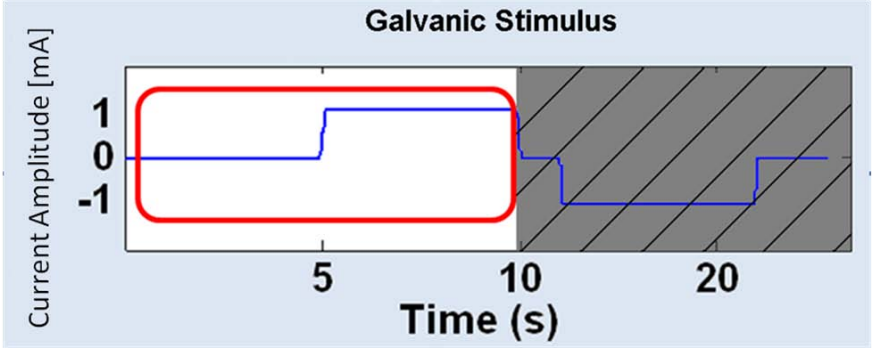

Figure 16. Schematic Representation of the galvanic stimulus with emphasis on the first five second of the stimulus. All data from the one second of rest and the five seconds of stimulation to the alternate pole are not analyzed.

The GVS was delivered using a manual trigger. During some of the gait trials, the current was delivered at the instant when the heel of the dominant limb struck the floor. This moment is called heel contact (HC). During the other trials, the current was delivered moments after the HC of the dominant limb; more specifically, the GVS was delivered when the non-dominant limb was half way between toe-off and HC. This instant of the gait cycle is termed mid-stance (MS) of the dominant limb. Delivering the GVS at different instances during the gait cycle may provide crucial insight into the separate phases of gait.

5.3 TASK

The lights in the laboratory were dimmed to minimize the presence of unexpected, unwanted reflections in the testing area that may unnecessarily complicate the data from the Vicon motion tracking system. Subjects were then allowed to practice walking in a straight line at a self-selected pace. Before every trial, subjects stood with their back to the testing area and listened to

loud music through headphones. During this time, subjects attempted to complete a word-search. By having the subject face away from the testing area, listen to music, and attempt a word-search, they were sufficiently distracted from any activity or changes that may occur in the testing area between trials. After one minute, the headphones were removed and the subject was instructed to turn around and face the testing area. Subjects were then told to begin walking with a consistent "ready, go" command. Twenty-one gait trials were collected using seven types of trials composed of: three GVS conditions (none, R^+, R^-), two eye conditions (EO, (EC), and two GVS trigger conditions (HC, MS). For each subject, the seven different types of trials were randomized and separated into three separate blocks, each of which was identical in condition sequence (see Appendix). Thus, a total of 21 gait trials were collected for each subject. Trial conditions of EO and R^- were not included. These trials were excluded because published literature has shown that minimal responses to GVS during gait are observed with EO. Furthermore, these trials were excluded to ensure that the testing sessions did not become too long and cause fatigue to the subjects. During the last trial of the testing session, subjects experienced an unknown slip. Data from the slip trials were not analyzed in this study. A detailed list of the gait conditions (Table 2) and abbreviations (Table 3) are listed below.

Table 2. GVS conditions tested during gait.

Condition #	Eye Condition	GVS Condition	Event Trigger	Current Amplitude (mV)
1*	EO	No GVS	-	0.0
2*	EO	R^+	HC	1.0
3*	EC	No GVS	-	0.0
4*	EC	R^+	HC	1.0
5*	EC	R^+	MS	1.0
6*	EC	R^-	HC	1.0
7*	EC	R^-	MS	1.0

* Conditions randomized for each subject. All conditions tested with a repeatability of three.

Table 3. Gait conditions and corresponding abbreviations.

Condition Abbreviation	Stance Condition
EO	Eyes open
EC	Eyes closed
R^+	GVS with anode right
R^-	GVS with anode left
HC	GVS triggered at heel contact of the right foot
MS	GVS triggered at mid-stance of the right foot

5.4 DATA ANALYSIS

5.4.1 Maximum Lateral Deviation during Gait

The maximum lateral deviations of the head, sternum, and pelvis were determined for each gait trial. The head center was defined as the midpoint of the four reflective markers placed on the head, using the modified full body Helen Hayes marker set (see Figure 5, Figure 6, and Figure 9; RFHD, LFHD, RBHD, LBHD). Two markers were placed over the right and left temples. The other two head markers were placed on the back of the head in an approximate horizontal plane. The mid-pelvis was defined as the midpoint of the four markers placed on the pelvis using the modified full body Helen Hayes marker set (see Figure 7, Figure 8, and Figure 9; RASI, LASI, RPSI, LPSI). The ML position of the head, sternum, and pelvis were recorded during control trials with EO and EC. Then, the same ML positions were recorded during trials with GVS. The ML positions during the control trials were subtracted from those of the GVS trials so to obtain differences in ML deviation due to GVS during gait.

5.4.2 Mid-Pelvis Displacement at Heel Contact

The position of the mid-pelvis was again obtained from the center of the four pelvic markers (see Figure 5, Figure 6, and Figure 9; RASI, LASI, RPSI, LPSI). The ML location of the mid-pelvis was calculated and averaged within subjects for control trials with EO and EC. The ML location of the mid-pelvis was then obtained during perturbation trials for six steps, starting with the right HC at GVS trigger. During control trials without GVS, the location of the mid-pelvis at a right

heel contact early in the trial was chosen and considered the zero location to compare to the perturbation trials. From this point, ML deviations of mid-pelvis were calculated at each of the following five steps; a total of six steps were analyzed. In any instance where subjects walked so fast as to achieve greater than six steps after the GVS trigger, these steps were not analyzed for this variable. Conversely, in any instance where subjects had not yet taken six steps before the one second period of rest in the galvanic stimulus, data for these steps was not reported. Trials with GVS were aligned to the moment of GVS trigger for HC and MS trials. The ML position of the mid-pelvis at each step was compared to the "zero location" of the right HC of a control trial. Alignment using the GVS trigger ensured the exposure of the GVS effect on gait. Since trials were aligned using the GVS trigger, small differences in position at time-zero do exist between the control and perturbation trials. These differences are a result of timing errors from the manual galvanic trigger.

5.4.3 Foot Deviation from Mid-Pelvis during Gait

The position of the heel relative to the mid-pelvis was obtained at each of the six heel contacts following (and including) the GVS trigger. Again, the mid-pelvis was defined as the center of the four pelvic markers (see Figure 5, Figure 6, and Figure 9; RASI, LASI, RPSI, LPSI). The AP and ML components of the heel deviation were recorded relative to the mid-pelvis at each of the six HCs of interest.

5.4.4 Stride Time

Heel contact times of the right and left foot were obtained using membrane footswitches attached to the bottom of the sole of the shoe (See Methods). Stride times (from right HC to right HC) were calculated for both control and perturbation trials. Stride time was calculated as the difference in time between a right HC and the previous right HC.

5.4.5 Segmental Tilt and Joint Angle

The tilt angle (in degrees) was obtained from the Vicon Workstation software for the head, thorax, and pelvis in the global coordinate system (GCS) using Euler angles. Maximum tilt angle responses were reported along with the time they occurred relative to the GVS trigger (or HC for no GVS trials). Positive values represent a tilting towards the subjects' right; negative values represent a tilting towards the subjects' left (Figure 17).

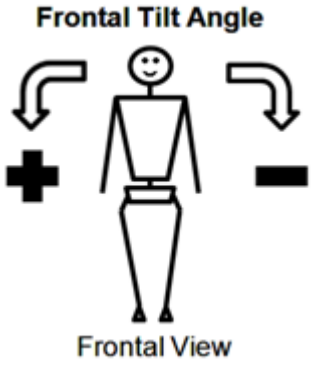

Figure 17. Schematic representation of the frontal tilt angle.

The joint angles were also obtained, using the Vicon Workstation software for the neck and spine in the local coordinate system (LCS). The neck angle was calculated based on the angle of the head relative to the thorax. The spine angle was calculated based on the angle of the thorax relative to the pelvis. Again, maximum values were reported along with the time they were obtained, relative to HC of the GVS trigger.

The time of maximum tilt angle for each segment and joint was reported. For control trials without GVS, the angle reported was the maximum tilt of a segment within a five second period from the second right HC of a trial after the "ready-go" command. For trials with GVS, the angle reported is the maximum tilt of a segment within a given second period from the moment of GVS trigger.

5.4.6 Statistical Analysis

Nine subjects were tested. During trials where the subjects were exposed to the GVS, the stimulus was applied for five seconds in one direction, turned off for one second, and then five seconds of stimulus were applied in the opposite polarity. Only motion data from the initial five second pulse were analyzed in this study; data from the final six seconds were truncated. Thus, any gait trajectories turning back towards the original gait target would be due to the subject's response to the initial polarity of the GVS and not the changing GVS polarity. The data collected from the accelerometers on the head, thorax, and pelvis were part of a larger study and were not analyzed as part of this thesis.

All data were checked for outliers. Probable outliers were visually determined from box plots of normalcy. The probable outliers were then further examined for cause of error. Only

data points that were clearly erroneous due to equipment or sensor failure were eliminated. Data from three trials were eliminated from the distribution of the ML deviation of the head center, thorax, and mid-pelvis. Data from five trials were eliminated from the distribution of the stride time. Data from nine trials were eliminated from the distribution of the heel deviation from mid-pelvis at HC. Data from seven trials were eliminated from the distribution of the ML mid-pelvis location at HC. Data from six trials were eliminated from the distribution of the frontal tilt angles in the global coordinate system (head, neck, and thorax). Data from two trials were eliminated from the distribution of the frontal tilt angles in the local coordinate system (neck and spine). All analyses were performed using repeated measures ANOVA, with specific models used to address the hypotheses of the study. The models used combinations of vision (EO/EC), GVS (Y/N), GVS direction (R^+/R^-), GVS trigger (HC/MS), and trial repetition number (1^{st}, 2^{nd}, 3^{rd}) as the independent variables depending upon the hypotheses. For models comparing across three trials, the average of the three trials was used. Dependent variables were lateral deviation of the sternum and mid-pelvis, foot deviation (AP and ML), global position of the mid-pelvis stride time, and frontal plane tilt of the head, thorax, pelvis, neck and spine within each condition for each subject. Variables with significant overall effects were also analyzed within condition. An alpha level of 5 % ($p = 0.05$) was used to determine statistical significance.

6.0 RESULTS

6.1 GAIT TRAJECTORY

Both the sternum marker and the mid-pelvis were tracked through three dimensional space to visualize the whole-body trajectory during gait. Figure 18 shows representative plots of the cyclical gait patterns of the sternum and mid-pelvis trajectories during control trials with EO (Figure 18 A) and EC (Figure 18 B) and without GVS. The condition abbreviations are reiterated in Table 4, below. As expected, the patterns of the sternum and mid-pelvis are nearly identical to each other. The trajectories of the sternum and mid-pelvis with EC and No GVS (Figure 18 B) follow a path deviation compared to the EO trial (Figure 18 A). This deviation is due to a drift of the subject since there is no vision to control navigation. However, the cyclical component is consistent throughout the entire trial; no sudden changes in lateral movement exist in the sternum or pelvic trajectories.

Table 4. Gait conditions and corresponding abbreviations.

Condition Abbreviation	Gait Condition
EO, No GVS	Eyes open, without GVS
EC, No GVS	Eyes closed, without GVS
EO, R^+, HC	Eyes open, GVS anode right triggered at heel contact
EC, R^+, HC	Eyes closed, GVS anode right triggered at heel contact
EC, R^+, MS	Eyes closed, GVS anode right triggered at mid-stance
EC, R^-, HC	Eyes closed, GVS anode left triggered at heel contact
EC, R^-, MS	Eyes closed, GVS anode left triggered at mid-stance

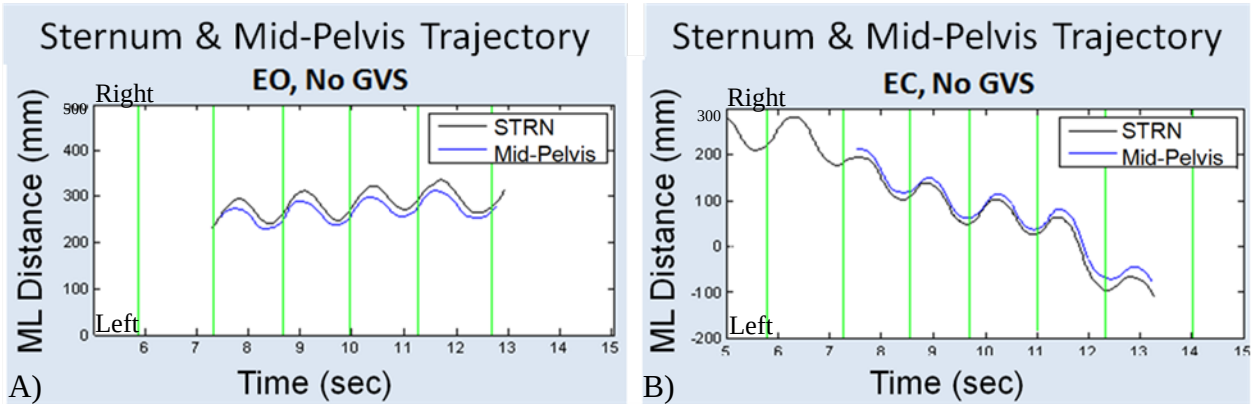

Figure 18. Representative plots of the position of the sternum and "center" of the pelvis during gait with EO (A, left) and EC (B, right), both without GVS. The sternum trajectory is shown in black. The mid-pelvis is shown in blue. The light green vertical stripes represent HC of the right foot. Positive vales represent movements to the subjects' right; negative values represent movements to the subjects' left.

Figure 19 shows representative plots of the sternum and mid-pelvis trajectory during perturbation trials with EO (Figure 19 A) and EC (Figure 19 B, C, D, E) and GVS. As expected, the patterns of the sternum and pelvis center mimic each other. Greater deviations from control trajectories are displayed in trials with GVS.

Figure 19. Representative plots of the position of the sternum and mid-pelvis during gait with EO (A) or EC (B, C, D, E), all with GVS. Specifically, trial conditions of EO, R^+, HC (A), EC, R^+, HC (B), EC, R^+, MS (C), EC, R^-, HC (D), and EC, R^-, MS (E) are displayed. The sternum trajectory is shown in black. The mid-pelvis is shown in blue. The light green vertical stripes represent HC of the right foot. GVS trigger is shown in pink. Positive vales represent movements to the subjects' right; negative values represent movements to the subjects' left. The scale on each plot is 500mm.

6.2 LATERAL DEVIATION

The maximum lateral deviation of the head center, sternum, and mid-pelvis across subjects are displayed in Table 5. Of all trials collected, the head, sternum, and pelvis all experienced the least amount of lateral deviation during the control trials (EO, No GVS). Removing vision approximately doubled the magnitude of lateral deviation (EC, No GVS). When subjects were exposed to the GVS during gait with EC, the head, sternum, and pelvis all experienced greater lateral deviations compared to the three control conditions (EO, No GVS; EC, No GVS; EO, R^+, HC). Of all EC trials collected with GVS, the condition of EC with R^- GVS triggered at HC experienced the greatest average maximum magnitude of lateral deviation during gait. The absolute value of the maximum lateral deviation was used to compare the R^+ and R^- conditions.

Table 5. Average Maximum Magnitude of Lateral Deviation (mm) of the Head Center, Sternum, and Mid-Pelvis during Gait

	Head Center	***Sternum***	***Mid-pelvis***
EO, No GVS	99 ± 41	109 ± 43	96 ± 54
EC, No GVS	204 ± 75	255 ± 82	211 ± 71
EO, R^+, HC	155 ± 68	168 ± 73	149 ± 68
EC, R^+, HC	277 ± 102	306 ± 106	269 ± 114
EC, R^+, MS	337 ± 133	356 ± 138	330 ± 127
EC, R^-, HC	422 ± 151	451 ± 154	428 ± 166
EC, R^-, MS	363 ± 157	402 ± 167	365 ± 157

The impact of GVS and vision on maximum lateral deviation was determined using a repeated measures ANOVA with independent measures being vision (EO/EC), GVS (Y/N), and their interaction applied to all collected movements. Thus, HC and MS conditions were

collapsed and not included in the statistical model. Each segmental movement was analyzed separately. Results showed a significant effect of GVS and vision for all segments. The head ($p < 0.0001$), sternum ($p < 0.0001$), and mid-pelvis ($p < 0.0001$) all experience greater maximum lateral deviation with EC compared to EO, both with and without GVS (Figure 20).

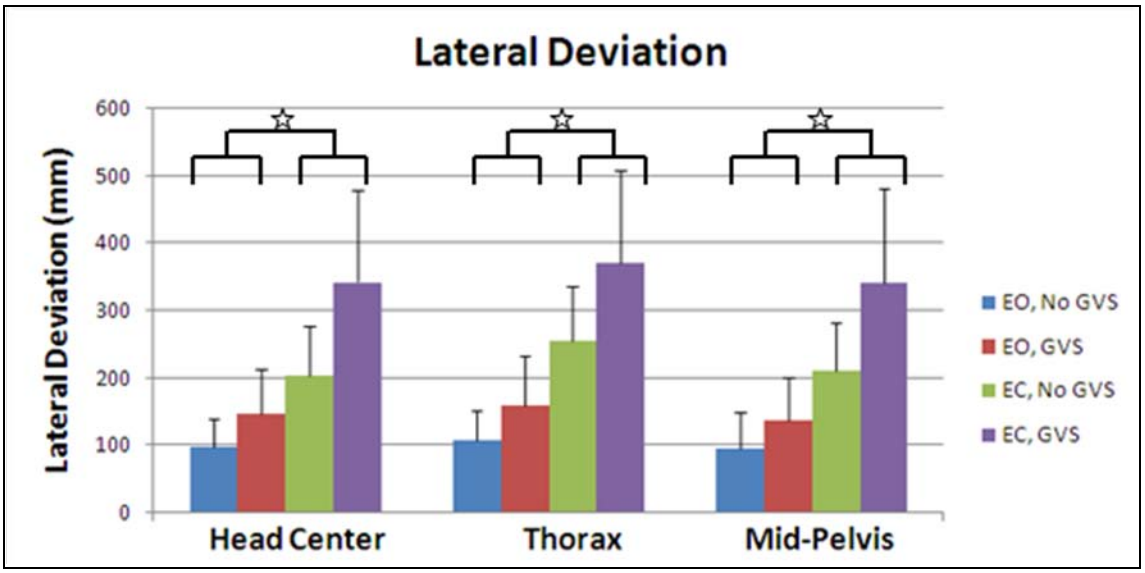

Figure 20. The effect of vision and GVS on lateral deviation (and standard deviation) of the head center, sternum, and mid-pelvis. Data averaged across subjects and trials for EO (No GVS (blue) and GVS (red)) and EC (No GVS (green) and GVS (purple)). The absolute value of the maximum lateral deviation was calculated to compare the R^+ and R^- conditions. Statistical significance is shown using a star.

The impact of GVS on the maximum lateral deviation was determined using a repeated measures ANOVA with independent measures being GVS (Y/N), across all trials (EO and EC). Again, HC and MS conditions were collapsed and not included in the statistical model The head experienced significantly greater maximum lateral deviations during trials with GVS exposure as compared to trials without GVS ($p = 0.02$). The sternum ($p = 0.06$) and mid-pelvis ($p = 0.06$)

experience greater maximum lateral deviations during trials with GVS exposure as compared to trials without GVS of borderline significance (Figure 21).

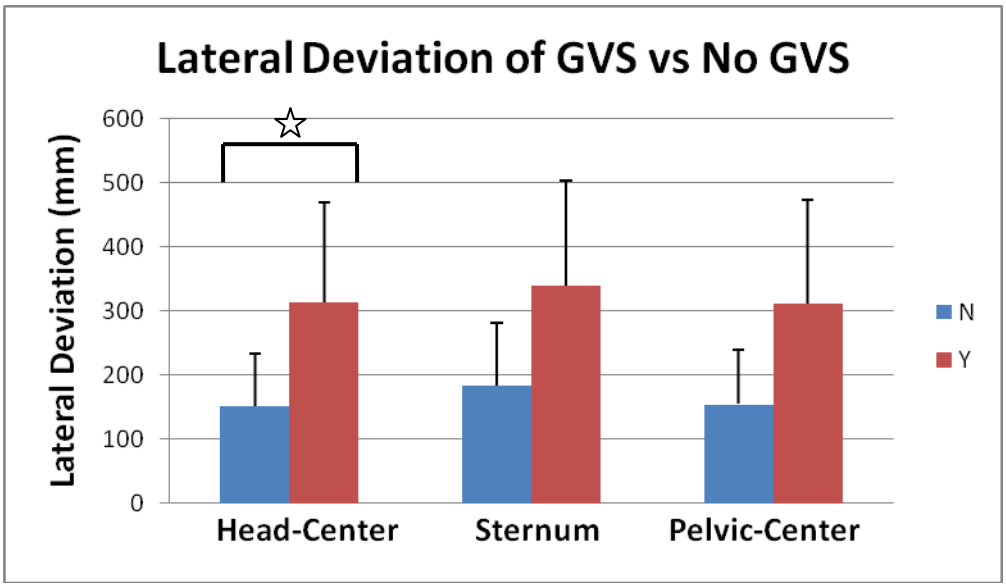

Figure 21. The effect of GVS on lateral deviation (and standard deviation) of the head center, sternum, and mid-pelvis averaged across subjects and trials with (red) and without (blue) GVS. Statistical significance is shown using a star.

A separate repeated measures ANOVA was performed to investigate the effect of GVS and gait cycle timing of the GVS trigger as well as the effect of repeated GVS exposure on GVS responses. For this model, only conditions with EC were included. The independent variables in the statistical model were GVS direction (R^+/R^-), GVS trigger (HC/MS), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interactions. Each segmental movement was analyzed separately. The head ($p = 0.01$), sternum ($p < 0.01$), and mid-pelvis ($p = 0.01$) experienced greater maximum lateral deviations when first exposed to a condition as compared to the second or third exposure

(Figure 22). There were no significant effects of GVS trigger, nor any interactions with this variable.

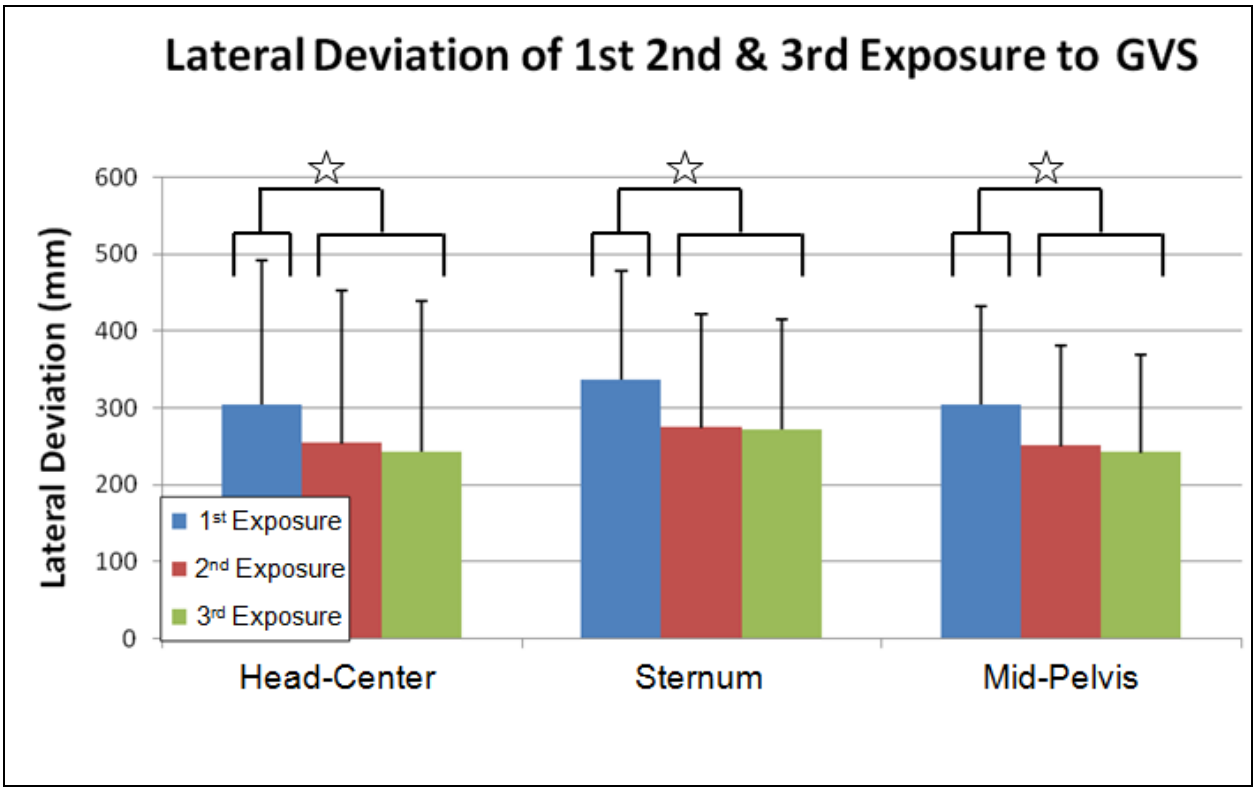

Figure 22. Lateral deviation (and standard deviation) to GVS for the first (blue), second (red), and third (green) exposure to GVS collapsed across trigger time and direction. Only conditions with EC were used in this model. Statistical significance is shown using a star.

Figure 23 (below) shows the lateral deviation of the head center, sternum, and mid-pelvis averaged across subjects for each of the seven gait conditions.

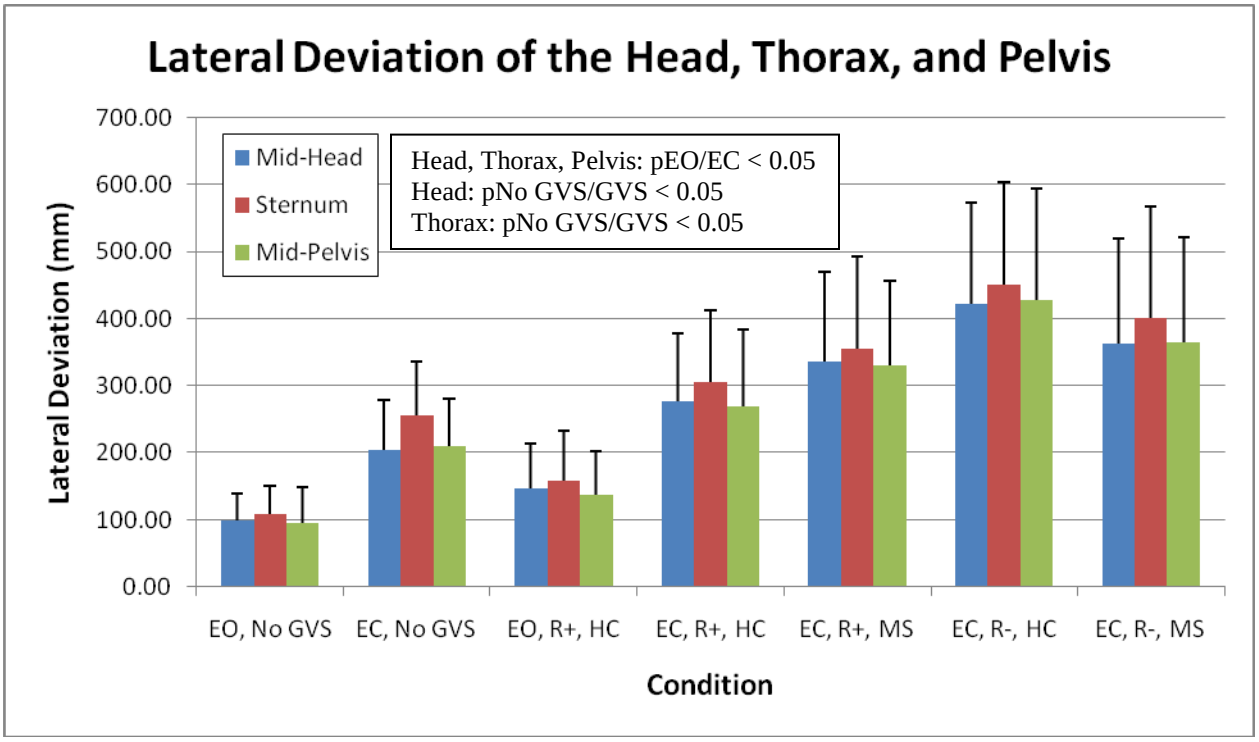

Figure 23. Lateral deviation (and standard deviation) of the head center (blue), sternum (red), and mid-pelvis (green) with standard deviation. The absolute value of the maximum lateral deviations of GVS R^- conditions are presented for comparison to GVS R^+ conditions.

6.2.1 Mid-Pelvis Deviation during Gait

Figure 24 displays a representative plot mid-pelvis trajectory during gait with EO and GVS. Note a movement towards the anode for all GVS trials compared to the no GVS condition.

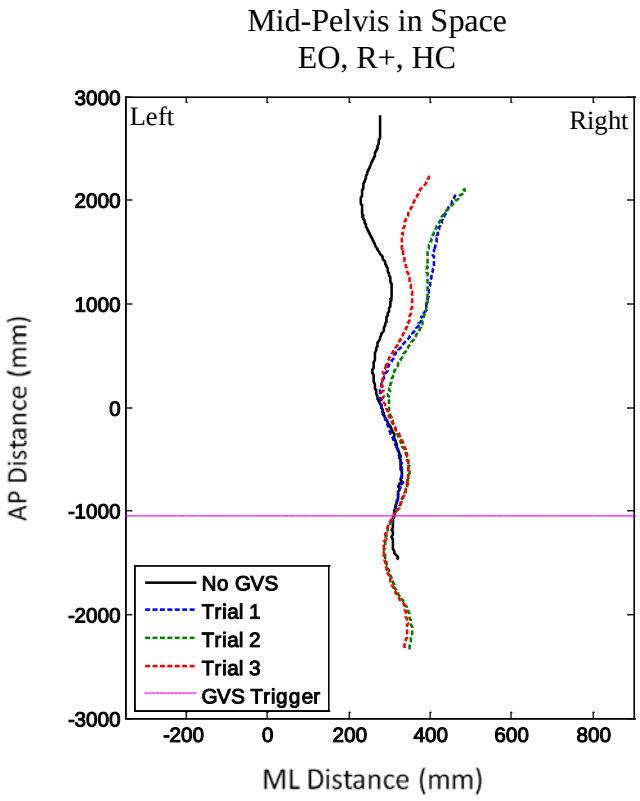

Figure 24. Representative plot of mid-pelvis trajectory for each of the three GVS condition (EO, R^+, HC) repetitions. Control walking (EO, No GVS) is shown in black. The first, second, and third exposure to the GVS perturbation condition (EO, R^+, HC) are shown in blue, green, and red, respectively. GVS trigger is shown in pink.

The plots below (Figure 25) display representative trajectories of the mid-pelvis during gait with EC and GVS. Note that GVS with EC had greater lateral responses compared to EO (Figure 24, above). Also note that the first GVS exposure with EC had the greatest response compared to the second and third exposure.

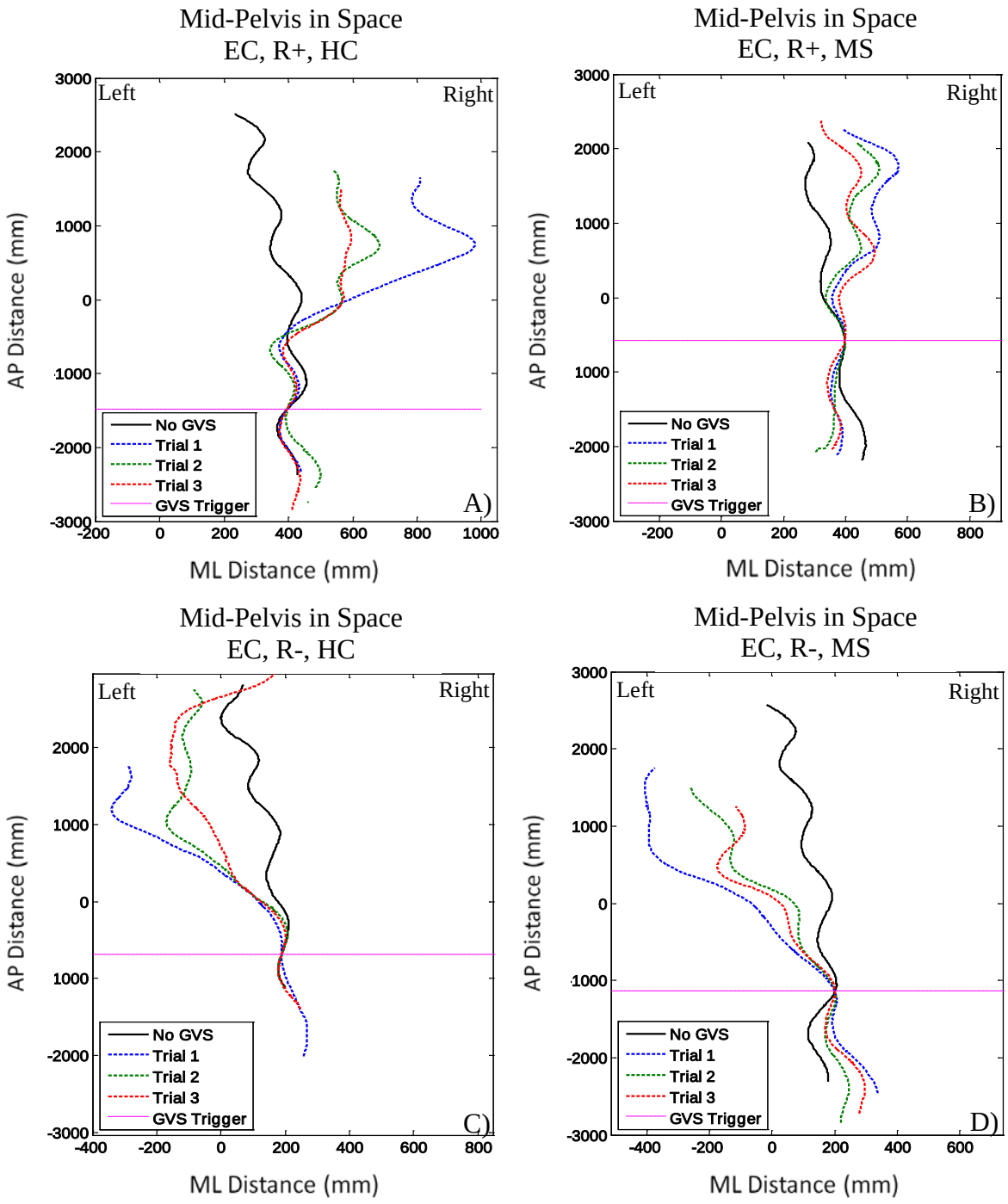

Figure 25. Representative plots of mid-pelvis trajectories for each of the three GVS condition repetitions. Control walking (EC, No GVS) is shown in black. GVS direction R^+ is displayed in A (top left) and B (top right); GVS direction R^- is displayed in C (bottom left) and D (bottom right). The first, second, and third exposure to the GVS perturbation condition are shown in blue, green, and red, respectively. The GVS trigger is shown in pink.

6.2.1.1 Mid-Pelvis Displacement at Heel Contact during Gait

The global position of the mid-pelvis was determined at each HC during gait for the right and left foot for the first six steps after (and including) the step of GVS trigger. Thus, six steps are analyzed in this section of the report. Step one is the right HC step that coincides with the GVS trigger. Step 3 is the right HC that completes the first stride. Step 5 is the right HC that completes the second stride. Steps 2, 4, and 6 are left HCs. In control trials, the variance of the pelvic displacement increases as the trial progresses. The variance greatly increases for trials with GVS. The within subject displacement of the mid-pelvis at HC for one subject during the EO condition with GVS (R^+, HC) is displayed below (Figure 26).

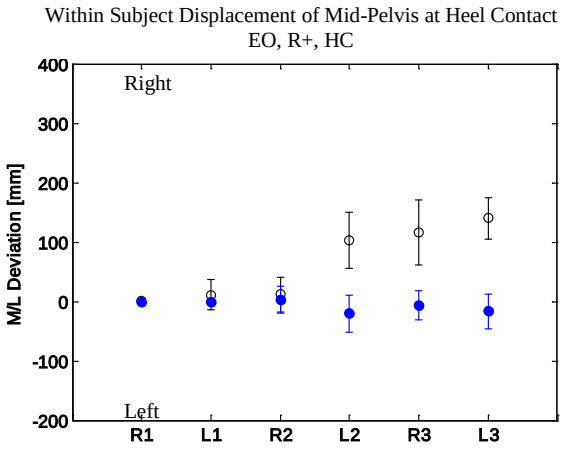

Figure 26. Representative plot of within subject displacement (and standard deviation) of mid-pelvis at HC. Plot generated from a single subject. Control trial (EO, No GVS) is shown in blue. Perturbation condition is shown as open black circles. R1 is the right HC at GVS trigger. R2 and R3 are sequential right HCs after GVS trigger. L1, L2, and L3 are the first, second, and third left HCs after GVS trigger. Standard deviation bars are also presented. Positive vales represent movements to the subjects' right; negative values represent movements to the left.

Figure 27 displays within subject displacement of the mid-pelvis at HC for a particular subject during EC conditions with GVS R^+ (Figure 27 A, B) and GVS R^- (Figure 27 C, D). The variance greatly increases for conditions with EC and GVS as compared to conditions with EO and GVS (Figure 26, above).

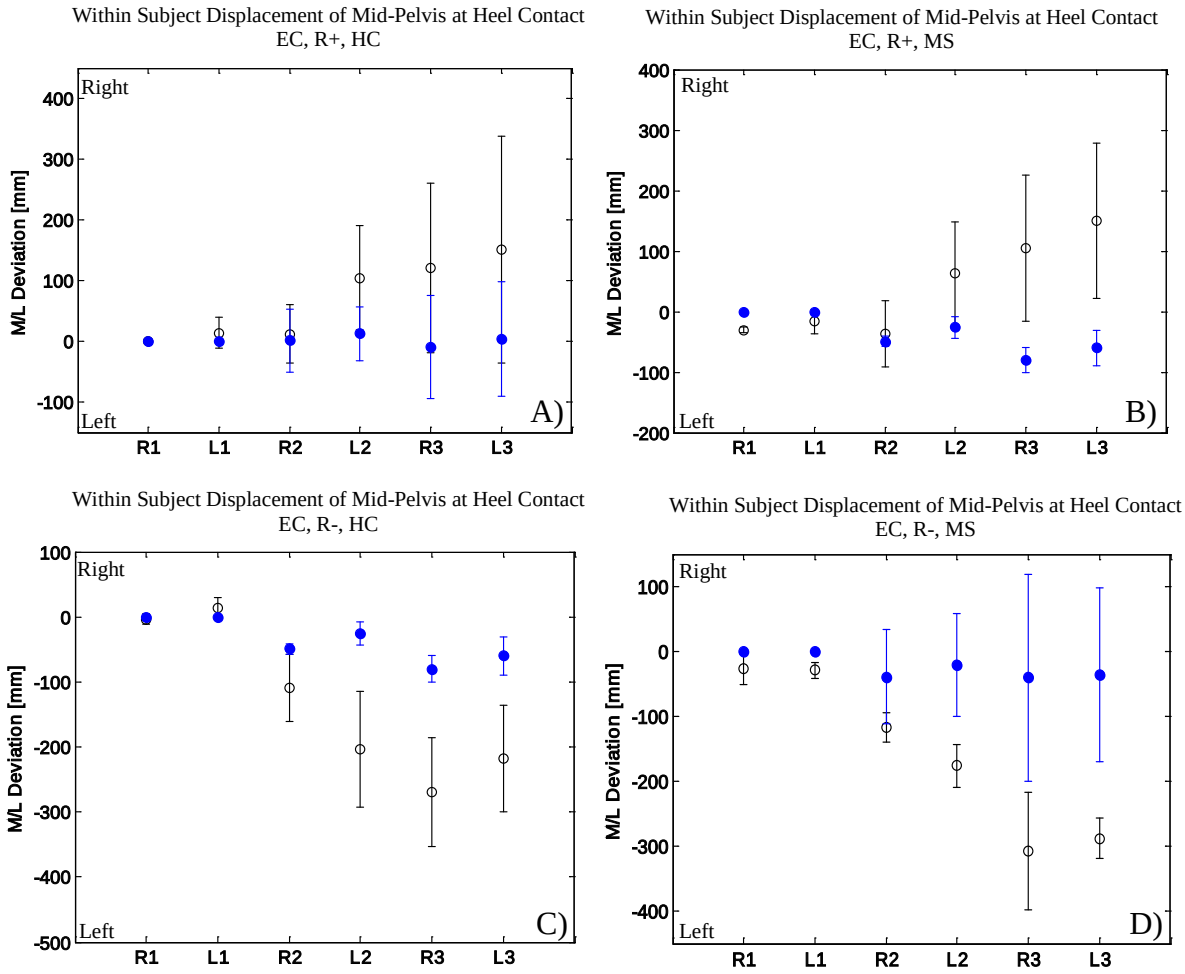

Figure 27. Representative plots of within subject displacement (and standard deviation) of mid-pelvis at HC. Each plot is taken from a single subject. Control trial (EO, No GVS) is shown in blue. Perturbation conditions are shown as black circles. R1 is the right HC at GVS trigger. R2 and R3 are sequential right HCs after GVS trigger. L1, L2, and L3 are the first, second, and third left HCs after GVS trigger. Standard deviation bars are also presented. Positive vales represent movements to the subjects' right; negative values represent movements to the subjects' left. The scale on each plot is 600mm.

A repeated measures ANOVA was used to examine the effects of GVS during conditions with EO on the global position of the pelvis at each of the six steps after (and including) GVS trigger. The statistical analysis included two conditions (EO, no GVS) and (EO, R^{+}, HC), with

the independent variable being GVS (Y/N). Each step was analyzed separately. Results indicate that with EO, the presence of GVS significantly impacts the ML deviation of the mid-pelvis at steps 4 ($p < 0.02$) and 5 ($p < 0.02$) (Figure 28). At step 6, GVS did not significantly alter the ML deviation of the mid-pelvis with EO ($p > 0.05$).

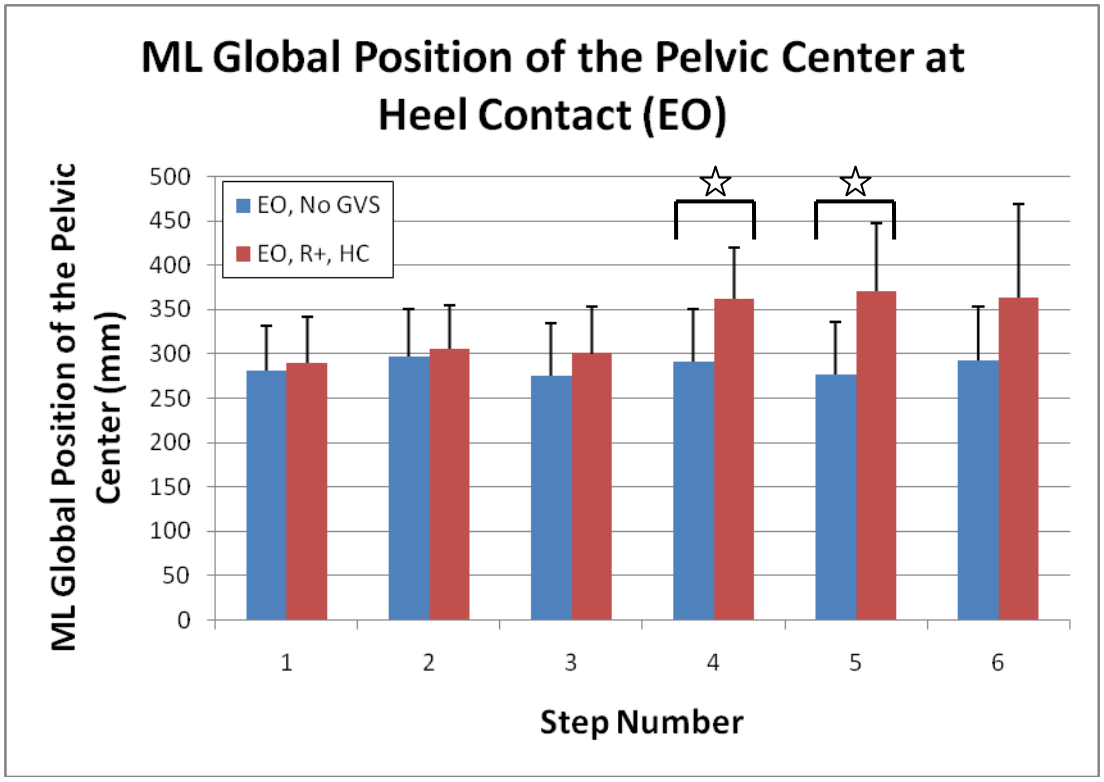

Figure 28. Mediolateral global position (and standard deviation) of the mid-pelvis at HC with EO conditions only. Control condition with EO and no GVS shown in blue. Perturbation condition (EO, GVS R+, HC) shown in red. Statistical significance is shown using a star.

A separate repeated measures ANOVA was performed to determine the effects of GVS on GVS trigger, GVS direction, and trial repetition exposure. Thus, the independent variables were GVS trigger (HC/MS), GVS direction (R^+/R^-), trial repetition exposure (1^{st}, 2^{nd}, 3^{rd}), and

their interactions. Only conditions with EC were included in this model. Each step was analyzed separately. Lateral pelvic deviation was significantly affected by GVS at steps 3 ($p < 0.01$), 4 ($p < 0.01$), 5 ($p < 0.01$), and 6 ($p < 0.01$) (Figure 29). Trials with GVS R^- experienced global positioning of the pelvis farther to the subjects' left than control trials or trials with GVS R^+. The GVS trigger does not significantly alter the ML position of the mid-pelvis in the global space ($p > 0.05$).

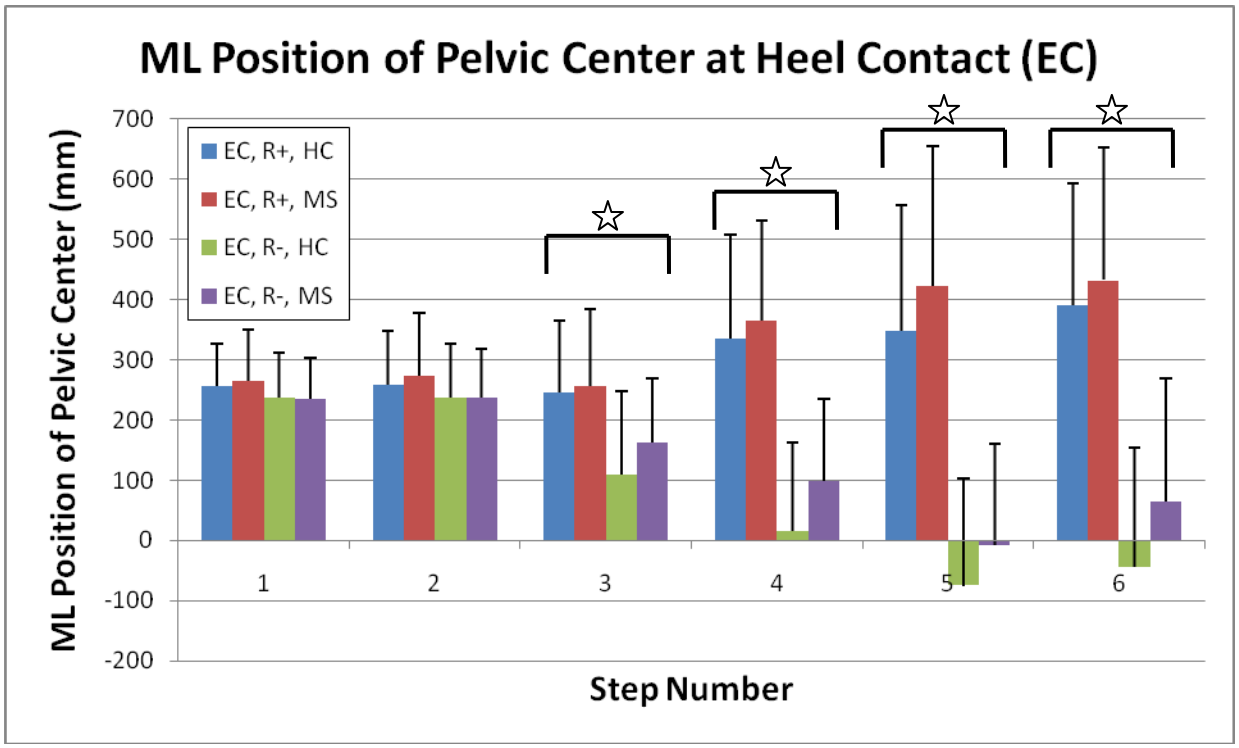

Figure 29. Mediolateral global position (and standard deviation) of the mid-pelvis at heel contact with EC conditions only. Perturbation condition with EC, R+, HC is shown in blue. Perturbation condition with EC, R+, MS is shown in red. Perturbation condition with EC, R-, HC is shown in green. Perturbation condition with EC, R-, MS is shown in purple. Statistical significance is shown using a star.

6.3 FOOT PLACEMENT DURING GAIT

Displayed below are spatial representations of the thorax, pelvis, and feet in the laboratory testing area during gait with EO (Figure 30 A) and EC (Figure 30 B), both without GVS. Similar to the sternum and mid-pelvis trajectories (Figure 18, above), the cyclical and sinusoidal pattern of gait is displayed. The black squares, black circles, and black trajectory represent the trajectory of the mid-pelvis. The center of the thorax was defined as the point half way between the C7 and clavicle. The trajectory of the mid-thorax is represented in light green. As expected, the mid-pelvis and mid-thorax trajectories are nearly identical in EO walking without galvanic perturbation (Figure 30 A). The right and left HC are also displayed in red circles and blue squares, respectively. During gait with EO (Figure 30 A) and EC (Figure 30 B) that lack perturbation by GVS, the feet are typically positioned beneath the center of the body (in the ML direction) at HC. It should be noted however, that the feet are slightly anterior to the center of the body at each HC.

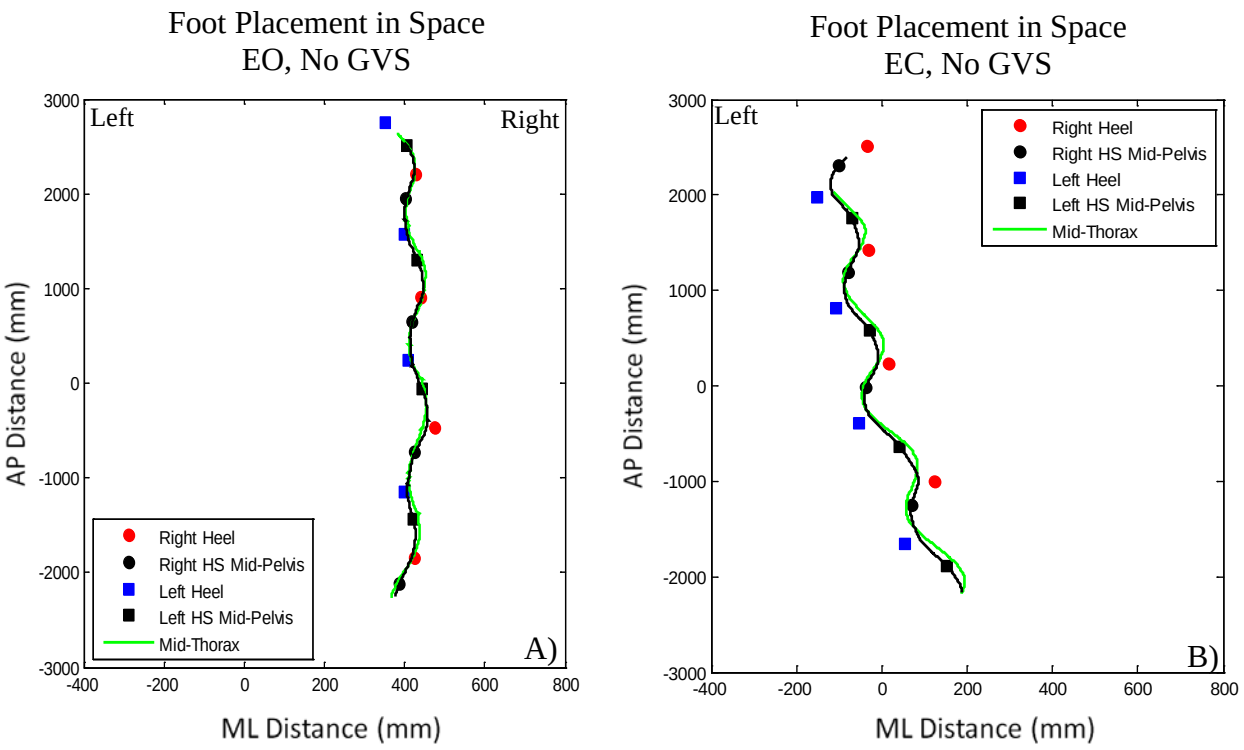

Figure 30. Representative plots of foot placement, mid-pelvis location, and mid-thorax location at right and left HC during a trial with EO (A, left) and EC (B, right), both without GVS. Data relating to the right HC are shown as circles. Data relating to the left HC are shown as squares. Location of the right heel at right HC shown as red circles. Location of the left heel at left HC shown as blue squares. The trajectory of the mid-thorax is shown in light green. The trajectory of the mid-pelvis is shown in black.

Figure 31 shows a representative plot of the thorax, pelvis, and feet during gait with EO and perturbation by GVS (R^+, HC). Slight ML deviations are observed shortly after the GVS trigger.

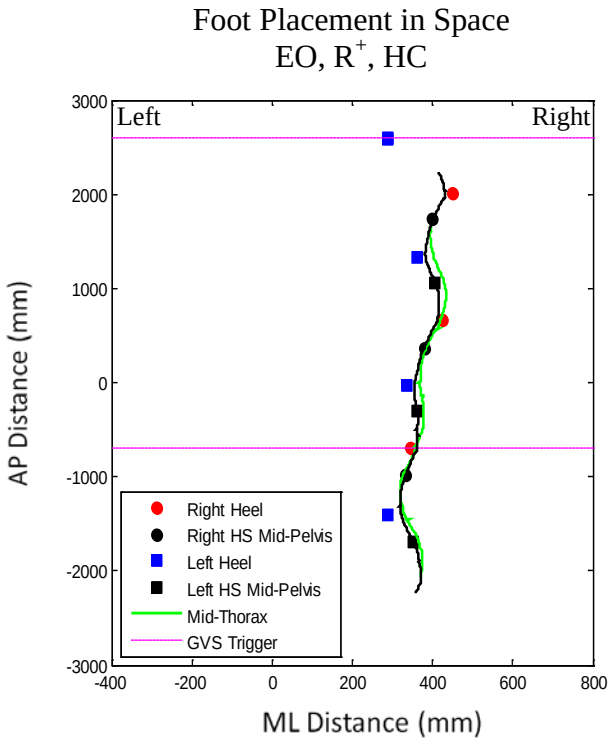

Figure 31. Representative plot of foot placement, mid-pelvis location, and mid-thorax location at right and left HC during a trial with EO and GVS. Data relating to the right HC are shown as circles. Data relating to the right HC are shown as circles. Data relating to the left HC are shown as squares. Location of the right heel at right HC shown as red circles. Location of the left heel at left HC shown as blue squares. The trajectory of the mid-thorax is shown in light green. The trajectory of the mid-pelvis is shown in black.

Figure 32 shows representative plots of the thorax, pelvis, and feet during gait with EC and GVS R^+ (Figure 32 A, B) as well as GVS R^-(Figure 39 C, D), each for a particular subject. Again, the GVS trigger is shown in pink. Lateral deviations are observed shortly after the GVS trigger. See the Appendix for a complete summary of the heel deviation from the mid-pelvis for the first six steps after GVS trigger.

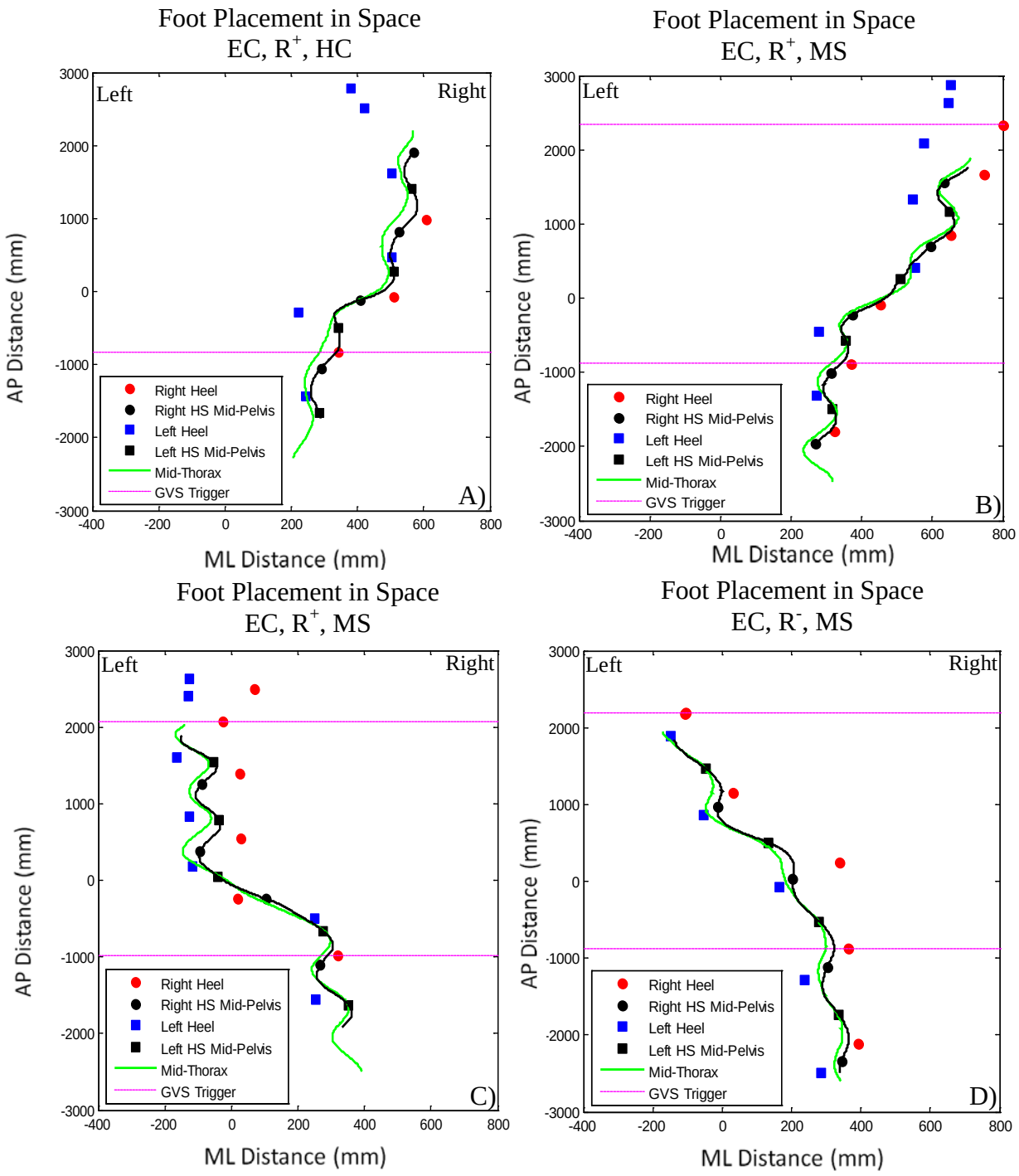

Figure 32. Representative plot of foot placement, mid-pelvis location, and mid-thorax location at right and left HC during a trial with EC and GVS. Data relating to the right HC are shown as circles. Data relating to the right HC are shown as circles. Data relating to the left HC are shown as squares. Location of the right heel at right HC shown as red circles. Location of the left heel at left HC shown as blue squares. The trajectory of the mid-thorax is shown in light green. The trajectory of the mid-pelvis is shown in black.

6.3.1 Foot Deviation from Mid-Pelvis during Gait

A repeated measures ANOVA was performed to examine the effects of vision and GVS on the deviation of the heel placement relative to the mid-pelvis during gait. The AP and ML deviations for the heel placement relative to the mid-pelvis were calculated and termed ML heel deviation and AP heel deviation (Figure 33).

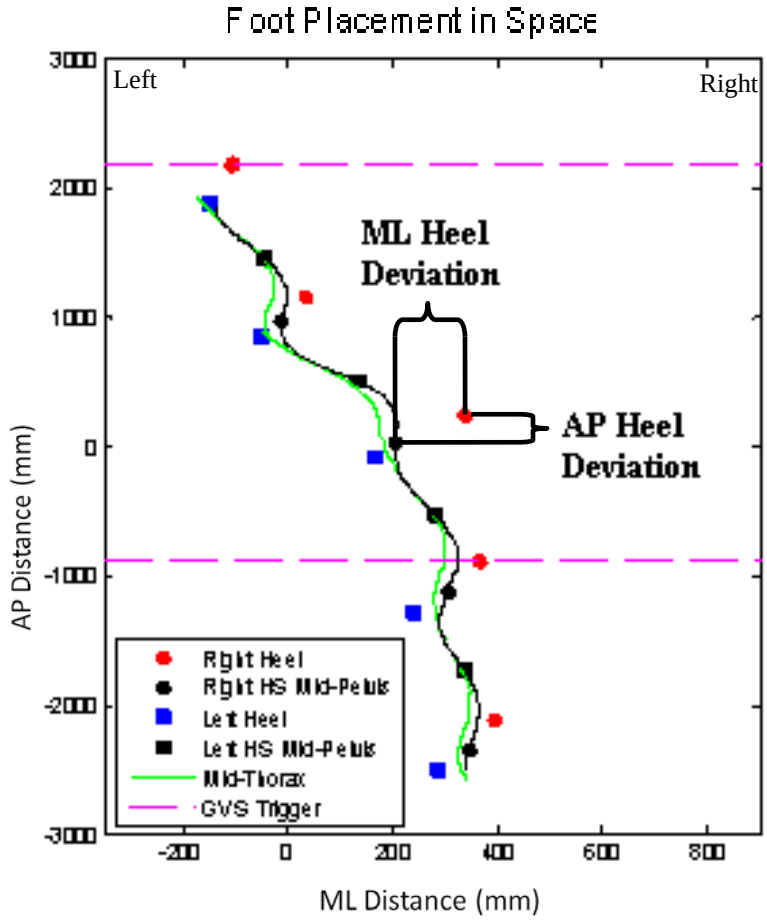

Figure 33. Graphical representation of the AP and ML heel deviation from the mid-pelvis at a particular step.

The position of the heel relative to the position of the mid-pelvis of the same leg at each of the six steps after (and including) GVS trigger during EO conditions only were analyzed to determine the impact of GVS on the heel position at each step using a repeated measures ANOVA. The statistical analysis included two EO conditions (EO, no GVS; EO, R^+, HC) with the independent variable being GVS (Y/N). Each step was analyzed separately. The presence of GVS (R^+ triggered at HC) was found to significantly alter the ML heel deviation from the mid-pelvis at steps 3 ($p < 0.05$), 4 ($p < 0.03$), and 5 ($p < 0.03$) (Figure 34).

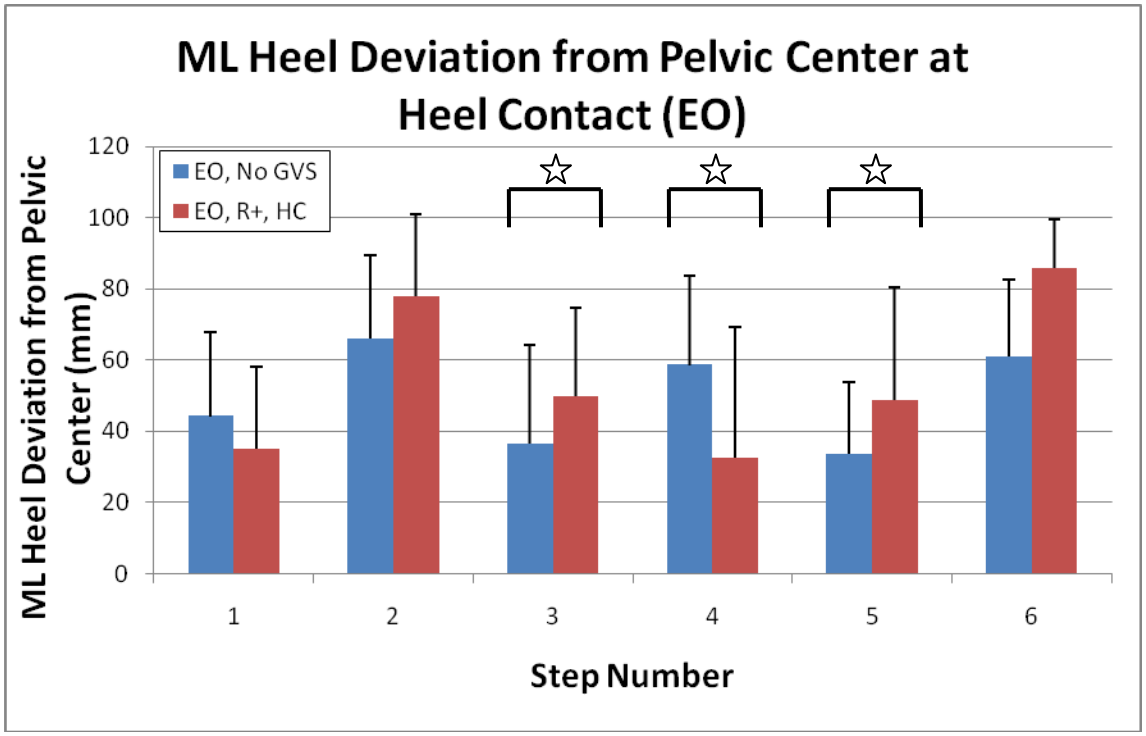

Figure 34. Mediolateral deviation (and standard deviation) of the heel from the mid-pelvis at heel contact with EO conditions only. The control condition (EO, No GVS) is shown in blue. The perturbation condition (EO, R^+, HC) is shown in red. Statistical significance is shown using a star.

The position of the heel placement relative to the position of the mid-pelvis of the same leg at each of the six steps after (and including) GVS trigger during EC conditions were statistically compared through a repeated measures ANOVA with independent measures being GVS direction (R^+, R^-), GVS trigger (HC/MS), and their interaction. The four conditions included in the statistical analysis were: EC, GVS R^+, HC; EC, GVS R^+, MS; EC, GVS R^-, HC; EC, GVS R^-, MS. Each step was analyzed separately. The GVS trigger had no significant effect on the heel deviation from mid-pelvis in any conditions ($p > 0.05$). GVS direction had a significant effect ($p < 0.001$). GVS R^+ caused significant differences from GVS R^- trials at steps 2 ($p < 0.0001$) and 6 ($p < 0.0001$) in the ML direction for the heel deviation from mid-pelvis. At step 2, the ML heel deviation was significantly larger for R^+ trials than control or R^- trials. At step 4, greater heel deviations relative to control trials were present for R- trials. At step 4, lesser heel deviations relative to control trials were present for R^+ trials.

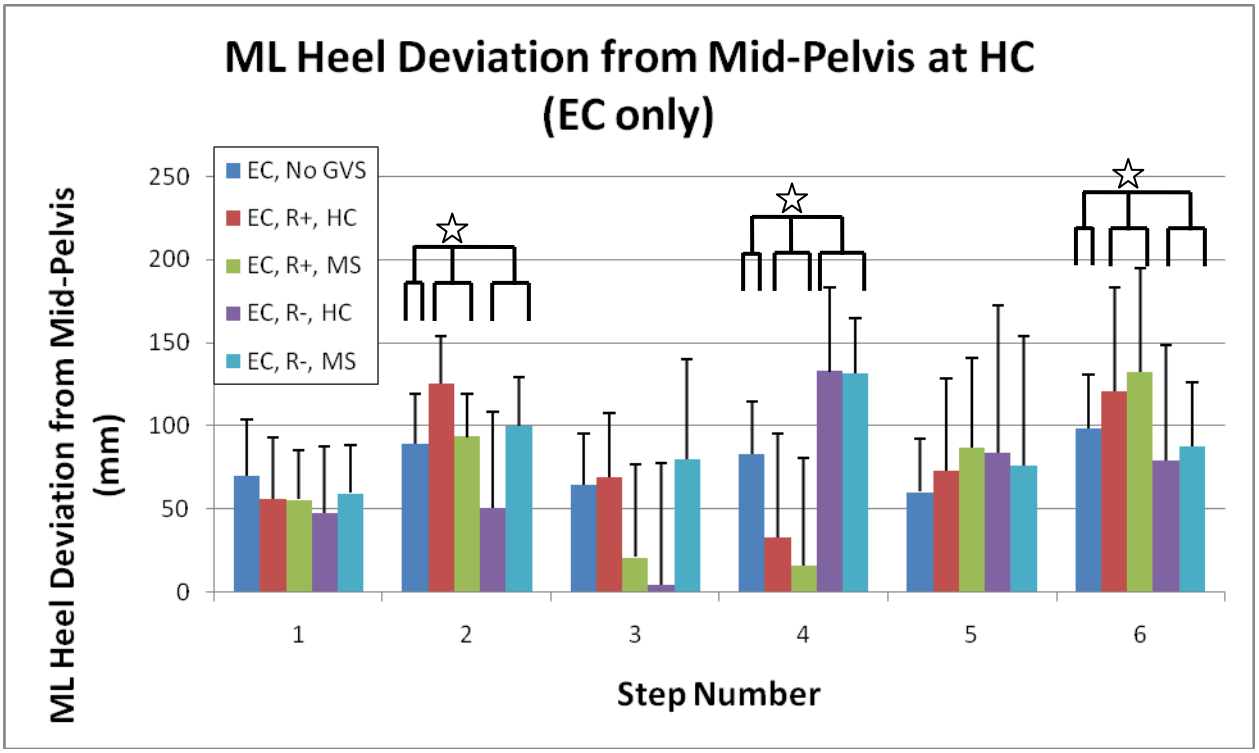

Figure 35. Mediolateral deviation (and standard deviation) of the heel from the mid-pelvis at HC with EC only. Condition with EC, GVS R^+, HC is shown in blue. Condition with EC, GVS R^+, MS is shown in red. Condition with EC, GVS R^-, HC is shown in green. Condition with EC, GVS R^-, MS is shown in purple. The absolute value of ML heel deviations from the mid-pelvis at HC towards the left (GVS R^-) are presented. Statistical significance is shown using a star.

6.4 STRIDE TIME

The stride time (based on the HCs of the right foot) starting with the right HC of GVS trigger during all seven conditions were statistically compared through a repeated measures ANOVA with independent measures being vision (EO/EC), GVS (Y/N), and their interaction. The effect

of GVS trigger (HC/MS) and GVS direction (R^+/R^-) were collapsed and not included in the statistical model. Together, the first two strides of galvanic exposure were compared to two complete strides of controlled gait without GVS. Stride times were calculated based on the first three right HCs after (and including) the GVS trigger (Figure 36). Stride time decreased with the presence of GVS ($p < 0.05$) and was not affected by vision ($p > 0.05$). Table 6, shows the stride times averaged, within subjects for each condition.

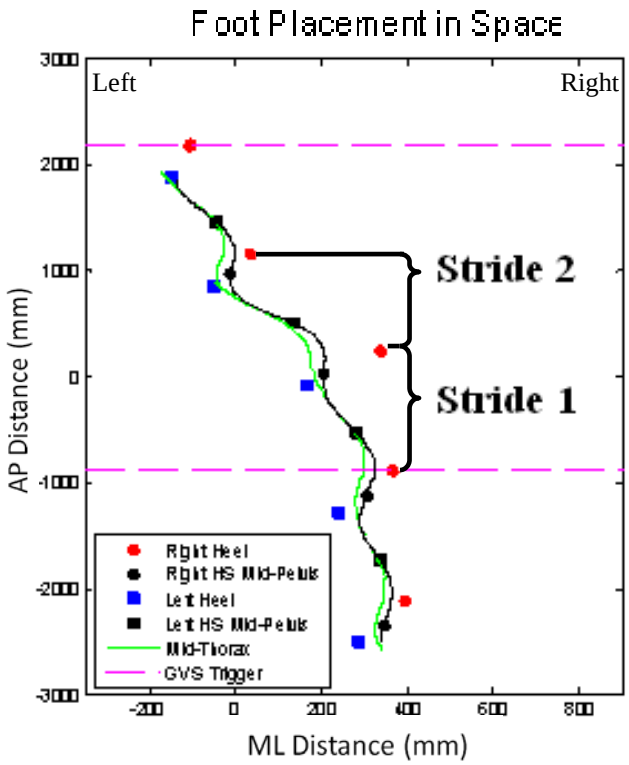

Figure 36. Graphical representation of the variables Stride 1 and Stride 2.

Table 6. Stride Time (± Standard Deviation) Averaged Within Subjects

	Stride 1	Stride 2
EO, No GVS	1.23 ± 0.12	1.23 ± 0.13
EC, No GVS	1.24 ± 0.15	1.26 ± 0.13
EO, R+, HC	1.20 ± 0.11	1.23 ± 0.14
EC, R+, HC	1.08 ± 0.24	1.26 ± 0.27
EC, R+, MS	1.21 ± 0.09	1.27 ± 0.29
EC, R-, HC	1.30 ± 0.23	1.08 ± 0.14
EC, R-, MS	1.26 ± 0.16	1.19 ± 0.25

In a separate analysis, the stride time of the right foot during conditions with EC only were statistically compared through a repeated measures ANOVA with independent measures GVS (Y/N), GVS trigger (HC, MS), GVS direction (R^+/R^-), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interactions. Stride time was significantly less, in trials with GVS than in the control trials with EC lacking GVS ($p < 0.05$). Neither the GVS trigger, GVS direction, nor the trial repetition number significantly affected the stride time ($p > 0.05$).

Additionally, separate analyses investigated the effect of GVS on individual strides using a repeated measures ANOVA with independent measures of vision (EO/EC), GVS (Y/N), and their interactions. Each stride was analyzed separately. When examined in terms of individual strides, across all trials, neither vision nor GVS have a significant effect on stride 1 or stride 2. Strong correlations do exist however, for GVS ($p = 0.06$) and the interaction between vision and GVS during stride 2 ($p = 0.09$).

The stride time of the right foot during conditions with EC only were statistically compared through a repeated measures ANOVA with independent measures GVS (Y/N), GVS direction (R^+, R^-) and their interactions. Each stride was analyzed separately. With EC, shorter stride times are attained when subjects are exposed to GVS. Furthermore, the shortest stride

times are achieved when subjects experience GVS with EC. Stride 2 had a significantly shorter stride time during trials with GVS R^- than GVS R^+ when exposed to GVS with EC ($p < 0.01$).

6.5 RIGHT TILT

The degree of tilt of the upper body in the frontal plane was obtained using two separate measures. The tilt of the head, thorax, and pelvis were examined in the global coordinate system. In addition, the neck and spine were also examined in their respective local coordinate systems. The neck angle is the angle of the head relative to the thorax. The spine angle is the angle of the thorax relative to the pelvis.

6.5.1 Right Tilt in the Global Coordinate System

During typical controlled gait, the body cyclically leans towards the left and right in an oscillatory fashion. Tilts toward the subjects' "right" (when the right ear rotates closer to the ground on the right side of the body) are considered to be positive; tilts towards the subjects' "left" are considered to be negative (Figure 17). The head, thorax, and pelvis all reach maximum tilt angles approximately at HC. Figure 37 shows representative plots of right tilt during control trials with EO (Figure 37 A) and EC (Figure 37 B), both without GVS.

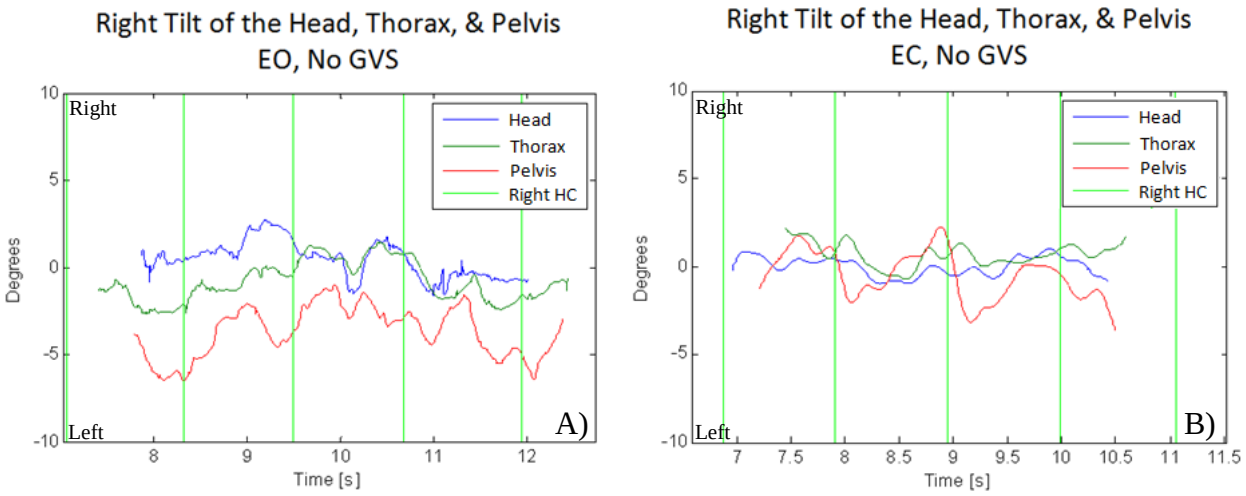

Figure 37. Representative plots of the head, thorax, and pelvis tilt during gait with EO (A, left) and EC (B, right), both without GVS. The rotation (degrees) of the head, thorax, and pelvis are shown in blue, dark green, and red, respectively. The light green vertical lines represent HC of the right foot. Positive values represent a tilt to the subjects' right; negative values represent a tilt to the subjects' left.

Figure 38 shows representative plots of the frontal tilt of the head, thorax, and pelvis during perturbation trials with EO (Figure 38 A) and EC (Figure 38 B, C, D, E), each with exposure to GVS. As expected, the patterns of the head, thorax, and pelvis deviate after GVS trigger, most dramatically in conditions with EC.

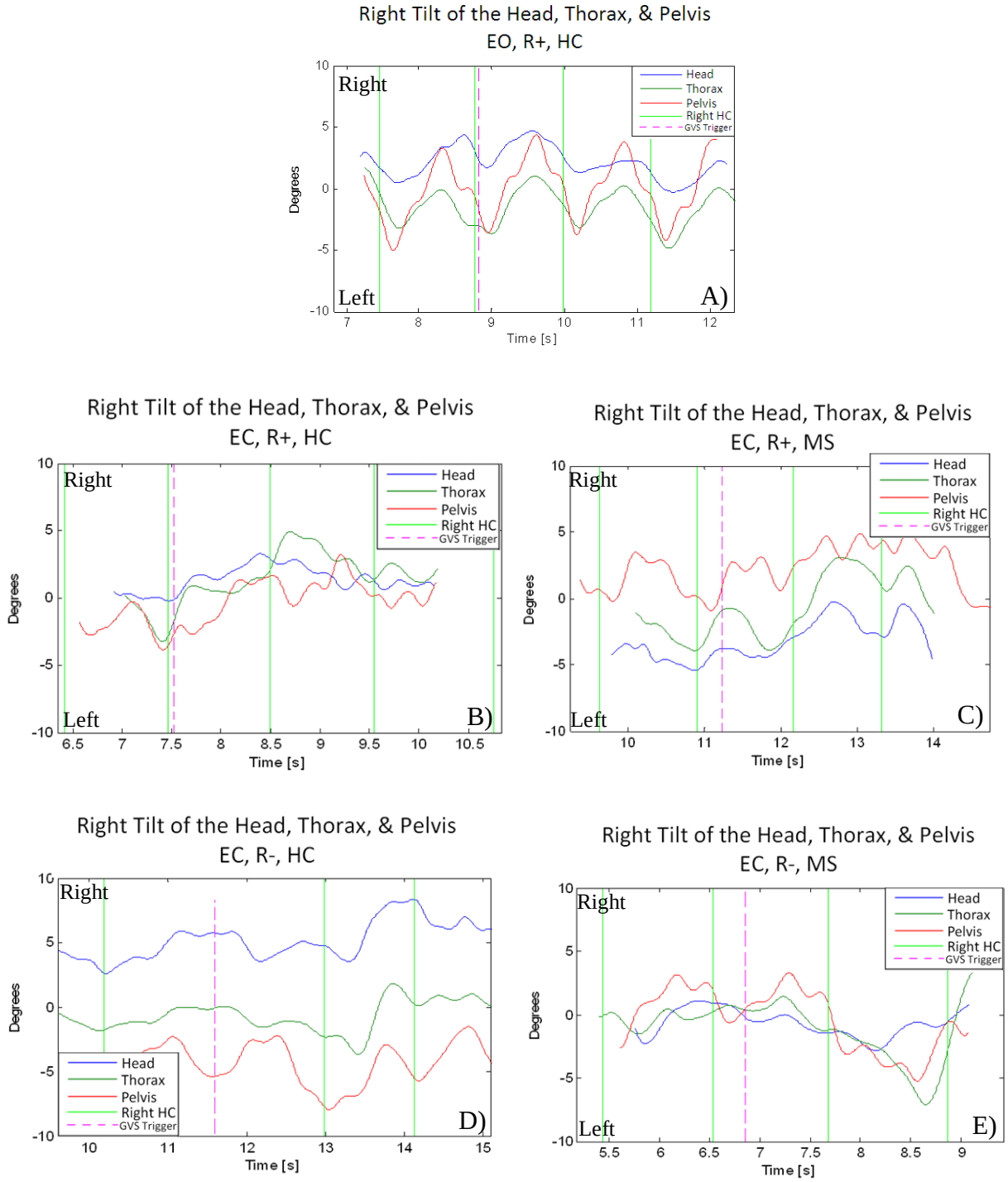

Figure 38. Representative plots of the head, thorax, and pelvis tilt during gait with EO (A, top) and EC (B, C, D, E), each with GVS. The rotation (degrees) of the head, thorax, and pelvis are shown in blue, dark green, and red, respectively. The light green vertical lines represent HC of the right foot. Positive values represent a tilt to the subjects' right; negative values represent a tilt to the subjects' left.

6.5.1.1 Maximum Head Tilt Angle

A repeated measures ANOVA was used to investigate the effects of GVS and vision on the maximum tilt angle of the head (in the frontal plane) during all seven conditions. The independent variables in the statistical model were vision (EO/EC), GVS (Y/N), and their interaction. The segmental movement and time were analyzed separately. The maximum tilt angle of the head was unaffected by the presence of vision. In addition, the maximum tilt angle of the head was unaffected by GVS. The average maximum segmental tilt (degrees) in the frontal plane of the head, thorax, and pelvis during gait is displayed in Table 7, below.

A separate repeated measures ANOVA was used to investigate the impact of GVS on the tilt angle of the head with independent variables being GVS trigger (HC/MS), GVS direction (R+/R-), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interactions. For this analysis, only EC conditions were included in the model. The maximum tilt angle of the head in the frontal plane was greater in trials that first expose subjects to a particular condition, as compared to the second or third exposure to the same condition ($p < 0.03$). Other repetitions of individual gait conditions are indeterminable from the control conditions ($p > 0.05$).

A separate repeated measures ANOVA was performed to investigate the time it took to attain the maximum head tilt angle (in the frontal plane). The independent variables in the statistical model were vision (EO/EC), GVS (Y/N), and their interaction. Across all trials, the presence of GVS caused significant alterations in the time to attain the maximum tilt angle of the head. The maximum head tilt angle was obtained earlier in trials with GVS than trials without GVS ($p = 0.01$). The timing of the maximum head tilt angle was not affected by vision.

Furthermore, a new repeated measures ANOVA was performed to investigate the temporal effect of GVS where only trials with EC and GVS were included in the model. The independent variables in this statistical model were GVS trigger (HC/MS), GVS direction (R^+, R^-), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interaction. When exposed to GVS with EC, the time at which the head obtained its maximum tilt angle was earlier during the trial of first exposure to a particular condition, as compared to the second or third exposure to the same condition ($p < 0.03$).

6.5.1.2 Maximum Thorax Tilt Angle

A repeated measures ANOVA was used to investigate the effects GVS and vision on the maximum tilt angle of the thorax (in the frontal plane) during all seven conditions. The independent variables in the statistical model were vision (EO/EC), GVS (Y/N), and their interaction. The segmental movement and time were analyzed separately. The presence of vision did not have a significant effect on the maximum tilt angle of the thorax. When exposed to GVS during gait however, subjects experienced greater maximum thorax angles than they did in trials without GVS (Figure 39) ($p < 0.01$).

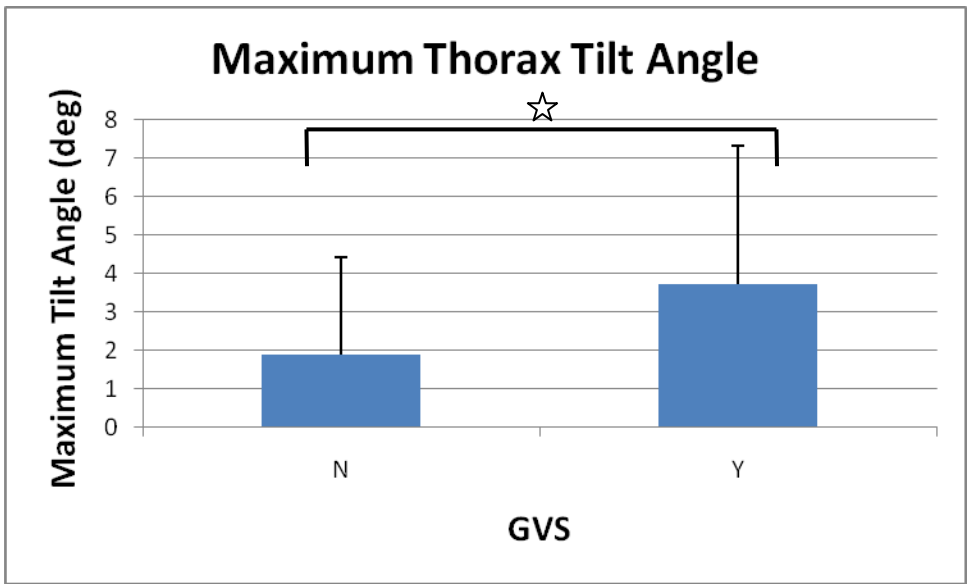

Figure 39. Maximum tilt angle (and standard deviation) of the thorax for GVS and No GVS gait conditions. Statistical significance is shown with a star.

A second repeated measures ANOVA was performed to investigate the effect of repeated trials of GVS, GVS direction, and gait cycle timing of the GVS trigger on GVS responses, using only the conditions with EC and GVS. The independent variables in the statistical model were GVS trigger (HC/MS), GVS direction (R^+/R^-), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interactions. The direction of the galvanic current significantly altered the maximum tilt angle of the thorax ($p < 0.01$). When exposed to GVS with EC, subjects experienced a greater thorax angle with GVS R^+ than GVS R^-. The interaction of trial repetition number and direction also caused significant differences ($p = 0.04$). The first trial of GVS R^+ has greater maximum thorax tilt angles for the first trial repetition as compared to the other two repetitions of the same conditions.

Yet another repeated measures ANOVA was performed to determine the time to achieve the maximum thorax tilt angle in the frontal plane. The independent variables in the statistical

model were vision (EO/EC), GVS (Y/N), and their interaction. Across all trials, the presence of GVS caused significant alterations in the time to attain the maximum tilt angle of the thorax. Gait conditions that exposed subjects to GVS result in maximum thorax angles that occur sooner in the trial than compared to trials without GVS ($p < 0.01$).

6.5.1.3 Maximum Pelvic Tilt Angle

A repeated measures ANOVA was used to investigate the effects of GVS and vision on the maximum tilt angle of the pelvis (in the frontal plane in the global coordinate system) during all seven conditions. The independent variables in the statistical model were vision (EO/EC), GVS (Y/N), and their interaction. The segmental movement and time were analyzed separately. The maximum tilt angle of the pelvis (in the frontal plane) was greater when exposed to GVS ($p = 0.03$). The presence of vision had no statistically significant effect on the maximum pelvic tilt angle.

A separate repeated measures ANOVA was used to investigate the impact of GVS on the tilt angle of the pelvis with independent variables being GVS trigger (HC/MS), GVS direction(R^+/R^-), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interactions. For this analysis, only conditions with EC were included in the model. Greater maximum pelvic tilt angles are achieved during GVS R^+ than GVS R^- ($p < 0.01$). The presence of trial number had no statistically significant effect on the maximum pelvic tilt angle.

Furthermore, a separate repeated measures ANOVA was performed to investigate the time it took to attain the maximum pelvic tilt angle (in the frontal plane). The independent variables in the statistical model were vision (EO/EC), GVS (Y/N), and their interaction. Across all trials, the presence of GVS caused significant alterations in the time to attain the maximum

pelvic tilt angle. The pelvis obtained the maximum tilt angle sooner during trials with GVS than trials lacking GVS ($p = 0.01$).

A new repeated measures ANOVA was performed to investigate the effect of GVS where only conditions with EC were included in the model. The independent variables in this statistical model were GVS trigger (HC/MS), GVS direction (GVS R^+/R^-), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interaction. The maximum pelvic tilt angle in the frontal plane was statistically significant depending upon trial repetition number ($p = 0.02$), GVS trigger ($p = 0.03$), and the interaction of trigger and direction ($p = 0.04$).

Lastly, a separate repeated measures ANOVA was performed to investigate the time required to attain the maximum pelvic tilt angle (in the frontal plane). The independent variables in the statistical model were vision (EO/EC), GVS (Y/N), and their interaction. Across all trials, the time to achieve the maximum pelvic tilt angle was significantly less for the first trial repetition of conditions with GVS as compared conditions without GVS ($p < 0.04$). In addition, the maximum pelvic tilt angle is obtained earlier during trials when the GVS is triggered at MS as compared to HC.

Again, the average maximum segmental tilt (degrees) in the frontal plane of the head, thorax, and pelvis during gait is displayed in Table 7, below.

Table 7. Average Maximum Segmental Tilt (degrees) of the Head, Thorax, and Pelvis

Averaged Degree of Maximum Right Tilt for Each Condition			
	Head	**Thorax**	**Pelvis**
EO, No GVS	2.44 ± 3.46	1.79 ± 2.68	3.56 ± 3.55
EC, No GVS	1.99 ± 3.32	2.03 ± 2.37	3.67 ± 3.67
EO, R+, HC	2.67 ± 4.01	2.99 ± 2.94	4.64 ± 3.59
EC, R+, HC	4.28 ± 7.12	5.73 ± 3.19	6.20 ± 4.27
EC, R+, MS	3.51 ± 4.03	5.72 ± 3.64	6.59 ± 4.03
EC, R-, HC	3.22 ± 4.57	2.25 ± 2.50	3.06 ± 3.16
EC, R-, HC	1.96 ± 3.67	2.05 ± 3.73	3.15 ± 2.91

The time to attain the average maximum segmental tilt (degrees) of the head, thorax, and pelvis during gait is displayed in Table 8.

Table 8. Time to Attain the Average Maximum Segmental Tilt (degrees) of the Head, Thorax, and Pelvis

Time to Averaged Degree of Maximum of Right Tilt for Each Condition			
	Head	**Thorax**	**Pelvis**
EO, No GVS	2.25 ± 1.37	2.49 ± 1.51	2.99 ± 4.41
EC, No GVS	2.65 ± 1.49	2.81 ± 1.70	2.61 ± 1.57
EO, R+, HC	2.08 ± 1.14	1.51 ± 0.71	1.65 ± 0.69
EC, R+, HC	1.55 ± 0.78	1.75 ± 0.59	1.85 ± 0.57
EC, R+, MS	1.41 ± 0.60	1.68 ± 0.40	1.79 ± 0.45
EC, R-, HC	1.99 ± 1.34	2.21 ± 1.46	1.84 ± 1.28
EC, R-, HC	1.50 ± 1.45	1.66 ± 1.55	1.20 ± 1.24

6.5.2 Segmental Tilt in the Local Coordinate System

The tilt of the head, thorax, and pelvis were also analyzed relative to each other. The local angle between the head and the thorax is the "neck angle." The local angle between the thorax and pelvis is the "spine angle." Again, tilts toward the subjects' "right" (when the right ear rotates closer to the ground on the right side of the body) are considered to be positive; tilts towards the subjects' "left" are considered to be negative (Figure 17).

6.5.2.1 Maximum Neck Angle

The maximum tilt angle of the neck (in the frontal plane) during all seven conditions were statistically compared through a repeated measures ANOVA with independent measures being vision (EO/EC), GVS (Y/N), and their interaction. The segmental movement and time were analyzed separately. Neither GVS nor vision had a significant effect on the maximum neck angle.

A separate repeated measures ANOVA was used to investigate the impact of GVS trigger, direction, and trial repetition number on the maximum tilt angle of the neck. Thus, the independent variables of this model were GVS trigger (HC/MS), GVS direction (GVS R^+/R^-), trial repetition number (1^{st}, 2^{nd}, 3^{rd}), and their interaction. For this analysis, only EC conditions were included in the model. Greater neck angles were achieved when exposed to GVS R^- compared to GVS R^+, with EC ($p < 0.01$).

To determine the timing effect of GVS and vision on the maximum tilt angle of the neck, a final repeated measures ANOVA was used with independent variables being GVS (Y/N), vision (EO/EC), and their interaction. For this analysis, all seven conditions were included in the model. The maximum neck angle was achieved sooner in trials with GVS than without GVS (p

< 0.0001). No significance was determined for the timing of the maximum neck angle due to the presence of vision.

6.5.2.2 Maximum Spine Angle

The maximum tilt angle of the spine (in the frontal plane) during all seven conditions were statistically compared through a repeated measures ANOVA with independent measures being vision (EO/EC), GVS (Y/N), and their interaction. The segmental movement and time were analyzed separately. No significance was determined for the maximum spine angle for GVS or vision, or the interaction of these variables.

To determine the timing effect of GVS and vision on the maximum tilt angle of the spine, a final repeated measures ANOVA was used with independent variables being GVS (Y/N), vision (EO/EC), and their interaction. For this analysis, all seven conditions were included in the model. The maximum spine angle was achieved sooner in trials with GVS than without GVS ($p < 0.01$). No significance was determined for the timing of the maximum spine angle due to the presence of vision.

The average maximum tilt (degrees) in the frontal plane of the neck and spine during gait is displayed in Table 9, below.

Table 9. Average Maximum Segmental Tilt (degrees) of the Neck and Spine

Averaged Degree of Maximum Right Tilt for Each Condition		
	Neck	**Spine**
EO, No GVS	3.63 ± 3.73	2.76 ± 2.90
EC, No GVS	2.97 ± 4.10	2.30 ± 2.97
EO, R+, HC	2.59 ± 5.03	2.89 ± 3.02
EC, R+, HC	3.65 ± 7.76	3.05 ± 3.04
EC, R+, MS	3.31 ± 4.12	2.87 ± 3.34
EC, R-, HC	5.38 ± 5.53	2.66 ± 3.05
EC, R-, HC	4.00 ± 4.29	2.75 ± 5.12

The time to attain the average maximum tilt (degrees) in the frontal plane of the neck and spine during gait is displayed in Table 10, below.

Table 10. Time to Attain the Average Maximum Segmental Tilt (degrees) of the Neck and Spine

Time to Attain Averaged Degree of Right Tilt for Each Condition		
	Neck	**Spine**
EO, No GVS	2.00 ± 1.00	2.82 ± 1.26
EC, No GVS	2.33 ± 1.35	2.83 ± 1.43
EO, R+, HC	0.79 ± 0.82	0.98 ± 0.80
EC, R+, HC	1.99 ± 1.47	1.83 ± 0.84
EC, R+, MS	0.90 ± 0.87	1.59 ± 0.73
EC, R-, HC	1.59 ± 0.82	1.73 ± 1.39
EC, R-, HC	2.75 ± 5.12	1.76 ± 1.30

7.0 DISCUSSION

The specific aim of this study was to examine the specific biomechanical responses of the body segments in response to GVS during locomotion. Specific interests include head stability throughout internal vestibular perturbations during gait. Temporal parameters were investigated to aid in the determination of possible sequential segmental tilting of the upper body. Furthermore, segment interactions such as the neck (head-thorax interaction) and spine (thorax-pelvis interaction) are of special interest as well. The overall question of whether body segments (head, torso, pelvis, and legs) move together laterally in response to GVS, or if some temporal ordering of the movements and segmental tilting exists is addressed in this chapter.

7.1.1 Full-Body Biomechanical Response to GVS

Consistent with published literature, all subjects deviated towards the anodal side of the stimulation and showed a response to the GVS approximately one stride after GVS trigger. Hlavacka et al. showed that the first whole-body biomechanical signs of a galvanic current during stance are seen approximately one second after the trigger (Hlavacka et al., 1996). Subjects in our experiment walked at a self-selected pace, which was approximately 1.2 seconds per stride, and showed first signs of deviation with EC after the completion of one full stride.

Thus, the responses to GVS seen in the gait parameters are temporally consistent with what has been observed in standing trials by Hlavacka. This suggests that the delay seen in GVS responses during gait are due to some neural processing for postural control also seen in standing responses as opposed to a delay due to the phase of gait. The fact that there was no difference in the timing of the application (HC versus MS) is consistent with this interpretation. Though the deviation from control gait was observed approximately one second (or one stride) after GVS trigger, the time to achieve the *maximum* tilt angle was a half second (or one step) longer. Irrespective of the GVS trigger (HC or MS), an additional step was required after GVS response initiation to achieve the maximum tilt angle.

7.1.2 Repeated Exposure and the Learning Affect of GVS

Though adaptation to repeated GVS exposure was observed in our study, a learning effect to GVS has not been reported in published literature. Current published literature states that no "learning" or adaptation exists in response to GVS (Bent et al., 2000; Wardman et al., 2003). Furthermore, no signs of "turning back" to the original gait target had been observed and no learning had been attained between trials. In many different modalities, learning was indeed present in this current study. Greater maximum ML deviations were experienced during the first exposure to a specific GVS trial condition. Maximum tilt angle of the head and thorax were greater during first exposure to specific GVS conditions. Additionally, the timing of the maximum pelvic tilt angle was significantly different for the first exposure to a trial condition as compared to other repetitions of the same condition. Previously published literature from Chambers et al. has shown that learning has a significant effect on slip severity (Chambers et al.,

2007). Slip severity, a measure of biomechanical responses to external perturbations, is lessened after first exposure. It is possible that similar mechanisms adapt to lessen the effect of unexpected internal perturbations, such as GVS, as well as the effects of unexpected external perturbations, such as a slip.

7.1.3 The Effect of GVS Trigger on Gait

The GVS trigger (HC or MS) significantly affected the timing of the maximum tilt angle during gait, but did not affect the lateral deviation distance, global position of the mid-pelvis, or heel deviation from mid-pelvis. Subjects attained a maximum tilt angle more quickly after GVS trigger when exposed to the GVS at MS as opposed to at HC. Previously, Bent et al. observed greater deviations in foot placement when the galvanic stimulus onset was triggered at HC. They did not observe differences in the magnitude of ML head, trunk, or pelvis deviation when delivering GVS at HC as opposed to mid-stance or toe-off (Bent et al., 2004). While our study used a manual, button-press to activate the GVS, Bent et al. utilized a 5N threshold of the vertical ground reaction force to activate the GVS. Though this difference in methods may appear to be slight, it is possible that the sensitive intricacies of the gait cycle are affected by this possible source of error. Still, the exact mechanisms that control these responses are still unclear. Though Bent et al. and our current study both find some small portion of relevance to the GVS trigger, the trigger does not play a major role in affecting balance during gait. In future works, more time and attention should be focused on the responses of foot placement, GVS adaptation, head stability, and temporal ordering than the importance on GVS trigger.

7.1.4 The Importance of Vision

Vision dominates the inputs to the balance system. Contributions to the balance system from proprioception and the vestibular system are overpowered by the contributions from vision. Significantly less ML deviations in gait were observed with EO compared to EC, irrespective of the presence of GVS. When comparing control gait without GVS for EO versus EC, the magnitude of the lateral deviation was approximately twice as much for EC than EO trials. Clearly, vision plays a role in stability and navigation in locomotion. It should be noted that in gait trials with EC, much of the increase in ML deviations may be attributed to navigation errors as opposed to an error of the steady state gait. The reliance on vision may be due to the high precision, accuracy, and repeatability of the system. When present, vision accounts for a significantly large contribution to the balance system as compared to proprioception or the vestibular system.

7.1.5 Preservation of Head Stability

The head experienced significantly less tilting in the frontal plane than did the thorax or pelvis. In addition, the tilt angle of the head was unaffected by vision, GVS trigger, or the trial repetition number. Meanwhile, the thorax and pelvis both experience significant tilting due to GVS exposure during gait. If each of the upper-body segments (head, thorax, and pelvis) were responding in a similar manner during GVS exposure, then one would expect the higher segments to attain greater maximum tilt angles than the segments below. This trend was not present.

The head remained relatively "level" in the global coordinate system during gait when exposed to GVS, especially when compared to the thorax and pelvis. Thus, there is a counter rotation of the head compensating for the tilt of the thorax in order to preserve the level reference frame of the head. This is surprising considering the existence of the vestibulocollic reflex, which stabilizes the head in space, and other sensory inputs known to impact head control. One would anticipate a vestibular perturbation to create an angular rotation of the head that was not seen. One explanation may be that the GVS stimulus does not impact rotational vestibular senses (i.e. canal afferent outputs) as much as the linear acceleration senses (i.e. olotith afferent outputs). Thus, rotational control by the canals would be less affected by GVS compared to the otolithic lateral acceleration inputs.

7.1.6 Mediolateral Mid-Pelvis & Foot Placement during Gait

Significant differences in the ML displacement of the mid-pelvis during gait were observed as early as step 4 with EO and as early as step 3 with EC. The lack of vision during EC trials causes an increased contribution of the vestibular system. Thus, the effects of the GVS significantly altered the trajectory of the mid-pelvis just one full stride (two steps) after GVS trigger with EC, but not until three steps after GVS trigger with EO. With EO, as opposed to with EC, there was no significant deviation of the mid-pelvis at step 6. The most probably explanation of this "turning back" towards the pre-GVS gait path is that with EO, vision is competing to override the other inputs to the balance system: the proprioception and vestibular systems. As subjects approached the end of the experimental walkway, the increased clarity of the gait target provided enough visual stimuli to guide subjects back towards the original gait

target. This visual gait target was obviously lacking in EC trials and thus no turning back towards the pre-GVS gait trajectory was observed with EC.

The ML heel deviation from mid-pelvis may provide crucial insight to the internal control of balance loss. The ML heel deviation from the mid-pelvis was observed as early as step 3 with EO and step 2 with EC. Since other variables, such as the global pelvic deviation, do not attain statistical significance until later in the trial one may infer that the feet are propelling the deviation of the whole-body system during the loss of balance.

7.1.7 Temporal Ordering of ML Movement & Segmental Tilting

Determining the temporal ordering of the ML segmental movements may aid in determining whether the body segments deviate together laterally due to an internal perturbation or if a pattern of segmental tilting exists. Though not statistically significant, specific temporal sequences of attaining maximum tilt angles exist. When subjects were exposed to GVS R^+ with EC, the head reached a maximum tilt angle first, then the thorax, and finally the pelvis. When subjects were exposed to GVS R^- with EC, the pelvis reached a maximum tilt angle first, followed by the head, and then the thorax. These sequences of segmental tilting may provide valuable insight to the hierarchy of temporal ordering of movements.

GVS was triggered when the right foot was in contact with the floor during this study. When the GVS evoked ML deviations to the right (GVS R^+), the head achieved its maximum tilt before the thorax or the pelvis. Since the head is the first to attain said maximum angle, it is logical to assume that the thorax, pelvis, and feet are then also deviating laterally in an attempt to regain balance and avoid a fall. When the GVS evoked ML deviations to the left (GVS R^-), the

pelvis attained the maximum tilt angle first, followed by the head and the thorax. Thus, one would assume that falls away from the stance limb are "driven" by the pelvis. Combining this information with the fact that significant ML deviations are observed in the foot placement earlier after GVS trigger than pelvic deviations, one may assume that the overall gait deviations are driven by the lower-body. During falls away from the stance limb, the feet and pelvis act to thrust the body laterally, but the head remains stabilized in the global coordinate system.

The temporal ordering of segmental movements may depend upon the fall direction as well as the mechanical positioning of the human body. During a loss of balance or fall during gait, a loss of balance is most likely to occur either during single support or at HC or toe-off. It is during these times that the balance system has the least amount of reliable information from the proprioception system due to the limited physical contact with the floor. During a loss of balance or fall towards the stance limb, the stance limb itself may somehow prevent the pelvis from achieving significant tilt angles. During a loss of balance towards the stance limb, the contralateral limb must cross in front of the body, around the stance limb. The head however, is relatively free of motion constraints and is thus the first to attain a maximum tilt angle. During a loss of balance away from the stance limb, the contralateral leg is free to deviate laterally and pelvic tilting is not hindered. During this type of movement (away from the stance limb) the pelvis is able to tilt freely before the effects are seen in the head or thorax. Irrespective of the temporal ordering of the head, thorax, and pelvis, it is clear that segmental tilting exists during gait. In all conditions, our results were consistent with the findings of Day et al. in that a segmental tilting towards the anodal ear was observed (Day et al., 1997).

When combining the information that the head is relatively unaffected by vision or GVS, one may hypothesize that the segmental tilting of the human body during gait acts to stabilize the

head in space as opposed to stabilizing the body as a whole. Further testing with a larger number of subjects and a larger age range may add certainty and clarity to this hypothesis.

7.1.8 Limitations

The following limitations may have hindered the overall significance of the current study.

7.1.8.1 Limited Subject Population

The statistical significance of this study was diminished due to the limited subject population size. The necessity of vestibular screening made subject recruitment relatively difficult. A greater number of subjects would have provided crucial additional information that may have added significance to the effects of the variables of interest. In addition, the subject population in this work was limited to the young and healthy. The inclusion of an older population or a population with known vestibular diseases may provide further insight into the specific biomechanical responses to GVS during locomotion.

7.1.8.2 Manual GVS Trigger

The GVS was delivered during gait using a manual, button-press trigger. The GVS was delivered using a button press when the researcher visually identified the subject to be at HC. Uncontrollably, human error is present in a system that utilized a button press. More accurate data may be recorded using a trigger that automatically delivers the galvanic current based on a specific gait event. One possible solution is to trigger the GVS based on a specific ground

reaction threshold of an embedded force plate. This would further ensure that the GVS was truly delivered precisely at HC or MS.

7.1.8.3 GVS Sensitivity

Within subject current impedance was not evaluated in this project. Though a standardized 1mA current was delivered to all subjects in gait, it is likely that each subject had a unique galvanic sensitivity. One possible solution is to record the magnitude of subjects' responses to specific levels of GVS. This would allow the GVS current delivered during the gait testing to be standardized based upon predetermined subject sensitivity, which would further normalize the testing procedure.

7.1.8.4 Testing Area

The testing area of the Human Movement and Balance Laboratory is large enough to allow approximately six full strides and capture full-body human movement during gait. Due to the physical positioning and setup limitations of the Vicon cameras, only approximately three and a half of the six strides are fully captured by the motion system. Thus, for some subjects, some data was lost due to a lack of capture by the Vicon system. A longer testing area would allow for the collection of additional "control" data before GVS trigger as well as additional steps while receiving the GVS. The capture of these additional steps would allow for a more significant comparison between control walking and perturbed walking. Furthermore, subjects were asked to walk with their eyes closed during many trials. Though the gait path was clear and the subjects were protected from all objects and falls by the safety harness, the fear of bumping into other large, hard objects while their eyes were closed may have altered the gait speed or gait path of the participants.

7.1.8.5 Safety Harness

To ensure the safety of all participants, subjects wore a safety harness to protect from any ground contact injuries that may result from a fall. Though this harness did not hinder the physical motion of the participants, the mental effect of knowing that they were in a safe environment and in no danger of getting injured may have affected their gait. Fear of falling has been shown to play a significant role in many gait parameters (Cham et al., 2002). Perhaps the presence of the safety harness reduced the innate fear of falling, and consequently altered the biomechanical responses to GVS.

8.0 CONCLUSION

The aim of this project was to examine the specific biomechanical responses of the body segments in response to GVS during locomotion. Basic and general results were consistent with published literature; GVS increased the mediolateral deviation of whole-body movement towards the side of the anode during gait. Results indicate that head stability is of key importance to the balance system. The reference frame of the head was held relatively constant throughout gait irrespective of the presence of vision or galvanic stimulation. Many biomechanical responses act to minimize the disruptive movements of the head during gait as to standardize the reference frame and control center for other segments and movements. Though minimal learning or adaptation effects have been reported in current literature, some subjects turned back towards the original gait target during the exposure to GVS, specifically with EO. Future works will aid in determining if the turning of gait trajectory is a function of the vestibular system, physical laboratory setup, or a separate undiscovered entity. Vision was found to be of paramount importance during gait. When walking with eyes open, GVS had very little effect on the gait trajectory, spatial foot placement parameters, or tilt angle of the head, thorax, and pelvis. Lastly, temporal ordering of the tilt angles of the head, thorax, and pelvis provide preliminary evidence that segmental tilting exists during gait. Thus, the inverted pendulum model is incorrect for balance losses during gait, else it requires strict assumptions. Though limitations of this study certainly exist, the data presented still have significant meaning and much may be learned from

this study. Future testing of a greater number of subjects with a larger range of ages and physical condition may provide a greater insight to the intricacies of the human vestibular system.

APPENDIX A

SUBJECT TESTING SHEETS

The testing sheets of this section of the appendix display the condition sequence for each subject.

GVS_01					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Back	1
		T	EC	R-/Back	1
		T	EC	R+/Front	1
		T	EC	R-/Front	1
Block 1		G	EC	R+	MS
		G	EC	R+	HC
		G	EO	R+	HC
		G	EC	No GVS	-
		G	EC	R-	HC
		G	EC	R-	MS
		G	EO	No GVS	-
Block 2		G	EC	R+	MS
		G	EC	R+	HC
		G	EO	R+	HC
		G	EC	No GVS	-
		G	EC	R-	HC
		G	EC	R-	MS
		G	EO	No GVS	-
Block 3		G	EC	R+	MS
		G	EC	R+	HC
		G	EO	R+	HC
		G	EC	No GVS	-
		G	EC	R-	HC
		G	EC	R-	MS
		G	EO	No GVS	-
Slip		US	EO	No GVS	-

GVS_02					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Back	1
		T	EC	R+/Front	1
		T	EC	R-/Front	1
		T	EC	R-/Back	1
Block 1		G	EC	No GVS	-
		G	EO	R+	HC
		G	EC	R-	HC
		G	EC	R+	HC
		G	EO	No GVS	-
		G	EC	R-	MS
		G	EC	R+	MS
Block 2		G	EC	No GVS	-
		G	EO	R+	HC
		G	EC	R-	HC
		G	EC	R+	HC
		G	EO	No GVS	-
		G	EC	R-	MS
		G	EC	R+	MS
Block 3		G	EC	No GVS	-
		G	EO	R+	HC
		G	EC	R-	HC
		G	EC	R+	HC
		G	EO	No GVS	-
		G	EC	R-	MS
		G	EC	R+	MS
Slip		US	EO	No GVS	-

GVS_03					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Back	1
		T	EC	R-/Back	1
		T	EC	R-/Front	1
		T	EC	R+/Front	1
Block 1		G	EO	R+	HC
		G	EO	No GVS	-
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EC	R+	HC
		G	EC	R-	HC
		G	EC	R-	MS
Block 2		G	EO	R+	HC
		G	EO	No GVS	-
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EC	R+	HC
		G	EC	R-	HC
		G	EC	R-	MS
Block 3		G	EO	R+	HC
		G	EO	No GVS	-
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EC	R+	HC
		G	EC	R-	HC
		G	EC	R-	MS
Slip		US	EO	No GVS	-

GVS_04					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Back	1
		T	EC	R-/Back	1
		T	EC	R+/Front	1
		T	EC	R-/Front	1
Block 1		G	EC	R+	MS
		G	EC	R+	HC
		G	EO	R+	HC
		G	EC	No GVS	-
		G	EC	R-	HC
		G	EC	R-	MS
		G	EO	No GVS	-
Block 2		G	EC	R+	MS
		G	EC	R+	HC
		G	EO	R+	HC
		G	EC	No GVS	-
		G	EC	R-	HC
		G	EC	R-	MS
		G	EO	No GVS	-
Block 3		G	EC	R+	MS
		G	EC	R+	HC
		G	EO	R+	HC
		G	EC	No GVS	-
		G	EC	R-	HC
		G	EC	R-	MS
		G	EO	No GVS	-
Slip		US	EO	No GVS	-

GVS_05					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Front	1
		T	EC	R-/Front	1
		T	EC	R-/Back	1
		T	EC	R+/Back	1
Block 1		G	EC	R-	HC
		G	EO	No GVS	-
		G	EC	R-	MS
		G	EC	R+	HC
		G	EC	R+	MS
		G	EO	R+	HC
		G	EC	No GVS	-
Block 2		G	EC	R-	HC
		G	EO	No GVS	-
		G	EC	R-	MS
		G	EC	R+	HC
		G	EC	R+	MS
		G	EO	R+	HC
		G	EC	No GVS	-
Block 3		G	EC	R-	HC
		G	EO	No GVS	-
		G	EC	R-	MS
		G	EC	R+	HC
		G	EC	R+	MS
		G	EO	R+	HC
		G	EC	No GVS	-
Slip		US	EO	No GVS	-

GVS_06					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Front	1
		T	EC	R+/Back	1
		T	EC	R-/Front	1
		T	EC	R-/Back	1
Block 1		G	EO	R+	HC
		G	EC	R+	MS
		G	EC	R-	HC
		G	EC	R-	MS
		G	EC	R+	HC
		G	EO	No GVS	-
		G	EC	No GVS	-
Block 2		G	EO	R+	HC
		G	EC	R+	MS
		G	EC	R-	HC
		G	EC	R-	MS
		G	EC	R+	HC
		G	EO	No GVS	-
		G	EC	No GVS	-
Block 3		G	EO	R+	HC
		G	EC	R+	MS
		G	EC	R-	HC
		G	EC	R-	MS
		G	EC	R+	HC
		G	EO	No GVS	-
		G	EC	No GVS	-
Slip		US	EO	No GVS	-

GVS_07					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Back	1
		T	EC	R+/Front	1
		T	EC	R-/Back	1
		T	EC	R-/Front	1
Block 1		G	EO	No GVS	-
		G	EC	R-	HC
		G	EC	R+	HC
		G	EC	R-	MS
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EO	R+	HC
Block 2		G	EO	No GVS	-
		G	EC	R-	HC
		G	EC	R+	HC
		G	EC	R-	MS
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EO	R+	HC
Block 3		G	EO	No GVS	-
		G	EC	R-	HC
		G	EC	R+	HC
		G	EC	R-	MS
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EO	R+	HC
Slip		US	EO	No GVS	-

GVS_08					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R-/Front	1
		T	EC	R+/Back	1
		T	EC	R-/Back	1
		T	EC	R+/Front	1
Block 1		G	EO	R+	HC
		G	EC	R+	HC
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EC	R-	HC
		G	EO	No GVS	-
		G	EC	R-	MS
Block 2		G	EO	R+	HC
		G	EC	R+	HC
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EC	R-	HC
		G	EO	No GVS	-
		G	EC	R-	MS
Block 3		G	EO	R+	HC
		G	EC	R+	HC
		G	EC	No GVS	-
		G	EC	R+	MS
		G	EC	R-	HC
		G	EO	No GVS	-
		G	EC	R-	MS
Slip		US	EO	No GVS	-

GVS_09					
	Trials	Type	Eye Condition	GVS Condition	Length/GVS Type
Static		ST	-	-	-
Controls		FT	EO	No GVS	1 min
		FT	EC	No GVS	1 min
Standing		FT	EC	R+	0.25
		FT	EC	R-	0.25
		FT	EC	R+	0.5
		FT	EC	R-	0.5
		FT	EC	R+	1
		FT	EC	R-	1
Tandem		T	EC	R+/Front	1
		T	EC	R-/Back	1
		T	EC	R+/Back	1
		T	EC	R-/Front	1
Block 1		G	EC	R-	MS
		G	EC	R-	HC
		G	EC	No GVS	-
		G	EO	R+	HC
		G	EC	R+	MS
		G	EO	No GVS	-
		G	EC	R+	HC
Block 2		G	EC	R-	MS
		G	EC	R-	HC
		G	EC	No GVS	-
		G	EO	R+	HC
		G	EC	R+	MS
		G	EO	No GVS	-
		G	EC	R+	HC
Block 3		G	EC	R-	MS
		G	EC	R-	HC
		G	EC	No GVS	-
		G	EO	R+	HC
		G	EC	R+	MS
		G	EO	No GVS	-
		G	EC	R+	HC
Slip		US	EO	No GVS	-

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