The Adaptation of Lower Leg Muscles During Gait to Galvanic Vestibular Stimulation

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Abstract

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Fall prevention is a growing concern as our elderly population reflects a greater proportion of our population. Some muscles have been shown to exhibit a decrease in response as they become accustomed to certain types of stimulation and perturbations, dependant on the task and the muscle observed. This is possible by analyzing the relationship between muscle activity and stimulation in human participants.

We measured the response to galvanic vestibular stimulation in the medial gastrocnemius and soleus muscles. Galvanic vestibular stimulation is when electric current is sent through pads placed over the mastoid processes on each side, which are found behind the ears. This induces a nerve impulse to be generated and sent from the vestibular nerve to the appropriate processing centers in the brain. This results in the brain thinking the body is losing its balance, since they head is being stimulated to change its orientation, causing a sway in the posture.

15 healthy participants were recruited from the local university, and screened for any neurological disease. The goal was to determine if the medial gastrocnemius and soleus muscles also experience a decrease in response, over one hour of walking with the stimulation on a treadmill. Through the analysis of the relationship between muscle activity and stimulation, we did not find any significant decrease in muscle activity over time. The results cannot however be widespread to other muscles or other tasks, and so more research is needed to better understand how muscle response to dynamic tasks is organized.

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CD performed all the data collection at a prior time. He showed me how to analyze the data in MATLAB and explained the relevance of data to other research. He was also greatly involved in the editing of the manuscript. GD was responsible for preparing the meetings of the committee and also involved in the editing of the manuscript. PF was involved in committee meetings as well as providing feedback and editing the manuscript.

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Introduction

Gait is important for human survival and well-being, and it is a strong predictor of our independence. Because of the important role gait plays in our independence, it is essential to understand the mechanisms that contribute to its effectiveness, to train them or rehabilitate them, in the event gait becomes impaired. Gait is complex, however. It relies upon many interacting systems for its successful performance. Sensory systems such as the visual, somatosensory and vestibular systems, all provide information to the brain describing where the body is in space and in relation to its environment. At a finer level, each of these sensory systems provides an important contribution to the different phases of the gait cycle.[1,2] For example, when we lose balance, sensory systems throughout our body, such as in the vestibular system, sense the inappropriate motions associated with the loss of balance and send that information to the central nervous system. The central nervous system then sends efferent signals to contract the appropriate muscles to counter the disturbance.

The body is very quick to react and compensate for sensory signals resulting from the disturbances it encounters daily. However, when these sensory signals do not need to be compensated for, such as when they can be predicted or are the result of an internal error, the body can 'tune out' or reduce its response to these signals.[3] This allows normal functioning to continue, despite erred information from one or more sensory systems. This 'tuning out' phenomenon is a form of adaptation called habituation, where the body's systems will adapt and disregard an erred or unhelpful sensory signal.[3] Understanding such adaptation becomes particularly important in the event of disease or sensory disorders, and therefore unveiling the mechanisms underlying this adaptation is a topic of interest.

As we age, our senses deteriorate, which affects our ability to respond and adapt to ongoing stimuli.[4,5,6,7,8,9,10,11,12,13] A study done by Miwa et al[8] using aging rats to evaluate the activity of muscle spindles showed a decrease in their sensitivity with age.[8] This was found to be due to the increase in collagen around the spindles, causing them to be less receptive to stimuli.[8] These changes negatively affected muscle spindle function and central nervous system processing, which was concluded to result in deficits in balance.[8] Another study done by Burke et al[9] analyzed the patellar tendon reflex in aging adults, and found a deterioration in muscle spindle presynaptic inhibition pathways, which was correlated with a deficit in movement preparation and execution.[9] They explained that this could contribute to movement problems in the elderly population.[9] Adaptation, as mentioned above, is one mechanism by which the nervous system can change how it uses and processes sensory information in overcoming problems associated with aging. If the pathways or centers involved in adaptation have lost their sensitivity to stimuli, this might hinder the adaptation that needs to take place to maintain proper functioning. Therefore, it can be hypothesized that the adaptation that should take place to allow normal functioning might also be affected by aging.

The mechanisms underlying the deterioration of our senses and how they affect our ability to respond to postural disturbances are not well understood. In addition, the mechanisms that adapt to overcome unhelpful or erred stimuli are also not well understood. However, identifying the mechanisms of sensory adaptation affecting postural control may be key to understanding the changes that occur with aging, which are essential in understanding how to reduce fall risk in the elderly.

Literary Review

The importance of fall prevention

Fall prevention is a critical concern in the elderly because falls can have severe long-term or fatal consequences. This concern is being exacerbated by the increasing elderly population, in which people aged 60 years and over are expected to account for 20% of the world's population by 2050.[14] Fall-related hospitalization of people aged 60 years and over occurs at a rate of 1.6 to 8.9 per 10,000 people, and fall-related fatalities in this group account for up to 40% of all injury-related deaths.[15] In addition to injury, fall-related disruption of gait can also severely impair independence thus decreasing quality of life if autonomy cannot be maintained.[16] Given the frequency of falls and their consequences, understanding the mechanisms of falling, to better prevent them, and ensure a positive quality of life is important.

Falls often occur as a result of a suddenly imposed disturbance, whether it be from an unanticipated obstacle, movement of the supporting surface, or surrounding events.[17] To prevent a fall, a person's muscles must contract rapidly to counter the disturbance and keep the body in an upright position. The act of retaining an upright posture can be described as balancing and the coordination of muscle activity in response to a disturbance to balance, or lack thereof, will often determine if someone will fall. A better understanding of the mechanisms underlying balance, and how they change with age, could lead to increased efficacy of interventions aimed at improving balance and a reduced likelihood of falls. Currently, researchers use several different 'model' disturbances to investigate the mechanisms that contribute to balance control.

Models to evaluate balance

Having an appropriate model to investigate the mechanisms underlying the compensatory response to a balance disturbance is key to understanding balance control. One such model is a slip-initiated disturbance from which we can analyze compensation strategies.[18] By analyzing the muscle response, or muscle activation latency, resulting from an induced slip, it becomes possible to learn about the recovery strategy through observation of the muscular response.[18] The challenge with a slip-initiated postural disturbance, however, is concealing when the stimulus will occur, as most falls are unpredictable and could be easily compensated for if advanced knowledge is available. A fall recovery is normally engaged once the body has begun to lose balance and the recovery itself can be considered a dynamic task. To better understand the mechanisms underlying a dynamic response to a fall, the setting should be similar to the real event, and thus take place in a dynamic environment. The results from a static test can be difficult to relate to a response in a dynamic environment.

Another model for studying balance recovery is a lean and release. During a lean and release, a research participant in a harness is tethered to the wall behind them. The tether allows the patient to lean forward so that their center of mass is past their toes. When the cable is released, the patient is forced to take a step to recover, otherwise they will fall.[19,20] To understand the mechanisms contributing to the balance recovery following a lean and release, the kinematics of the compensatory step and the muscle activity are often recorded.[19,20] The benefit of this type of balance disturbance is that it can resemble the circumstances that precede a real-life fall, but it does so in a safe environment. A limitation of this type of balance disturbance model is that it does little to reveal the mechanisms underlying real-time balance control during a dynamic movement, such as walking. A dynamic environment would provide more accurate information in the body's response to a fall, which can be translated to a real-life setting.

Falls often occur during walking[21,22] and therefore balance disturbance models that incorporate gait are particularly important to understanding these types of falls. Specifically, treadmill walking has been used successfully to analyze walking biomechanics.[1,2,3] The addition of some form of sensory-derived disturbance to treadmill walking has allowed further investigation into the sensory mechanisms that contribute to balance control during walking.[1,2] One specific way to probe these sensory mechanisms is by inducing a small sensory error and examining how the body responds to it throughout the gait cycle. The vestibular system can be easily probed in this manner by applying a small electric current behind the ears to stimulate the vestibular nerve and then the behavioral impact on the body can be measured. Below, I review vestibular anatomy and physiology to lead into a discussion of recent improvements in vestibular stimulation methods and how they have allowed investigation into the vestibular systems' role in balance control during walking.

Vestibular System

The vestibular system is responsible for relaying information about the head and body's position in space to the brain, and it is often thought of as our balance system.[23] Information from the vestibular system is combined with sensory information from senses, such as sight and touch[24,25,26] , which, in the event of a disturbance, the brain uses to generate an appropriate compensatory response to a postural disturbance.[23] The vestibular end organs are found in the inner ear and are comprised of the otolith organs, which detect head tilt relative to gravity and acceleration[27,28], and the semicircular canals, which detect head angular motion.[28] Each of these end organs is lined with hair cells and nerves that receive and transmit ongoing sensory information about our motion and orientation relative to gravity.[24,25] During natural head motion, the end organs' hair cells are bent, and depending on the direction of the head and consequently the direction of the hair cells' bend, can depolarize or hyperpolarize the associated vestibular afferents which informs the brain of the direction of the head motion.[27,28] Importantly, such motion can also be partially simulated by electric stimulation of the vestibular nerves. This process, called *galvanic vestibular stimulation*, involves electric current being sent to the vestibular nerve through pads placed bilaterally over the mastoid processes.[24] By changing the polarity of the current flow stimulating the vestibular nerves, it is possible to induce a sensory error that results in postural sway and this sway can be used to better understand the body's response to a vestibular derived balance disturbance.[24]

Galvanic vestibular stimulation (GVS)

Galvanic vestibular stimulation is often used as a means to probe and analyze the vestibular influence on gait and balance. GVS is the process of delivering a small electric current bilaterally to the mastoid processes behind each ear that alters the firing rate of the nearby vestibular nerves. A cathodal current increases the vestibular nerve's firing rate whereas an anodal current decreases the vestibular nerve firing rate.[29] Importantly, these changes in firing rate are not consistent across vestibular afferents, as it seems irregularly firing vestibular afferents are affected to a greater degree than regularly firing vestibular afferents by the electrical current.[18] The overall response to changing vestibular afferent firing rate in this way is to cause a compensatory sway response toward the anode electrode side.[29] The sway response is caused by a whole-body muscle response thought to correct for the perceived body motion caused by the stimulus.[29] A major benefit of GVS is that it is thought to be a relatively isolated probe of the vestibular system, without other inputs being disturbed.[30] It is therefore believed that the isolated vestibular error signal, caused by the stimulus, is at least partially interpreted as a disturbance to posture that must be corrected for, resulting in the observed postural response. Such postural responses can then be interpreted as a direct consequence of the vestibular stimulation. Importantly, this stimulation can also be applied during a dynamic task, thus permitting inspection of balance correction during movement. While GVS is an isolated probe of the vestibular system, interpreting the signals arising from the vestibular system depends on knowledge of the orientation of the head in space and on the body, and therefore controlling head orientation is an important component of using this stimulus.

GVS and Head Orientation

The vestibular end organs are fixed in the skull, and therefore the information they encode is in relation to the skull's orientation to the body and gravity. The head's orientation relative to the body is therefore an important consideration when responding to a balance disturbance, as it will influence how the vestibular system encodes and responds to a disturbance. [30,31] In fact, the position of the head with respect to the body determines the direction of the vestibular derived postural responses.[32] For example, if a disturbance causes a head motion directed towards the left, it will result in an efferent muscle response aimed at directing the body to the right.[33] If the head is turned 90° to the right however, the same disturbance would result in a backward correction.[33] When delivering GVS in a binaural bipolar electrode configuration with the head facing forward and the nose tilted upward 18° from the horizontal, the postural response to the stimulus is largely restricted to the frontal plane.[25,34] Because the stimulus activates afferents from all vestibular end organs, when their activity is summed, and asymmetries in the semicircular canals and the otolith organs are considered, a bipolar binaural electric stimulus will result in a vestibular signal largely comprised of roll around a posteriorly directed vector angled 18° up from Reid's plane.[30] Therefore, by tilting the head and nose up by 18° from the horizontal, the postural response is largely restricted to the frontal plane. To aid in constraining motion to this plane, researchers also often monitor head orientation by attaching a laser to the head, fastened by an elastic band, and asking participants to point the laser beam at a point on the wall in front of them during testing.[35] Deviation from this position will change the direction of the postural response due to its craniocentric nature and introduce variability within and between research participants. In addition, vestibular responses also vary depending on the task at hand and the muscles involved in balance control. Consistency between tasks and muscles evaluated must be achieved in order to properly compare results and state conclusions.

Variability in GVS Responses

The size of the response to GVS also appears to relate to the degree of instability of posture.[35,36,37] More specifically, when the body is stable, GVS has little effect on posture. However, when the body is unstable, like standing on a soft surface, the size of the response to GVS is much larger.[36,37] This behavior can also be observed at the muscular level, where muscles seemingly engaged in the act of balance control will respond to GVS whereas muscles not involved in balance control tend not to. For example, if the hand is used to maintain balance, responses will be observed in the muscles of the arm.[37,38,39] Specifically, responses in the supporting triceps brachii muscle can be observed when subjects hold a handle for stability during the vestibular stimulation.[37] The size of this response depends on the orientation of the head relative to the body, with the largest responses visible when the disturbance caused by the stimulus aligns with the plane of action of the muscle.[37] A response is also observed when only one arm is active in maintaining balance by light touch or grip.[38] The muscle response is therefore dependent on head orientation and the type of grip (no grip, slight touch, full grip).[38] The observation that arm movements can be part of the whole-body response to vestibular stimulation demonstrate that responses to the vestibular stimulus are task-dependant.[37,38,39] In addition, variation in responses is not restricted to interlimb differences, responses can also differ within a limb between muscles with similar function.[40]

Although muscles with similar functions might be expected to respond to GVS the same way, variation still exists. Recently, the response to GVS was examined in two muscles in the lower leg with seemingly similar function: plantar flexion.[40] Even though these muscles superficially appear to have similar functions during standing, the medial gastrocnemius is more responsive to the vestibular stimulus than the soleus.[40] The reason for this may lie in their anatomical and physiological differences.[40] The soleus has a very large cross-sectional area and is said to be more continuously active during standing.[40] In contrast, the gastrocnemius has a much smaller cross-sectional area, and is more phasically active during standing, providing only small corrections on demand.[40] In addition to these behavioral differences, the soleus also has much higher spindle density, which could mean muscle spindle feedback provides a higher proportion of sensory input to this muscle, potentially making it less receptive to other sensory inputs compared to the medial gastrocnemius.[40] Functionally, the larger response in the medial gastrocnemius may reflect greater inclination to contribute to dynamic balance control compared to the soleus.[40] Even though these differences were observed during standing, similar differences might also be present during more dynamic tasks such as walking.

Dynamic balance control

The size of vestibular induced muscle responses observed during walking depends on the muscle, phase of the gait cycle, and the cadence.[1] For example, muscle responses observed at the ankle are only correlated to the stimulus before and during stance whereas muscle responses at the knee and hip are present periodically throughout the gait cycle.[1] In general, the vestibular signals' influence on posture during gait is present over the duration of the gait cycle, but its local influence depends on the muscle examined.[1] The largest response is seen early in the stance phase, which corresponds to the highest postural deviation from the stimulus, seen at heel strike.[1] Stabilization of the body during a dynamic task involves many factors, such as muscles analyzed, type of stimulation and task at hand.[41] The amount of stabilization is dependent on the need of the body to correct for changes in balance, which depends on the specific situation and the need for compensations.[41] In order to compare results to a real fall-recovery, the stimulation and task at hand must be as closely related as possible.

Stochastic Vestibular Stimulation

Typically, GVS is delivered using a step or square wave stimulus. Extracting the behavior seen through the vestibular responses is difficult with these transient stimuli due to the need to average over many precisely timed instances of stimulation. Recently however, the use of a random waveform stimulus has become popular. Stochastic vestibular stimulation (SVS) is a branch of GVS in which the stimulus has a random amplitude and is continuously sent to avoid anticipatory behavior by the participant.[1,33,34,42,43] Because the responses from GVS are rather small, many trials are averaged to get a clear and precise response.[2] SVS has been shown to produce similar responses as GVS, but in less time and with potentially less postural disturbance.[2] One important use of SVS is to extract vestibular influence during cyclic tasks, such as walking, because this method allows efficient data collection with resolution sufficient to visualize how vestibular influence changes over the gait cycle.[2] This method was used to examine the aforementioned muscles' responses in the leg during walking that found that much of the influence of the vestibular stimulus occurred during the extension phase of gait.[2] Because of this stimulus' ability to show time varying behaviors, it can be a useful tool for investigating repeatable muscular responses correlated to vestibular influence. These responses vary between muscles, between limbs and under certain contexts.

Variation in Muscle Response Throughout the Body

Muscles exhibit different responses based on their placement in the body and their line of action. Some muscles are responsible for generating the force and torque behind movement and muscle patterns, while others are responsible for correcting slight postural disturbances during tasks.[44] The muscular responses are always dependant on the task and the muscle analyzed, as mentioned earlier.[1,35,36,37,38,39,40,41] Muscles can therefore be sensitive to receiving ongoing stimulus from the environment and their respective proprioceptors to generate movements accordingly, while different muscles can be more sensitive to feedback in maintaining a homeostatic and stable environment. A muscle's response is dependent upon many factors, such as the task at hand, the type of stimulation and the disturbance setting.[45,46] A study done by Carpenter et al[45] analyzed muscular responses when participants where subject to balance disturbances and concluded that different trunk, hip and lower leg muscles respond at different times throughout the task depending on the specific disturbance, and at different angles from the original feedback sent to the muscle.[45] This suggests the muscular response is varied based on the direction of the disturbance.[45]

Some muscles may be more sensitive to respond to vestibular disturbance, while others may be more sensitive to respond to visual or somatosensory disturbances.[46,47] A study done by Porras et al[46] evaluated muscular responses to visual stimuli sent to induce a balance disturbance.[46] They concluded that vision plays an important role in balance, shown by a longer response when various visual stimulation settings were applied.[46] The role vision plays however is dependent on each person, as some may rely on it more than others, depending on how much weight their higher brain orders place on the incoming stimulus.[46,48] A fall recovery situation where the visual system is heavily relied upon might prioritize the hip and trunk musculature to get in proper positioning.[46] These muscles are also involved in other situations, but their involvement in visual stimulus-driven falls helps in gaining knowledge on how the fall recovery is processed and prepared. This shows that along with variations throughout the body's muscular response, there can be variations in response depending on the type of stimulation received by the brain's processing centers. A different setting can induce a different response, and each one analyzed can bring its own set of conclusions and further questioning.

The complexity to which the body must respond when correcting for a postural disturbance has been documented.[45,46,49,50,51] For example, the postural trunk muscles are numerous and must work syngerstically with many other muscles to respond as efficiently to a balance disturbance as possible, to attempt to keep the body in an upright position during stance and various dynamic tasks. The muscles that have been analyzed during balance recovery tasks in studies looking at co-activation are the erector spinae bilaterally, the internal oblique and external oblique bilaterally, the rectus abdominus, the gluteus medius, the soleus, the paraspinal muscles, the tibialis anterior, the medial deltoid, the lateral gastrocnemius, the medial gastrocnemius, the rectus femoris and the biceps femoris.[41,45,46,49,50] Balance is a task that requires the entire body to be engaged through the collective work of many muscles, and this is why many muscles have been investigated. [45,46,49,50] Some muscles will be more inclined to respond to certain stimuli or tasks. Each muscle has its role and needs to be activated correctly to allow the task or fall recovery to be successful. It has been documented that spinal muscles, specifically, are directly related to the muscular responses needed to maintain balance in response to vestibular stimulation.[41] The implication of lower leg muscles in balance has been documented as task specific, and therefore is highly variable.[41] There are many aspects of fall recovery that still need to be evaluated to understand how all these variations occur.

Understanding the relationship and respective responses of the muscles and how they work together could help in the overall understanding of the mechanisms involved in fall prevention. Muscles respond to external disturbances based on their anatomical and physiological properties.[40] For example, the angle at which the muscle is oriented, the number of fibers per muscle, and the type of receptors in the muscle, all render the muscle a unique function, and this varies for each muscle across the body.[40] As fall prevention becomes more common with the growing elderly population, it would be beneficial to understand how specific muscles respond to different types of disturbances, in order to train muscles accordingly. It could also be beneficial to understand how these muscles' responses change throughout a particular task and if they can adapt to compensate for errors in signalling or information processing.

Adaptation to galvanic stimulation

Often during periods of erred signals, the central nervous system can tune out or lower the weight it places on the erred signal when planning movement or making decisions. Such a 'tuning out' can be a particularly important mechanism for overcoming problems or deterioration of our senses, particularly in certain situations. A loss of precision of the information provided by the senses can accompany aging, which may play a role in the increased risk of falls seen with advanced age.[7,8,9,10,11,17,14,15] The vestibular system is no exception to this behavior. During periods of prolonged vestibular stimulation, the body can adapt and reduce the size of its response to it [3]

Vestibular adaptation or attenuation during prolonged stimulation appears to be task-dependent.[52,53] When participants are subject to random waveform GVS over a period of time, there is an initial period of rapid attenuation followed by further attenuation that appears to be associated with walking.[53,54] Of the studies that have examined this attenuation over time[52,53,54], the most recent inferred this behavior by observing the forces at the feet.[3] Generally, the forces at the feet are thought to represent the sum of all of the muscle responses throughout the body. One might infer that a muscles' behavior should be similar to the force response, however, as I have discussed, this is not necessarily true. Here, my aim is to determine whether muscles in the lower leg exhibit response attenuation over time similarly to the whole-body force response.

Significance of research question

Understanding how our body adapts to prolonged stimulation is essential to determining the clinical effectiveness of such stimulation. When it comes to the growing concern of the impact of falls on our population, having more precise information on the mechanisms and pathways involved in balance control could be very beneficial. Previous research has demonstrated that the full body response to GVS indeed adapts overtime. It is possible that specific muscle responses to the GVS also adapt over time, but this is not certain. Because the full body response is the sum of all muscle activities, not all muscles need to follow the same trend.

Hypothesis:

Here, I investigate whether lower limb muscle responses to GVS decrease overtime, as is observed in the whole-body force responses. I hypothesize that vestibular responses measured in the medial gastrocnemius and soleus muscles will decrease over an hour of walking with stimulation.

Methods

Participants: Fifteen healthy participants were recruited from the local university. The institutional review board of the university approved this study protocol.[1,2] All participants were screened for any known neurological disease or past injury.[1,2] Participants were provided informed written consent prior to their participation in this study.

Protocol: Participants were screened for physical capability using a Physical Activity Readiness Questionnaire (PAR-Q) and a GVS Pre-Screening Questionnaire prior to participation. During the experiment, participants were asked to walk for six 10-minute periods on a treadmill with stimulation to determine whether vestibular responses in the muscles decrease over time.

Set-up: Once screening is completed, a wireless force transducer (Delsys Trigno, Natick, MA, USA) was placed on participant's left heel to record foot contact during each stride. After placing the force transducer, two conductive carbon rubber electrodes (3.8 cm x 4.4 cm, Covidien Uni-patch, Dublin, IE), coated with a conductive gel, were placed bilaterally over participants' mastoid processes. The electrodes pass the electric stimulus, which was generated in Labview, from the stimulator (Biopac Systems, Inc, Goleta, CA, USA) to the vestibular nerves. During data collection participants were asked to stay looking at a dot on the wall in front of them in order to reduce head motion. Two stickers were also placed on the left side of participants faces; one at the corner of the eye and another above the ear, 18 degrees up from Reid's plane. During trials, participants received feedback to keep their nose tilted up to keep the line intersecting the stickers horizontal to the ground. By keeping the head in this orientation, the postural response to GVS was restricted to the frontal plane. Electromyographic electrodes were placed on the soleus and medial gastrocnemius of the left leg. Prior to electrode placement, the sites were shaved and cleaned with rubbing alcohol.

Prior to data collection, participants were provided the opportunity to experience the stimulus. Each participant was provided 2 seconds of stimulation with a peak amplitude of 3mA and 2 additional seconds of stimulation with a peak amplitude of 5mA. If they were willing to continue, the experiment proceeded.

Electromyography (EMG) readings: EMG sensors were placed on the muscle belly of the medial gastrocnemius and the soleus of the left leg for each participant. EMG was sampled at a frequency of 2000Hz and bandpass filtered offline between 25-500Hz. Filtering is used to reduce the noise that can enter the EMG recordings, either from nearby muscles' activity or movement of the skin under the EMG pad.

Stimulus: During data collection participants were provided a bandwidth limited 0-25Hz random noise peaking at 5mA. Stimuli was generated by low-pass filtering a white noise signal using a 4^{th} order Butterworth filter, with cut-off of 25Hz. The signal was then be rescaled to 5mA.

Data Collection: During data collection, participants walked on the back force-plate of a two force-plate instrumented treadmill arranged in series as there is a small space between force plates that might interfere with walking over time. During each of the six 10-minute walking periods, participants walked at a metronome synchronized cadence of 76 bpm. This cadence has been used before to measure vestibular response to GVS during walking.[1,2,55] To determine if vestibular responses decrease over time, I compared the size of responses in the first 10-minute period to the last 10-minute period.[1,2,55]

Data Analysis: To determine whether vestibular evoked muscle responses decrease over time, I measured the coherence and gain between the GVS signal and the muscles' electromyographic responses. Coherence quantifies the linear relationship between two signals where a perfect linear relationship has a coherence of one and a coherence of zero indicates no linear relationship. Gain is used to assess the scaling of the output muscle activity relative to the GVS. A gain greater than one indicates that the amplitude of the electromyographic signal is greater than the GVS signal. Using these measures, I expected a decrease in vestibular influence over time to present as a decrease in both coherence and gain.

To calculate gain and coherence, the stimulus and muscle data was first cut into strides based on the left heel strike as identified using the force sensitive resistor. Each stride was padded with an additional 25% of data from the stride preceding and following the stride to prevent distortion at the edges of the stride. Stride data was then converted to the frequency domain using a Morlet wavelet transform using a modified version of the method outlined by Zhan.[56] To account for differences in the length of each stride, the auto and cross spectra of the stride lengths was interpolated to each participants' average stride length. Coherence and gain for each step were then averaged within each subject to provide a single time-frequency representation of the muscles' behavior over the stride cycle.

Statistical Comparison: Coherence and gain were compared between the start and end of walking using a bootstrapping procedure. First, fifteen subjects were drawn randomly with replacement from the first 10-minutes of walking and the last 10-minutes of walking. I then took the mean of these bootstrapped samples and then subtracted the mean for the first 10-minutes from the mean of the last 10-minutes. This process was repeated 10,000 times to generate a difference of means distribution. The difference of means distribution was then ordered and the 95% confidence interval determined by taking the 250th and 9750th datapoint. Regions in the coherence and gain in which the 95% confidence interval excludes zero were deemed statistically different from each other.

Results

The results from our study are shown below in Table 1. The medial gastrocnemius did not see a significant change in coherence or gain between the first 10 minutes of walking and the last 10 minutes of walking (Table 1). The soleus saw a slightly larger difference in coherence and gain between the first 10 minutes of walking and the last 10 minutes of walking (Table 1). The significance of these findings is discussed below.

Table 1: Medial gastrocnemius and soleus coherence and gain values

				Maximum	Time (%)	Frequency (Hz)
Medial gastrocnemius	**Coherence**					
		First 10 min	Mean	0.1347	27.3629	5.6602
			Standard Deviation	0.0671	12.6435	1.365
		Last 10 min	Mean	0.142	34.6162	5.4141
			Standard Deviation	0.0781	13.0178	0.5655
	Gain mV/V		Mean	0.0138	19.3671	3.7916
		First 10 min	Standard Deviation	0.0085	12.0664	1.9759
			Mean	0.0106	23.6383	3.8704
		Last 10 min	Standard Deviation	0.0084	7.8208	1.6659
Soleus	**Coherence**					
		First 10 min	Mean	0.0829	35.2321	5.0061
			Standard Deviation	0.0448	23.8105	2.1236
		Last 10 min	Mean	0.0668	39.2639	6.0723
			Standard Deviation	0.0519	23.0598	5.0697
	Gain mV/V		Mean	0.0048	50.7384	6.2029
		First 10 min	Standard Deviation	0.0034	38.4013	8.3045
			Mean	0.0029	64.8791	7.4734
		Last 10 min	Standard Deviation	0.0016	33.0432	9.3491

Table 1: The results of the coherence and gain measurements for the first and last 10 minutes, for the medial gastrocnemius and soleus muscles. The maximum values and their standard deviations, the time (%) it occurred in the gait cycle, at the frequency at which it occurred.

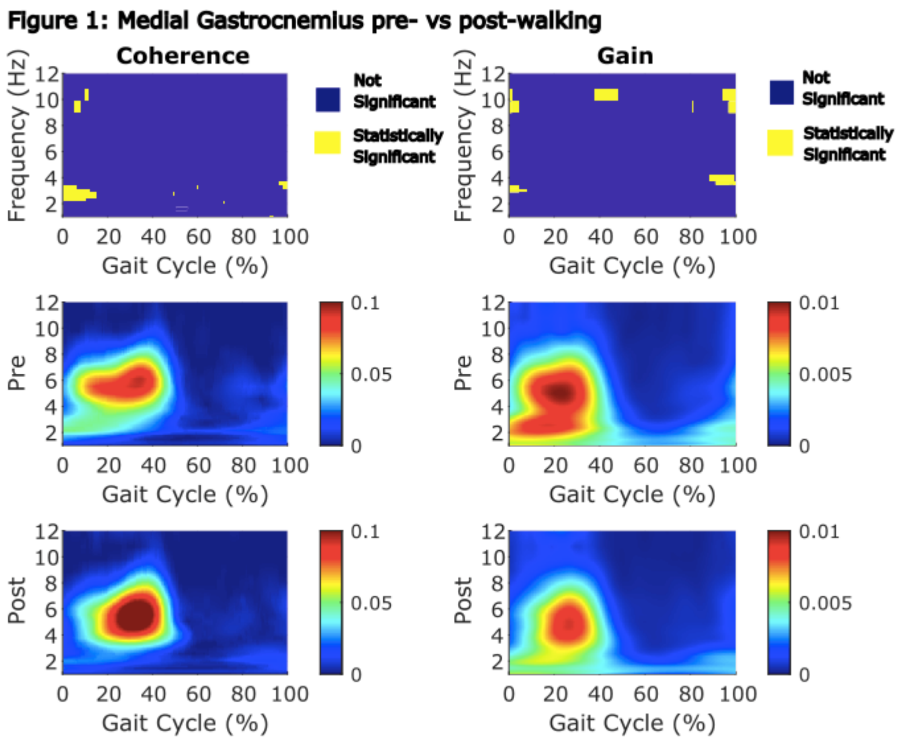

Figure 1: The muscle activity for the medial gastrocnemius muscle in the first 10 minutes (Pre) and the last 10 minutes (Post), with significance shown in yellow of the top two graphs.

The medial gastrocnemius did not experience a broad change in coherence and gain between the first and last 10 minutes of walking. Coherence and gain showed small regions of statistical differences at the beginning and end of the gait cycle, where Figure 1 (top row) is yellow. The coherence peaks at around 30% of the gait cycle. The gain peaks first at around 20% of the gait cycle, then a little at 90% of the gait cycle. The mean peak coherence in the first 10 minutes was 0.14+/- 0.07, occurring at 27.36 +/- 12.64 percent of the gait cycle, at a frequency of 5.66 +/- 1.37 Hz. The mean peak coherence in the last 10 minutes was 0.14 +/- 0.08, occurring at 34.62 +/- 13.02 percent of the gait cycle, at a frequency of 5.41 +/- 0.57 Hz. The mean gain in the first 10 minutes was of 0.01 +/- 0.01 mV/V, occurring at 19.37 +/- 12.07 percent of the gait cycle, at a frequency of 3.79 +/- 1.98 Hz. The mean gain in the last 10 minutes was of 0.01 +/- 0.01 mV/V, occurring at 23.634 +/- 7.82 percent of the gait cycle, at a frequency of 3.87 +/- 1.67 Hz. As shown by Figure 1, there is a small statistically significant difference in coherence and gain at the beginning and the end of the gait cycle, where there is yellow on the top graph.

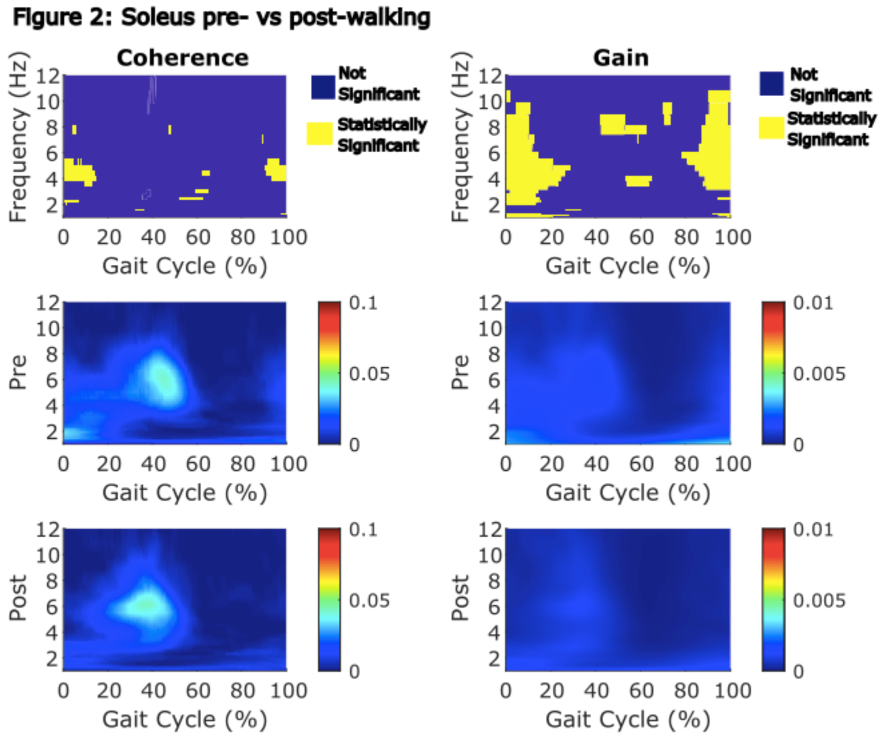

Figure 2: The muscle activity for the soleus muscle in the first 10 minutes (Pre) and the last 10 minutes (Post), with significance shown in yellow of the top two graphs.

There was a small change in gain and a slight change in coherence for the soleus muscle between the first 10 minutes of walking and the last 10 minutes of walking, though not in the region of greatest coherence. The coherence peaked at approximately 40% of the gait cycle. The gain peaked at around 35% of the gait cycle. The mean coherence in the first 10 minutes was 0.08 +/- 0.04, occurring at 35.23 +/- 23.81 percent of the gait cycle, at a frequency of 5.01Hz +/- 2.12. The mean coherence in the last 10 minutes was 0.07 +/- 0.05, occurring at 39.26 +/- 23.06 percent of the gait cycle, at a frequency of 6.07Hz +/- 5.07. The mean gain in the first 10 minutes was of 0.005 +/- 0.003 mV/V, occurring at 50.74 +/- 38.40 percent into the gait cycle, at a frequency of 6.20 +/- 8.30 Hz. The mean gain in the last 10 minutes was of 0.003 +/- 0.002 mV/V, occurring at 64.88 +/- 33.04 percent of the gait cycle, at a frequency of 7.47+/- 9.35 Hz. As shown by Figure 2, there is a statistically significant difference in coherence and gain at the beginning and the end of the gait cycle, where there is yellow on the graph.

Discussion

The primary aim of this study was to determine if there is any adaptation to GVS in lower leg muscle activity during walking. I analyzed the medial gastrocnemius and the soleus muscles of the left leg. My goal was to gain more knowledge on the mechanisms that act to adapt to external disturbances applied to the moving body. As a general representation from the figures, there was a greater significant difference between the pre-post gain than coherence, particularly in the soleus muscle. This means that there was a greater output muscle activity per unit of input of vestibular stimulation, but the proportion of vestibular correlated muscle activity relative to other sources of activity did not change. The areas of the graph that show a statistical difference were not, however, the regions with the greatest coherence. The only significant finding of this study was a difference in gain near heel contact for the soleus muscle, whose muscular response was generally less correlated to the vestibular stimulus. Overall, these results suggest that adaptation to the stimulus is not necessarily evenly represented across all muscles, in this setting, and that further investigation is necessary.

Previous investigations have found that vestibular stimulation produces a whole-body response, and that this whole body response, measured by analyzing the forces at the feet, decreases over time.[3,57] Hannan et al.[3] studied the change in forces at the feet in relation to the application of galvanic vestibular stimulation.[3] They found that there was a decrease in the postural response evoked by the vestibular stimulus over time during standing and walking.[3] The decreased response observed during walking did not transfer to standing, and so habituation to the stimulus was proposed to be task-dependent. Similarly, Johansson et al in 1995[57], demonstrated that the whole-body response to a galvanic vestibular stimulation during a static stance exercise exhibits adaptation during standing.[57] Their hypothesis was that the neural feedback systems in the brain sense the signal as being erroneous, and therefore the brain reduces the weight attributed to it and its influence on the body therefore decreases.[57]

Our study found that the muscular response to vestibular stimulation generally did not undergo substantial changes over time. The lack of adaptation in this specific setting is important because it suggests that individual muscles may not behave in a manner similar to the whole-body response observed in the forces at the feet during walking trials of one hour, contradicting our hypothesis. Because my results do not align with previous studies, further investigation is necessary to better determine where the adaptation observed in the forces at the feet might be originating from and the mechanisms underlying it. Based on these results, it is possible the change in force seen in the previous studies does not come from the soleus or the medial gastrocnemius muscles. The lack of adaptation might be due to the physiological and anatomical properties of the soleus and medial gastrocnemius muscles. As stated earlier, the soleus muscle may be more responsible for producing a baseline force for dynamic tasks.[40] Its high muscle spindle density makes it more receptive to stretch feedback from its muscle fibers, and therefore may be less receptive to vestibular stimuli.[40]

As far as we know, there is not much evidence to support a lack of adaptation in the medial gastrocnemius and the soleus muscles in response to galvanic vestibular stimulation during a one-hour walking task. This study is one of the first to look at adaptation over a period longer than 15 minutes, and this could be a reason. Previous experiments looking at adaptation to galvanic vestibular stimulation either noted a decrease in sway in the first 40s of a sinusoidal stimulation[52] or adaptation in response to a 10 minute noisy stimulus while performing various dynamic tasks[54]. Perhaps the adaptation is more dependent on the task performed.[3,53] The brain can learn from ongoing stimulus and decrease its response to erred stimuli, in order to maintain its normal functioning.[58,59] More research needs to be done to better understand the long term mechanisms involved in adaptation, and where this adaptation is controlled from.

The absence of adaptation in the soleus and gastrocnemius raises several questions. Perhaps the medial gastrocnemius and soleus might be more sensitive to other aspects of balance, as opposed to GVS stimulus. Other factors related to balance may affect the medial gastrocnemius and soleus muscles more than the stimulus. For example, they might be more sensitive to visual or somatosensory disturbances, more than vestibular inputs, as seen in other studies discussed earlier. The study done by Porras et al.[46] found that muscles' responses to a visual postural disturbance results in a direction-specific correction.[46] They also found that through the use of visual stimulation, the muscular responses are organized accordingly to the task at hand.[46] The best way to facilitate adaptation might be to use other types of stimulation, which could facilitate visualizing stimulus-specific adaptations. Perhaps the medial gastrocnemius and soleus muscles would exhibit greater muscular response attenuation through the use of a different stimulation type than GVS. Alternatively, perhaps the whole-body response produces an attenuation that is clear because certain muscles in the trunk and pelvis girdle have a larger affinity and responsiveness to vestibular cues than other muscles, perhaps in the lower limb, and this results in the net change in forces at the feet.[41] For most muscles examined by Porras et al., the left paraspinal muscles especially had a greater magnitude of muscle activation during a trial where visual perturbations were applied.[46] Thus, maybe trunk muscles contributing to core balance and force transfer exhibit most of the attenuation. Similarly, neck muscles that are responsible for head movements may be more sensitive to sensory stimulus and therefore adapt to it to reduce head variability for eye fixation.[41] The attenuation in muscular response does not seem to be consistent across situations. It therefore becomes difficult to classify some muscles as having specific roles, since these roles can change depending on the dynamic task they are performing.[41]

Of the regions known to contribute to adaptation, the cerebellum appears to be one of the most frequently associated. The cerebellum plays a role in adaptation to ongoing surrounding events, and in particular, adapting to an errors between a movement prediction and its associated sensory return.[58,59] This suggests that the cerebellum's role might be diminished in unanticipated reflexive and reactive actions associated with responses to suddenly imposed disturbances due to their lack of predictive component.[58,59] However, prediction does not appear to be absolutely necessary to observe cerebellar involvement in movement. Patients that cannot predict movements but rather rely on responding to ongoing stimuli, due to neurological deficits, still appear to have cerebellar involvement in their muscle involvement for tasks .[58,59] In the healthy participants used here, it is possible that the cerebellum is involved in the adaptation process, through recognition of the erred sensory signal, which cannot be predicted and recalibrated to. Vestibular signals sent in our study were random, meaning the body could not adapt to or learn from them. It seems plausible that the most effective way to respond to a sense that is unpredictable is to turn down the body's reliance on it. Such a mechanism could also contribute to the aging process if the deterioration of the senses that occurs with aging results in a less reliable or predictable vestibular signal. [4,5,6,7,8,9,10,11,12,13] The reliance on the senses that have become deteriorated would be decreased, and therefore adaptation towards these senses would be hindered. However, such adaptation could also hinder our ability to detect sensitive information due to too much tuning out of what is thought to be an erred signal.

These are all important topics that could lead to a better understanding of how someone maintains their balance and recovers from a fall. If it was concluded that certain muscles are more sensitive or involved in responding to postural disturbances, measuring the strength of these muscles in an elderly person could allow for a tailored rehabilitation plan in fall prevention. Proper strength and conditioning programs for fall prevention and rehabilitation programs could be better constructed to each person's specific deficits in motor control.

Limitations

Our study is limited by the number of muscles analyzed. More information needs to be gathered to further the understanding of balance control. Varied tasks with different types of disturbances should be experimented with. Various types of stimulation should be applied, such as visual or somatosensory stimulation, to determine if the body adapts more to a specific disturbance modality. Various muscles in the trunk need to be assessed to determine if they are more receptive to vestibular stimulation, and more muscles in the legs can be assessed to determine if they are more involved in the adaptation process. Higher brain orders could be examined to determine if they play a role in the tunning out or lowered reliance on certain stimulus in the long term.

Conclusion

Here I attempted to determine if there is habituation in two lower leg muscles. The medial gastrocnemius and the soleus muscles do not follow the decreasing trend observed in the whole-body response over an hour of walking. If adaptation to the stimulus was observed, I would have expected to see a decrease in gain and coherence in the regions with the highest gain and coherence. Instead, differences in gain were observed in only the soleus outside the frequencies and times with the strongest relationship between the stimulus and muscle response. The small statistical difference observed appears insufficient to make a general conclusion about the presence of adaptation in the medial gastrocnemius and soleus muscles. There is no doubt that some muscles must experience adaptation, since the decrease in whole-body response observed is driven by muscular activity. However, more investigation needs to be done to determine which muscles are adapting and why only specific muscles experience adaptation. Better understanding of this adaptive mechanism could be useful to tailoring rehabilitation programs aiming to reduce falls, especially with a growing elderly population and heightened concern of a fall.

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