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The Vestibular Contribution to Balance Control in Older Adults During Locomotion and Stair Negotiation

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THE VESTIBULAR CONTRIBUTION TO BALANCE CONTROL IN OLDER ADULTS DURING LOCOMOTION AND STAIR NEGOTIATION

by

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Abstract

Background: Stability is known to decrease as we age, but currently we know very little about how the body's balance system, the vestibular system, contributes to balance control in older adults, particularly while walking and climbing stairs. The purpose of this study was to take the first step in understanding vestibular contribution to balance control during locomotion and stair negotiation, and how this changes with age.

Methods: Ten young adults and six older adults ascended and descended a nine-step staircase 78 times and walked on a treadmill for 10 minutes to complete a total of 300 complete steps in each condition. During each trial, a small amplitude, random electric current was applied behind the subject's ears to stimulate the nearby vestibular nerve, and surface electromyography was recorded from eight leg muscles. We used time-dependent correlations (coherence) to determine how the vestibular stimulus influences muscle behavior, how this influence is modulated by the phase of the step cycle.

Results: The vestibular stimulus influenced select muscles in a phase-dependent manner over the step cycle in both age groups. In general, in muscles where vestibular influence over the muscle's behavior was apparent in both the older and younger groups, the influence was stronger and longer-lasting in the older adults. Additionally, prominent vestibular influence over a muscle was observed in more muscles in the older group than the younger group.

Conclusions: This offers a first look at the functional contribution of the vestibular system to maintaining balance during locomotion and stair negotiation in older adults. These results suggest that as we age, we may rely more on vestibular signals in order to maintain balance during locomotion and stair negotiation.

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Introduction

Background. Falls are the third most common cause of accidental deaths in the US, rank first for unintentional- injury-related emergency department visits (National Safety Council, 2015), and become more common and more dangerous as we age. Approximately one third of adults over the age of 65 fall at least once each year (Campbell et al, 1981; Prudham and Grimley Evans, 1981), which can lead to fractures or other injuries, changes in lifestyle including loss of independence and reduction of quality of life, and even death (Prudham and Grimley Evans, 1981). Falls are the leading cause of traumatic brain injury (TBI), and adults over the age of 75 have the highest rates of hospitalization and death due to TBI (Taylor et al., 2017). In general, falls down stairs are more severe than falls on level surfaces. Falls down stairs account for 10 percent of fall deaths (Startzell et al, 2000) and are the second leading cause of fall-related TBI (Friedland et al, 2006). The high rates of occurrence and increased severity of falls in older adults are largely due to the fact that our ability to maintain balance significantly declines as we age (Nitz et al, 2002; Isles et al, 2004).

The vestibular system is one of the body's sensory systems and is essential for balance control (Fitzpatrick and Day, 2004). It consists of two groups of organs located in the middle ear that detect changes in linear and angular motion of the head. Information from these organs is used by the brain to infer the motion and orientation of the head in space. Vestibular signals are integrated with visual and proprioceptive information by the brain, and used to control the motion of our head and body in space through carefully orchestrated sequences of muscle activations. The relationship between the vestibular signal and the muscle activity can be observed by probing the vestibular system with electrical stimulation and recording the resulting muscle activity using electromyography (EMG). To probe the vestibular system, an electrical

stimulus is applied to the skin behind each ear where it modulates the firing of the vestibular nerve. The normal response to stimulation in this bipolar configuration is a postural roll toward the anodal electrode (Fitzpatrick and Day, 2004). To reduce the postural disturbance associated with electric vestibular stimulation, researchers often use a random, noisy waveform stimulus. This type of stimulus waveform has the added benefit of facilitating the extraction of the time-varying influence of the vestibular stimulus on muscle activity during repetitive cyclic tasks such as locomotion (Blouin, et al., 2011; Dakin, et al., 2013). The random waveform stimulus is therefore the ideal tool to a) examine how the vestibular system contributes to balance control during stair negotiation, b) identify how the vestibular contribution to balance control changes as we age, and c) identify how changes in the vestibular control of balance might lead to falls.

Two main factors suggest that we may become more reliant on vestibular cues to maintain our balance during stair negotiation as we age. First, vestibular influence on muscular activity is present only when the muscle is engaged in the control of balance, and increases as the muscle contributes more to balance control. Several studies have shown that as the difficulty of the balance task is increased and our stability decreases, vestibular influence becomes more important for balance control (Britton et al, 1993; Fitzpatrick and Day, 2004; Luu et al, 2012). Presumably, with cadence and velocity held constant, vestibular influence during stair negotiation is increased compared to locomotion on a level surface, because it is a more difficult balance task (Nadeau et al, 2003). Second, recent studies have also shown that our reliance on vestibular signals may increase as we age (Welgampola and Colebatch, 2002; Dalton et al, 2014). Together, the increased challenge of maintaining stability during stair negotiation and the increasing reliance on vestibular cues as we age suggests that the vestibular system may have an increasingly important role in maintaining balance during stair negotiation.

Purpose. The purpose of this study was to investigate how muscular responses to vestibular input vary across stair ascent, stair descent, and locomotion, and how this influence changes with age. This study aims to provide a better understanding of the interaction between the vestibular system and muscles involved in balance and how it changes with age. As we understand this relationship better, we may gain insight into mechanisms of falling, and strategies to reduce the occurrence and severity of falls in older adults could be developed.

We hypothesized an increased vestibular influence on muscle action in all populations in the stair negotiation task compared to locomotion on flat ground, as well as an overall increase in the aged population as compared to the young population.

Methods

Subjects. Ten healthy young adults (5 women, 5 men, aged 21 – 28 yr.) and six healthy and mobile older adults (3 women, 3 men, aged 57 – 70 yr.) were recruited by word of mouth and flyer from the Utah State University and Cache Valley populations to participate in this study. Written informed consent was obtained. Procedures were approved by the Utah State University institutional review board (Protocol #7952).

Test Procedures. Each participant ascended and descended a nine-step staircase 78 times in order to complete a total of 300 steps. Cadence was controlled by a metronome set at 76 steps/min. They also walked on a treadmill at a 0.4 m/s velocity and the same cadence for 10 minutes to match the 300 complete steps. This velocity and cadence were chosen to match the methods used in previous studies (Dakin et. al 2013). To avoid fatigue, the participants were offered a minimum of 2 breaks during the testing session, one when half of the stair trials were completed and one in between the stair and treadmill tasks. Snacks and water were offered

during these breaks. In addition, participants were told that they could stop for rest in between trials as needed. For safety, each participant wore a harness with a locking system that allowed them to move freely but would prevent a fall in the event of a loss of balance.

Stimulus. A small amplitude (±5 mA), random waveform electrical current was applied using a binaural bipolar electrode configuration with carbon rubber electrodes (9 cm^2) placed over each mastoid process in order to stimulate the vestibular nerve. Participants were directed to keep their head up and facing forward so that the perturbation induced by the stimulus was restricted to the medio-lateral plane (Fitzpatrick and Day, 2004). Stickers were placed at the upper margin of the external auditory meatus and below the inferior margin of the orbit such that when the head was held 18° nose up, the stickers formed a horizontal line, which was monitored visually by research assistants throughout the testing session. For the stairs task, the stimulus was delivered in 22 second increments, approximately the amount of time it took to complete one ascent and descent of the staircase, while on the treadmill the stimulus was delivered for a period of 600 seconds so that the stimulus was present throughout the entire step cycle for all 300 steps.

Electromyography. A wireless surface electromyography (EMG) system was used to record the electrical activity from eight muscles of the leg: tibialis anterior, medial gastrocnemius, soleus, rectus femoris, vastus medialis, semitendinosus, biceps femoris, and gluteus medius. These muscles were chosen because they span the ankle, knee, and hip joints. A unilateral configuration was used because in cyclical processes like walking or stair climbing, movement can be assumed to be bilaterally symmetrical (Blouin, et al. 2011). The EMG signal was bandpass filtered from 20-450 Hz during collection. Each participant had foot switches fastened beneath the heel and the first metatarsal that were used to estimate the start and end of

each stride, from the moment the toe made contact with the ground to the next point where toe contact occurred.

Signal Analysis. Coherence was calculated to determine the covariance of the applied stimulus and the concurrent activity in the muscles. Coherence is a measure of the relationship between two signals in the frequency domain. It is a linear measure on a scale of zero to one, with zero representing no relationship between the two signals and one representing a linear relationship. In this case, coherence is a measure of how much the vestibular system is influencing muscle activity, with coherence of one meaning vestibular input is the only influence modulating muscle activity, and zero meaning the vestibular system has no effect on the muscle. We computed coherence as a function of time to measure the modulation of the muscle activity due to the applied stimulus over the entirety of the step cycle.

To calculate these measures, first the EMG data were bandpass filtered between 20 and 450 Hz and full wave rectified, then each trial was cut into one step segments, from toe contact to toe contact, and pooled across participants for the stair and treadmill tasks separately. Each stride was padded at the start and end with data from the step preceding and following it (50% from each). Data were then were low-pass filtered and resampled at 200 Hz for data reduction.

Statistical Analysis. Coherence was determined as significant based on a 95% confidence limit based on the number of steps (Halliday 1995). In each subject, the peak coherence was extracted from each muscle to compare coherence between muscles and groups. A group (2: young and old) by muscle (5: soleus, medial gastrocnemius, tibialis anterior, biceps femoris, semitendinosus) by task (3: treadmill, stair ascent, stair descent) mixed model analysis of variance (ANOVA) was used to examine the main effects of and interactions between the within subject variables (the repeated measures muscle and task), and the between subjects variables

(group). Following the ANOVA, because we predicted older adults to have larger responses than young, we used a two sample one-sided t-tests to quantify whether the older group did indeed have increased vestibular influence on each muscle during each task.

Results

We observed several similarities and differences in how vestibular input was used to control balance during stair negotiation and locomotion between the older and younger groups. However, not every muscle exhibited a prominent relationship with the stimulus. In fact, modulation in stimulus coherence with rectus femoris, vastus medialis, and gluteus medius was limited over the step cycle. Because of this, we performed statistical analysis and reported results of only those muscles with prominent changes in coherence, specifically the soleus, medial gastrocnemius, tibialis anterior, biceps femoris, and semitendinosus.

Characteristics of vestibular-muscular interaction

In both groups the vestibular influence was modulated across the step cycle. However, there was no significant main effect for group ($F_{(1,14)} = 2.86$, $p = 0.11$), because differences between groups depend on the task and muscle. Overall, the three-way interaction between these three variables was not significant ($F_{(8,112)} = 2.02$, $p = 0.051$), however there were several two-way interactions.

Between groups, there were similar temporal patterns of high or low coherence in each muscle depending on the phase of the step cycle (Fig. 1). The pattern of activity between muscles varied considerably, and this was reflected by the presence of a significant main effect for muscle ($F_{(4,56)} = 28.31$, $p = 0.000$ * Greenhouse Geisser Adjusted). However, coherence between

the stimulus and a particular muscle also depended on the task, which presented as a significant muscle by task by interaction ($F_{(8,112)} = 5.24$, $p = 0.001$ Greenhouse Geisser Adjusted).

Generally, there was a decrease in peak coherence values during stair descent in both the aged and young populations as compared to the treadmill and stair ascent tasks (Fig. 1), Overall, this common behavior may have contributed to the significant main effect for task ($F_{(2,28)} = 21.95$, $p = 0.000$ * No GG Adjustment), but the effect of task also depended on the group examined ($F_{(2,28)} = 6.90$, $p = 0.004$). For example, during stair descent, stimulus coherence with the tibialis anterior increased in the older group whereas there was no change in the younger group.

To identify muscle specific group differences based on the hypothesis that older adults would exhibit larger coherence than younger adults, we decomposed the main results further using a one-sided t-test. Significantly higher peak coherence was found for older adults than young adults on the treadmill task in the soleus ($t_{(14)} = -1.925$, $p = 0.037$), medial gastrocnemius ($t_{(14)} = -2.05$, $p = 0.03$), tibialis anterior ($t_{(14)} = -2.17$, $p = 0.02$) and biceps femoris ($t_{(14)} = -3.03$, $p = 0.004$). Older adults also exhibited significantly larger coherence in the tibialis anterior during stair ascent ($t_{(14)} = -1.84$, $p = 0.044$) and descent ($t_{(14)} = -2.79$, $p = 0.007$).

Timing of vestibular influence relative to muscle activation

Overall, periods of high coherence with the vestibular signal did not necessarily occur at times when muscle EMG activity was high. For example, in the hamstring muscles (biceps femoris and semitendinosus) during stair ascent, the EMG activity was consistently low, but with a small increase at around 60% of the step cycle. The coherence, however, remained close to zero with a peak appearing at approximately the 40% mark of the step cycle (Fig. 1).

Additionally, while EMG patterns for each muscle were modified by the task, changes in the timing of coherence did not necessarily align with these changes seen in the EMG. This can be seen in the quadriceps muscles, specifically the vastus medialis. Muscle activity was steady and minimal during treadmill walking. During stair ascent, there was one large peak at about 10% of the step cycle with a gradual decline. For stair descent, there was one small peak around 50% of the step cycle. Despite these large changes in when the muscle was most active, there was no noticeable change in the timing of vestibular-vastus medialis coherence between tasks (Fig. 1).

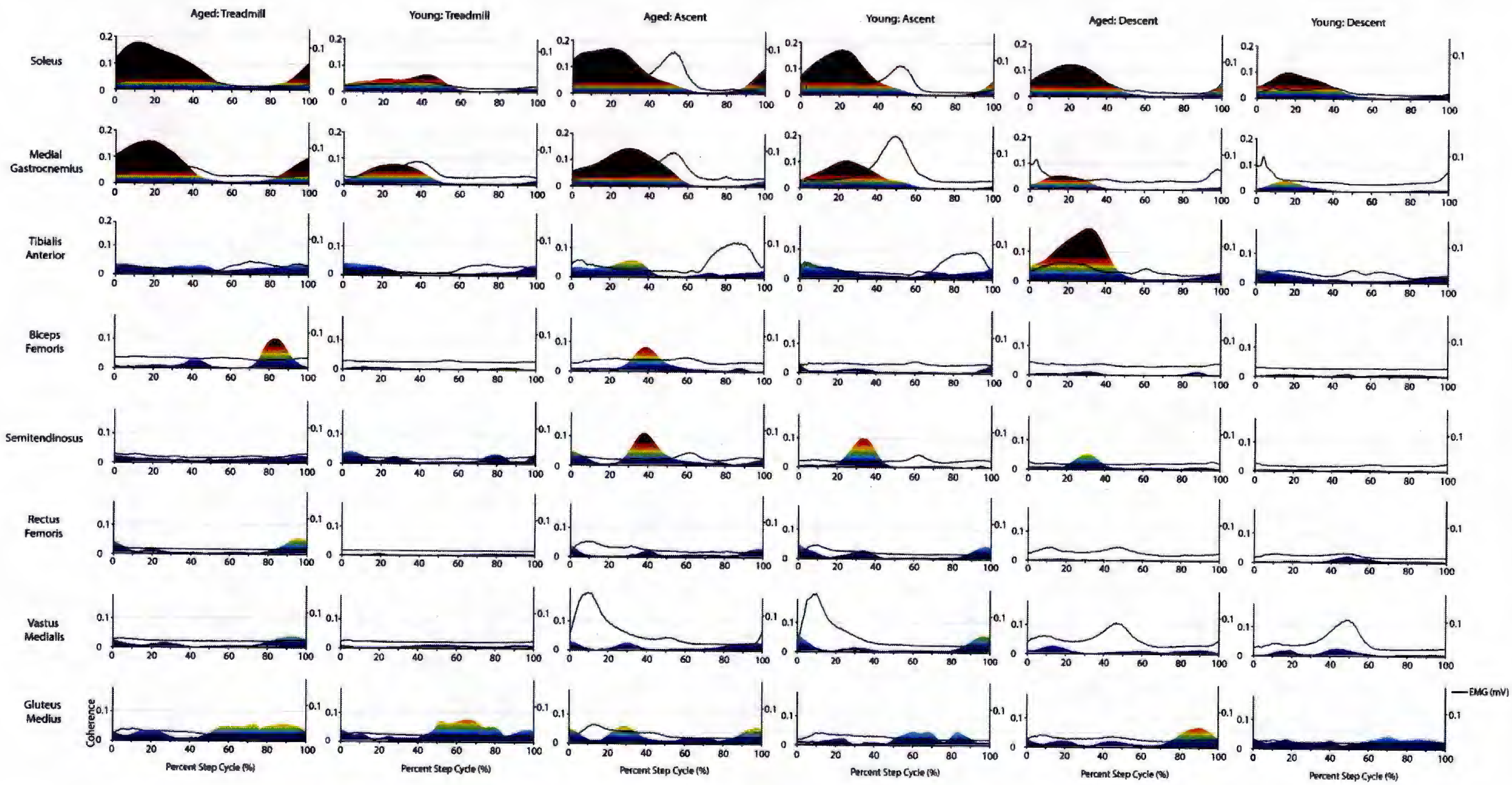

Figure 1 Coherence (colored area) of applied vestibular stimulus and electromyography for each muscle and condition for older adults and young adults. Electromyography of each muscle (black line) is overlaid. Each step cycle is cut from toe contact to next toe contact.

Discussion

Our original hypothesis was that older adults would have an overall greater reliance on vestibular input, characterized by increased coherence between the vestibular stimulus and the muscle EMG during each task. Instead of this general increase, we found that the relationship between the vestibular stimulus and muscle activity across age groups was dependent on the muscle examined and the task.

On the treadmill, older adults showed significantly higher coherence at the soleus, gastrocnemius, tibialis anterior, and biceps femoris. These muscles span the ankle, knee, and hip joints. The higher coherence values suggest that, for flat ground locomotion, older adults rely more on vestibular input to control these muscles in order to maintain balance than their younger counterparts. This, however, seems to be task specific, as no significant increase was seen in older adults on either stair ascent or descent.

For both groups, the coherence generally decreased during stair descent. One possible reason for this may be because the action of going down stairs manifests as more of a "controlled fall" than an active movement. Stair descent may therefore be inherently more stable than stair ascent due to the position of the leg relative to the body. For example, during mid-swing of descent, the leg is fully extended, preparing for weight acceptance when the foot makes contact, and the center of mass of the body may be closer to the point of contact of the foot meaning the body is in a more stable position (McFadyen and Winter, 1988).

The tibialis anterior, however did not exhibit this same decrease in coherence during stair descent, and in the older adults actually displayed the largest peak coherence of all of the tasks on descent. Stimulus coherence with tibialis anterior was greatest during the first half of the step cycle, peaking around 30% (Fig. 1). During this portion, the ankle is responsible for weight

acceptance and maintenance of balance on the stance leg while the swing leg moves to the next step (single support phase). Feedback control of the tibialis anterior may be especially important during this phase because it is so crucial to stability. One consequence of the "controlled fall" of stair descent is large braking forces required during the weight acceptance phase. Ankle plantar flexors are mostly responsible for producing the force necessary for slowing the fall, but co-contraction of the tibialis anterior with the soleus is seen at this phase, most likely to stabilize the joint (McFadyen and Winter, 1988, Hamill et al. 2015). While the joint range of motion necessary for stair descent is largely determined by the dimensions of the stairs, and therefore is consistent across ages, the angle required of the ankle joint during this single support phase is a greater percentage of maximum ankle joint range of motion for older adults due to declines in passive joint range of motion with age (Lark et al. 2004, Reeves et al 2008). Additionally, older adults have been shown to have lower margin of stability during this single support phase of stair descent, meaning the extrapolated center of mass (determined by position and velocity of the center of mass of their body) is further away from the base of support during this phase than in young adults (Bosse et al. 2012). Because of the tibialis anterior's importance in stability during this unstable phase of descent, input from the vestibular system and other sensory systems may be especially instrumental at this point.

One limitation of this study comes from our use of peak coherence as our dependent measure. While peak coherence between age groups was not significantly different, the older adults seemed to spend longer amounts of time near those peak values and over a broader frequency bandwidth. A coherence plot (Fig. 2) of the soleus and medial gastrocnemius shows a greater area of high coherence in the older adults, indicating that vestibular information may

have been used by those muscles for a longer period of time and over a wider range of frequencies in the older adults.

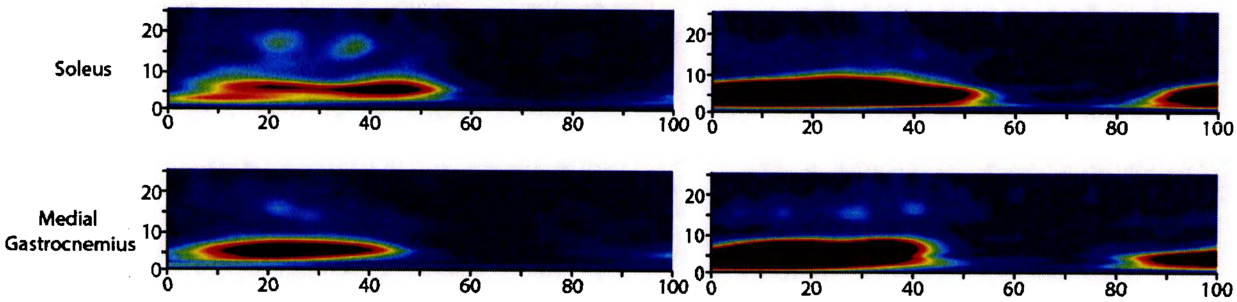

Figure 2 Time (x-axis) frequency (y-axis) coherence for the soleus and medial gastrocnemius muscles of young adults (left) and older adults (right) across the step cycle (toe contact to toe contact) during locomotion. The coherence begins earlier in the step cycle, occurs over a broader range of frequencies, and covers a greater overall area in the older adults than younger.

In conclusion, we did not see a general increase in coherence between vestibular stimulus and muscle activity in the older adults on stair ascent, stair descent, or locomotion. Our results suggest a more nuanced relationship between vestibular input and muscle activity, and in how that relationship changes as we age. When taking a closer look, differences in coherence between age groups were dependent on the muscle and task. This study offers a first look at the contribution of the vestibular system to balance control in older adults, both during locomotion and stair negotiation. These results, along with further exploration of why and how these changes occur, may help in development of fall prevention methods in the future.

Reflection

Completing this capstone was a highlight of my undergraduate education here at USU. Through this experience, I learned important skills that will be valuable to me in my future education and career goals, and I gained positive relationships and meaningful experience solving real problems that will be indispensable as I continue in my education and career goals.

This project was a true capstone, offering me depth and breadth of subjects and skills that I couldn't get from my classes. I was able to dive deeper into topics we didn't have time to cover in my classes, specifically the vestibular system. The vestibular organs are intricate and fascinating structures, so I enjoyed learning more about the structure and function of these organs and how they are related to the rest of the body as I prepared for and completed this study.

I was also able to see the real application of principles I had learned about in class, and with some practice, gain skills that may be useful in the future. For example, for the electromyography we used in this study, I learned how to locate the muscles we were examining, place the electrodes in the correct orientation, and makes sure we were getting a good signal. I would not have been able to become as proficient at these types of skills in a classroom setting.

One other skill that I was able to practice a lot of that will be very useful for me in the future was working with people and helping them feel at ease throughout the complex set-up process and what could be considered invasion of personal space. It was important to sure each participant knew what we were going to do before we began and before each step of the process, so that they were well informed and comfortable.

Communication is an important part of the research process in many forms, and this capstone experience also gave me practice writing and presenting our findings. I presented a poster at the student research symposium, which required me to consider how to visually display the information most clearly and gave me a chance to talk with people about what we had done and what it all means. Through writing this capstone I learned just how precise scientific writing needs to be, and how intensive the work is. This was probably the most difficult part of the entire process for me, but for that reason, it was also one of the most valuable.

In addition to concrete skills specific to this study, this experience highlighted the importance of many life skills that will be transferrable to many other situations. Any study of this magnitude requires a lot of work, but this one especially could not be done without the help of many people. Working together was key in solving many of the small problems that arose each day, and staying organized through the data collection and analysis process was vital. Without commitment from everyone involved, this wouldn't have been possible.

One of those key people in making this project possible was my faculty mentor, Dr. Chris Dakin. I began working as a research assistant in his neuromechanics lab in May 2018, after being a student in his biomechanics class. For the first few weeks there, my position was mainly to assist a couple of master's students with their projects. One of those involved the same methods of vestibular stimulation on the stairs so I became familiar with the equipment and necessary procedures. As I became more confident and independent in the lab, Dr. Dakin encouraged me to take on my own study, and write a proposal for the Undergraduate Research and Creative Opportunity grant. With his help writing that grant, I was actually rewarded that grant, something I never would have even tried on my own. This was a complex study, and a

couple of times I wondered if I had undertaken too much. Dr. Dakin was always supportive, and when it was broken down into smaller tasks it became manageable.

One thing I hadn't anticipated before I began this research, and I think is unknown to most honors students before they actually begin, is just how long the process takes from beginning to end. For this project, each testing session lasted three to four hours. We needed at least three lab assistants present for each testing session, and we all had very busy and very different schedules, so it was difficult at times to schedule subjects to come in. Because of this, data collection took twice as long as I had expected. Additionally, we had some difficulty finding older adults that were willing or able to participate. Stairs are a difficult task for many older adults, especially going down stairs, and in order to have appropriate data, we needed them to be able to go down the stairs at a specific cadence without the use of a handrail, while keeping their head up. It took some time to find older adults that were able to meet these demands, and for that reason we only were able to collect data from six older adults before the completion of this capstone project.

Despite the challenges, or more likely because of the challenges and the work it took to overcome them, the experience of working in the neuromechanics lab and completing this honors capstone has been pivotal in my education here at USU and I believe will serve as a good place to launch from as I continue on to graduate school and beyond.

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Author Biography

Megan Elwood was born and raised in Logan, Utah. In 2014, she followed in the footsteps of the previous four generations of her family by deciding to attend Utah State University. At first, she joined the honors program for the smaller class sizes and priority registration. Involvement in honors offered so much more, however, like making lifelong friends, traveling to Sweden for a study abroad program in the summer of 2016, and completion of this capstone, a major highlight in her undergraduate career.

During her time at USU, Megan has worked as an undergraduate teaching fellow and a research assistant in the Neuromechanics Lab, as well as spending many hours as an aide in several physical therapy settings. Some of her major accomplishments were making the Dean's List four semesters, receiving an Undergraduate Research and Creative Opportunity grant in the fall of 2017, and being awarded the Outstanding Undergraduate Researcher in the department of Kinesiology and Health Science in 2018.

Megan will graduate with a Bachelor of Science degree in Human Movement Science in May 2018. Following graduation, Megan will be attending The Ohio State University's Doctor of Physical Therapy program, with an option for a DPT/PhD dual degree. She plans on staying close to research and looks forward to being able to use the skills she's learned to help people move well and live healthy lives.