CHARACTERIZATION OF SENSES FOR HEAD-BODY ORIENTATION EXPLORING EFFECTS OF VISION, VESTIBULAR AND MUSCULAR PROPRIOCEPTION

A Thesis

by

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ABSTRACT

Spatial awareness of our orientational reference is derived from a network of sensory feedback modalities, collaborating to create a singular egocentric spatial representation of the body. With specific regards to the head-body orientation, the sensory inputs used to map this representation are vestibular, visual, and cervical proprioceptive feedback. However, visual and vestibular feedbacks have limited capability to properly distinguish the difference between rotations of the head and rotations of the body. In contrast, densely distributed muscle spindles within the neck muscle (Longus Colli and Multifidus), indicate that cervical proprioceptive feedback is perhaps dominating in the formation of the perception of head-body orientation. The significant impacts caused by defective cervical proprioception (e.g., dizziness, offset in spatial awareness, and gait and balance deficit) also suggests the critical role of the cervical proprioceptive feedback.

We hypothesized that the information from visual and vestibular feedback provide redundancies in the detection of the relative orientation between the head and the body, upon the normal operation of cervical proprioception. In addition, we hypothesis that cervical proprioception impacts the relative head-body orientation perception the greatest of the three sensory modalities. To test these hypothesizes, healthy human subjects were recruited (5 females, 5 males) and asked to turn their head by 45-degrees and return back to the starting position, which is a standard task to test the perception of relative head-body orientation. The error between the starting and returned position was used to test the effectiveness of cervical proprioception. In addition, the deviation from the initial reference position was recorded across each set of tests for the 10 subjects and recorded to examine the precision of the participants across the tests. The repositioning test was

done under 8 different conditions of sensory feedback combinations, to isolate and gauge the contribution of each sensory feedback individually and collectively. To test the effect of cervical proprioception, either the head was turned with the body staying still or both the head and the body turned as one. To test the effect of visual feedback, subjects performed tests blindfolded or unblindfolded with eyes open. To test the effect of vestibular feedback, subjects were tested with a slower rate of return, below the threshold for vestibular perception, towards the initial position versus a normal paced rate of return towards the initial position. Upon the completion of these tests, we hoped to gain more insight and create a profile how these sensory modalities (or loss of each sensory modality) contribute to our perception of the head-body orientation. This will help in designing sensory augmentation in a better way. For example, if neck proprioception dominates the formation of perception of head-body orientation, we may focus on proprioceptive augmentation instead of visual or vestibular augmentation, in treating the defective neck proprioception.

The tests revealed that cervical proprioception provided the greatest contribution towards the head-body orientation in instances of isolated available feedback ($p < 0.01$ for both proprioception vs vestibular and visual) and created the most error and deviation in instances where cervical proprioception was lacking versus instances in where vestibular or visual feedback were missing ($p_{vis} = 0.05$, $p_{vest} < 0.01$ for error; $p_{vis} = 0.03$, $p_{vest} = 0.01$ for deviation). Given these results, direct augmentation of the cervical spine muscle proprioceptors should be the most desired approach for resolving cervical proprioceptive errors that effect our orientational references. A functional biphasic electrical stimulator has been developed to begin testing on the effects and efficacy of electrical augmentation of the orientation perception sensation.

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Contributors

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NOMENCLATURE

EO	Eyes Open
EB	Eyes Blindfolded
HT	Head Turn
BT	Body Turn
COR	Cervico-Ocular Reflex
VOR	Vestibulo-Ocular Reflex
CCR	Cervico-Collic Reflex
VCR	Vestibulo-Collic Reflex
STH	Sternohyoid
SCM	Sternocleidomastoid
SPL	Splenius Capitis
SPC	Semispinalis Capitis
MUL	Multifidus
OCI	Obliquus Capitis Inferior
RCP	Rectus Capitis Posterior
IMU	Inertial Measurement System

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1. INTRODUCTION:

1.1 Importance of perceiving the head orientation relative to the body (i.e., head-body orientation)

Perception of head rotation relative to the body is important for creating an egocentric spatial representation of the body, which plays an important role in motor control ability and spatial awareness. Especially during complex motor tasks sensitive to body orientation, such as dynamic balancing, the importance of an accurate perception of head rotation relative to the body becomes greater [1]. Misperception of the head-body orientation leads to poor motor learning and degradation of rehabilitation processes, due to the conflict between the expected and actual motor outcome (in other words, inconsistencies between egocentric and allocentric spatial representations).

1.2 Formation of the head-body orientation perception

The head-body orientational perception is formed by a vast and complex system of various sensory modalities, working independently and together to form the perception and understanding of the head-body orientations. The three main contributors to this are the joints and muscle proprioceptors located in the cervical spine, the vestibule system and the visual system. The cervical spine is comprised of the 7 vertebrae (C1-C7) bones located in the cranial region of the spine. These are surrounded by a plethora of muscles which give support and allow for motion of the head relative to the body. The main dorsal contributors include the semispinalis capitis, spinalis capitis, levator scapulae, and trapezius. These will be referred to as a whole as the dorsal neck (DN) muscles. The main posterior muscles include the sternocleidomastoid (SMD), longus colli and longus capitis. The role of these muscles varies from stability and support for the scapula (shoulder blade) and cranium, lateral and horizontal motion of the cranium, to postural control [2]. It is typical to find a highly dense population of muscle spindles in these muscles, indicating a high importance in their functionality [3]. Next, the visual system, with regards to the head-body rotation, consists of the eyes which sends information to the optical lobe. The visually perceived rotations follow simulated head rotation, as opposed to gaze rotation [4]. That is to say, if the head turns to the left while the gaze flows to the right, the perception of rotation matches that of the head rather than the eyes. The eyes-in-head sense perceives changes in the outside world and relates it to a rotation relative to the head, creating a piece needed for the full profile of head-body orientational perception. Last, the vestibular system, is located in the inner ears with one residing on each side of the head. The vestibular system is comprised of two parts; the utricle and the saccule. Within the utricle there are tiny fluid filled tubes called the semicircular canal. Movement from the head elicits motion of tiny hair cells within these tubes that sends information about relative motion. Furthermore, the saccule is a layer of sensory cells that convert head motion into neural information for further processing. Somatosensory information from cervical muscle and joints converge with the visual vestibular afferences within multimodal neurons within vestibular nuclei (located within the hindbrain of the brainstem) and the thalamus[2]. This neural information is then sent to the associated sensory cortex in the anterior parietal lobe where the formation of the head-body perception is formed.

1.3 Compensatory reflexes of proprioceptive, visual and vestibular senses

While the above section paints a high-level picture where interconnections were minimized, in reality the three senses are highly entangled, influencing each other which is the biggest obstacle for understanding the importance of each independently. A majority of the dependencies come in the form of reflexes developed to counteract motion of one sense and stabilize the sensation of the others. For example, vestibulo-collic reflex (VCR) stabilizes the head on the body by creating compensatory muscular contractions on muscles opposite side of motion when the vestibular system relays motion information [5]. More of these interconnections are illustrated in Figure 1. Here we see the vestibulo–ocular reflex reflex (VOR) as the main compensatory reflex between visual and vestibular senses. This reflex takes the vestibular information and rotates the visual motion in the opposite direction of head motion to stabilize visual images. The VOR is thought to be unaffected by cervical spine afference signals [5]. The cervical proprioceptors, on the other hand, are more engrained with both inter- and intra-connections. The cervico-ocular reflex (COR) stabilizes the eyes to respond to muscular afferents as a result of head-body motion. The previously mentioned VCR works with this to allow us to compensate for head motion [6]. However, the VCR is lost in low frequency rotations. In stable and passive movement conditions, vestibular-only neurons still fire though [5]. The cervico-collic reflex (CCR) works similary but works by receiving muscular and joint proprioceptive information and relaying it back for compensatory muscular contraction. By recognizing the direction of the muscle strain, the opposite set of muscles can be contracted to compensate for the added stress.

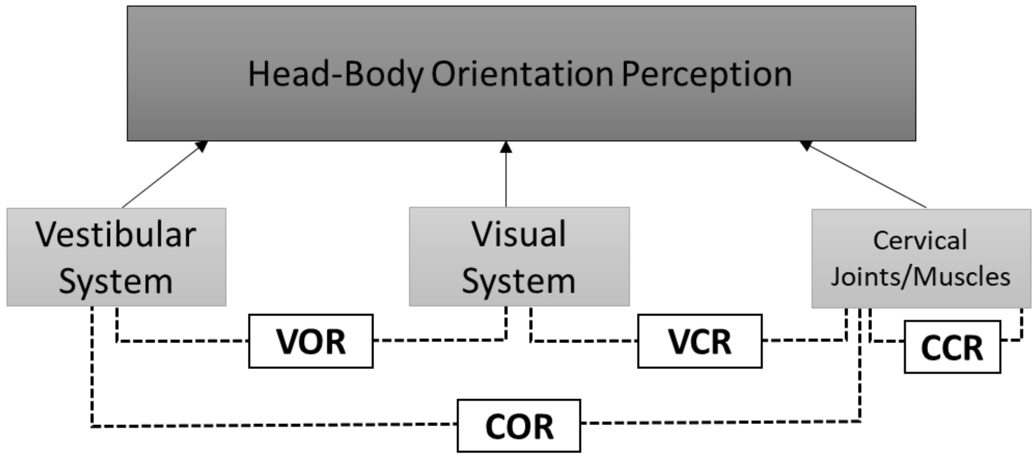


Figure 1. Compensatory reflexes associated with head-body orientation

This figure shows how the vestibular, visual, cervical spine muscular/joint system work together via inter and intra-reflexes to compensate for head-body rotation.

1.4 Importance of cervical proprioception in perceiving the static and dynamic head-body orientation

The joints and muscles in the cervical spine region play a crucial role in our awareness of relative orientation between the head and the body, in both static and dynamic situation (i.e., rotation). While the head can directly use visual and vestibular information to perceive its rotation, the trunk of the human body does not inherently have a sensory system designed to detect rotation independently from the head, except in the physical connection at the cervical spine, as the rotational medium. Visual feedback provides information of the static and dynamic head-body orientation, but it is typically limited as our gaze is usually centered towards our direction of motion rather than at our bodies. Vestibular feedback, on the other hand, can provide information regarding head orientation and body orientation but the inability to draw a definitive distinction between head and body limits the systems effectiveness. For example, head turning with the body and head turning without the body would result in similar information from the vestibule system. While both these senses play a bigger role than just the head-body orientation perception, the cervical spine region prioritizes this perception. The cervical spine region, along with the muscles surrounding it, is the critical instrument of the body to provide the perception of the rotation between the head and the body (trunk).

1.5 Defective cervical proprioception can happen in several cases

Engaging in high impact sports, which exposes the participant to either repetitive forces (i.e. car racing [7]) or excessive traumatic forces (i.e. football, rugby [8][9]), introduces the risk of causing neck injury responsible for defective proprioception, such as minor cervical strain, to the athlete. Indeed, participants in these sports who have been exposed to the risks for a prolonged time, have shown to perform significantly worse when tested on cervical range of motion and proprioception, compared to non-participants [7][8]. The tests result of cervical range of motion on patients who suffered from whiplash associated disorders (WAD) [10] and cervical dystonia (CD) [11], also showed the same defect in proprioception in the study on sport athletes.

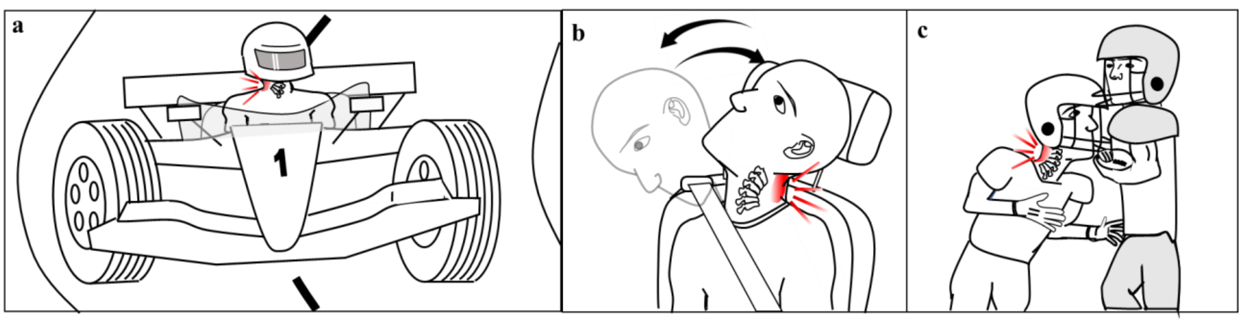


Figure 2. Situations in which cervical proprioception defect can occur.

Cervical damage can occur from a variety of situation. These range from repetitive traumatic forces that can result from car racing (a), damage to the cervical spine region as a result of whiplash (b), or excessive traumatic forces typically seen in activities such as football (c).

1.6 Defective cervical proprioception along with the following secondary effects, impedes normal control tasks such as balance

Firstly, defective cervical proprioception causes spatial dissonance of the body, as perceived orientation of the body heavily depends on the cervical proprioception [12]. Accordingly, visual and vestibular feedback have conflicts with the somatosensory feedback from the body, in determining the best motor output for the balance [13]. In the instances of damaged sternocleidomastoid muscle, anterior-posterior balance can be an issue as well because of defective proprioception with backwards head extension [14]. WAD patients, who have occurred damage in multiple neck muscles, often suffer from a disturbed equilibrium and posture control, even in static conditions [15]. Second, defective cervical proprioception causes improper head posture, as the relative orientation between head and body cannot be perceived and corrected well. The improper head posture results in fatigue in the neck muscles surrounding the cervical spine, which further degrades the balance control ability [16]. Third, muscle atrophy, as a result of limited physical activity over time, reduces neck muscle proprioception. The muscle atrophy, in combination with the defective neck muscle proprioception, aggravates issues in perceiving the head-body orientation and deteriorates postural control [17]. Fourth, defective cervical proprioception increases the possibility of exposure to secondary injuries. For example, WAD patients are prone to having secondary injuries during daily activities as well as strenuous exercises and sports, due to the significant impairment in spatial orientation and the increase in neck muscle fatigability [15][18]. Fifth, defective cervical proprioception leads to an impaired egocentric reference, which puts those suffering at risk of accident-related injury as a result of their inability to properly coordinate themselves in space [11]. Sixth, defective cervical proprioception attenuates cervico-collic reflex (CCR), which plays an important role in stabilization of the head relative to the body

[19]. Lacking the innate ability of CCR leads to further issues in regard to the increased cognitive burden, as the voluntary control needs to compensate for the lack of CCR.

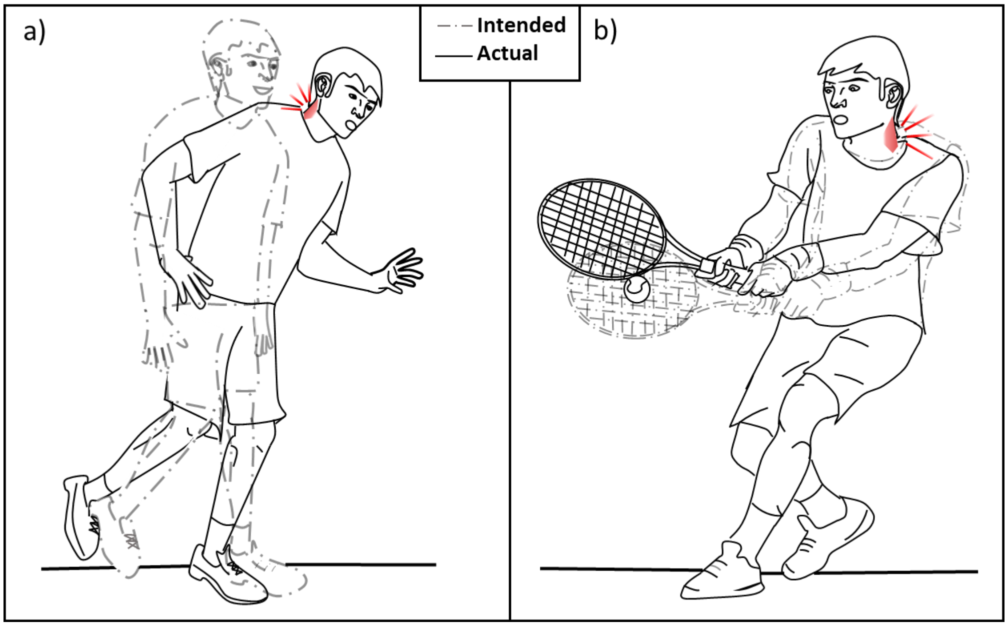


Figure 3. Effects of Defective Cervical Proprioception.

Defective Cervical Proprioception can impact gate, balance and spatial awareness (a) and impair egocentric reference which causes a risk of further injury and has negative effects on general motor performance (b).

1.7 Current approaches have limitations in addressing defective cervical proprioception

To improve spatial awareness and balance, degraded by the defective cervical proprioception, multiple approaches have been made through physical therapy, surgery, and assistive devices [20][21][22][23]. Cervical proprioception training has been linked with improvements in balance in chronic poststroke hemiparesis patients [24]. Similarly, subjects with chronic mechanical neck pain have noted reduction in pain with regular physical therapy treatment that focuses on eye-head coupling. This form of treatment has patients performing active head motion with their gaze locked on fixed and moving targets [20][22]. Physical therapies including stretching and hold-relax techniques also showed feasibility in reducing neck pain [22]. These therapies improved the balance, but it is uncertain whether the improvements were a result of proprioceptive improvements or long-term training on a specific task, as these tests typically ask patients to repeat the same task multiple times over the course of 6-10 weeks. In severe cases of neck injury, such as extreme damage to the cervical spine or cervical spine diseases such as herniated disc or spondylosis, neck surgery is necessary. Following the surgery, assistive devices have been introduced, in the form of neck braces, to fit onto the cervical spine [23]. However, the efficacy of these neck surgeries or neck braces on recovering neck proprioception has not been investigated well.

1.8 Defective cervical proprioception can be addressed by sensory augmentation approaches, which can either be direct approach (augmenting the neck muscle proprioceptors) or compensatory approach (augmenting visual or vestibular feedback)

While cervical proprioception appears to play an important role in balance, it is part of the overall balance system. The balance is maintained by the well-orchestrated coordination of multiple sensory feedback, including visual feedback, vestibular feedback, and somatosensory feedback on the leg. Due to this complexity we have seen various sensory augmentation approaches, which mitigate the effect of sensory loss and improved spatial awareness and balance function. Visual augmentation has been mainly investigated with virtual reality, and has shown effectiveness in addressing defective cervical proprioception, by increasing range or motion and decreasing the vestibular dependency [25]. A recent study has found that visuo-proprioceptive interaction is important in the case of defective cervical proprioception [21]. Vestibular augmentation, via caloric, electrical, and vibrational stimulation [26][27][28][29], also showed effects on gaze, body posture and sway. Haptic feedback has also been investigated, mainly by mechanical vibration or electrical stimulation, and showed effects on improving body spatial representation, gait, and balance [30][31][32][33].

1.9 To properly design the sensory augmentation method, it is important to know the contribution of each sensory feedback on perceiving head-body orientation

However, although those sensory augmentation approaches were found as effective on improving the perception of head-body orientation, there is still a large gap in our understanding of how to design the sensory augmentation properly. Although we know that these sensory feedback work cohesively with each other to form the perception of relative orientation between the head and the body, it is still not clear how important each one is. For example, if contribution of cervical proprioception is significantly more important than that of visual or vestibular feedback, on perceiving relative orientation between the head and the body, visual or vestibular augmentation would have a clear limitation and cervical proprioception should be directly augmented. The contribution of each sensory feedback, in the formation of the egocentric spatial representation of the relative orientation between the head and the body, is also in question. To address the defective cervical proprioception and select the right approach of sensory augmentation, it is crucial to know the contribution of each sensory feedback for the brain to perceive the relative orientation between the head and the body.

It is known that sensory information from neck proprioceptors work in tandem with afferent information sent from vestibules [34][35]. While this relationship seems intrinsic due to the necessity of the vestibular system to rotate with head turn, interrelationship with visual feedback makes the sensory coordination very complex. For example, vestibular neurons associated with eye gaze and head velocity are firing even in the instances of body rotation while the head is stationary [36]. Even simple eye motion has a strong effect on the firing pattern of vestibular neurons, which creates even further complexity [37]. Another study also showed that vision can reset the proprioceptive illusion made by the vibration of neck proprioceptors [38]. However, cervical proprioception seems to have the capability of replacing the role of visual feedback, in terms of perceiving the head-body orientation; tested with head-trunk rotation [39]. With each added layer of detail to account for, it is easy to see the importance of pinpointing the contribution of each sensory feedback in different situations. It is still not understood well about how much we rely on each individual sensory system to create our egocentric spatial references. Furthermore, there is a bigger gap in the exploration of the consequences of losing one or more of modes of sensory inputs and how the other sensory information compensates for this sensory deficiency. To properly design the sensory augmentation in case of sensory deficiency, we realize the need to investigate the contribution of each sensory feedback on perceiving the head-body orientation and egocentric spatial references, under the condition where part of the sensory feedback is imperfect.

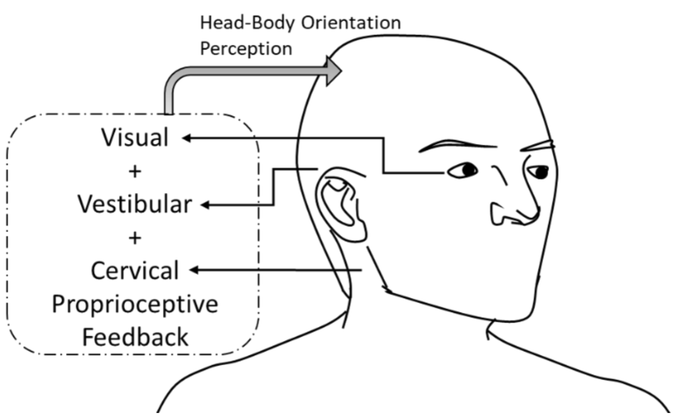


Figure 4. Visual feedback, vestibular feedback and cervical proprioceptive feedback are all contributors to the head-body orientational perception.

1.10 Goals and Hypothesis

This study aims to garner a better understanding of the contribution of each modality of sensory feedback on the relative orientation between the head and the body. In doing so, we hope to shed light on the proper direction for sensory augmentation needed to help cervical proprioceptive defects. Following this, the implementation of the chosen sensory augmentation method can be addressed. We expect to see at least minimal contributions from cervical proprioception, vision, and vestibular feedback. How much contribution each sensory modality offer is unknown, though. When discussing temporal longevity of each sensory feedback, both visual and cervical proprioception will offer a constant absolute reference for orientation. On the other hand, vestibular information is all relative to previous reference orientations and doesn't last nearly as long as the other feedback modalities, implying a lower dependency for absolute orientational positioning.

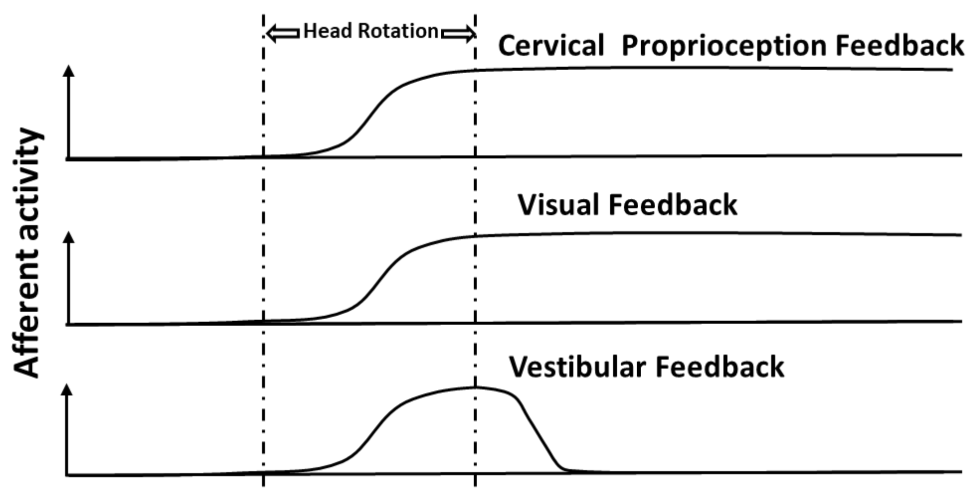


Figure 5. Temporal longevity of information received from three modalities primarily responsible for developing the head-body lateral orientational perception

While it is known that sensory receptors primarily responsible for perception of general muscle proprioception are muscle spindles [40], the perception of the head-body orientation is a unique case in which both vision and vestibular feedback are directly involved [25-39]. However, the concentration of the two latter (vision and vestibular) is distributed to more than just the cervical region, implying a less significant workload focus strictly towards the perception of the head-body orientation. That is to say, visual and vestibular information contributions are far more diverse towards the entire body than the role of neck proprioceptors, whereas the neck proprioceptors focus is solely on the task of perceiving the head-body orientation. Additionally, the high concentration of muscle spindles in the longus colli and multifidus muscles within the cervical spine [3] suggests that the neck proprioception would play a significant role in perceiving the head-body orientation. Furthermore, in instances of the natural loss of vestibular functions, cervical proprioception has been shown to successfully compensate for the sensory loss [39]. This example also suggests that cervical proprioception is the sensory method that the body relies on the most for perceiving the head-body orientation, whereas vestibular and visual feedbacks are used more for fine-tuning and corrective feedback. In this study, we expect to see results that align with this thought process. In addition, we hypothesize that the visual and vestibular feedback provide redundant information to detect the relative orientation between the head and the body, upon the normal operation of cervical proprioception. In other words, the perceived error in relative head-body orientation will not be different with or without visual and vestibular feedback.

2. METHOD

2.1 Rationale of Tests

10 normal subjects (5 females, 5 males), ages 18-45, were chosen to participate in this study. None of the subjects had a known previous neurological disease, vestibular damage, cervical muscle proprioceptive defects or visual impairment (corrective lenses are permittable). Recruiting

and screening of subjects followed the protocol laid out in IRB and informed consent was obtained prior to the start of experimentation, following an explanation of the procedures.

To test cervical orientational proprioception a variant of the subjective straight ahead (SSA) test was conducted to gauge the proprioceptive error throughout the experiment. This method is common practice to test cervical proprioception [8][9][10][39] and is accepted as a satisfactory method to indirectly measure proprioception of the cervical spine due to the high concentration of spindles present within this region [3]. In these tests, subjects are asked to turn their heads to a given direction and degree of rotation and then return their heads back to the initial position. The difference in degrees between where the subjects began the trial and where they ended the trial will be measured as the error. This is sufficient for measuring the role of neck proprioception in referencing spatial orientation and will allow for measuring the independent contribution of vision and neck proprioception. However, it limits the ability to isolate between vestibular and proprioceptive processes. Due to this factor, an additional variant was added in which subjects were seated in a rotating chair, facing the ‘straight ahead’ position and passively turned by the investigator. They were then turned 45 degrees, keeping the head aligned stationary with line of vision perpendicular to the shoulders while sitting in an upright position. The chair was then rotated back as the subject attempted to align themselves with the initial ‘straight ahead’ position, giving a verbal cue to stop the rotation. These two tests (shown in Figure 5), head-turn (HT) and body-turn (BT), were completely under four different conditions. The first of which was used to test the effects of vision; eyes-open (EO) vs eyes-blindfolded (EB). The second tests consist of *slow return* rate vs normal return rate instances, where the participants were either returned to their initial position at a rate comfortable and normal or returned at a rate slower than the vestibular threshold for perceiving lateral motion. The return rate was at or below 2 deg·s^{-1}. Randomization of return rate was done to limit the participants ability to use counting of motion time as a method for returning to the proper position. The rate of return for *slow return* tests was determined based on studies on vestibular perception threshold [41][42].

2.2 Finding Real Time Angular Displacement

The most critical part of the experimental process is solving for the angular displacement. This will be the angle between the initial starting position and any other point along the path of rotation. There are a number of methods to do this, depending on the resolution, stability, precision and acquisition rate desired. Knowing that the data we compiled would be heavily dependent on the reliability of the data acquired, the objective was to find a method that would yield the highest resolution with the sampling rate not being a huge priority as 10 samples/second would be more than enough to map the flow of rotation. The first method used for this was the use of an inertial measurement unit (IMU). A 9-dof IMU was selected (InvenSense MPU9250). The limiting factor in the sampling rate was the magnetometer at 100Hz. This was more than sufficient. Converting the raw data to angular data was done via an Arduino code created using the MPU-9250 DMP Arduino library. The magnetometer was calibrated by taking points across three axes while rotating the IMU. Once the IMU was calibrated and running two continuous problems, which ultimately led to scrapping the use of IMU's as an absolute angular detection method, were the stability (which impacts the actual resolution) and a constant drift, which is a common problem amongst IMU's. The IMU readout would fluctuate ±0.5° instable cases which would result in a low reliability in our readings when compared to the expected angle readout (0 to ±10°). In addition to the issue of drift (a slow constant accumulation of offset of the angular readout) this led to eventual removal of the IMU sensor angular measurement. While in the end these were not used, I felt it important to briefly note this process and the difficulties associated in case anyone reading can gain potential insight when considering the use of IMU's and out of respect for the headache the process truly was.

The final method of determining real time angular displacement was by using motion capture cameras (Prime 41, Motive: OptiTrack) paired with retro-reflective spheres. Optical measurements of the spheres relative locations were recorded in millimeters with mean error of approximately 0.8mm with a sampling rate of 16Hz and a mean error of 0.1°. By shining infrared light and sensing the reflected light, the optical measuring system with the software provided can create virtual dots in a 3D cartesian plane for further processing. Three retro-reflective dots represents a *body* (shown in Figure 7), located centrally within the dots, which have their own x,y, and z coordinates. This represents one end of a vector. A MATLAB API is then used to communicate to the OptiTrack software. A code was developed to receive the 3D Cartesian data of each body which was then used to solve for the angular displacement while accounting for any sway from the central line of rotation. The basic idea and trigonometry used are shown in Figure 8. Movement only the x-z plane was taken, as this correlates to lateral rotation.

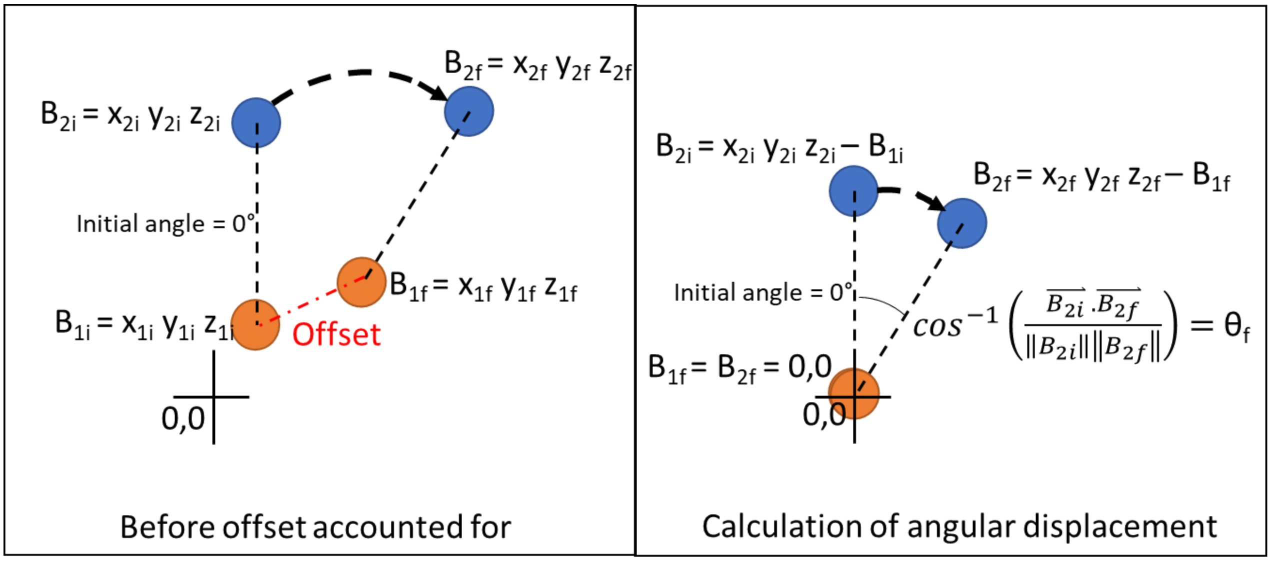


Figure 6. Solving for angular displacement

2.3 Test Setup

To measure rotated angle, a helmet fitted with retro-reflective spheres was placed on each participant. Using motion capture cameras, virtual dots in a 3D cartesian plane were created to give relative positioning of the retro-reflective spheres. A MATLAB code was created to communicate with the Motive software and give real-time angle measurements. Here any offset resulting from slight motion from full body sway that doesn't contribute to rotational orientation was compensated for. The real-time data is displayed and the variance of angles between the initial starting reference and current head position throughout the entirety of the test was automatically saved into an excel sheet. Angle variances measurements were taken approximately every 62ms (16 samples/second) with a mean 3D error of 0.1°. The difference between the final value and initial value was stored in a table as the results of the experiment, corresponding with the current test being run.

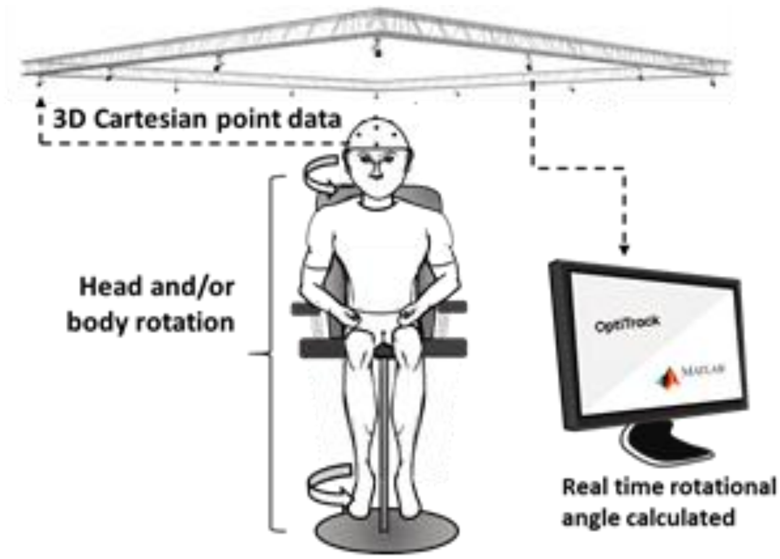


Figure 7. Test Setup

Above head cameras receive 3D Cartesian locational information from retro-reflective spheres places on helmet. This information is sent to a MATLAB program that calculated the rotational angle changed from the subjects starting position.

A total of 8 trials across 10 different subjects were conducted with 8 different experimental conditions, listed in Table 1 below, as follows: 1) HT with EO, 2) HT with EO with *slow return* rate 3) HT with EB 4) HT with EB with *slow return* rate, 5) BT with EO 6) BT with EO with *slow return* rate 7) BT with EB and 8) BT with EB with *slow return* rate.

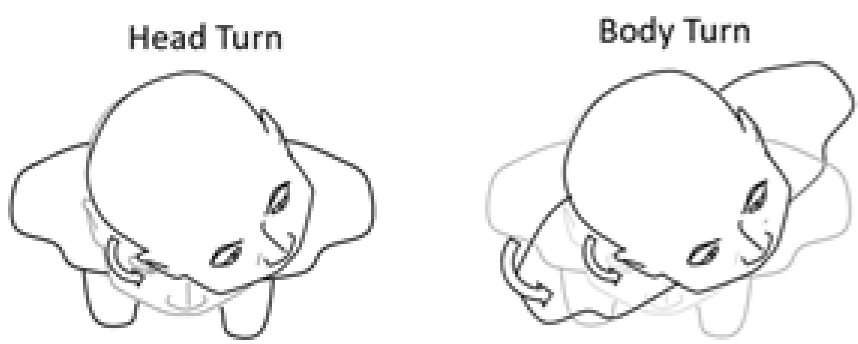


Figure 8. Illustration of Two Turning Conditions.

Head-Turn (HT) and Body-Turn (BT) tests each have instances of Eyes-Open (EO) and Eyes Blindfolded (EB). Participants will be asked to return to the initial position after their 45° rotation.

Each of these tests is important as it allows us to independently test the effect of each sensory feedback and measure quantitative results with regards to how they affect the perception of the head-body orientation. With this information we can create a better map of the contribution each sensory on the perception of head-body orientation. In the table below, the sensory feedback contributing in each test is shown.

HT = Head-Turn; BT = Body-Turn; EO = Eyes-Open; EB = Eyes-Blindfolded				
Test #	Test Conditions	Sensory modality involved in the condition		
		Cervical Proprioceptive Feedback	Visual Feedback	Vestibular Feedback
1	HT + EO	✓	✓	✓
2	HT + EO + Slow Return	✓	✓	
3	HT + EB	✓		✓
4	HT + EB + Slow Return	✓		
5	BT + EO		✓	✓
6	BT + EO + Slow Return		✓	
7	BT + EB			✓
8	BT + EB + Slow Return			

Table 1. Test conditions with associated sensory modalities involved in each test condition.

3. RESULTS

3.1 Absolute Mean and Actual Variance Reveal Accuracy and Precision of Head-Body Orientation

The data was analyzed by two metrics; the mean of the absolute value of error (independent of direction of error) between starting and returned position and the variation of the actual error (dependent on direction of error) of each trial of across the ten subjects. While the absolute value of error provides insight on the accuracy of each sensory feedback, or combinations of them, the variance between individual subjects provides useful information on the precision of the perception of the head-body orientation. The calculated precision will provide us more insight on the confidence and effectiveness of the contribution as well. Through this experimental method, we expect to have more clarity on the contribution of each sensory feedback and the effect of the loss of one or more sensory feedback on the overall perception of head-body orientation. Due to the results tendencies to be skewed towards positive values, a non-parametric evaluation of the data was determined as the best option for analyzing the data. A two-tailed Mann-Whitney U test with 95% confidence interval was performed on the data to verify the significance of the findings. For deviation tests, variance of the 8 trials of each test for the individual subjects was used. A critical U value (Ucrit = 23.0) was found as comparison of significance of deviation across the 10 subjects. In absolute error tests, all 80 test trials across 10 subjects were pooled as independent values, which exceeds the values available for U values found on U-tables. Here, the sample size was large enough to use z-values to calculate significance of the findings.

3.2 Comparison of Each Modality of Sensory Feedback Working Independently

A control test was performed on participants in which no sensory feedback was used for the head-body orientational perception. As expected, subjects performed poorly in the control tests with low precision and accuracy during the repositioning tests (Error = 15.54°; Deviation = 13.94°). Three tests were designed to isolate the use of cervical proprioception (Test 4), visual (Test 6), and vestibular (Test 7) feedback. Compared to the control participants showed significant improvements when able to use any one of these sensory modes independently ($p < 0.01$ for all feedbacks for both error and deviation). However, as can be seen in Figure 7, participants performed significantly better when asked to rely on strictly neck proprioception versus relying strictly on either visual or vestibular feedback ($p < 0.01$ for both senses in error; $p = 0.02$ for visual deviation and $p < 0.01$ for vestibular deviation), which aligns with our initial hypothesis that neck proprioceptors have the greatest impact to the head-body orientational perception. It is also to be noted that slight improvements were shown between visual and vestibular isolated feedback tests, with vision having a slight edge in precision ($p = 0.03$ for deviation) but no discernable difference shown in accuracy ($p = 0.2$ for error). This implies that visual feedback may be provide slightly more reliable sensation than vestibular feedback for orientational awareness.

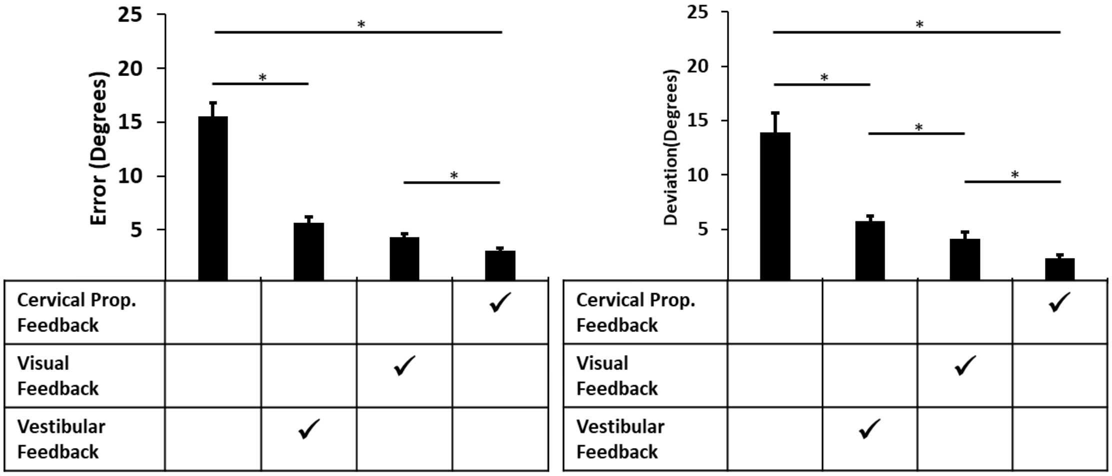


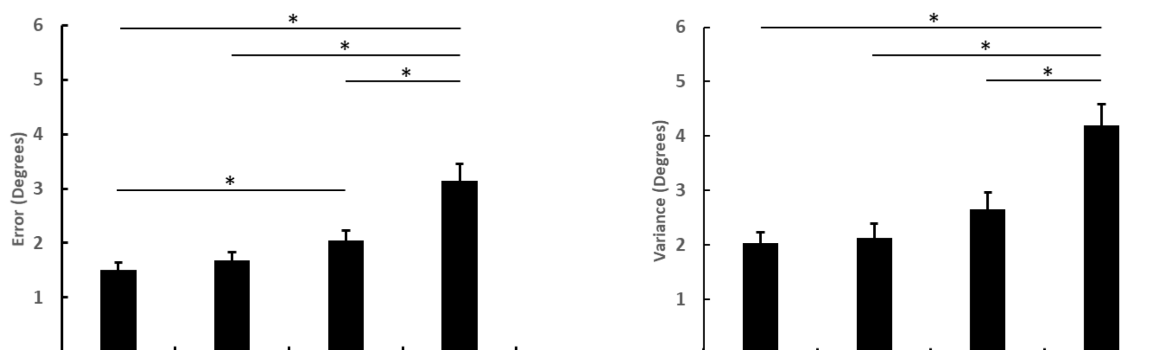
Figure 9. Comparison of effects of using only single sensory feedback mode.

Comparison of absolute value of error independent of direction relative to starting 0-degree reference (Left) and deviation of actual error relative to starting 0-degree reference (Right) of isolated sensory modalities. This is compared to a control case in which no sensory feedback was used to percieve head-body orientation. Error bar indicates the standard error across subjects and asterisk (*) indicates statistical difference with 95% confidence interval via two-tailed Mann-Whitney U tests for absolute error and deviation.

3.3 Comparison of Effects of Losing a Single Modality of Sensory Feedback

A second control test was done in which participants were able to rely on all three sensory modalities together (HT with EO and normal return rate). As expected, participants performed best under these conditions with lower error and lower deviation recorded (Mean = 1.5°; Deviation = 1.7°). Three tests were done to isolate instances in which a single mode of sensory feedback was removed. Test 2 had participants rely on cervical proprioception and visual feedback, with the effect of visual feedback mitigated. Test 3 had participants rely on cervical proprioception and vestibular feedback, with visual feedback removed. Finally, Test 5 had participants rely on visual and vestibular feedback, with cervical proprioception not present. The results of these tests along with the control test are shown in Figure 8. While subjects did perform best under control conditions, it was found that there wasn't statistically significant advantage to adding vestibular feedback when proprioception and visual were already present (p = 0.41 for error, p = 0.71 for deviation). That is to say, having all three sensory feedbacks seems to provide the same advantages as having just functional neck proprioceptors and visual.

When proprioception was paired with either vestibular or visual there didn't appear to be any statistically significant benefit (p = 0.10 for error; p = 0.55 for deviation). This aligns with our second hypothesis, that there is redundancy in the information provided from vestibular and visual feedback, especially in instances that cervical proprioceptive feedback is working properly.



Cervical Prop. Feedback	✓	✓	✓	
Visual Feedback	✓	✓		✓
Vestibular Feedback	✓		✓	✓

Cervical Prop. Feedback	✓	✓	✓	
Visual Feedback	✓	✓		✓
Vestibular Feedback	✓		✓	✓

Figure 10. Comparison of loss of single sensory feedback mode

Comparison of absolute value of error independent of direction relative to starting 0-degree reference (Left) and deviation of actual error relative to starting 0-degree reference (Right) of instances of loss of a single sensory modality. This is compared to a control case in which all sensory feedback modes were used to perceive head-body orientation. Error bar indicates the standard error across subjects and asterisk (*) indicates statistical difference with 95% confidence interval via two-tailed Mann-Whitney U tests for absolute error and deviation.

3.4 Comparison of Cervical Proprioceptive Feedback Versus Vestibular and Visual Working Together

When comparing tests under the condition of only vestibular and visual feedback present versus tests where proprioceptive feedback was isolated, there was no statistical significance between the two in terms of the error of the return angle. However, as Figure 9 shows, the deviation was higher in the vestibular with visual feedback test. In other words, while the total number of degrees of error was about the same between the two tests, in the isolated neck proprioception case subjects were more likely to undershoot the 0° reference, as opposed to the vestibular with visual feedback case where subjects were more likely to show inconsistent results between undershooting and overshooting. This lack of accuracy implies that proprioception alone is even a more reliable source of sensory feedback than vestibular and visual feedback paired together.

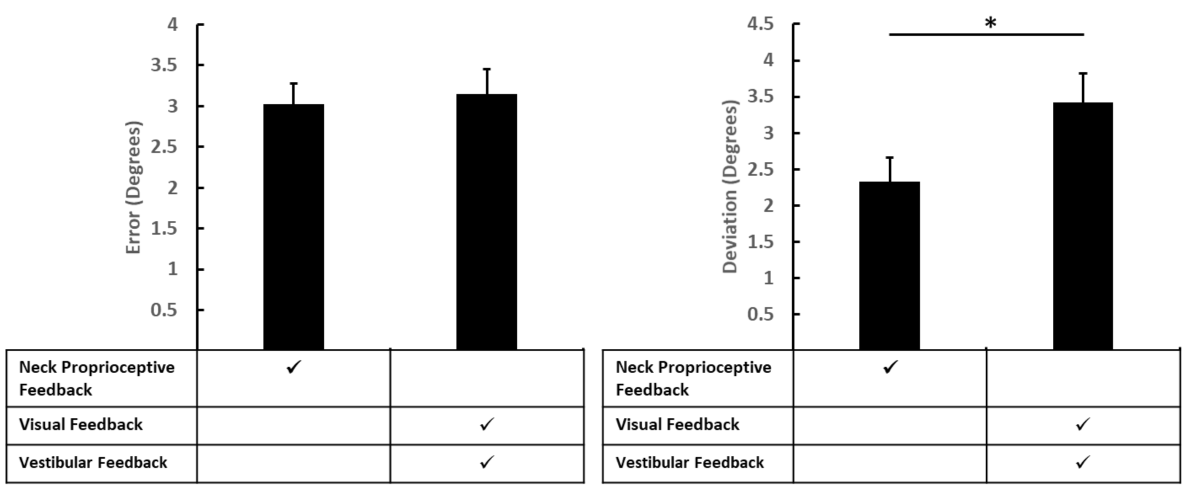


Figure 11. Comparison of cervical proprioception vs visual + vestibular feedback

Comparison of absolute value of error independent of direction relative to starting 0-degree reference (Left) and deviation of actual error relative to starting 0-degree reference (Right) of strict reliance on proprioceptive feedback versus reliance on visual and vestibular feedback working together for the head-body orientational perception. Error bar indicates the standard error across subjects and asterisk (*) indicates statistical difference with 95% confidence interval via two-tailed t-test for absolute error and deviation.

4. CONCLUSION/DISCUSSION

4.1 Cervical Proprioception Provides the Most Contribution for the Head-Body Orientation Perception

Through the results it is clear to see that the modality of sensory feedback that most benefits the perception of head-body orientation is cervical proprioception. The comparison of individual isolated feedbacks compared to the control with no feedback (Fig. 7) indicates that cervical proprioception working alone is the most reliable source of sensory feedback. While accuracy (represented by the error in degrees) suffered, the worst results in isolated tests were shown in the deviation. Neck proprioception yielded the highest precision amongst all isolated tests. A high precision (represented by the deviation) is preferable when discussing augmentation as an offset in the feedback would be the main point of mitigation. As opposed to a low precision which implies a deeper issue in the afferent signals and reliability of the system entirely. Neck proprioceptors were nearly 2x more precise than visual feedback and nearly 3x more precise than vestibular feedback alone. This trend was also present in cases where participants had 2 different sensory modalities. This aligns with previous studies, where lack of proprioception caused significant deficiency in body control, motor output, and perceived body orientation [12-19]. Furthermore, bilateral vestibular loss has been previously shown to have no effect on cervical proprioception [43], which is consistent with what our tests show while visual feedback was still present as well. The worst-case scenario in which only a single form of sensory feedback was missing is neck proprioception.

4.2 In Cases of Permanent Loss of Cervical Proprioception, Visual Feedback is More Important than Vestibular Functionality

In some instances, cervical proprioception cannot be regained, leaving only visual and vestibular feedback. In these cases, visual feedback should be targeted for augmentation to resolve head-body orientational defect. Improving visual field and contrast sensitivity have shown to have more impact than the acuity itself [44]. In lateral rotation, vestibular feedback does not play a significant role except for when forced to worked independently. That is not to say that vestibular function isn't important for overall orientation in the horizontal field, as a gravitational indicator. However, exploring this dimension was outside the scope of this study.

4.3 Vestibular Feedback is Redundant in the Presence of Visual Feedback and Cervical Proprioceptive Feedback

It is well documented that visual and vestibular interactions are prevalent in motion, balance, head motion and target recognition [45-49]. While visual feedback has greater effect in certain instances (i.e. compensation for displacement of eyes vs body, linear horizontal self-motion [47][49]), vestibular is useful in others (i.e. dynamic analyzing range [49]). However, when it comes to lateral orientation, it is common knowledge that vestibular information is indistinguishable at constant velocity while visual can still be useful. Furthermore, acceleration and self-motion have been shown to be dictated by the entire visual field of the observer [50]. Knowing this information, along with the results from Figure 8 (proprioception + visual and proprioception + vestibular are shown to have no statistical significance), we can inference that vestibular information is redundant as visual provides enough information for the orientational awareness. Due to the higher dynamic range [49], vestibular can be said to give a higher resolution and aid in minute precision calibrations.

4.4 Direct Augmentation of Cervical Proprioception Should be Targeted the Most for Resolving Defects in Head-Body Orientation

While the main objective of this study was to characterize the effect of the senses necessary for this rotational awareness, we hoped to open a dialogue about the proper approach for sensory augmentation to help head-body orientation perception defects. It's clear from this study that augmenting the cervical spine, when possible, should always be the approach taken as a reliable cervical proprioception yields the best results in instances of isolated use. It even is more preferable than visual and vestibular feedback paired together (Fig. 9). While direct haptic augmentation has been attempted in many cases [30-33][51], the most efficient haptic augmentation method still needs to be further researched. We aim to do this by testing results with electrical stimulation on the cervical muscles.

4.5 Electrical Stimulation: Muscles for Electrical Stimulation of the Cervical Spine Region

Knowing that direct stimulation of the cervical spine muscles is the method of proper electrical augmentation of the cervical spine proprioception the next concern is knowing the location of stimulation for each proprioceptive direction; horizontally up and down, and laterally left and right. These directions can be thought of as up, down, left and right rotations. An important recent study [52] showed the amplified EMG signals in cervical neck muscles due to isometric contractions when a left yaw moment, right yaw moment, flexion moment and extension moment were all applied to the head. Indwelling electrodes were placed on the right and left sternohyoid

(STH), splenius capitis (SPL), semispinalis capitis (SPC), multifidus (MUL), obliquus capitis inferior (OCI), and rectus capitis posterior (RCP) muscles (SOURCE). Indwelling these electrodes allowed for isolation in the dorsal neck muscles with limited cross-talk. Transcutaneous electrodes were placed on the SCM muscles on both sides of the cervical spine. The results found increased level of activity in the right SCM, left SPL, and left OCI in left-yaw contractions, increased activity in the left SCM, right SPL, and right OCI in right-yaw contractions, increased activity in both STH's and RCP's and SCM's during flexion contractions, and both SPL and MUL in extension contractions.

To keep the transcutaneous electrical system, localize and remove redundant stimulation, the electrical stimulation of the MUL will be removed as it runs down the entire spine and the flexion sensation can be accomplished via the SCP. OCI and RCP will be removed from consideration for stimulation as they are over one another but elicit different sensations that would be contradictory. A transcutaneous method for stimulation would not be ideally feasible. This leaves the SCM, STH, SPL, and SPC (Figure 12) as locations desired for electrical stimulation. Figure 13 shows which muscles saw increased activity level in each contraction direction.

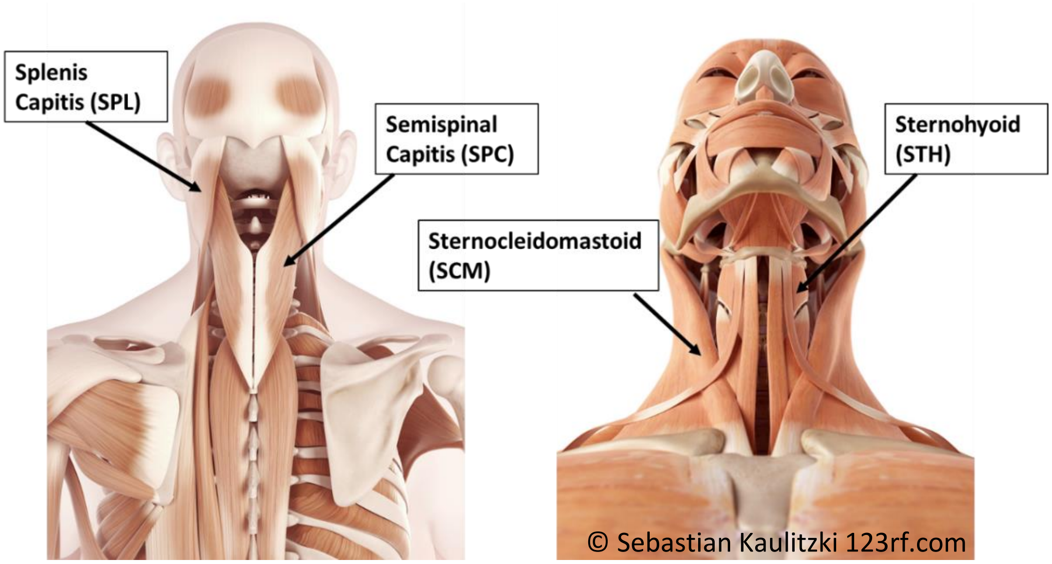


Figure 12. Muscles chosen for electrical stimulation

The four muscles indicated in the figure (SCM, SPC, SCM, STH) show the muscle groups that will be electrically stimulated for modulation of head-body rotational perception. Both right and left sides of the muscles will be targeted.

Muscle(side)	Left Yaw	Right Yaw	Flexion	Extension
SCM(R)		X	X	
SCM(L)	X		X	
STH(R)			X	
STH(L)			X	
SPL(R)	X			
SPL(L)		X		
SPC(R)				X
SPC(L)				X

Table 2. Activation chart of muscles under isometric moments

The table shows the muscles activated under each contraction direction. An 'X' represents a muscle group that showed activity. No 'X' represents no activity seen.

4.6 Electrical Stimulation: Role of Muscle Spindles in Proprioception

Muscle spindles are receptors that convey the stretch or contraction of muscles to the central nervous system. This information is then relayed to the brain via the dorsal column to create the sensation of proprioception. Motor and sensory components are present in the muscle spindles. Type 1a sensory fibers wrap around muscle fibers located within the spindle. These fibers wrap in a spiral pattern and allow for responses in both stretch and velocity changes. When movement occurs sodium channels within the membrane of the sensory neurons open to allow for sodium ions to enter the membrane and increase the electrical potential across the membrane. At rest the potential across the membrane is -70mV. As these ions begin cross the membrane, the potential will increase. Once the threshold potential is reached at -55mV, voltage-gated channels open allowing for a depolarization of the neuron and a significant increase in the potential (~40mV). This process along with the repolarization of the cell is known as an action potential. The action potential sets off a chain reaction as it propagates down the axon to sending an electrical signal with it. As the voltage changes in one region, the local current is strong enough to change the voltage of the regions around it causing a flow of current that travels along the axon to the axon terminal. The signal is converted to a chemical signal which is passed along to the dendrites of another neuron to be converted back into an electrical signal again. This signal is eventually sent to the central nervous system which relays the information to the brain.

4.7 Electrical Stimulation: Hypothesis and Rationale

The primary cause of our proprioceptive sensation is action potentials within muscle spindles. For this reason, we aim to augment these to elicit a pseudo-sensation. This would be a sensation that is a result of an electrically-evoked action potential rather than a potential that is a result of natural biological response to motion. By passing a current through the muscles, the muscle spindles, and in turn the sensory fibers wrapping around these motor fibers, will gain charge and become polarized. This polarization will trigger an action potential which will send pseudo-information down the neural pathway, to the CNS, and to the brain where it will process this information based on the afferent signal received. Voltage amplitude and frequency vary by person and muscle type. The frequency of the external electrical signal applied is dependent on the firing rate of the muscle in question. The firing rate is dependent on the refractory period, a period where the neuron can't respond to other signals due to its depolarized state. For the SCM muscle it is known that the frequency of firing ranges from 9-40ms between fired signals [53]. This leads to the rationalization for inputting a signal of 100Hz (10ms between fires) for electrical stimulation assuming surround muscles behave similarly. The voltage will be variable between subjects as internal resistance (which will effectively control the current) varies between people and muscles.

Using the results from the study discussed in section 4.5 and Table 2 we begin to see a clearer picture on which muscle or muscle groups need to be stimulated to correspond to a desired proprioceptive sensation. Both left and right SCM and STH should be aimed for evoking an illusion of proprioception in the downward direction (flexion). Both left and right SCM and STH are contracted when the neck is in flexion, therefore augmenting the muscle spindle activity in this region would evoke an illusion of proprioception in the downward direction. Both left and right SPC are contracted for upward motion (extension), therefore augmenting the muscle spindle activity in this region would elicit an illusion of proprioception in the upward direction. For lateral yaw(left/right) rotation sensation right SCM with left SPL should be stimulated for proprioception in the right yaw rotation direction. These two muscles are contracted in right head turn motions, therefore excited these spindles should electrically-evoke a proprioceptive sensation in the right-yaw direction. Following this same logic, left SCM with right SPL should be stimulation for left yaw rotation. For transcutaneous electrical stimulation a biphasic pulse across the muscle will be used. The biphasic pulse, as opposed to monophasic, was selected as biphasic has been shown to have less adverse skin effects on those treated with it [54].

4.8 Electrical Stimulation: Electrical Stimulation of the Cervical Spine Region

To create the biphasic pulse an H-bridge was designed to allow for the switching of polarities of the signals. The outputs of the H-bridge (where a motor would typically be located) are connected to the pair of gel electrodes, which will fluctuate from positive to negative polarities as the H-bridge changes logic. The input signals are sent from an Arduino microcontroller (Arduino Mega 2560). Here a code to feed 2 different pulses of the same frequency (100Hz, 10% duty cycle, 3.3V) with one pulse delayed by the width of the other are sent in to the two logic inputs of the H-bridge. Values for transcutaneous stimulation can be expected to range from 10-25V, which far exceed what the microcontroller can output. For this reason, a level shifter that shifts the microcontrollers output voltage up to a value determined by a variable power supply source. The full circuit is shown in Figure 13 with specific parts used (CD4007 CMOS, 2N3904 NPN), with the expected and actual inputs and outputs of the circuit shown below in Figure 14.

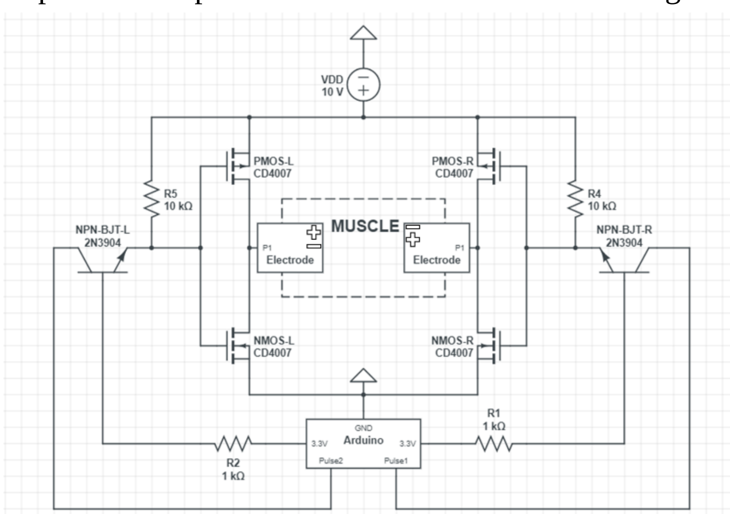
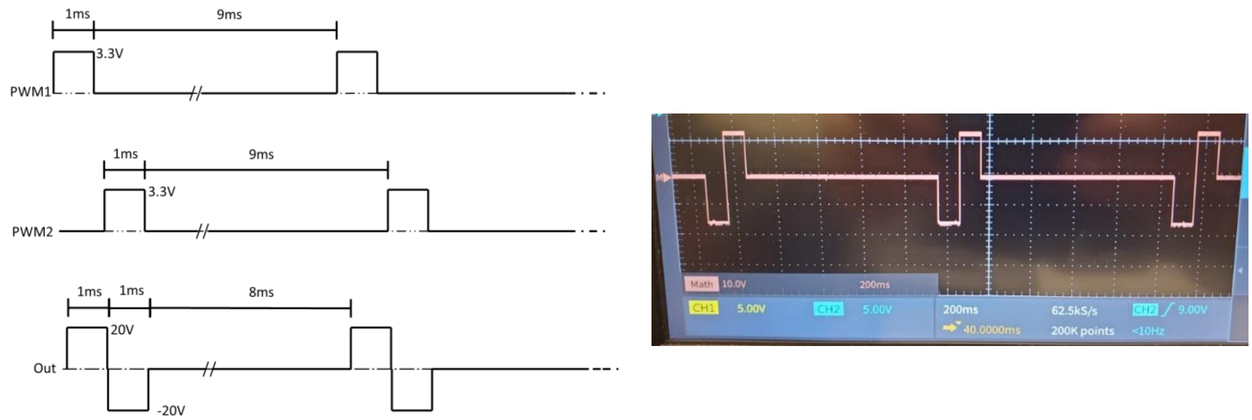


Figure 13. Circuit used for biphasic pulse generation



Two individual pulses from the same MCU source were used to create a biphasic pulse at 100Hz. The left shows the expected inputs and resultant signal. The right shows the actual waveform received from the biphasic pulse generator.

Figure 14. 100Hz biphasic signal.

Preliminary self-tests have been done with mild perception augmentation sensation in the upwards horizontal direction through stimulation of the STH, yaw-rotation perception sensation through stimulation of the SCM and perceived downwards sensation via stimulation of the STH. Quantitative data has yet to be recorded. A full system integrating 8 gel electrode pairs along the SMC, STH, SPL, and SPC pairs of muscles is hopeful by the end of the semester, which will allow for a full test with quick stimulation of multiple muscle regions at once.

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APPENDIX A

MATLAB CODE

```
% Optitrack / Matlab
function NatNetPollingSample

    prompt = 'Test Name and Number?';

    Trial = input(prompt,'s');
    filename = strcat(Trial,'.xlsx');
    recycle on; % Send to recycle bin instead of permanently deleting.
    delete(filename); % Delete (send to recycle bin).
    Data = [];
    i = 0;
    t0 = clock;
    prompt = 'What is the Rate of return for the camera?';
    ReturnRateSkew = input(prompt);


    clear s;
    clear MEGA;

fprintf( 'NatNet Polling Sample Start\n' )

% create an instance of the natnet client class
fprintf( 'Creating natnet class object\n' )
natnetclient = natnet;

% connect the client to the server (multicast over local loopback) -
% modify for your network
fprintf( 'Connecting to the server\n' )
natnetclient.HostIP = '127.0.0.1';
natnetclient.ClientIP = '127.0.0.1';
natnetclient.ConnectionType = 'Multicast';
natnetclient.connect;
if ( natnetclient.IsConnected == 0 )
fprintf( 'Client failed to connect\n' )
fprintf( '\tMake sure the host is connected to the network\n' )
fprintf( '\tand that the host and client IP addresses are correct\n\n' )
return
```

```
end

% get the asset descriptions for the asset names
model = natnetclient.getModelDescription;
if ( model.RigidBodyCount < 1 )
return
   end


   MEGA =  arduino('COM4');
   s = servo(MEGA, 'D7');
   configurePin(MEGA,'A8','DigitalInput');

   java.lang.Thread.sleep( 10 );
data = natnetclient.getFrame; % method to get current frame
   initialx = (data.RigidBody( 1 ).x * 1000)-(data.RigidBody( 2 ).x * 1000);
   initialy = (data.RigidBody( 1 ).y * 1000)-(data.RigidBody( 2 ).y * 1000);
   initialz = (data.RigidBody( 1 ).z * 1000)-(data.RigidBody( 2 ).z * 1000);
   MagInitial = sqrt(initialx^2 + initialz^2);
   initialTime = data.Timestamp;



% Poll for the rigid body data a regular intervals (~1 sec) for 10 sec.
fprintf( '\nPrinting rigid body frame data approximately every second for 10 seconds...\n\n' )

   t0 = clock;
   while etime(clock, t0) < 10 %%Change Time Period
java.lang.Thread.sleep( 10 );
data = natnetclient.getFrame; % method to get current frame


if (isempty(data.RigidBody(1)))
fprintf( '\tPacket is empty/stale\n' )
fprintf( '\tMake sure the server is in Live mode or playing in playback\n\n')
return
end

         if(readDigitalPin(MEGA,'A8') == 0)
         disp('1');

         Currentx = (data.RigidBody( 1 ).x * 1000)-(data.RigidBody( 2 ).x * 1000);
         Currenty = (data.RigidBody( 1 ).y * 1000)-(data.RigidBody( 2 ).y * 1000);
         Currentz = (data.RigidBody( 1 ).z * 1000)-(data.RigidBody( 2 ).z * 1000);

         DotProduct = (initialx*Currentx + initialz*Currentz);
```

```
  MagCurrent = sqrt(Currentx^2 + Currentz^2);
  AngleRadians = acos(DotProduct/(MagInitial*MagCurrent));
  AngleDegrees = AngleRadians*(180/3.14);

  if (Currentx >= initialx)
     angle = 0.5 + double(abs(AngleDegrees/180));
  elseif (Currentx <initialx)
     angle = 0.5 - double(abs(AngleDegrees/180));
     AngleDegrees = -AngleDegrees;
  end


  fprintf('%0.3f %8.3f\n %8.4f\n', [AngleDegrees,angle]');
  writePosition(s, angle);
  i = i+1;
  A(i) = AngleDegrees;
  Time(i) = data.Timestamp - initialTime;

  end
if(readDigitalPin(MEGA,'A8') == 1)
  disp(ReturnRateSkew);
  ReturnRateSkew = 1;
  Currentx = (data.RigidBody( 1 ).x * 1000)-(data.RigidBody( 2 ).x * 1000);
  Currenty = (data.RigidBody( 1 ).y * 1000)-(data.RigidBody( 2 ).y * 1000);
  Currentz = (data.RigidBody( 1 ).z * 1000)-(data.RigidBody( 2 ).z * 1000);

  DotProduct = (initialx*Currentx + initialz*Currentz);
  MagCurrent = sqrt(Currentx^2 + Currentz^2);
  AngleRadians = acos(DotProduct/(MagInitial*MagCurrent));
  AngleDegrees = AngleRadians*(180/3.14);

  if (Currentx <= initialx)
     angle = 0.5 + ReturnRateSkew*double(abs(AngleDegrees/180));
  elseif (Currentx >initialx)
     angle = 0.5 - ReturnRateSkew*double(abs(AngleDegrees/180));
     AngleDegrees = -AngleDegrees;
  end


  fprintf('%0.3f %8.3f\n %8.4f\n', [AngleDegrees,angle]');
  writePosition(s, angle);
  i = i+1;
  A(i) = AngleDegrees;
  Time(i) = data.Timestamp - initialTime;

  end
```

```
end
disp('NatNet Polling Sample End' )
   Label = {'Time(s)','Angle(degrees)'};
   tableData = table(Time',A');
   tableData.Properties.VariableNames = {'Time(s)','Angle(degrees)'};
   writetable(tableData,filename);

   plot(Time,A);

   totallow = 0;
   totalup = 0;
   lowcount = 0;
   highcount = 0;
   prompt = 'What is the lower bound time(s)?';
   LowerBound = input(prompt);
   prompt = 'What is the upper bound time(s)?';
   UpperBound = input(prompt);

   for i = 1:length(A)
      if Time(i) <= LowerBound
      totallow = A(i) + totallow;
      lowcount = lowcount + 1;
      end
      if Time(i) >= UpperBound
      totalup = A(i) + totalup;
      highcount = highcount + 1;
      end
   end
   StartAverage = abs(totallow/lowcount);

   EndAverage = abs(totalup/highcount);

   Difference = abs(StartAverage - EndAverage)
   difftitle = {'Difference(degrees)'};
   xlswrite(filename,difftitle,1,'C1');
   xlswrite(filename,Difference,1,'C2');

end

%StoreData(Variance/NonAbsoluteValues)

prompt = 'Name of Subject?';
name = input(prompt,'s');
prompt2 = 'What Test is being run?';
testname = input(prompt2,'s');
```

```
%prompt3 = 'How many trials per test?';
%Trials = input(prompt3, 's');
NameAndTest = strcat(name,testname);
difference = 0;
Totaldifference = 0;
FileForData = strcat(name,'VarData');
char dataCol;

%for i = 1:str2num(Trials)
for i = 1:8

file = strcat(NameAndTest,num2str(i));
dataLoc = num2str(i+1);

if strcmpi('All',testname)
        dataCol = 'B';
    elseif strcmpi('AllDelay',testname)
        dataCol = 'C';
    elseif strcmpi('EyesClosed',testname)
        dataCol = 'D';
    elseif strcmpi('EyesClosedDelay',testname)
        dataCol = 'E';
    elseif strcmpi('OpenVest',testname)
        dataCol = 'F';
    elseif strcmpi('OpenVestDelay',testname)
        dataCol = 'G';
    elseif strcmpi('ClosedVest',testname)
        dataCol = 'H';
    elseif strcmpi('ClosedVestDelay',testname)
        dataCol = 'I';
end
LocCoord = strcat(dataCol,dataLoc);

difference1 = mean(xlsread(file,1,'B2:B25'));
final1 = strcat('B',num2str(length(xlsread(file))));
final2 = strcat('B',num2str((length(xlsread(file))-17)));
final = strcat(final1,':',final2);
difference2 = (mean(xlsread(file,1,final)));

difference = abs(difference2 - difference1);
if difference1 > difference2
    difference = difference * -1;
    disp('OVER');
    disp(i);
end
```

```
xlswrite(FileForData,difference,1,LocCoord);

Totaldifference = difference + Totaldifference;
end

Average = Totaldifference/8

ColumnLabels =
        {'All','AllDelay','EyesClosed','EyesClosedSlow','OpenVest','OpenVestSlow','ClosedVest',
        'ClosedVestSlow'};
xlswrite(FileForData,ColumnLabels,1,'B1');

aveLoc = str2num(Trials)+2;
stdLoc = str2num(Trials)+3;
aveLabLoc = strcat('A',num2str(aveLoc));
stdLabLoc = strcat('A',num2str(stdLoc));
avelabel = {'average'};
stdlabel = {'std'};
xlswrite(FileForData,avelabel,1,aveLabLoc);
xlswrite(FileForData,stdlabel,1,stdLabLoc);

if strcmpi('All',testname)
    xlswrite(FileForData,Average,1,strcat('B',num2str(aveLoc)));
    elseif strcmpi('AllDelay',testname)
        xlswrite(FileForData,Average,1,strcat('C',num2str(aveLoc)));
    elseif strcmpi('EyesClosed',testname)
        xlswrite(FileForData,Average,1,strcat('D',num2str(aveLoc)));
    elseif strcmpi('EyesClosedDelay',testname)
        xlswrite(FileForData,Average,1,strcat('E',num2str(aveLoc)));
    elseif strcmpi('OpenVest',testname)
        xlswrite(FileForData,Average,1,strcat('F',num2str(aveLoc)));
    elseif strcmpi('OpenVestDelay',testname)
        xlswrite(FileForData,Average,1,strcat('G',num2str(aveLoc)));
    elseif strcmpi('ClosedVest',testname)
        xlswrite(FileForData,Average,1,strcat('H',num2str(aveLoc)));
    elseif strcmpi('ClosedVestDelay',testname)
        xlswrite(FileForData,Average,1,strcat('I',num2str(aveLoc)));
end
```

%StoreData(AbsoluteValue)

```
prompt = 'Name of Subject?';
name = input(prompt,'s');
prompt2 = 'What Test is being run?';
testname = input(prompt2,'s');
prompt3 = 'How many trials per test?';
```

```
Trials = input(prompt3, 's');
NameAndTest = strcat(name,testname);
difference = 0;
Totaldifference = 0;
FileForData = strcat(name,'Data');
char dataCol;

for i = 1:str2num(Trials)

file = strcat(NameAndTest,num2str(i));
dataLoc = num2str(i+1);

if strcmpi('All',testname)
        dataCol = 'B';
    elseif strcmpi('AllDelay',testname)
        dataCol = 'C';
    elseif strcmpi('EyesClosed',testname)
        dataCol = 'D';
    elseif strcmpi('EyesClosedDelay',testname)
        dataCol = 'E';
    elseif strcmpi('OpenVest',testname)
        dataCol = 'F';
    elseif strcmpi('OpenVestDelay',testname)
        dataCol = 'G';
    elseif strcmpi('ClosedVest',testname)
        dataCol = 'H';
    elseif strcmpi('ClosedVestDelay',testname)
        dataCol = 'I';
end
LocCoord = strcat(dataCol,dataLoc);

difference = xlsread(file,1,'C2');
xlswrite(FileForData,difference,1,LocCoord);

Totaldifference = xlsread(file,1,'C2')+ Totaldifference;
end

Average = Totaldifference/str2num(Trials)


ColumnLabels =
        {'All','AllDelay','EyesClosed','EyesClosedSlow','OpenVest','OpenVestSlow','ClosedVest',
        'ClosedVestSlow'};
xlswrite(FileForData,ColumnLabels,1,'B1');

aveLoc = str2num(Trials)+2;
```

```
stdLoc = str2num(Trials)+3;
aveLabLoc = strcat('A',num2str(aveLoc));
stdLabLoc = strcat('A',num2str(stdLoc));
avelabel = {'average'};
stdlabel = {'std'};
xlswrite(FileForData,avelabel,1,aveLabLoc);
xlswrite(FileForData,stdlabel,1,stdLabLoc);

if strcmpi('All',testname)
    xlswrite(FileForData,Average,1,strcat('B',num2str(aveLoc)));
    elseif strcmpi('AllDelay',testname)
        xlswrite(FileForData,Average,1,strcat('C',num2str(aveLoc)));
    elseif strcmpi('EyesClosed',testname)
        xlswrite(FileForData,Average,1,strcat('D',num2str(aveLoc)));
    elseif strcmpi('EyesClosedDelay',testname)
        xlswrite(FileForData,Average,1,strcat('E',num2str(aveLoc)));
    elseif strcmpi('OpenVest',testname)
        xlswrite(FileForData,Average,1,strcat('F',num2str(aveLoc)));
    elseif strcmpi('OpenVestDelay',testname)
        xlswrite(FileForData,Average,1,strcat('G',num2str(aveLoc)));
    elseif strcmpi('ClosedVest',testname)
        xlswrite(FileForData,Average,1,strcat('H',num2str(aveLoc)));
    elseif strcmpi('ClosedVestDelay',testname)
        xlswrite(FileForData,Average,1,strcat('I',num2str(aveLoc)));
end
```