DISSERTATION

SOUND, CENTRAL AUDITORY NERVOUS SYSTEM FUNCTION AND HUMAN GAIT

THE EFFECT OF QUIET AND LOCALIZED SOUND SOURCES ON THE GAIT OF PEOPLE WITH NORMAL AND ATYPICAL CENTRAL AUDITORY NERVOUS SYSTEM FUNCTION

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY CHARLES HUBBELING ENTITLED SOUND, CENTRAL AUDITORY NERVOUS SYSTEM FUNCTION AND HUMAN GAIT BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

SOUND, CENTRAL AUDITORY NERVOUS
SYSTEM FUNCTION AND HUMAN GAIT

A kinematic gait analysis system was used to determine the 3-D motion of human gait under varying sound conditions. This analysis was conducted in nine adults with normal central auditory nervous system (CANS) function (Group1), and nine adults with CANS dysfunction (Group2). The analysis was completed with reduced lighting in a semi-anechoic chamber fitted with five speakers around the calibrated gait area. Seven sound cases were presented to each subject: for five localized sound (LS) inputs, muffed under a reduced sound (RS) condition, and natural walking under RS.

The objectives of this study were to (1) quantify the gait and head movement of people in Group1 and Group2, (2) determine the difference of the gait between the groups induced by localized sound sources, and (3) demonstrate the correlation between Central Auditory Processing Test Battery diagnosis and the gait of Group2.

This study found that the gait in both groups is affected by the presence of sound. In going from RS to LS, both groups have opposite responses. For RS, Group1 reduces walking speed and stride width while lowering the head towards the chest when compared to LS. Group2, in contrast, increases stance width, and walking speed, and lowers the head more for RS than for LS. Group2 was also found to have a wider variance in head nod than Group1.

This study found that the drifting of the center of mass (COM) in the lateral (Z) direction for Group2 changes significantly under LS. Interestingly, two sub-groups within Group2 have different COM movement dependent upon the diagnosis of weak-ear. Also, the movement of the head in the transverse plane was found to be significantly different between Group1 and Group2 for RS versus LS.

This study was the first to show the difference in gait between groups of people based upon CANS function. Furthermore, the reduced visual stimuli of this study may have emphasized the impact of the localized sound input on human gait. This research helps set parameters for forthcoming studies into the effect of sound on human motor function.

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Charles Hubbeling
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1. INTRODUCTION

1.1 Introduction

This chapter acquaints the reader with the present study and the associated literature background. Studies that have researched the efficacy of sound localization in humans are presented as well as project related gait analysis investigations. The central auditory nervous system (CANS) and connected Central Auditory Processing (CAP) tests are introduced. The importance of the project is emphasized through the lack of related research on the subject of sound, the central auditory nervous system and human gait.

1.2 Project Motivation

This biomechanical project was part of a larger investigation into the rehabilitation and function of people with central auditory nervous system (CANS) dysfunction (See Section 1.3 for CANS information). Dr. Joan Burleigh of Colorado State University has done extensive work with patients diagnosed with CANS dysfunction (Burleigh, 1996; Willeford and Burleigh, 1985; Willeford and Billger, 1978). During her preliminary study of one such subject, the person displayed improved motor function under various sound conditions (J. Burleigh, personal communication, August, 1997; Burleigh et al., 1999a; Burleigh et al., 1999b). Continuing this preliminary study, this current work complemented Dr.

Burleigh's research by biomechanically quantifying the influence of sound on human gait.

The research hypotheses of this dissertation concerning auditory input were formed after viewing the video data from the preliminary study subject. In the presence of sound, the subject with CANS dysfunction moved her head from side to side during an auditory condition that was later found to be most adverse for her motor and speech function. Side-to-side head movement is the primary method for auditory localization (Durlach, 1991; Middlebrooks and Green, 1991). However, it has been shown that during normal gait the head moves primarily in the vertical plane, with little side-to-side movement (Cappozzo, 1981; Perry, 1992). Thus, although sound was not a parameter in these two studies (nor was it controlled), it was assumed that the increased head movement seen in the pilot gait study was due to adverse auditory conditions. It was also assumed the subject's head movement was an attempt to reduce the effect of her CANS dysfunction on her ability to properly localize sound.

As reasoning for this movement, there is an indication that the motor and sensory systems are connected (Baloh and Honrubia, 1990; Casseday and Covey et al., 1987). Ishikawa et al. (1994) ran a gait study on people with unilateral peripheral vestibular disorders using foot switches and electromyography. This study found a correlation between reduced visual cues (eyes closed) and increased variance of gait parameters such as the time from hind foot strike to forefoot strike.

It was hypothesized that humans react to their environment through several orientation methods including visual and auditory localization (Stiles-Davis et al., 1988). Visual orientation was by far the most prevalent found by scientific research (See reference list in Georgopoulos, 1998), but auditory orientation has also been shown to have an impact (See reference lists in Schöne, 1984).

Mountcastle (1998) found the cortexes of the brain are arranged in vertical columns connected through horizontal projections. Summarizing studies of animal sensory development, Moore (1992) showed an association between the visual and auditory spatial mapping capabilities that was emphasized when the stimulation to the visual system was subdued. By dark-rearing guinea pigs, the topographic representation of auditory space in the superior colliculus was abolished. Even though the superior colliculus is not part of the primary auditory pathway, this finding showed definite influence between the two systems.

Realizing this connection between the systems of the brain, it was hypothesized that the focal source of sound has a great effect on people's navigation, especially in low-light situations. To the author's knowledge, the simultaneous study of sound localization and gait had not been previously undertaken. Using the hypothesis that gait is influenced by the location of sound, it was further speculated that by anchoring a sound during walking, the human system could then react to the surrounding environment.

Just as the sensory system depends upon visual cues for spatial orientation, it also depends upon auditory localization for spatial cues (Berthoz et al., 1993; Wasiams, 1983). This is especially true when the availability of visual cues are reduced or are masked such as in low light conditions or from physical impairment. Consequently, localization and sound input could become more important to motor control in these conditions. Based on sound localization and motor connections, a study was inspired to investigate the effects of auditory input upon motor control of humans with normal and atypical CANS function.

1.3 Central Auditory Nervous System Literature Review

This section acquaints the reader with the CANS and the Central Auditory Processing (CAP) test battery. This information pertains to the method of diagnosis of a CANS disorder that was completed by Dr. Joan Burleigh.

The complex auditory system is grossly divided into two separate parts. The peripheral auditory mechanism consists of the external, middle, and inner ears and the vestibulocohlear nerve (CN VIII) (Marieb, 1995). The inner ear is made up of the cochlea utricle, saccule, and semicircular canals and the vestibular system. This apparatus contains three semicircular canals (or kinetic labyrinth) and the vestibule (or static labyrinth). The semi-circular canals approximate the three-dimensional axis of the human motor system, and respond to head movement. The vestibule responds to head position and linear acceleration.

The CANS involves the remainder of the auditory system and grossly begins at the cochlear nucleus in pons-medulla where CN VIII terminates. The neurons of the CANS follow a pathway through the brainstem, cerebellum, and into the cortex of the temporal lobe. The neurons cross to the contra-lateral side at various levels allowing for bilateral auditory processing and thus, localization.

The information transmitted from the peripheral auditory system to the CANS must be received bilaterally in a synchronous manner in order to trigger the binaural response of the brainstem and cortex. This is especially true at the levels of the superior olivary complex, the reticular activating system and the cortex (Nolte, 1981). While the pathways of the brainstem are clearly delineated. the cortical functioning of the auditory system is less well described. However, Brodmann's areas 41 and 42 are known to house the primary auditory cortex on the superior gyrus of the temporal lobe.

Processing difficulties in the CANS can be functionally delineated by using a central auditory processing battery of tests. These tests are broken down into four classifications (Willeford and Burleigh, 1985):

> (1) tests in which speech stimuli are presented monotically (one ear at a time), including patterned or distorted verbal messages, messages that are embedded in competing signals, and pattern sequencing tasks with tones, the latter being a notable exception to the use of speech; (2) tests that present stimuli in a dichotic paradigm (different signals presented to the two ears at the same time [*sic*]; (3) tests that require the listener to

sequence or sum complementary signals that are spatially separated in the two ears, and (4) electrophysiologic tests that objectively measure the physiologic response to auditory stimulation. (p. 98)

1.4 Auditory Localization Literature Review

To fully understand the connection of sound and the human sensory system, this portion of the paper will present relevant localization studies and discuss the connections between the CANS disorders and the inability to localize sound. Finally, the technique of measuring localization in an anechoic chamber is given for later reference.

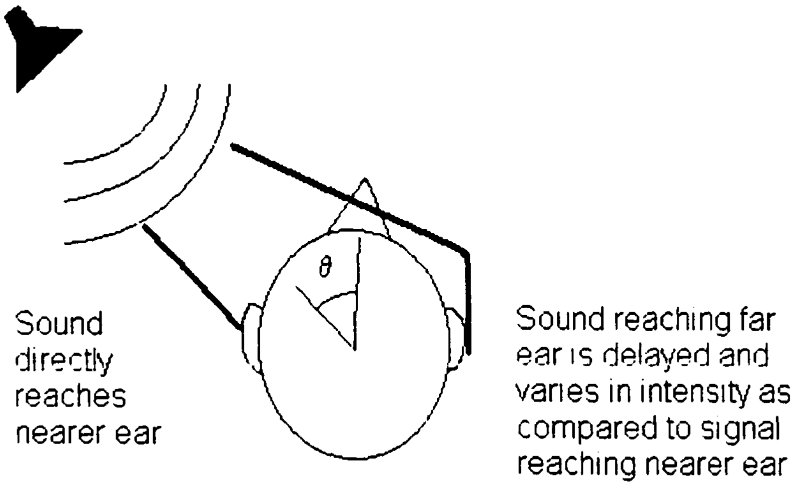
It is interesting to note that in general people with a CANS dysfunction have normal peripheral auditory function. However, they cannot integrate the auditory information in a meaningful manner (Burleigh, 1997). It is well established that noise or background sound has an effect on many different types of human function (Pollack and Rose, 1967).

Willeford and Billger (1978) and Burleigh (1996) address children's lack of speech recognition in the presence of background noise. Fay and Feng (1987) tells of how noise or the "cocktail party" effect is a significant problem for people with auditory disabilities. Noble et al. (1995) conducted a survey that showed, albeit anecdotally, that sound location can pose an every-day problem for people with sensiorineural or mixed/conductive hearing loss, especially in noisy environments.

Auditory localization, the perceived location of a given sound source, is an example of between-ear intensity and time differences in sound. Auditory localization is based upon these interaural time differences (ITD) and interaural sound intensity differences (IID) that vary upon the location of a sound source (Häusler et al., 1983). They are produced by the interaction of the human torso, head and external ear (pinna) with an incoming sound. By turning the head, the human sensory system attempts to change the IIDs and ITDs of the incoming sound source, thus the typical side-to-side head movement when trying to localize. The interaural differences caused by these reflections and diffractions are used as cues by the human sensory system to locate a sound source (Kuhn, 1987).

Several models of ITDs and IIDs have been developed, and most assume symmetry of the head. Middlebrooks and Green (1991) constructed a model with a sine function: $Delay = \left(\frac{Head\ Radius}{c}\right)[\theta + \sin(\theta)]$ where c is the speed of sound in air and theta is the azimuth angle of the sound source (See Figure 1.1).

Figure 1.1 – Simplified diagram of Auditory Localization



This model is valid for gross localization measurements (Middlebrooks and Green, 1991) and helps to account for the front/back sound source confusion that is often seen (Häusler et al., 1983). This confusion manifests itself when a subject believes that a sound is coming from the rear rather than from the front, and vice-versa. This is due to the sine function in this having an ambiguity of $\sin(\theta) = 0$ at $\theta = 0$ or a multiple of π.

Human sound localization has been extensively researched by several authors (Durlach, 1991; Häusler et al., 1983; Middlebrooks and Green, 1991; Noble et al., 1997; For earlier review see Searle et al., 1976). The general method for testing localization is to seat the subject before an array of speakers in an anechoic chamber (Noble and Byrne, 1990; Noble et al., 1995).

An anechoic chamber (i.e., a room with minimal reverberation) has also been used in the study of sensorineural hearing loss. McAlister (1990) tested the use of several different types of hearing aids in a semi-anechoic chamber. An array of different test sounds was also explored: speech, noise, and a four-talker babble tape. By testing the speech discrimination of ten normal-hearing subjects, the hearing aids' lack of correction for sensorineural loss was shown to be a large factor of error in noisy environments.

In Noble et al. (1994) sound was presented in an anechoic chamber to a subject sitting in front of a large cross of speakers, the center of which was at head height. The two hemicircumferential arcs (1.22m radius) contained twenty 10-cm-diameter loudspeakers. The loudspeakers were 18 degrees apart with five in each arm of the cross. Noble tested the subjects both frontally and laterally with recorded pink noise. This noise had equal energy per third-octave band from 0.25 to 8 kHz and consisted of 150 ms bursts that totaled 0.9 seconds. The subjects were free to move their head and torso, and responded by identifying the location of the source for each of the twenty trials. Noble found that the sensorineural hearing-impaired listeners (N = 87) had deficits in localization ability related to the configuration of their hearing loss.

1.5 Head Motion Literature Review

This section provides an introduction into current research of head motion during gait. The movement of the head has been found to be significant for the control of movement. Most important in this section is the study by Pozzo et al. (1990,1991) who present recent findings of the movement of the head. These conditions mirror those found in the gait laboratory used in the present study.

With research such as that performed by Noble, the human system of sound localization has been vigorously studied. The interaction of head motion and auditory localization has also been studied. However to date, the studies have only looked at head motion with the person seated in front of an array of speakers (Noble: et al., 1994; Perrett and Noble, 1997; Pollack and Rose, 1967).

In motion analysis, the movement of the head during locomotion is usually lumped together in models with the arms and trunk (Winter, 1990). Although, researchers have investigated the influence of various conditions on head movement during gait, no one has studied the influence of sound on head movement during gait. None of the following head movement studies controlled for sound.

Waters et al. (1973), showed that the head has definite motion patterns that repeat over three different walking speeds. Waters measured displacement by transducers attached to subjects (N=5) walking on a treadmill. The amplitude of the vertical motion of the head was found to be the same over the three walking speeds at 4.2 cm. However, the lateral displacement of the head was not as consistent. In fact, only one speed, normal pace, produced approximately the same consistent change at 5.0 cm of lateral movement.

In a study of EMG activity of seven normal women (in tennis shoes), Murray et al. (1984) found that normal subjects decrease their walking speed by taking shorter steps. In addition, at slower speeds, the total vertical excursion of the head was less than at greater speeds.

Cappozzo (1981) did a harmonic analysis of head and trunk displacement at different speeds using four 35 mm cameras. This study (N=5) normalized stride length and walking speed to stature and found that the pelvis has greater excursions than that of the head. Along the anterior-posterior axis, Cappozzo (1981) found that the head moved approximately 20 mm with respect to tne pelvis. This result had minor changes attributable to variations in speed. Along the latero-lateral axis, the head moved from approximately 20 to 65 mm with respect to the pelvis. Grossman et al. (1988) also did a frequency analysis of locomotion for the stability of gaze with a search coil system attached to the head. This study (N=9) showed that the head is stabilized in space incompletely but adequately for the vestibulo-ocular reflex.

In two studies, Pozzo et al. (1990, 1991) indicated that head angular rotation is minimized in the vertical plane within a few degrees. Pozzo et al. (1990, 1991) used an optical automatic TV-image processor (E.L.I.T.E. system) and placed 10 markers on 10 subjects (1 female, 9 males). Two of the markers defined the line between the lower border of the eye-socket and the meatus (opening) of the ear. This study also placed markers at the neck (C7 on the trapezius muscle), the shoulder on the acromial process and on the lateral condyle of the elbows and wrist. The other points marked were the iliac crest, the lateral condyle of the knee, the lateral malleolus (ankle) and the 5^{th} metatarsal. Barefoot subjects walked a distance of approximately 6 m at their normal pace in light and then in darkness.

Pozzo et al. (1990, 1991) hypothesized that the motor system is visually coupled to provide a stabile motor base. This study found that the head angle of the ear marker from the vertical was within 6° upward to 10° downward from the earth horizontal.

Most interestingly, for normal subjects in darkness, the mean head angular position is from 3° to 15° downward from the horizontal (head tilted forward). Resting position for the head was found to be 87° ± 6°. However, the vertical head translation (up and down) did not change significantly from light to darkness. Translation and rotation of the head were always in opposite directions. That is to say that when the head translated up during walking, the head also rotated down. In addition, head angular displacement was always higher in darkness than in light (i.e., the head was held down).

Pozzo et al. (1990, 1991) concluded that while the angular displacement was higher, the effect of darkness on head stability was negligible in that the head was held with little if any oscillation. Their supporting theory for this conclusion was that head stabilization and the associated reflex action of the head is under voluntary control. This study found that the relationship between head rotation and translation was compensatory for increased head stabilization.

Additionally, when the inertial guidance system of the body is taxed by lack of visual input, it requires a stable environment for the vestibular system. Thus, Pozzo et al. (1990, 1991) further hypothesized that when head and trunk stabilization is of great importance, the locomotor system will lock the head on the trunk (i.e., holding the chin down towards the chest). Pozzo, et al, found that head oscillations probably decrease in darkness due to this effect.

Finally, Pozzo et al. (1990, 1991) tested the head stabilization of several people with peripheral vestibular deficits (N=7) as determined by the following procedures: caloric test, electrooculography, and gaze stabilization in the horizontal plane. In darkness, these subjects had a slower, wider-based gait than people without vestibular deficits. However, the subjects with vestibular defects of this study did not show the same relationship between head translation and rotation mentioned earlier. This group did not have the same compensatory relationship between head rotation and translation as was found in the normals. In addition, the atypicals showed an increase in head oscillation amplitude and velocity in contrast to the decrease stated earlier.

1.6 Gait and Motion Analysis Literature Review

(Please note: A second review of literature is presented in Section 9.4 for the convenience of the reader. The literature in that section directly relates to the results provided and is referenced there for comparison to collected data.)

This section presents pertinent gait studies that help explain the gait analysis method used in this study. It is shown that gait is both repeatable over time and representative of the sensory-motor system. Several studies are discussed to relate the parameters measured, including: center of mass displacement, asymmetry, and vestibular system testing utility.

In addition to the gait studies mentioned earlier, several have looked at the complexity of the human system in other situations. Walking is an example of a complex succession of propulsion, foot clearance, and balance, requiring a unified effort of the body (Winter, 1990). When this unified effort is not completely fulfilled, the result is an uncoordinated set of actions. This effect has been studied for several conditions including stroke (Wagenaar and Beck, 1992; Özgirgin et al., 1993; Knutsson, 1994; Morita et al., 1995), Parkinson's disease (Klein et al., 1986; Bowes et al., 1990; Blin et al., 1991; Tohgi et al., 1993; Weller et al., 1993), and limb amputation (Boonstra et al., 1993). Gait analysis has also been used to analyze the effect of a hip replacement on a subject's ability to walk (Arnold and Schliebe, 1992), to describe the loads placed upon bodily joints (Seireg and Arvikar, 1975), and to predict movement in pathologic locomotion (Iida and Yamamuro, 1987).

Gait studies have also introduced environmental variables, realizing that gait is an integrative process, taking in many variables. Moe-Nilssen (1998a, 1998b) has developed a system to measure the acceleration of the center of mass of a person that can be worn outside of the laboratory. As a pilot, this study found that using accelerometers strapped near the lumbar spine effectively measures gait and balance.

Some major components of gait are stride length, stride width, double support time, and stance time. The gait cycle measured for this project is that of the period between two heel strikes from the same foot as shown in Figure 1.2.

This complete stride is recorded after several steps so that the gait initiation that happens within the first few steps is complete (Nissan and Whittle 1990).

The ability to measure gross motor function of a subject makes gait analysis useful for sensory-motor interaction quantification. Pozzo et al. (1990, 1991), referenced earlier, showed the influence of light and dark on head and body movement. Hirasaki et al. (1993) confirmed this research in a study of head movements of the elderly in varying light conditions. Subjects were required to walk with eyes open and then repeat the trial with eyes closed.

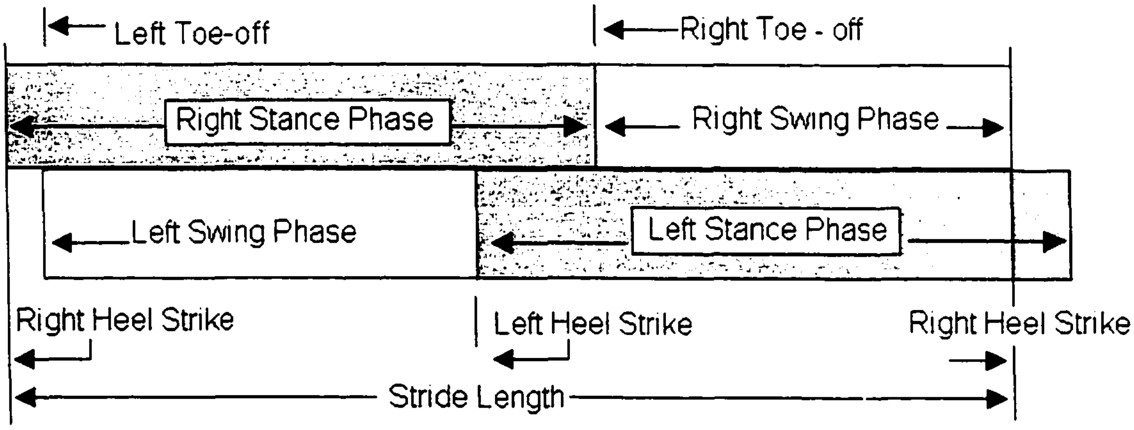


Figure 1.2 – Components of a Gait Stride

As in Pozzo et al.'s studies, the effect of eyes closed on head movement was that of a forward tilt to the head below the earth horizon. In addition, Hirasaki et al. found that step length decreased when the eyes were closed.

In another example of the use of gait as a measure of sensory-motor interaction, Thaut et al. (1992) found that gait symmetry increased when rhythmic auditory cueing in the form of music was applied. By varying the amplitude of a sound input to normal subjects (N = 16), it was found that subject stride time became more even between right and left legs as compared to the no-rhythm case.

In a related study, Thaut et al. (1993) repeated the 1992 study on ten hemiparetic patients who had a recent cerebrovascular accident. In both studies, data was collected along a walkway consisting of voltage coded pressure-sensitive switch mats with a rubber surface. In this latter study during which repeated measurements were taken over several weeks, an improvement of gait symmetry was seen.

Obviously, the abundant amount of background gait data available is an advantage for the use of gait analysis in this project. Normative or baseline data are available for a variety of subjects - including gender specific, age specific, and pathological disorder specific (Dobbs et al., 1993; Elble et al., 1994).

The parameters most often used for motor quantification are joint angle and translational data. These displacements are a combination of transitional and rotational change. By taking derivatives over time, both velocity and acceleration are determined from the positional data (Wasiams, 1992).

The magnitude of one of the velocities is of particular interest - walking speed. This parameter is an excellent measure of gait ability across varying external conditions (Boonstra et al., 1993; Turnbull et al., 1995; Wagenaar and Beck, 1992). By comparing the speed of a person's gait across several conditions, improvement in gait is indicated as data approach the normal speed for the subject's age group.

Likewise, plotting the movement of the center of mass (COM) demonstrates the effective change in a person's gait (Iida and Yamamuro, 1987). The COM is calculated based upon Dempster's anthropomorphic data found in Winter (1990). The change in walking speed and the movement of the COM is plotted versus time and in plane angle maps (Hurmuzlu et al., 1994). The use of these maps is explained in the Method section.

Gait analysis provides an excellent method for the quantification of pathologic motor patterns (Sienko-Thomas and Barnett, 1994; Craik and Oatis, 1995). Assessment of an individual with a disorder includes both comparisons with subject baseline data and with normative gait statistics (Dobbs et al., 1993).

Winter (1984) and Andriacchi (1977) confirm that gait is a repeatable measure. Kadaba et al. (1989) used a VICON™ gait analysis system to measure gait three times a day over three days in normal light without controlled visual or auditory cues for forty normal subjects. Intrasubject repeatability was excellent for kinematic data in the sagittal plane within and between test days. For joint angle motion in the frontal and transverse planes, repeatability was found to be good on same-day testing, but poor on between-day testing.

Being repeatable, kinematic gait measures can be used to compare the power of outside influence and to measure asymmetry parameters. Asymmetries are an important measure of gait normality (Kaufman et al., 1996). It has been shown that if a disproportionate amount of time is spent on one leg versus another, there may be an asymmetry in the pattern of gait (Murray, 1967).

Another form of asymmetry measurement is movement of the center of mass (COM) during the gait cycle. It has been shown that the raising and lowering of the COM is an important factor in gait efficiency (Czerniecki, 1996). Whittle (1997) illustrated that the COM moves in a sinusoidal fashion in all three dimensions, and is shown to be a large factor in motion analysis (Cappozzo, 1981).

Knowing that people with longer legs take bigger steps, gait studies often minimize the influence of height by dividing the walking speed by the subject's height. Benedetti et al. (1998) conducted a kinetic gait analysis (N = 20) with a video E.L.I.T.E.™ system to verify repeatability of kinetic data. Yamasaki et al. (1991) conducted a foot-switch treadmill study of the movement of the lower limbs. Grieve (1968) was one of the first to divide kinematic data by stature to reduce the influence of height. In this study (N = 13), it was shown that adult gait could be modeled as a function of relative gait. Grieve asked subjects to walk at increasing speeds for each trial so that a function could be fit for the data for speed/stature.

1.7 Vestibular System Literature Review

In the present study a vestibular test was given to each subject after each gait test. This procedure helped explore the influence of the vestibular system as a factor in this study. The relationship between the vestibular system and the control of movement, body stability, and balance has been thoroughly studied (for a good review of the associated literature see Baloh and Honrubia, 1990; Marieb, 1995). One function of the vestibular system is to provide feedback to the brain in relation to head position. Nystagmus is an involuntary, rapid, back-and-forth movement of the eyes following stimulation of the semicircular canals of the vestibular system. The Southern California Postrotary Nystagmus Test (SCPNT) is designed to examine this in relation to rotation of the head (Ayres, 1975).

Although the results of the SCPNT are more qualitative than quantitative (Polatajko, 1985), it is a non-behavioral, low-brainstem, tonic vestibular test. The duration of nystagmus after cessation of motion has been correlated to the normalcy of the brain's integrative processes in children (Ayres, 1975). In addition, the SCPNT has been used to evaluate impairments of the vestibular systems in adults, which has been linked to deficits in gross motor coordination (Fisher et al., 1986). Fisher et al. tested 10 adults without dysfunction and 7 with suspected vestibular dysfunction but normal peripheral vestibular responses. This study found post-rotary nystagmus duration in a controlled setting to be a good indicator of tonic vestibular processing dysfunction (i.e., at the level of the brainstem). Fisher went on to caution researchers that the SCPNT does have outside factors such as lighting and measurement method that may affect the results. Consequently, by ruling the vestibular system out as a determinant factor, the effect of sound on gait parameters will become more significant.

1.8 Synopsis of Literature Review

The literature presented in this review primarily deals with the function of the CANS, its connection to the motor system and gait, and the measurement of the function of the human system. Studies are referenced that show the battery of tests used to diagnose a person with a CANS disorder. Sound localization and the CANS are connected and this association may pervade into the motor system as well.

Several studies are presented as background for the analysis of gait. Gait is a repeatable and reliable measure of human gross motor function. Head and COM movement measurement techniques are presented for later reference.

The need was demonstrated for a better analysis of human gross motor function in relation to auditory input. A study of the gait of humans under differing sound conditions has never before been undertaken. By quantifying the gait of people with normal and atypical CANS function, the ability to understand the connection between the sensory and motor systems were enhanced.

2. PROBLEM STATEMENT

The connection between auditory input and human gait had not been previously investigated. This project characterized the effects of auditory input and localized sound upon gait, which was used as a measure of gross motor function. The findings of this biomechanical study were used to explore the connection between sound location and gait performance in people with normal and atypical CANS function.

3. HYPOTHESES

I) The effect of sound on gait can be measured for people with a normally or an atypically functioning CANS.

I.A) The effect of localized sound sources will differ between the two subject groups.

II) The gait of people with a normal CANS is affected in a different manner than the gait of people with an atypically functioning CANS.

II.A) Differences between the two groups in translational and rotational head movement will be demonstrated in relation to the effect of sound.

II.B) The side-to-side movement, drifting and asymmetry will be significantly different between the two groups in relation to sound.

III) The gait of people with an atypically functioning CANS can be correlated to the results of the Central Auditory Processing Test Battery.

4. OBJECTIVES

A) Quantify the gait parameters, CANS function, head movement, vestibular function, and ability to localize sound for people with normal and atypical CANS.

B) Determine the difference of the effect of localized sound sources on the two groups through gait parameters.

C) Measure gait asymmetry under reduced and localized sound.

D) Determine the effects of head movement on walking speed, width, and side to side movement.

D) Analyze the data to determine the variability of gait in both groups as a function of speaker location.

E) Demonstrate the correlation of CAP test battery diagnosis of weak ear to the gait performance of people with an atypical CANS.

5. PROTOCOL DESIGN

5.1 Selection of Auditory Cases

Auditory localization is performed in the human by using the interaural time and intensity differences between the two ears. To recreate the interaural effects of sound in a controlled environment, a semi-anechoic chamber ("chamber") was constructed (See Section 6.1). Within the chamber, an array of five speakers was placed to create a varying auditory environment.

In order to eliminate fatigue as a factor, the test matrix was limited to these five localized sound conditions (LS) in the frontal plane of human hearing and two reduced sound (RS) conditions of muffed (Polter earmuffs, Model 6 A/V, -20 dB) and open (or natural) without amplified sound. Also, to reduce the number of conditions and since sound localization is symmetric about a person's head (See Section 1.4), the 180-degree hemisphere in front of the subject was chosen. Consequently, the array of speakers was presented to the front half of the subject during testing. The test conditions were administered with a randomization routine.

The auditory conditions of this study are listed here for reference:

Condition 1) Walking with earmuffs (Muffed under reduced sound)

Condition 2) Walking without earmuffs (Open under reduced sound)

Condition 3) Localized sound source 90° to left of subject (Speaker one)

Condition 4) Localized sound source 45° to left of subject (Speaker two)

Condition 5) Localized sound source in front of subject (Speaker three)

Condition 6) Localized sound source 45° to right (Speaker four)

Condition 7) Localized sound source 90° to right (Speaker five)

5.2 Population

Twenty subjects participated in the research study (See Section 9.3 for statistical review of population demographics). The subjects ranged from 18 to 59 years of age and were paired on the basis of age and gender. Of these, nineteen finished the study protocol. One subject's data was eliminated from the study due to equipment failure. Of the remaining eighteen, nine had normal CANS function and nine had an atypical CANS function.

Participants with a CANS disorder were originally referred at the Center for Central Auditory Research at Colorado State University for central auditory processing assessment. The subjects with normal CANS function were originally either referred for central auditory testing and found to have a normally functioning CANS, or volunteered for the study. No testing was performed before approval by the CSU Human Subject Protocol Committee (See Appendix 12.1).

Each subject read, consented to, and signed the protocol before the start of testing.

Criteria for participation in the motor study included: (1) being greater than 13 years of age and (2) showing no joint deformity or stiffness through a rudimentary range-of-motion (ROM) test. The auditory criteria for subject selection (both groups) were: (1) passing a pure tone air conduction test with demonstrated hearing sensitivity of at least 25 dB hearing threshold (re: ANSI 1989, S3.6) from 250 Hz through 8000 Hz, (2) speech reception thresholds no poorer than 15 dB HL, and (3) speech discrimination scores in quiet under earphones at 30 dB SL of 90%-100% (Burleigh, 1996).

All subjects were given a CAP test battery to determine the integrity of each subject's CANS function. The central auditory processing test battery is presented in a double-walled sound-proof room under earphones. Testing is conducted separately by Dr. Joan Burleigh at the Colorado State University Center for Central Auditory Research.

This CAP test battery has been shown to be highly effective in differentiating between people with normal and atypical function CANS (Burleigh, 1996). The significance of CAP test battery results between normal and atypical CANS function groups for Burleigh (1996) is shown in Table 5.1.

The battery of tests administered to each subject includes:

(1) the Competing Sentences Test (CST) (Willeford and Burleigh, 1985; Willeford, 1978),

(2) the Filtered Speech (FS) Test (Ivey, 1969; Willeford, 1978)

Table 5.1 – CANS Group Differences for CAP Battery in Burleigh (1996)

Test	*p*
Competing Sentences (Right Ear)	$p > 0.05$
Competing Sentences (Left Ear)	$p < 0.05$
Filtered Speech (Right Ear)	$p < 0.01$
Filtered Speech (Left Ear)	$p < 0.01$
Binaural Fusion (Right Ear)	$p < 0.001$
Binaural Fusion (Left Ear)	$p < 0.001$
I/C – CST Dichotic (Right Ear)	$p > 0.05$
I/C – CST Dichotic (Left Ear)	$p < 0.05$
I/C – CST Ipsilateral (Right Ear)	$p < 0.05$
I/C – CST Ipsilateral (Left Ear)	$p < 0.001$
SSI – Ipsi (Right Ear)	$p < 0.001$
SSI – Ipsi (Left Ear)	$p < 0.001$
Dichotic Digits (Right Ear)	$p < 0.05$
Dichotic Digits (Left Ear)	$p < 0.001$

(3) the Binaural Fusion Test of the Willeford Central Auditory Test Battery (BF) (Ivey, 1969),

(4) the Ipsilateral/Contralateral Competing Sentence Test (IC-CST) (Willeford and Burleigh, 1985),

(5) the Dichotic Digits (DD) Test (Musiek, 1983),

(6) the Synthetic Sentence Identification Test (SSI) (Jerger and Jerger, 1974, 1975),

(7) the Rapidly Alternating Speech Test (RSR) (Willeford, 1978),

and (8) the Masking Level Differences Test (MLD) (Olsen et al., 1976).

Classification of a subject as having a normal or atypical CANS was based on the results of the above central auditory processing (CAP) test battery. Furthermore, Dr. Joan Burleigh classified subjects with atypical CANS function as having a weak right or left ear.

6. GAIT LAB CONSTRUCTION

6.1 Semi-Anechoic Chamber

In order to provide a uniform environment in which to run the gait tests, a semi-anechoic chamber was designed and built for this study. Previous work had not performed gait analysis in a semi-anechoic chamber or with significant controls on the sound field. A simple acoustic model was constructed to estimate reverberation times in standard and large rooms. The objective of the room design was to emulate typical classroom reverberation characteristics to be recreated in a controlled environment (M. Peterson, personal communication, August, 1999).

Treatment of the walls with acoustic foam (Illbruck, Inc.) was used to reduce reflections. Reverberation times were long enough (or amplitudes sufficiently low) that the room was taken as representative of the sound field in an open or large room with high damping. Additional design features of the room emphasized minimal reflection from the standpoint of a practical gait laboratory.

Speakers were placed at 0, 45, 90, 135, and 180 degrees for the five auditory cases (See Figure 7.1 - Gait Walkway Speaker Configuration). Multi-talker babble was played at a sound level set to be within three dB of 56 dB SPL in the calibrated area of the anechoic chamber as determined with a sound level meter. The sound level meter used was a Metrosonics dosimeter, Model dB307, (Class Type 2A, Rochester, NY) using an A weighting, interval of one minute, a weighting of 6 dB, and a reference sound pressure level of 20 micropascals. The noise level in the chamber when the speakers were on was near the ambient sound level for an elementary classroom (Willeford and Billger, 1978).

The sound level settings were repeatable due to the step-switches connected to the amplifier. The speakers had a nominally flat response range (+/- 3 dB) over a range from 50 to 20000 Hz (Mirage Brochure 3PMB023E, Scarborough, Ontario, Canada). This provided a realistic output of the multi-talker babble signal used as auditory input. Multi-talker babble demonstrates consistent sound level and signal randomness (McAllister, 1990).

Dr. Michael Thompson of Baylor University, Texas, developed the eight-person multi-talker babble tape. This recording initially consisted of four people reading aloud at the same time. The volume of this signal was dynamically adjusted to have no more than a 0.5 dB RMS difference across time. This was accomplished by grabbing random segments of the signal and adding them to the original signal. This doubled four-person tape was then filtered to remove editing "clicks" and noise and was thereafter called the eight-person multi-talker babble tape (M. Thompson, personal communication, August, 1999).

6.1.1 Video Acquisition Requirements

The sizing of the semi-anechoic chamber was limited by the requirements of the video acquisition system. For the direct linear transform (DLT) of the motion analysis system to function within error limits (See Appendix 12.2), the cameras were at least 60 degrees apart. In addition, three cameras were needed in the chamber to have each biomechanical marker available in at least two camera views. The cameras had a minimum focal length limiting the field of view to eight feet across at a distance of ten feet from the subject of interest.

Gait measurement requires at least two to three steps before and after data collection in the calibrated area. This necessity is due to the change in gait resulting from motion initiation and completion phases of human walking (See Section 1.6 - Gait and Motion Analysis Literature Review). These conditions required the chamber to be at least thirty feet long and nine feet wide.

All materials used in the chamber are monochromatic (i.e., either gray or black) to reduce the influence of visual stimuli. To minimize this effect further, the room lighting was reduced to around 0.9 footcandles (equivalent to a moderately lighted parking lot). Light bulbs of 7.5 watts were placed in the lamps facing the subject as he or she proceeded through the gait test. The third lamp behind the subject was an adjustable halogen bulb that minimized glare while providing enough light for walking. All lamps were placed within one foot of the camera to allow for proper function of the retro-reflective tape on the biomechanical markers.

6.1.2 Construction

Video cable and wiring were strung, insulation was installed and drywall was hung on the walls and ceiling. Three-inch thick acoustic SONEX® baffles from Illbruck, Inc. (Minneapolis, MN) were attached in a checkerboard fashion to the walls and ceiling covering a majority of the chamber. Carpet and 5/8 inch thick berber pad were installed with base vinyl. The carpet pad was selected to be thick for reverberation minimization and firm for minimal biomechanical effect. Due to the lack of acoustic tiles on the floor (and the associated sound reverberation), the room was semi-anechoic, rather than anechoic (See Figure 6.1).

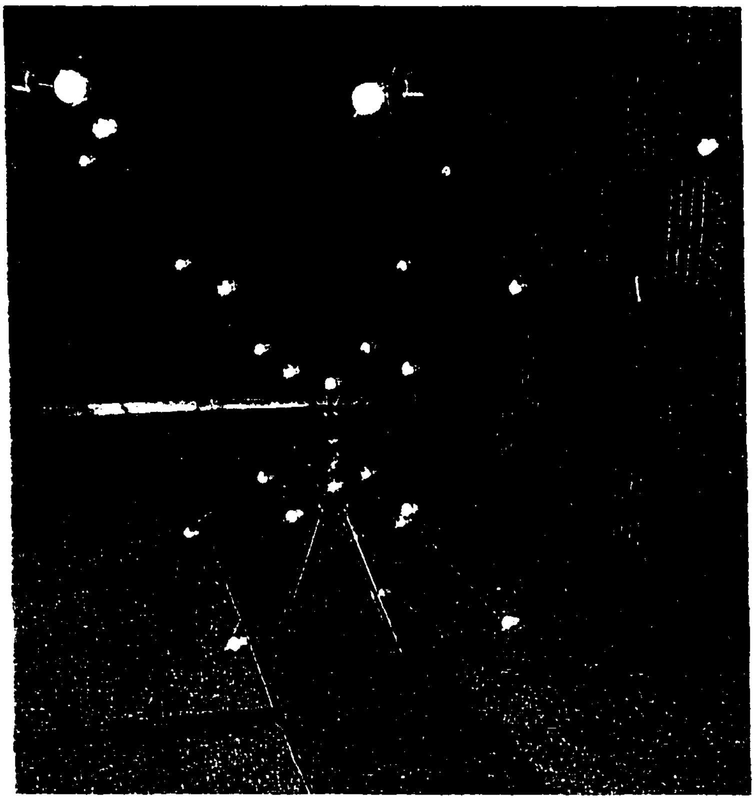


Figure 6.1 – Top ¾ of Calibration Frame in Gait Measurement Area

In the gait initiation area (approximately first ten feet), three-inch thick fiberglass 4' x 8' sheets were placed in wooden frames covered with burlap, and attached to the wall. The use of fiberglass sheeting was more economic and provided sufficient reverberation protection outside the gait measurement area. Lights and cameras (Burle, Model TC351A) were mounted and adjusted in order to view the calibrated area (See Figure 6.2).

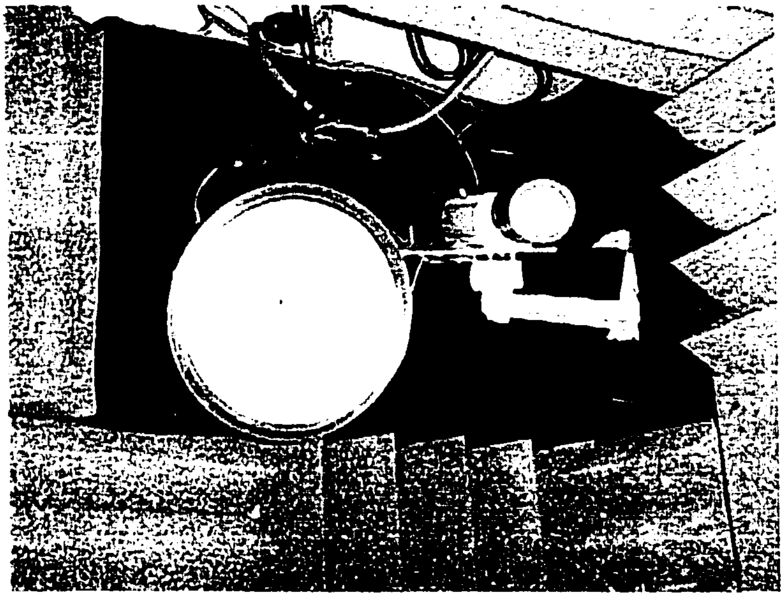


Figure 6.2 – Camera and Light

Due to the tiles being highly flammable, fiberglass bating was also placed around the lights in lieu of acoustic tiles. Speakers were hung at approximately ear level at the five sites relative to the calibrated area as specified in the Method Section (Section 7.2 - Test of Auditory Localization). Two pressure sensitive pads from Home Automation Systems (Irvine, CA) were installed for synchronization between the three camera views (See Section 6.1.1 - Video Acquisition Requirements). A twenty-six foot, 1/8-inch thick runner carpet was laid with

Velcro® strips on top of the pads with rubber "welcome" mats to level out the carpet.

The control room of the chamber was sealed off from the gait portion with a sound absorbent office partition (ATD American, Model # 52066) and acoustic baffles (Noisemaster by Proudfoot Architectural Acoustics, Botsford, CT). An amplifier (Marantz, Model # MA500U) and tape player (Sanyo, Model # RD 250) were connected to five individual rheostats to provide an effective method of controlling the sound pressure level for each speaker in the calibrated gait area. Three videocassette recorders (Panasonic, Model # AG-2550P) with an associated monitor were placed in conjunction with the Event Video Control Unit (EVCU).

6.2 Video Acquisition System

6.2.1 System Criteria

The video system for the gait lab had several requirements. The system needed to produce accurate and timely biomechanical data. The Motus™ system from Peak Performance Technologies, Inc. (Englewood, CO) was used for its ability to synchronize cameras within one frame of each other provided by the Event and Video Control Unit (EVCU). In addition the EVCU provided the means of incorporating an additional standard camera into the video measurement system. These features produced an accurate measurement system capable of handling the tight space in the chamber.

The video acquisition system used passive reflective markers. These retro-reflective markers were placed on the subject over specific body landmarks (See Section 7.5). The reflective tape used in these markers casts the incident light back at a reflected angle of approximately three degrees. This majority of the light was returned to the camera and consequently, a low wattage light source could be used to collect biomechanical data.

6.2.2 System Testing

The Peak Motus™ system was tested after installation by carrying a box of known lengths through the calibrated area. The video of the box was digitized and the data was determined to be within 0.007 m of the known lengths at all points. This margin of error was found acceptable considering cameras two and three are at the manufacturer's minimum allowable separation angle of 60 degrees.

6.2.3 System Modifications

After calibration testing, several test runs were made with subjects to smooth out the testing method. After each set of test trials, several modifications improved the gait method by reducing sensory stimuli (i.e., light and sound levels), and adding additional head and neck markers in order to record head movement more accurately.

Minor modifications were made to the video analysis system. The most notable example was that the supplied calibration frame was wrapped with retro-reflective tape on all calibration points. This allowed the frame to be seen with much greater ease in the reduced lighting atmosphere of the chamber. The error of calibration was checked against manufacturer values before and after wrapping the frame and found unchanged.

6.2.4 Training and Use

After the initial test phase of the motion analysis system, three undergraduate students were trained in the use of the program. These students provided support during testing and help in digitizing subject video clips after testing. The training required approximately two weeks of instruction before the work-study students felt comfortable with the system.

7. METHOD

7.1 Preparative Exams

(For a summary of this procedure, see Gait Laboratory Procedure Summary – Appendix 12.3)

Eighteen subjects with normal hearing (nine with normal CANS function, nine with atypical CANS function) participated in gross motor control testing. Criteria for subject selection are given above (See Section 5.2 - Population).

After acceptance as a subject and signing a consent form, each subject was invited back for gross motor testing in the gait lab. Before the gait examination, each subject completed a questionnaire about previous motor problems and other factors that might affect gait or motor control (See Appendix 12.6). In order to gauge the extent to which each subject would be able to complete gross motor testing, a simple range of motion (ROM) test was performed. ROM testing includes the head, arms, trunk, ankles, knees, and hips. In addition, simple anthropomorphic data was measured for the subject's weight and height without shoes.

7.2 Test of Auditory Localization

Since this study examined the effect of sound location upon gross motor function, subjects were tested for their ability to localize sound. This auditory localization test was given before the gait trials begin and used each of the gait lab speakers for a total of five test conditions (See Figure 7.1 - Gait Walkway Speaker Configuration).

To conduct the localization test, the subject was asked to stand facing the array of speakers in the calibrated area of the gait laboratory. Multi-talker babble was then presented in a randomized fashion by the researcher and the subject was asked to point to the speaker from which the sound is coming. To pass the localization test, the subject had to properly point to each of the five speakers individually as sound was presented.

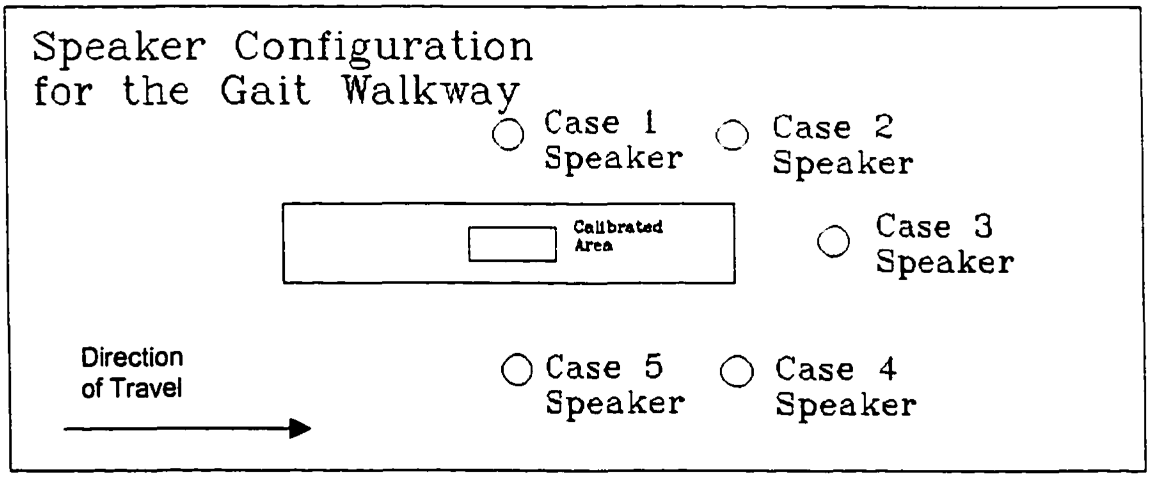


Figure 7.1 - Gait Walkway Speaker Configuration

7.3 Video Analysis Preparation

As mentioned in Section 6.1.2, the video analysis system contained two pressure-sensitive trigger pads that provided synchronization points for the three cameras. In addition, these mats allowed the gait cycle to be evaluated accurately from heel strike on the first pad to heel strike for the same foot on the second pad. This gait cycle measured the period between two heel strikes from the same foot.

The distance between the mats was adjusted within the calibrated video area for each subject's stride length (See Figure 7.2). Before testing began, each subject was asked to stand on each pad to ensure that the entire body was within each camera's field of view. Thereafter, the subject was asked to walk towards the back of the chamber. A tape marker was placed on the runner carpet at the point of last heel strike near the end of the runner carpet. This tape marker was used as a starting point for each gait trial to help ensure that the subject would hit the two pressure pads through his or her gait stride. Several test walks were taken for each subject to adjust the marker and the pads; and to allow the subject to familiarize his or herself to the chamber and the procedure.

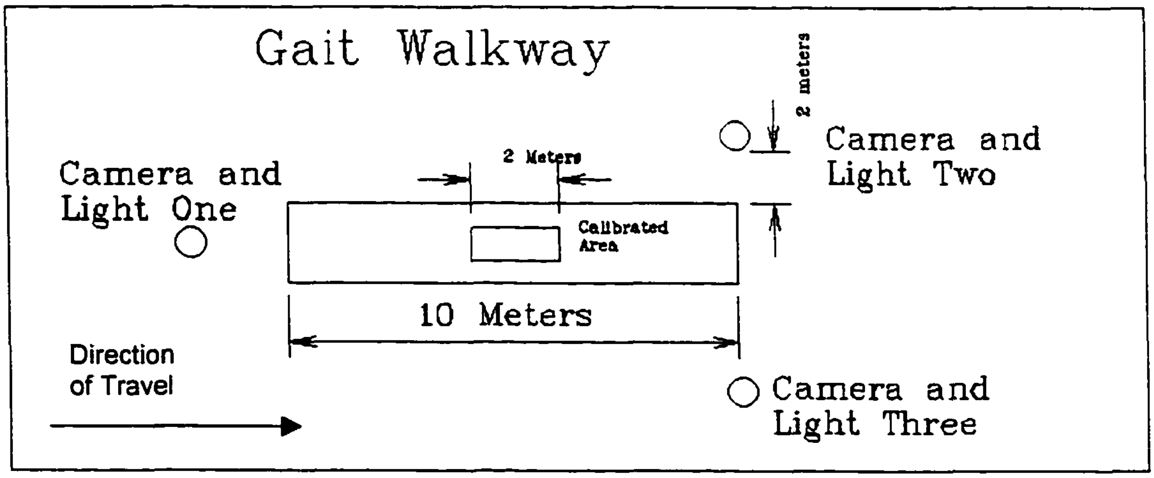


Figure 7.2– Gait Walkway Camera and Light Setup

After a few practice runs, each subject stood in the calibrated area and each camera view was double-checked for a complete head-to-toe view of the subject. The brightness of the lamps was checked and adjusted if necessary. In addition, before each gait run, a sequential number was flashed to each camera view to allow greater ease of video capture and digitization. Due to the number of items that need to checking, a gait test checklist was used (See Appendix 0).

7.4 Calibration Procedure

The gait walkway contained a calibrated area based upon the measured frame included in the Peak Motus™ system (See Figure 7.2– Gait Walkway Camera and Light Setup). To allow the conversion from a two-dimensional plane to a three-dimensional space, this calibration frame (See Figure 6.1) was recorded for each of the subjects in each camera view (See Appendix 12.2).

Since the whole calibration frame would not fit into the gait lab, this study used a modified version of the original frame. By videotaping this calibration frame in the same space in which data were taken, an accurate description of the data was accomplished (averaging within 0.005 m). This procedure was completed before and after each gait test set.

7.5 Testing Procedure

The order of the auditory trial sequences was performed with a randomization routine. The gait sequences were numbered to correspond to each particular auditory condition.

A calibrated three-dimensional video gait analysis was completed for each of the subjects with three camera views. In order to facilitate accurate motion analysis of the various body parts, each subject was tested barefoot and while wearing minimal dark (black or navy-blue) form-fitting clothing (e.g., bicycle shorts and a tank top).

As part of the motion analysis system, retro-reflective markers were mounted on the skin. On the head, two markers were placed on a lycra swim cap pointing upward directly above the ears. As in Pozzo et al. (1990, 1991) (See Section 1.5 - Head Motion Literature Review), these markers were placed to measure head movement in two axes. However, Pozzo et al.'s method to use the area directly ahead of the ear opening was not used due to the requirement of earmuffs in one of this study's conditions. Markers were placed on the vertebra prominens (C7 vertebra), shoulders, elbows, wrists, greater trochanters, knees, and ankles. Figure 7.3 displays marker placement on a volunteer graduate student (not a test subject).

The three video cameras record at 60 Hz the gait of each subject. The cameras are approximately two and one-half meters off of the floor and three and one-half meters from the walkway at approximately forty-five degree angles from the subject testing area (See Figure 7.2). Each subject is recorded walking straight ahead at a comfortable pace for five steps. The calibrated testing area, which is a little longer than one normal stride length, is used for gait data (See Section 7.4).

Figure 7.3 – Person with Biomechanical Markers Applied

Three valid runs for the heel strike of the same foot (right or left) were collected for each auditory condition. The subject continued to walk until three gait cycles were recorded between the pressure pads for the same foot. The averaging of three gait runs for each auditory condition required having the same foot's heel strike for each run. This averaging method was not valid when a mixture of left-right-left and right-left-right cycles were incorporated.

7.6 Post-Rotary Nystagmus Exam

After all gait trials were completed, a physiologic non-cognitive vestibular test was conducted. This test was conducted at the Gait Lab to rule out the vestibular system as a source of motor problems. The vestibular system is responsible for controlling body stability and balance. When it does not function properly, the motor system degrades to a state of ataxia. Consequently, it is necessary to correlate the effects of auditory input on the motor control to the performance of the vestibular system. The post-rotary nystagmus exam was conducted on a voluntary basis. The subject could stop the test at any time.

The Post-Rotary Nystagmus Test used a lazy-Susan-type platform that allows free rotation, whereby the top board rotated while the bottom board remained fixed to the ground. To test the duration of nystagmus, the subject sat cross-legged on the platform with his or her neck at 30 degrees forward from the vertical. This placed the horizontal semicircular canal relatively horizontal to the earth's surface. The subject was then passively rotated to his or her left 10 times in 20 seconds and then stopped. The duration of horizontal nystagmus was recorded to the nearest second. After a rest period of about two minutes, the test was repeated in the opposite direction (Ayres, 1975). The results for both directions were then compared to normative data to evaluate possible peripheral vestibular system impairment.

8. ANALYSIS

8.1 Kinematic Calculation

An extensive procedure for digitizing the gait videos was used in order to facilitate data analysis. Each auditory condition consisted of three runs. The video of each run of each associated trial was captured for three frames before and after the heel strike event (Peak Motus™, 1997).

The researcher used the Peak Motus™ system to capture individual video clips of every other video frame (i.e., at 30 Hz) of each gait run. The clip was digitized point by point for each captured frame. The Peak Motus™ program then took the digitized video position relative to the image frame and converted it into digitized data relative to the calibration frame (Peak Motus™, 1997).

The Peak Motus™ system collected positional data (X,Y,Z) for each marker point for each frame of the stride. Three trials of a participant's gait were averaged where possible. Due to the fact that individual trials have different number of video frames, the trials were interpolated over 200 points for the complete gait cycle. This was accomplished by splitting up each stride into 200 pieces with each piece containing 0.5 % of the gait cycle. Each piece was then averaged with the corresponding piece in the other trial runs.

The interpolated points refer to equivalent points in the gait cycle since each video trial segment starts three frames before the HSE. The averaging and interpolation was done for each marker point on the body.

As previously stated, the time period captured in each data file included three frames before the initial heel contact, and three frames after the second heel contact of the same foot. These additional frames were necessary for calculating velocity and acceleration for each point at the initial and final heel strike. The velocity of each segment was calculated by taking the difference in position divided by the associated amount of time for that movement. Similarly, accelerations were calculated from the difference in velocities over an associated time.

After digitization, each gait run was checked for accuracy. Each body segment length was checked for significant change. Since body segments were of constant length, if a digitized trial showed significant change in a body segment length the trial was reviewed. The problem was usually corrected by inspecting the digitization points for crossovers. These crossover points were common for the wrist and hip as the hand passed the side of the body.

For reference, the axes of the gait lab were situated so the subject walked in the negative X direction. The Y direction was up (positive) and down (negative), and the Z direction ran in the positive direction from right to left (while travelling in the negative X direction) (See Figure 8.1). The sagittal plane bisected the human body from anterior to posterior into right and left portions. The transverse plane crossed the body at midline effectively partitioning it into top and bottom halves.

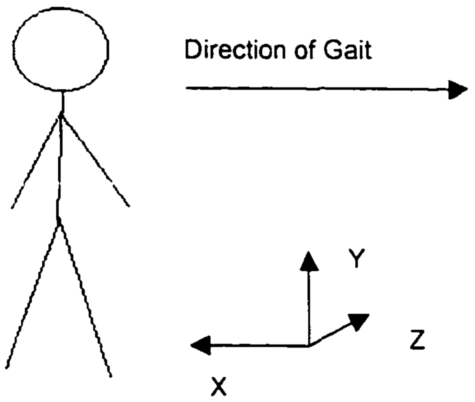


Figure 8.1 – Stick Figure for X, Y, and Z Axes

Each set of linear data was normalized based upon the subject's height. The linear position, velocity, and acceleration data were divided by the person's height in meters. This created a dimensionless length parameter for length, (m/m or % height), velocity (%height/s), and acceleration (%height/s/s). This normalization allowed people of short stature to be compared to people of large stature on the basis of gait.

Using the collected data, the following clinical parameters were calculated: speed of walking (m/s, %height/s), stride length (m, %height), an approximation of the duration of single stance for the right and left leg (% of stance) through the velocity of the ankles, and angular head movement in the transverse plane (degrees, zero being forward). These factors and others are listed in Table 8.1.

Table 8.1 – Selected Gait Parameters

Parameter	Direction/Plane	Dimension
Ankle Velocity in X	X	(%height/sec)
Avg. Head Acceleration	X, Y, Z	(m/s/s)
Avg. Head Velocity	X, Y, Z	(m/s)
Center of Mass Position	X, Y, Z	(%height)
Head Nod Absolute Value	Sagittal Plane	(degrees)
Head Nod Change	Sagittal Plane	(degrees)
Head over C7 Angle	Transverse Plane	(degrees)
Hip Angle Change	Sagittal Plane	(degrees)
Stride Length	X	(m, %height)
Walking speed	X	(m/s, %height/sec)
Stride Width	approximately in Z	(%height)

The averaged and normalized positional data were then exported to separate text files for each marker, condition, and subject. These text files were imported into Microsoft® Excel™ to calculate the various gait parameters. Each of the auditory condition was then ported within Microsoft® Excel™ to a more condensed version for each subject. Next, each subject's data were imported to separate comparison spreadsheets. From these spreadsheets, gait data were transferred into Minitab® for Windows release 12.21 (1998).

For clarity, several of the gait factors need explanation. Taking the difference in the X position of the respective ankle from heel strike to heel strike assessed stride length. The velocity of the COM in the X direction approximated walking speed. Stride width was measured from ankle to ankle in the gait cycle (See Figure 8.2).

The velocity of the ankle was a measure of gait asymmetry. By taking the X component of the individual ankle velocities (a good approximation of the total ankle velocity), it was possible to compare the performance of the two halves of the body. The ankle velocity was nearly zero during the stance phase of the gait cycle. By examining the amount of time spent at approximately zero for each ankle, it was possible to obtain a measure of single- and double-stance times, which was a measure of asymmetry.

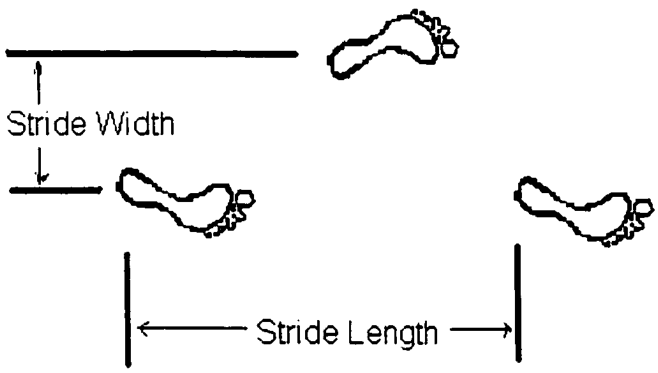


Figure 8.2 – Definition of Stride Width and Length

Another measure of asymmetry was the motion of the hip as measured by the hip angle (See Figure 8.3). By comparing the magnitude of each hip's movement, an aspect of the symmetry of gait could be seen. Two lines demarcated this angle, the first being a line drawn parallel to the Y-axis. The second line was drawn from the marker on the hip to the marker on the knee. This formed an angle projected onto the XY plane which was defined to be positive when the knee is forward of the hip. From these, graphs of the joint angles of the hip were generated.

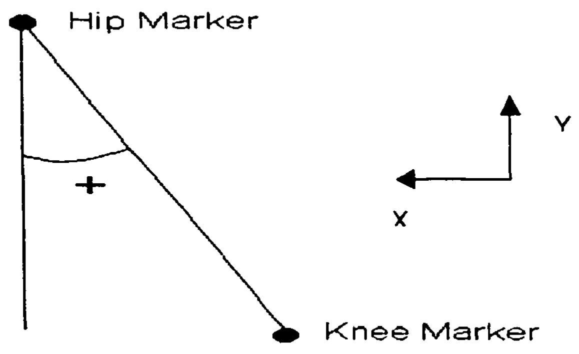


Figure 8.3 – Definition of Hip Angle - Sagittal View

Additionally, movement of the center of mass (COM) was used as an asymmetry measure. The center of mass was a calculated value based upon the length (and associated volume and mass) of the subject's body segments. The center of mass position was obtained using standard body mass data (Dempster, in Winter, 1990). The Peak Motus™ program performed this calculation using height and body segment data given to it by the researcher.

The absolute measurement of COM position (COM) was the distance from the origin as set by the calibration frame. The relative COM (COM Del) was the difference of position between the first heel strike and the time of measurement. Plotting the calculated center of mass (COM) position versus time graphically represented this parameter (See Section 9.11). Consequently, if large side-to-side movements were seen, this indicated an increase in gait variability. If one side of a person's gait was measurably different from the other, that may have been an indication of an affect of the auditory condition on the motor response.

As a measure of head influence, average head velocity and acceleration were determined. These parameters were taken at the midpoint of the head between the two swim-cap markers. In addition to velocity and acceleration, two angles were measured on the head.

The first was the included angle between the head markers and the C7 markers (See Figure 8.4). Projected on the XZ plane, this angle was defined by the line drawn through the head markers to the intersection with the line drawn through the C7 markers. It was undefined at zero when the lines were infinitely long and consequently parallel. A zero was inserted for this case, which happened to be straight-ahead. The angle was defined as positive for both right and left turns and therefore measured the deviation of the head from the straight-ahead position.

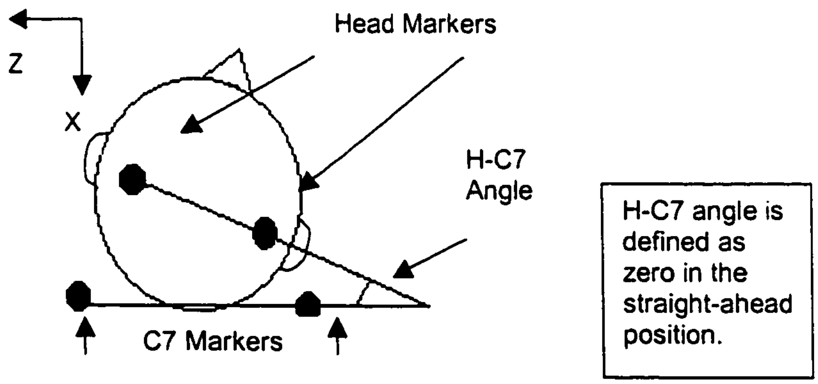


Figure 8.4 – Definition of Head over C7 Interior Angle - Top View

The second defined angle was that of head nod (Nod). One side of this angle was delimited by the center point between the head markers to the center point of the C7 markers. The other side of the angle was a line drawn parallel to the X-axis from the C7 center point. The head nod angle was then defined as positive from the X-axis to the head. In other words, looking down made Nod more positive (See Figure 8.5).

Nod was dependent upon the individual and the placement of the lycra swim-cap at the time of testing. This subject dependence differs from Pozzo et al.'s (1990, 1991) study, but as previously mentioned, the requirement of free-field hearing precluded a marker on the ear opening. To minimize this difference, the value of head Nod was compared as a difference of the angle from its position at the first heel strike (Nod Del).

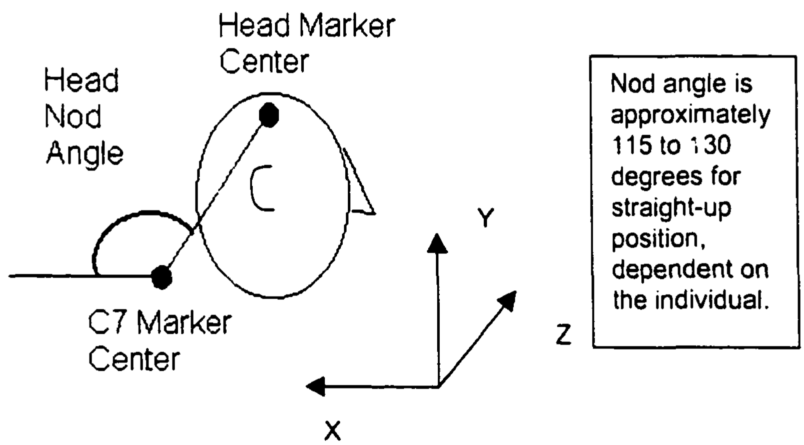


Figure 8.5 – Definition of Head Nod Angle - Sagittal View

From these data, angular velocities and accelerations were calculated and visualization of the gait data was undertaken through computer generated stick figures (See Figure 8.6). This allowed the researcher to quickly compare the data from several runs by watching animations of each trial. Illustrated in Figure 8.6 is an example stick figure including the COM for the figure as a point above the hips. This point is tracked throughout the gait cycle (i.e., from heel strike to heel strike).

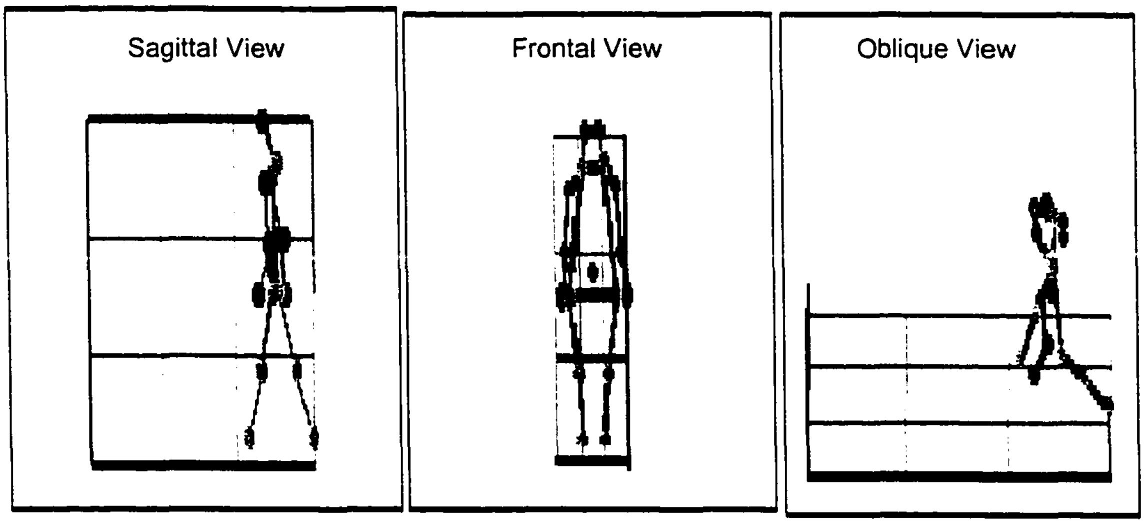


Figure 8.6 – Stick Figure in Three Views

(From Peak Motus™. Used with Permission from Peak Performance Technologies)

8.2 Statistical Background

A repeated measures ANOVA on the same subject or experimental unit was used in this study (See Figure 8.7). Due to the model design, subject variation within the two groups and not individual data points was compared.

General Linear Models (GLM) performed univariate analysis of variance for each response variable. Calculations were done using a regression approach. The response variable was regressed against a matrix design which contained each factor (Minitab®, 1998).

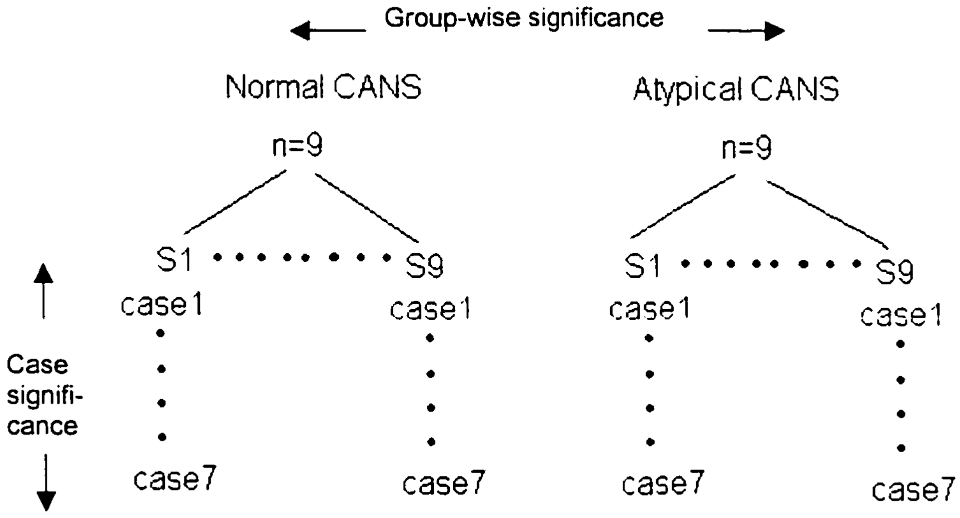


Figure 8.7 – Nested Study Model

A GLM was used to determine whether a difference is significant. A simplified form of a GLM could take the form of a least-squares equation such as that shown in the following equation:

$$\begin{aligned} Walking\ Speed &= \beta_0 + \beta_1(Group) + \beta_2(Subjects(Group)) \\ &+ \beta_3(SoundCondition) + \beta_4(SoundCondition * Group) + Error \end{aligned} \quad \textbf{Equation 8.1}$$

The response in this example, Walking Speed, was a linear function of the collected data in the given sound conditions. The error in the model was assumed to be normally distributed (i.e., follow a normal bell curve distribution). In addition, *Group* (i.e., the two CANS function groups) and *SoundCondition* were combined to illustrate an interaction term of

*Group*SoundCondition* to reflect the association of these terms (Kleinbaum et al., 1998).

This equation can be used to build an ANOVA table for an overall summary of the contributions of each variable. This is built from the total sum of squares given in the following equation where Y is the *Walking Speed* response given above.

$$\sum(Y-\bar{Y})^2 = \sum(\hat{Y}-\bar{Y})^2 + \sum(Y-\hat{Y})^2$$ **Equation 8.2**

The first term is the total amount of variation of Y from the mean of the response (*SSY*). The second and third terms are the amount accounted for by the fitted regression line (*SSY-SSE*, also called *SS*) and the amount unaccounted for by that line (*SSE*), respectively. By taking the sum of squares term (*SS*) and dividing it by the number of degrees of freedom for the model, the mean sum of squares (*MSS*) is obtained.

Please note that this linear regression model is a reduced form of the repeated measures ANOVA that is calculated by Minitab®. The ANOVA model used in this program could take the form of the following equation:

$$Y_{ij} = \mu + S_i + \tau_j + E_{ij}$$ **Equation 8.3**

Y_{ij} in this equation is the response (e.g., Walking Speed), μ is the mean response, S_i is the random effect of subject number i, τ_j is the fixed effect of treatment j (i.e. *Sound Condition*), and E_{ij} is the random error for treatment *j* within subject *I* . In Table 8.2, both groups are combined to illustrate the layout of a possible data matrix for the above equation. The random effect terms $\{S_i\}$ and the error terms $\{E_{ij}\}$ are mutually independent, but the responses on the same subject are assumed to be correlated (i.e., not mutually independent) (Kleinbaum et al., 1998).

Table 8.2 – Subject by Treatment Matrix

Subject Number	*Sound Condition 1*	*Sound Condition 2*	...	*Sound Condition 7*
1	Y_{11}	Y_{12}	...	Y_{17}
2	Y_{21}	Y_{22}	...	Y_{27}
...	...	...	...	...
20	Y_{201}	Y_{202}	...	Y_{207}

Since the responses were not independent on an intra-subject basis, the response proper F ratio for group-wise comparisons had to be calculated separately. Minitab® assumed that every number was an individual data point, and consequently, the given F-ratios for the group variable were erroneous as given by Minitab®, as were the associated p-values. (However, the case comparison term given by Minitab® was correct.)

The correct ratio was obtained by dividing the mean sum of squares of the response (*MSS for Y*) by the mean sum of squares of the error term (*MSSE*). For the model in this study, the *MSSE* was estimated by the variation of each subject within both groups. Stated differently, the comparison of the variation between groups and not the individual runs of a particular subject was sought, consequently the F-ratio and p-value had to be calculated by hand by dividing the given *MSS* of *Y* by the *MSSE*. By taking the adjusted mean sum of squares for the variable group, and the dividing it by the adjusted mean sum of squares for subjects(Group), the correct F ratio was obtained.

The results presented later in Table 9.14 were group-wise comparisons (i.e., between two CANS function groups) and were represented by the column-wise comparison in Figure 8.7. The intra-subject variation across conditions was represented by the row-wise comparison of Figure 8.7. These comparisons were between subjects and were not the focus of this study due to the inherent variation of human motor function. The data obtained from the case by case portion of the GLM models are presented later in Table 9.15.

Appendix 12.7 contains an example of a general linear model. The sample model, and the other GLM models for this study, has parameters for determination of CANS grouping ("Group"), the variation of individual subjects in the group, ("subjects(Group)"), the condition of interest ("case12_3"), and interaction terms (Group*case12_3-7).

9. RESULTS AND DISCUSSION

Please note: Due to the number of variables involved, the Results and Discussion chapter is written together for the ease of the reader.

9.1 CAP Test Battery Results

Each subject was found to have normal hearing through an audiological evaluation (See Section 5.2 - Population). Testing included the central auditory processing (CAP) battery discussed earlier. Based upon the results of the CAP battery as defined in Burleigh, 1996, the 18 subjects were split into two groups. Group1 included nine people with a normally functioning CANS and Group2 had nine people with an atypically functioning CANS.

In addition, based upon the individual CAP test battery scores, members of Group2 were diagnosed to have either a weak left or weak right ear. Six members of Group2 had a weak left ear (Group2L) and three had a weak right ear (Group2R).

Table 9.1 – Group Nomenclature

Group Name	CANS Function	Weak Ear Diagnosis
Group1	Normal	N/A
Group2	Atypical	N/A
Group2R	Atypical	Right
Group2L	Atypical	Left

9.2 CAP Test Battery Discussion

Placing the participants into two groups based upon CAP test battery scores was necessary to conduct a study of the difference in gait between the two groups. The further sub-grouping based upon weak-ear diagnosis was needed to effectively examine the effect of CANS function on gait.

9.3 Inter-Group and Literature Comparison Results

An analysis of the population gender characteristics revealed that two-thirds of the subjects were female (See Table 9.2 – Group Gender Characteristics). This study did not aim to have equivalent numbers of males and females due to the limited number of subjects within the population group.

Table 9.2 – Group Gender Characteristics

Gender	*Group1* *N=9*	*Group2* *N= 9*	*Total* *N=18*
Male	33%	33%	33%
Female	67%	67%	67%

However, the gender ratio was not a major source of concern as the two groups are gender equivalent, and the majority of the statistics performed contrasted the two groups. A significant gender difference was not found between the two groups based on 2-sample t-test ($p = 0.44$).

The age range of the subject population was from 18 to 59 years of age. The mean, median and standard deviation for the two groups and the total are given in Table 9.3. A two-sample t-test did not find a significant age difference between the two groups (p = 1.0).

Table 9.3 – Group Age Characteristics

	Group1 N=9	*Group2 N= 9*	*Total N=18*
Mean	34.78	38.89	36.83
Median	32.00	42.00	37.50
SD	8.2	12.56	10.51

The subject height for the two groups was important for the normalization of the gait data (See Section 7.1). The two groups' subject heights range from 1.55 m to 1.98 m. The mean, median and standard deviation are shown in Table 9.4. A two-sample t-test showed no significant height difference between the two groups (p=0.97).

Table 9.4 – Group Height (m) Characteristics

	Group1 N=9	*Group2 N= 9*	*Total N=18*
Mean	1.74	1.74	1.74
Median	1.78	1.73	1.75
SD	0.0869	0.1276	0.1059

To validate that the normal population data (Group1, N=9) was in fact representative of normal walking, the collected gait data were compared with comparable data from literature (See Table 9.5). These data were taken from various gait studies that include a normal population. The following short review of the literature is included here in the Results section for convenience.

Boonstra et al. (1993) investigated the validity of walking speed recording in 15 normal subjects, 16 trans-femoral amputees, and 8 knee disarticulation amputees (mean age of 30 years). The variability of gait using electrogoniometers and aluminum strips on shoes was investigated. Normative walking speed data from this study are included in Table 9.5.

Dobbs et al. (1993) collected data from 144 subjects to construct speed and height-specific reference ranges for stride length and an age-specific reference range for free-walking speed. The data was collected twice for each subject - once with shoes and once without. The normal data for free walking speed are taken from the graph for the age range of 25 to 55 years old, which is a flat region of that plot. Of particular note in this study is that shoes increased the subject walking speed 5% ($p < 0.00005$), and stride length 7% ($p < 0.00001$). Normative walking speed data from this study are included in Table 9.5.

Kadaba et al. (1990), also cited in Section 1.6, collected kinematics with a VICON™ video system. The study recorded the movement of the lower limbs of 40 barefoot normal subjects on three different days. Normative walking speed and length data from this study are included in Table 9.5.

Table 9.5 – Normative Gait Data from Literature

Study	N	Walking speed (m/s)	Stride Length (cm)	Stride Width (cm)	Lateral Head Dpl. (cm)	Vertical Head Dpl. (cm)
Boonstra et al. (1993)†	15	1.45 ± 0.2				
Dobbs et al. (1993)†	144	1.12				
Kadaba et al. (1990)						
Men	28	1.34	141‡			
Women	12	1.27	130‡			
Kawamura et al. (1991)	17	1.28 ± 0.2	136 ± 12‡	14 ± 3.1‡		
Murray et al. (1984)† (All women)	7	1.33 ± 0.1	140.7 ± 3 (or 85% ht)	7.6 ± 0.6‡	3.2 ± 0.3‡	4.9 ± 0.2‡
Murray (1967)†	60	1.51 ± 0.2	156.0		2.0 to 3.0‡	4.0‡
Robinson et al. (1981)	15	1.12 ± 0.5	132.0			
Waters et al. (1973)†	5				5.0 to 5.4‡	2.6 to 4.8‡

† Used shoes in at least part of the study.
‡ Data used in statistical analysis of normative gait literature.

Kawamura et al. (1991) studied the gait of 17 barefoot men walking on a slope of varying inclination. The slope platform was fitted with a matrix of strain gages to allow measurement of stride parameters and center of pressure (COP). Normative walking speed, length, and width data from this study are included in Table 9.5.

Murray (1967), in a comprehensive look at gait, used interrupted-light photography to look at several gait conditions and parameters. Several sub-studies were included and the one referenced in the above table included 30 normal men (most probably in shoes). This sub-study found that the lateral pathway of the head is more variable than that of the vertical pathway. Normative walking speed, and length data with lateral and vertical head movement are included in Table 9.5.

As previously mentioned in Section 1.5, Murray et al. (1984) found that normal subjects decrease their walking speed by taking shorter steps. In addition, at slower speeds, the total vertical excursion of the head was less than at greater speeds. Normative walking speed, length, and width data as well as lateral and vertical head movement from this study are included in Table 9.5.

Robinson et al. (1981), in an effort to provide easy, economical access to gait analysis, developed a method to measure gait with a stopwatch, tape measure, tape recorder, and a grid pattern. By visually marking the gait of 15 people with normal gait (in shoes) on the grid pattern, the results seen in the table above were obtained. The data have greater variability but are definitely within the range of the more accurate (and expensive) methods. Normative walking speed and length data from this study are included in Table 9.5.

Waters et al. (1973) used a treadmill and lightweight fiberglass cords to measure the vertical and lateral progression of the head and trunk of five normal males. Connected to accelerometers, these cords were attached to T-10 and S-2 on the spine, the iliac crest and to a headband. Stride parameters were measured through electric switches attached to shoes. Normative vertical and lateral head movement data from this study are included in Table 9.5. The statistics of the collected data for the present study are presented in Table 9.6.

Table 9.6 – Overall Descriptive Statistics of Group1 Gait Data

Variable	*Mean*	*Median*	*SD*	*Minimum*	*Maximum*
Stride Length (cm)	149.53	140.51	23.68	123.10	207.33
Head Vertical Displ (cm)	7.25	7.19	1.91	3.87	10.49
Stride Width (cm)	19.62	19.85	1.88	15.64	22.91
Walking speed (m/s)	1.21	1.15	0.26	0.84	1.83

It can be seen that the Group1 data matched well for the normative literature parameters of stride length and walking speed. The difference between the collected normal (Group1) data and that from literature was not statistically significant for these parameters ($p > 0.05$), thus validating the methods used in the study (See Table 9.8).

The collected Group1 data did differ significantly from that in literature for the parameters of stride width and vertical head displacement. If the reduced sound input cases (muffed and natural without amplified sound) were separated out (See Table 9.7) and compared to the literature, the correlation with normative data increased for every parameter except stride width (See

Table 9.8). This parameter and the measure of vertical head displacement continued to be statistically different from literature values.

Table 9.7 – Descriptive Statistics of Group1 Gait Data – Reduced Sound Cases

Variable	*Mean*	*Median*	*SD*	*Minimum*	*Maximum*
Stride Length (cm)	150.00	141.19	24.21	125.63	206.30
Head Vertical Displ (cm)	7.24	7.07	1.99	3.87	10.20
Stride Width (cm)	19.45	19.87	1.99	15.64	22.85
Walking speed (m/s)	1.20	1.13	0.26	0.85	1.83

Table 9.8 – Difference between Literature Normal and Group1 Data

Variable	P-Values	
	Muffed & Open Cases	All Cases
Stride Length (cm)	0.318	0.330
Head Lateral Displ (cm)	0.055	0.060
Head Vertical Displ (cm)	0.008	0.018
Stride Width (cm)	0.004	0.016
Walking speed (m/s)	0.340	0.556

Group2 was not compared to background data due to lack of a literature reference regarding groups with CANS dysfunction. The descriptive statistics for Group2 are presented below for referral.

Table 9.9 – Overall Descriptive Statistics of Study Group2 Gait Data

Variable	*Mean*	*Median*	*SD*	*Minimum*	*Maximum*
Stride Length (cm)	148.41	154.87	19.05	110.40	174.48
Head Lateral Displ (cm)	14.02	12.58	7.79	2.62	33.13
Head Vertical Displ (cm)	6.25	5.79	2.03	2.83	10.88
Stride Width (cm)	19.15	19.27	1.81	15.26	23.67
Walking speed (m/s)	1.17	1.22	0.21	0.83	1.51

9.4 Discussion of Inter-Group and Literature Comparison Results

It was assumed the testing conditions of reduced noise and lighting caused the gait data to differ from the literature norm for stride width and vertical head displacement. To demonstrate this phenomenon, the cases with sound input were removed and the data is re-analyzed improving the correlation (See Table 9.8). These two conditions emulated more closely the normal literature testing conditions for gait.

The differences between the data for stride width and head vertical displacement were significant. This may have been due to the lack of background data, but not significantly due to difference in method. Murray (1967) strapped a marker to the top of the head very close to this study's placement of H-C7 markers. However, the influence of testing subjects in reduced visual stimuli and with increased auditory stimuli had to be taken into account. Due to the lack of related studies, this theory could be tested against literature. Another reason for the variance of this data from literature norms was probably due to the subjects' reaction to sound and the associated gait changes.

With the main parameters of walking speed and stride length in line with reference data, the study used the collected normal data as a control for the influence of auditory input. The parameters of stride width and head movement could be considered when comparing groups with atypical and normal CANS function. In addition, the subject-specific baseline data (natural walking with reduced sound input) was used as an intra-study control for the influence of auditory input.

9.5 *Localization and Vestibular Results*

As part of the gait testing, vestibular and sound localization tests were given to each subject. The entire normally functioning CANS group passed these two tests. A portion of the atypically functioning CANS group did fail either one or both of the tests (See Table 9.10).

Table 9.10 – Results of Vestibular and Localization Testing

Test	*Group1*		*Group2*	
	Pass	Fail	Pass	Fail
Post-Rotary Nystagmus – Vestibular	9	0	4	5
Sound localization	9	0	6	3

Of the subjects in Group2 who failed the localization test, two were diagnosed in the CAP test battery as weak in the left ear, and one as weaker in the right ear. The effect of failure of these two tests on gait performance was explored through statistical general linear models (GLMs). These models did not show any significant difference in the gait parameters between the subjects who passed the two tests or those who failed (See Table 9.14).

In Figure 9.1 and Figure 9.2, it is seen that those people in Group2 who failed the localization test tended to have less variance in their stride width than do those who passed the test.

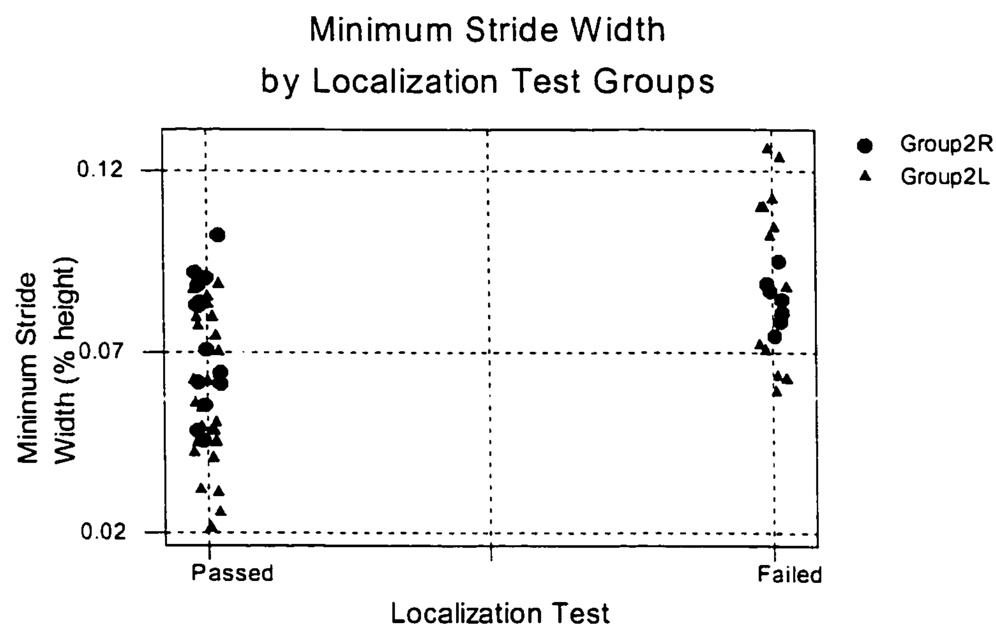


Figure 9.1 – Minimum Stride Width vs. Localization Test Performance

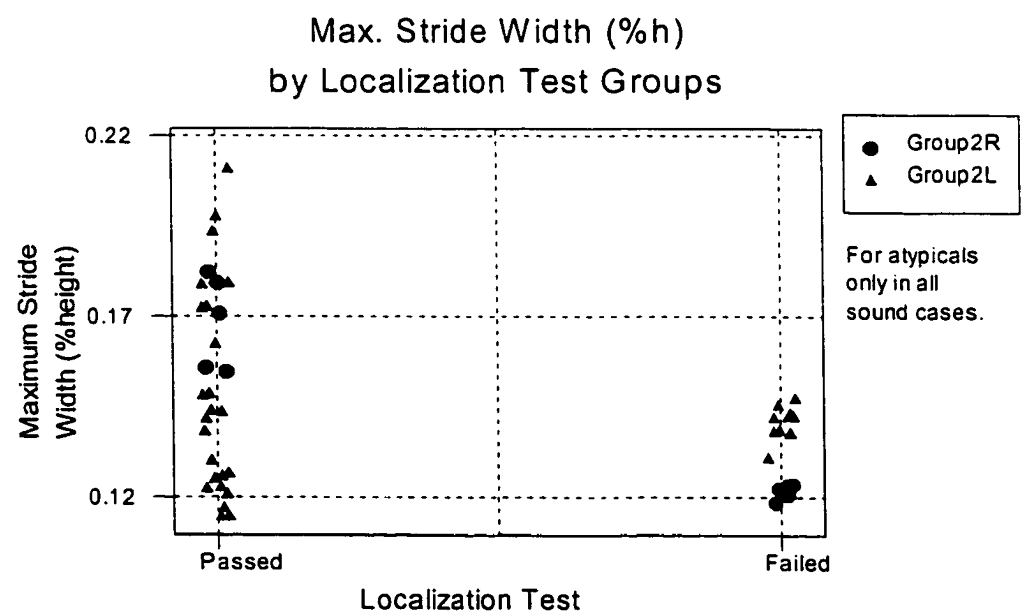


Figure 9.2 – Maximum Stride Width vs. Localization Test Performance

9.6 *Discussion of Localization and Vestibular Results*

The value of conducting the post-rotary nystagmus test was to rule out vestibular dysfunction as a statistically significant factor. Due to the lack of statistically significant difference with Group2, the gait of those who failed the vestibular test could be correctly measured using this study's protocol.

The meaning of the difference in stride length based on the localization test is yet to be explained, and is not statistically significant in this study. However it is illustrated here out of importance of stride width. Stride width has been shown to be a major factor in gait (Rose et al., 1994). A change in stride width causes a significant change in the pelvic movement, which is related to the center of mass and gait efficiency.

As a person moves through the gait cycle, the pelvis and hips tilt to allow the legs to swing in a figure eight pattern. If this tilt is not achieved, the person has a gait deficiency that is demonstrated by a person walking with a narrow stance. The efficiency of a person walking with narrow stance is much reduced (Rose et al., 1994) due to the fact that the whole body must be in essence picked up and put down over a greater distance causing a greater amount of work.

Therefore, the decrease in variation of stride width in those who failed the localization test may have indicated a lower gait efficiency. Since this trend was not statistically significant, it was not investigated further in this study. However, this may be a subject of interest for a study with more subjects to demonstrate significance.

This efficiency difference in sound cases for Group1 over Group2 was supported by Cases "Quiet vs. Sound" and "Far Left vs. All Other Speakers" (See later results for explanation). In these cases the difference in interactions in minimum stride width were significantly different ($p = 0.05$ and $p = 0.03$ respectively) between groups.

9.7 Initial Statistical Gait Parameter Results

Many parameters were included initially in the statistical gait model to explore the group-wise response of the human motor system to auditory input. No parameters were significantly different between groups when compared across individual cases and consequently conditions were combined to reveal more significance. After this combination (explained in the following discussion section), several of the gait parameters turned out to be significant in at least one combined condition (See later Table 9.16 which summarizes the information in Table 9.14). After this initial screening of non-significant parameters, the significant factors were kept in the statistical matrix to be further explored as in Section 9.8.

Of note are two factors, hip angle and the position of the COM in Y, which was expected to show significance but do not. Hip angle, for left versus right, was used as a measure of asymmetry and was not significantly different between the normal and atypical CANS function groups. The second non-significant factor was that of vertical displacement of the center of mass. This vertical displacement did not show statistical significance.

9.8 Discussion of Initial Statistical Gait Parameter Results

The reason for non-significance of the hip angle and COM movement in Y may have been due to the small population size. The population was limited because of the lengthy video analysis needed for each subject.

As mentioned above, when taken in an individual case comparison, the factors listed later in Table 9.16 (See Table 8.1 for reference) were not statistically significant ($p>0.05$). Since the number of subjects in this study was too small to get significant results for the large amount of variation in the data, conditions were logically combined in order to effectively increase the subject size (i.e., increase the number of data points per condition). The speaker cases were linked together to investigate localized sound input (LS) and reduced sound input (RS) conditions. Conditions one (muffed under RS) and two (natural under RS) were combined to create the combined RS conditions. The five LS speaker cases were combined into several conditions to explore the subjects' reaction to sound. Of these combinations, those with the front speaker and with the extreme speakers (conditions 3 and 7) were the most statistically significant.

For reference, the original conditions are tabulated in Table 9.11 and shown in Figure 9.3. The names to be lumped are listed in Table 9.12. The combined conditions are listed in Table 9.13, with associated names that were used for the rest of the paper.

Table 9.11 – Original Testing Conditions and Names

Original Case Name	*Description*
Muffed	Walking with earmuffs without LS
Natural	Natural walking without LS
Speaker 1	Walking with LS (Far Left)
Speaker 2	Walking with LS (45° Left)
Speaker 3	Walking with LS (Center)
Speaker 4	Walking with LS (45° Right)
Speaker 5	Walking with LS (Far Right)

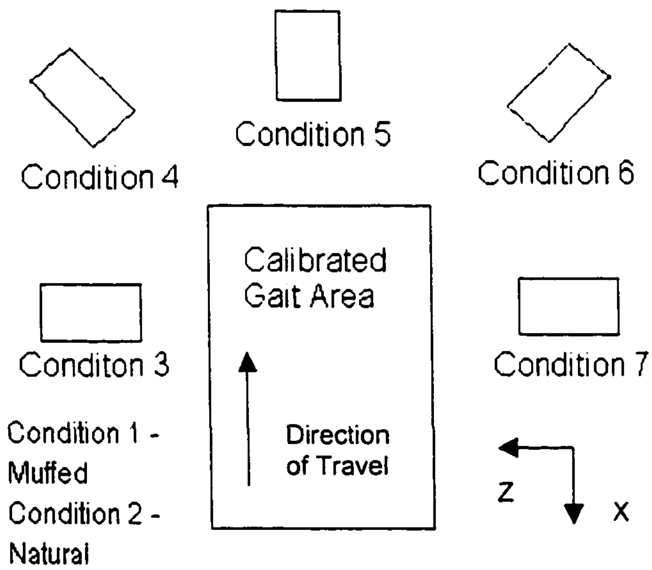


Figure 9.3 – Diagram of Speakers and Original Conditions

Table 9.12 – Names for Combined Conditions

Names to be Lumped	*Description*
Reduced Sound (RS)	Muffed and natural walking without LS
Localized Sound (LS)	All localized sound conditions
Far Left	LS from Far left speaker
Middle Left	LS from 45° left speaker
Center	LS from Center speaker
Middle Right	LS from 45° right speaker
Far Right	LS from Far right speaker

Table 9.13 – Statistically Significant Combined Case Names

Comparisons of Combined Conditions	*Description*
"LS vs. RS"	Localized sound input to reduced sound conditions
"Far Left vs. All Other Speakers"	Far left vs. other speaker conditions
"Center Speaker vs. All Other Speakers"	Center vs. other speaker conditions
"Far Right vs. All Other Speakers"	Far right vs. other speaker conditions
"Far Right & Left vs. Frontal Speakers"	Far speakers vs. other speakers

To confirm the validity of the use of combined conditions in this study, a comparison was made of two statistical general linear models (GLM). The first model included the individual cases as they appear in Table 9.11, and the second model had the combined cases of Table 9.13. The comparison of the original group case and the subgroup "LS vs. RS" showed the "LS vs. RS" case to have 77% of the sum of squares of the original speaker case variable (i.e., conditions 1-7) for head angle performance.

In other words, the subgroup "LS vs. RS" contained 77% of the statistical differentiation of the original speaker cases for this parameter while reducing the number of conditions. This in effect raised the number of trials per condition, and also the significance, while maintaining a true model of the system. This demonstrated that the combined cases increased the probability of finding a statistically significant and yet real result. Of course, future studies will need to include more subjects per condition and also fewer conditions to effectively compare individual sound conditions.

Table 9.14 – Summary of Function Group-wise Comparison Statistics

This table is presented here for later reference.	Walking Speed (%h/s)	Str. Len. (%height)	Min. Str. Width (%h)	Max. Str Width (%h)	H-C7 Max. (deg)	H-C7 Min. (deg)	H-C7 Avg. (deg)	Nod Del Min. (deg)	Nod Del Avg. (deg)	COM Delta Z (%h)
<u>Preliminary Test Groups</u>										
Vestibular Pass Group vs. Vestibular Fail Group	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Localization Pass Group vs. Localization Fail Group	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
<u>Atypical CANS Function vs. Normal CANS Function</u>										
LS vs. RS	p=0.03	ns	p=0.05	ns	ns	ns	ns	p=0.035	p=0.04	ns
Far Left Speaker vs. All Other Speakers	p=0.04	ns	p=0.03	ns	ns	ns	ns	p=0.03		ns
Center Speaker vs. All Other Speakers	ns	ns	ns	ns	ns	p=0.05	ns	ns	ns	ns
Far Right Speaker vs. All Other Speakers	ns	p=0.05	ns	ns	ns	ns	ns	ns	ns	ns
Far Left and Far Right vs. Frontal Speakers	ns	ns	ns	ns	ns	ns	ns	p=0.01	ns	ns
<u>Atypical CANS – Strong Right Ear vs. Strong Left Ear</u>										
LS vs. RS (Group2 Only)	ns	ns	ns	ns	ns	ns	ns	ns	ns	p=0.01
Center Speaker vs. All Other Speakers (Group2 Only)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Far Right Speaker vs. All Other Speakers (Group2 Only)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Far Left and Far Right vs. Frontal Spkrs (Group2 Only)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

All p values are group-wise comparisons.

Table 9.15 – Summary of Function Case (Inter-subject) Comparison Statistics

	Walking Speed (%h/s)	Str. Len. (%height)	Min. Str. Width (%h)	Max. Str Width (%h)	H-C7 Max. (deg)	H-C7 Min. (deg)	H-C7 Avg. (deg)	Nod Del Min. (deg)	Nod Del Avg. (deg)	COM Delta Z (%h)
<u>Preliminary Test Groups</u>										
Vestibular Pass Group vs. Vestibular Fail Group	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Localization Pass Group vs. Localization Fail Group	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
<u>Atypical CANS Function vs. Normal CANS Function</u>										
LS vs. RS	ns	ns	ns	ns	ns	ns	p = 0.02	ns	ns	ns
Far Left Speaker vs. All Other Speakers	ns	ns	ns	ns	ns	ns	ns	ns		ns
Center Speaker vs. All Other Speakers	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Far Right Speaker vs. All Other Speakers	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Far Left and Far Right vs. Frontal Speakers	p = 0.04	ns	ns	ns	ns	ns	ns	ns	ns	ns
<u>Atypical CANS – Strong Right Ear vs. Strong Left Ear</u>										
LS vs. RS (Group2 Only)	ns	ns	ns	ns	ns	ns	p = 0.03	ns	ns	ns
Center Speaker vs. All Other Speakers (Group2 Only)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Far Right Speaker vs. All Other Speakers (Group2 Only)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Far Left and Far Right vs. All Other Spkrs (Group2 Only)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

All p values are are across groups by case.

Table 9.16 – Group- wise Significant/Non-significant Gait Parameters

Parameter	*Significant (p<0.05)*	*Non-significant (p>0.05)*
Ankle Velocity in X left (%height/sec)		X
Ankle Velocity in X right (%height/sec)		X
Avg. Head Accel. in X (m/s/s)		X
Avg. Head Accel. in Y (m/s/s)		X
Avg. Head Accel. in Z (m/s/s)		X
Avg. Head Velocity in X (m/s)		X
Avg. Head Velocity in Y (m/s)		X
Avg. Head Velocity in Z (m/s)		X
COM Movement in X (%height)		X
COM Movement in Y (%height)		X
COM Movement in Z (%height)	X	
Head Nod Avg. Absolute Value (deg)		X
Head Nod Avg. Change (deg)	X	
Head Nod Max Absolute Value (deg)		X
Head Nod Max Change (deg)		X
Head Nod Min Absolute Value (deg)	X	
Head Nod Min Change (deg)	X	
Head to C7 Angle Avg. (deg)	X	
Head to C7 Angle Max (deg)		X
Head to C7 Angle Min (deg)	X	
Hip Angle Change Avg. left (deg)		X
Hip Angle Change Avg. right (deg)		X
Hip Angle Change Max left (deg)		X
Hip Angle Change Max right (deg)		X
Hip Angle Change Min left (deg)		X
Hip Angle Change Min right (deg)		X
Stride Length (%height)	X	
Stride Length (m)		X
Walking speed (%height/sec)	X	
Walking speed (m/sec)		X
Stride Width Avg. (%height)		X
Stride Width Avg. (m)		X
Stride Width Max (%height)		X
Stride Width Max (m)		X
Stride Width Min (%height)	X	
Stride Width Min (m)		X

9.9 *Stride Results*

The results of the gait study were split up into three sections, each with associated discussion: (1) Stride Results, (2) center of mass position (COM), and (3) Head Angles. The first portion of the results was presented here on the variance of stride length, walking speed, and stride width over the combined cases described in the last section. All of the models presented here were general linear models (GLM) formed in Minitab®. The general linear form was used to extract the proper data from the model (See Section 8.2 - Statistical Background).

The first interaction studied was that of sound input on walking speed. A comparison of the combined case "LS vs. RS" revealed that there is a significant difference ($p = 0.027$) between the walking speed of people with a normally functioning CANS (Group1) and those with an atypically functioning CANS (Group2). The mean walking speed of Group1 was slower during quiet than during the sound cases and the response of Group2 was exactly the opposite (See Figure 9.4).

The significant difference in the walking speed between Groups 1 and 2 was also shown in "Left Speaker vs. All Other Speakers". The between-group difference ($p = 0.04$) was not as large, but was still significant. In Figure 9.5, the change in the response for Group1 was not large from the extreme left speaker to the other speakers. While Group2 increased speed for speakers other than the left speaker, the change in walking speed for Group1 differed significantly from the change in walking speed for Group2.

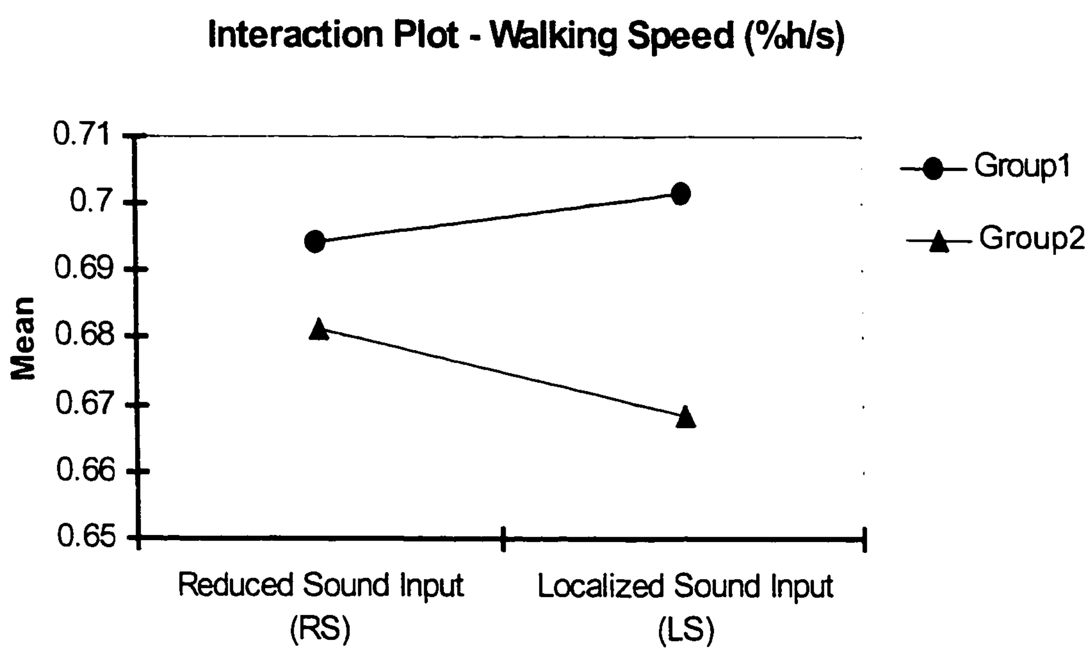


Figure 9.4 – Walking Speed for Quiet vs. Sound

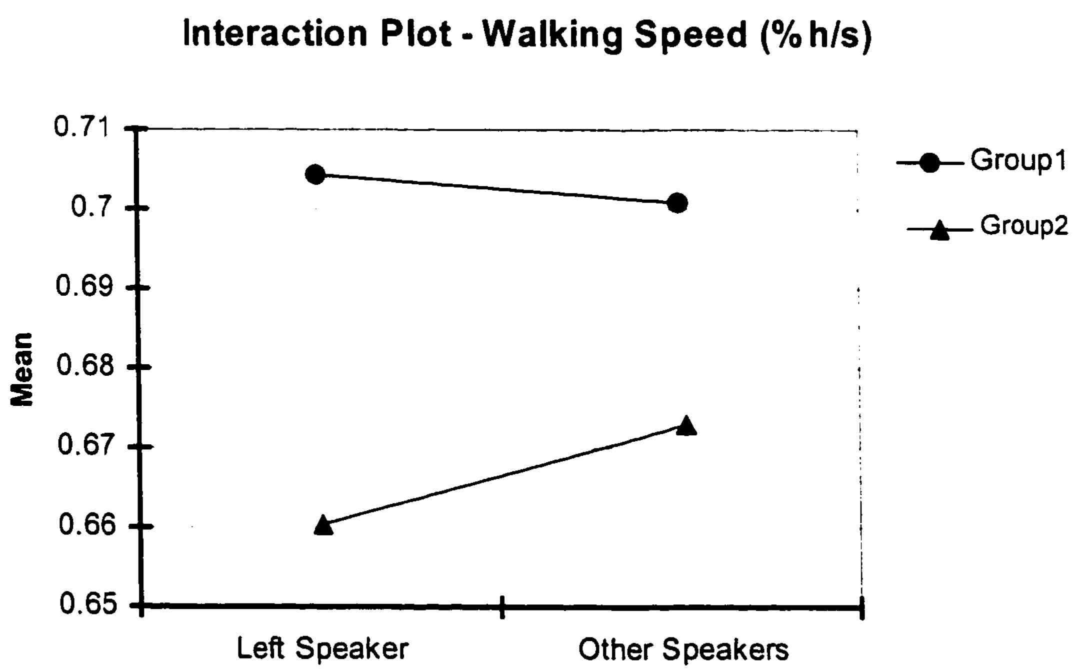


Figure 9.5 - Interaction Plot of Walking speed for "Far Left vs. All Other Speakers"

Error bars were drawn on each point to represent the statistical error of each interaction mean. This error included subject to subject variation as well as the error of measurement. The significance of each interaction was based upon the interaction of the four means and not the absolute measurements of each of the four means. Consequently, even though the error bars of two interaction means overlapped slightly, the statistical significance of the four individual means was still highly significant.

The stride length, associated with walking speed, did not change significantly in interaction for either group ($p = 0.9$). In "LS vs. RS", the stride length remained statistically equivocal (See Figure 9.6).

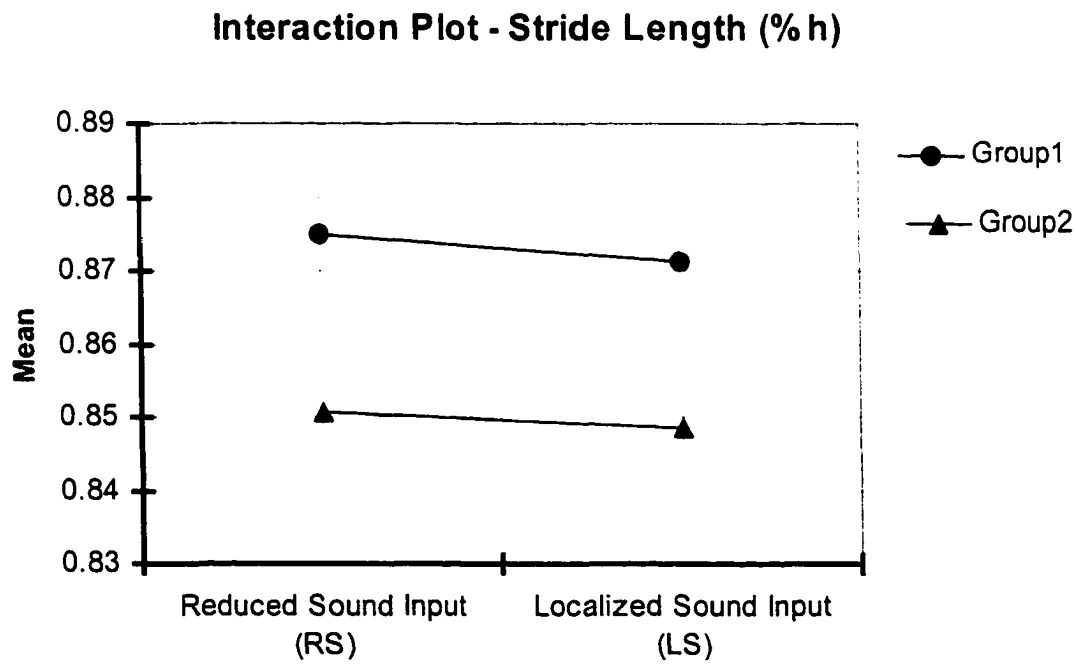


Figure 9.6 - Interaction Plot of Stride Length for Case LS vs. RS

A significant interaction in walking speed was also seen within a subset of Group2. The reaction of the subjects with an atypically functioning CANS appeared to differ dependent upon sound location.

In Figure 9.7, for Case "LS vs. RS" a significant difference (p = 0.027) was found for walking speed between the atypical CANS groups (Please note that the axes in Figure 9.7 have been switched from the previous layout for clarity. See Section 5.2). Based on CAP Test Battery results, the classification of a weaker right ear (Group2R) or a weaker left ear (Group2L) appeared to correlate to walking speed. Across conditions, Group2R moved more quickly than Group2L.

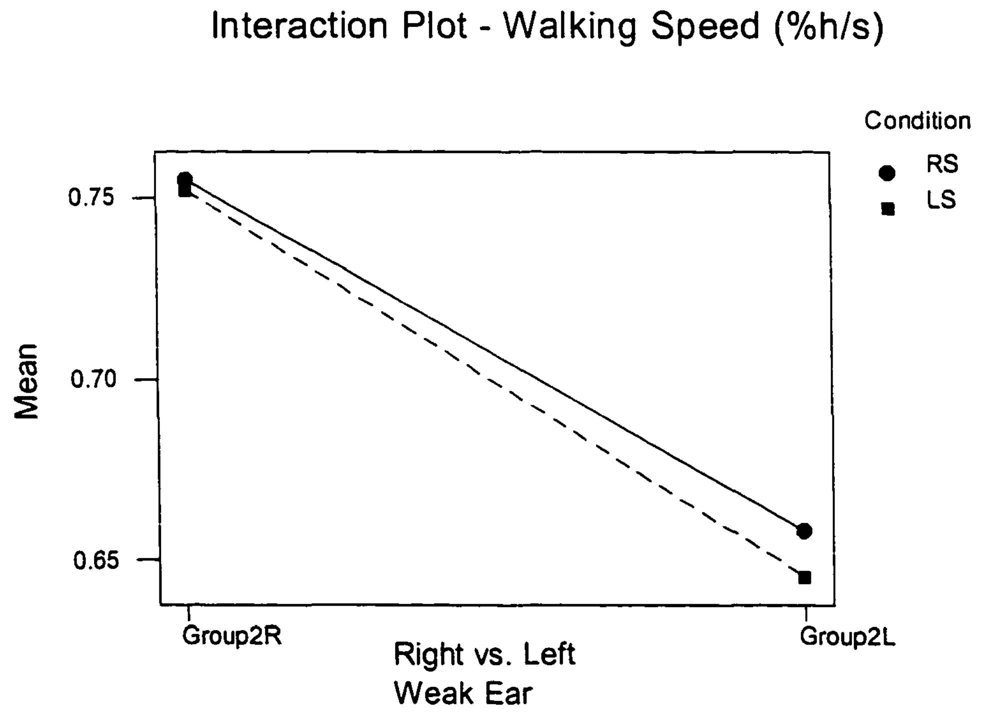


Figure 9.7 - Interaction Plot of Walking speed for CAP Diagnosis

9.10 Discussion of Stride Results

As confirmation of the trend in Group2R walking faster than Group2L also manifested itself in Case "Far Right vs. All Other Speakers" but not significantly (p = 0.061, graph not shown). The significant interactions and non-significant trends in the differing Group2R and Group2L responses may have been due to whether sound was present or not, and where the sound was located. This would tend to suggest that sound localization played an important part in the motor control of people within Group2.

Referring to the initial results for stride, Group1 walked at a faster rate than Group2 for "Far Left vs. All Other Speakers". In contrast to the lack of change of Group1 in this case, Group2 saw a significant increase in walking speed when sound was present in the speakers other than the far left one (See Figure 9.5). By slowing down, Group2 was demonstrating an adverse reaction to the presentation of sound in the far-left speaker. The reason for this reaction could have been due to a localization effect, causing confusion in Group2 and therefore an associated slowing in gait.

Consequently, the presence and location of sound was shown to cause changes in both Group1 and Group2. The changes were significantly different between the groups, with Group1 slowing for RS and Group2 slowing for the LS cases.

Of note was the lack of group-wise significant difference in the change of the stride length. This meant that both groups reduce their stride length in reaction to sound. However, the group-wise significant difference in walking speed in connection with these data pointed to a difference in group cadence - not measured in this study.

9.11 Center of Mass Position Results

Another way of demonstrating the improvement of gait was the movement of the center of mass between heel strikes of the same foot (COM Delta). COM in the Z direction demonstrated one statistically significant group-wise interaction. Looking at difference in the Z delta in Figure 9.8, it was seen that Group2L has much less movement in the Z direction than those in Group2R. Both groups showed more drift during all sound cases.

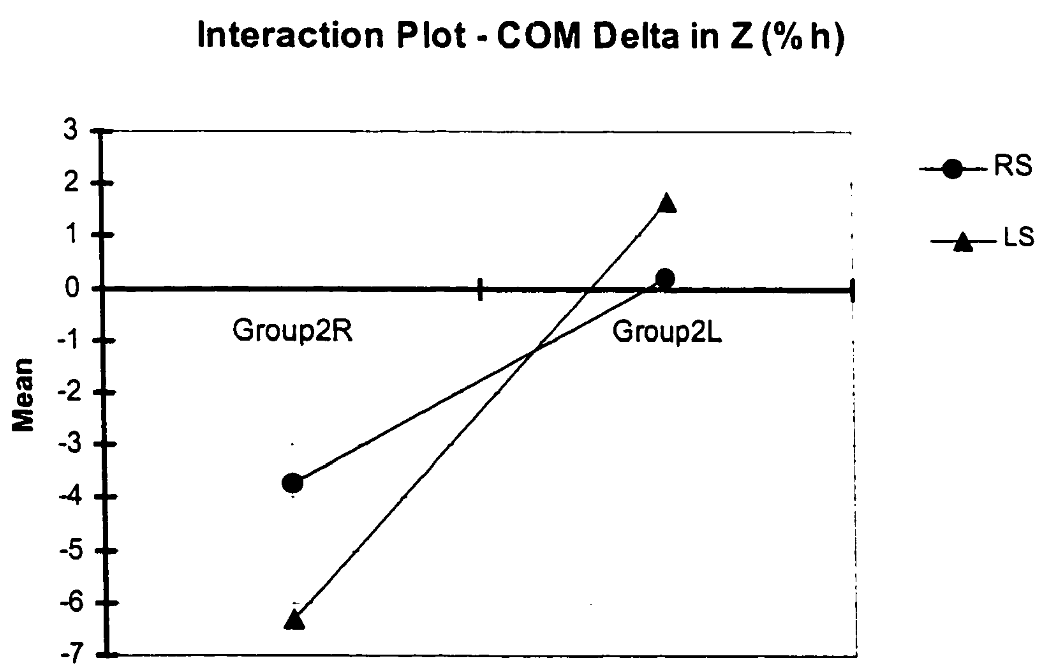


Figure 9.8 – Interaction Plot of COM Delta in Z for Groups 2R and 2L

While too little movement in the Z is an indication of inefficiency, too much is an indication of drift. Drift is movement of the whole body to the side during gait. Instead of returning to its original position in a harmonic manner, a drifting COM will continue to the side. Drift is an indication of a problem in a person's gait, whether caused by a neurological or otherwise physical problem (Saunders et al., 1953).

By way of illustration, Figure 9.9 and Figure 9.10 show a sequential set of graphs of the COM absolute position in Z for subject number one of Group1 and subject number 17 of Group2. Each case is plotted along the X-axis in numerical order (however, not necessarily in the order of testing).

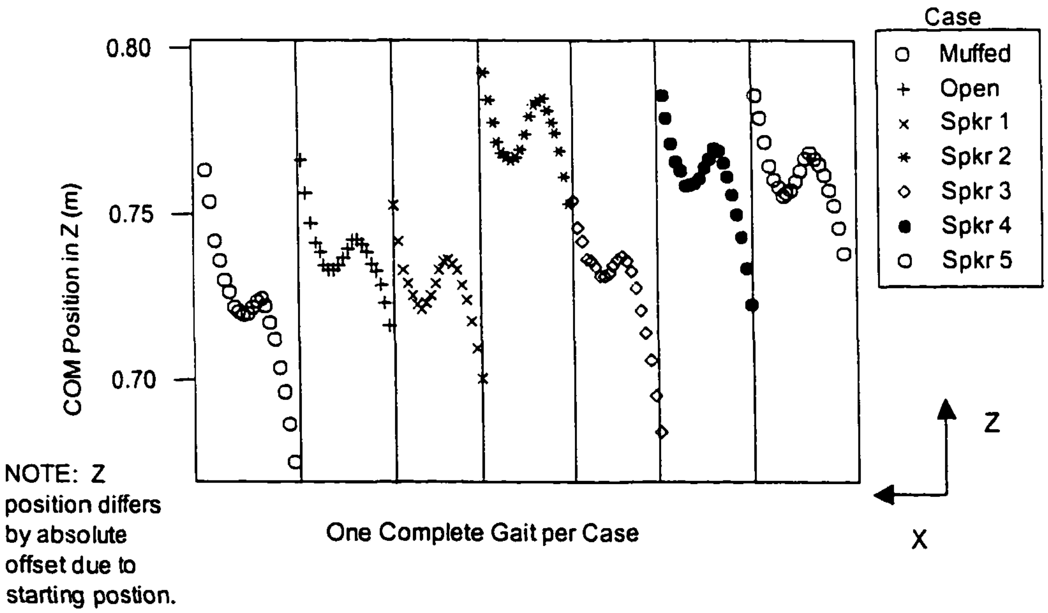


Figure 9.9 – Sequential COM Graph for Subject 1 – All Cases

9.12 Discussion of Center of Mass Results

The COM graph for a subject with normal motor function for a single step should look like those in Figure 9.9. The individual plots are essentially even and symmetric. Additionally, subject one's plots show the shift of weight from one side of the pelvis to the other.

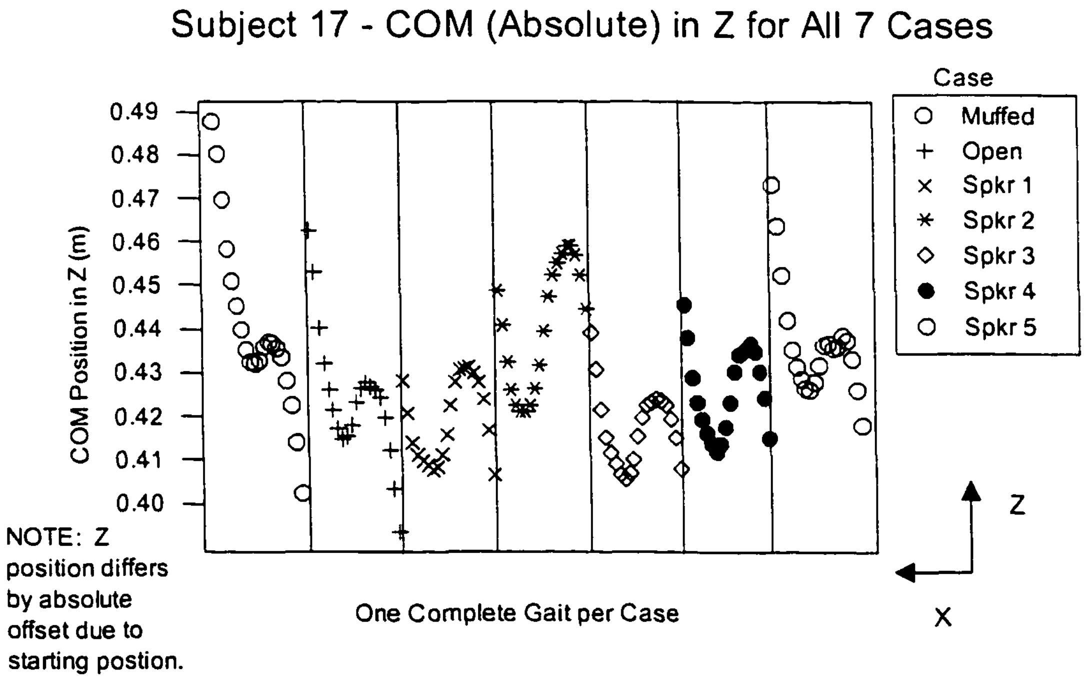


Figure 9.10 - Sequential COM Graph for Subject 17 – All Cases

The plots in Figure 9.10 are symmetric for Cases 1 and 2 (Quiet) and show the shifting of the weight as seen in Figure 9.9. However, for Cases 3-7, the weight shift is definitely gone and the symmetry disappears.

By not shifting the COM during gait, Subject 17 was reducing his or her gait efficiency by requiring the body to lift the COM over a greater vertical distance with each step. The asymmetry shown in the sequential plots was also an indication of a problem under the sound conditions. These conditions seemed to affect this subject's equilibrium greatly.

The sequential COM plots did find gait asymmetry, but with only one stride, it was difficult to gauge whether the gait was truly symmetric. The physical limitations of the gait laboratory precluded the inclusion of two strides. In addition, individual (separate) strides from each starting foot were not collected since trial averaging required that the heel strike events be from the same foot.

In addition, referring to Figure 9.8, it appeared that Group2R and Group2L had different methods for reacting to sound. Group2L collapsed the gait, not allowing much pelvic movement. Group2R drifted with large changes in COM Z position, seeming to lose direction. Both reactions were indications of gait deficiency, albeit of different types. Additionally, it appeared that people with a left weak-ear (Group2L) drifted to the left and those with a right weak-ear (Group2R) drifted to the right.

All of these deficiencies deserve more study. A future study could pinpoint the COM movement with more accuracy by adding a third pelvic biomechanical marker. This would allow a finer resolution of Group2's reaction to the "LS vs. RS" condition.

9.13 Head Angle Results

9.13.1 H-C7 Angle Results

Two angles were measured on the head in this study. Head nod measured the angle from the intersection of the X-axis with the C7 marker to the center of the head. The (H-C7) head angle versus C7-spine marker measured the deviation of the head from the straight-ahead position (See Section 8.1).

Of the conditions defined earlier, two cases were significant for the H-C7 angle: (1) Case "Center Speaker vs. All Other Speakers" and (2) a case-wise intra-subject reaction to Case "LS vs. RS". In the Case "Center Speaker vs. All Other Speakers", Group1 tended to have a greater H-C7 angle for the center speaker versus the other speakers. Group2 had a greater H-C7 angle in the other speakers than the center one (See Figure 9.11).

Additionally, subjects within Group1 and Group2 appear to react very differently across sound cases. In Figure 9.12, it is seen that Group1 as a whole has the least head turn for the muffed case and the most for the natural walking case. Group2 as a whole has the greatest H-C7 angle for the muffed case, with the angle value dropping sharply for the other cases. Group1 demonstrates increased head turn for case 3 (center speaker). These data are in concurrence with Figure 9.11, which shows increased head movement for case 5 (Center Speaker).

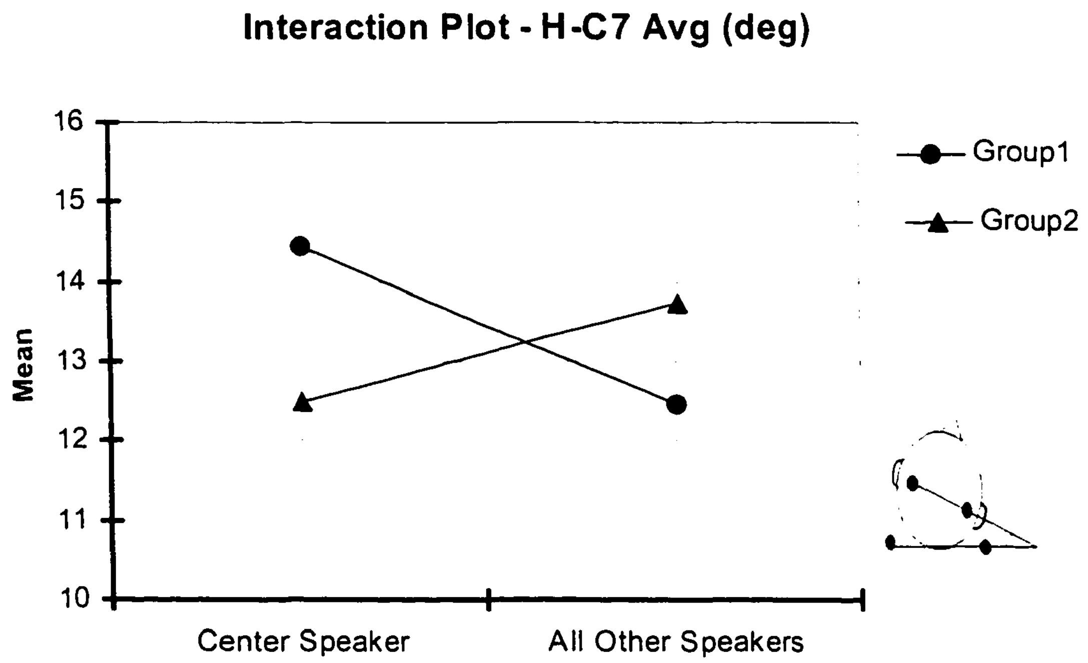


Figure 9.11 – Interaction Plot of H-C7 Angle for "Center Spkr vs. All Other Speakers"

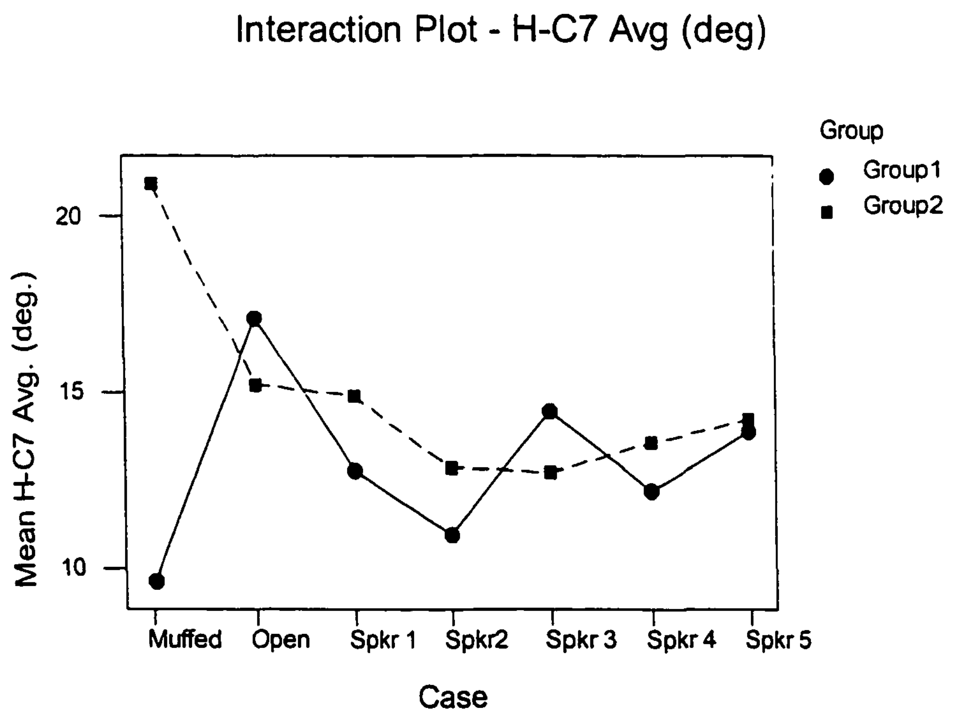


Figure 9.12 – Interaction of H-C7 Avg. by Case

9.13.2 Discussion of H-C7 Angle Results

Head position can be correlated to that of the COM. In order to have an efficient gait, the movement of the COM in the Y direction and the associated work done must be minimized. This is the reason for the shift of weight over the planted foot and the tilt of the pelvis mentioned in the previous section. By reducing the up-down motion of the COM, the motion of the head is also reduced, which is quite beneficial. A reduction in movement provides a stable environment in which the motor control system can work.

The data in Figure 9.12 must be taken as an illustration since it was truly the within subject variation between cases that was significant here. But this graph demonstrated the fact that humans perform poorly at localizing sound sources straight-ahead. This poor performance in Group1 for localization was probably a result of the lack of inter-aural differences due to the sound signal's arrival to both ears at the same time. This led to confusion of whether the sound location was to the front or the back of the person.

This study theorized that people with the ability to localize would turn their head slightly when presented with a sound straight ahead. This allowed the person to interpret the sound localization by inter-aural time and phase differences. Figure 9.11 supported this theory with the difference between the response interactions for Group1 and Group2 being significant ($p < 0.05$).

Figure 9.11 indicates that the subjects of Group1 tended turn their head more when the center speaker was on and less when the other speakers produced sound. Group2 participants had the opposite interaction and turned their head more when a speaker was on other than the straight-ahead speaker. The error bars of Figure 9.11 did overlap slightly for the center speaker case due to the relatively few numbers of subjects involved. However, the interaction was still significant.

With the limited number of subjects in this study, it was difficult to draw generalizations. A person with a CANS problem might have been able to localize more effectively in the straight-ahead direction due to the phase and time differences engendered by the disability actually causing a "shift" in the auditory localization structure. If this were the case, the person with the CANS disability would have difficulty localizing at a slight angle offset from the sagittal plane. This offset theory could be illustrated by the increase in Group2 of H-C7 angle for the speakers other than the center and middle-left.

In addition to the significance of Cases "LS vs. RS" and "Center Speaker vs. All Other Speakers", the diagnosis of CANS dysfunction also correlates with the H-C7 angle for Group2 (See Figure 9.13). As an illustration, Figure 9.13 shows how the members of Group2L have a greater variance of the H-C7 for the RS portion of Case "LS vs. RS". This statistically significant difference ($p = 0.025$) needs further investigation to determine if the effect is due to a localization function or due to other neurologic effects.

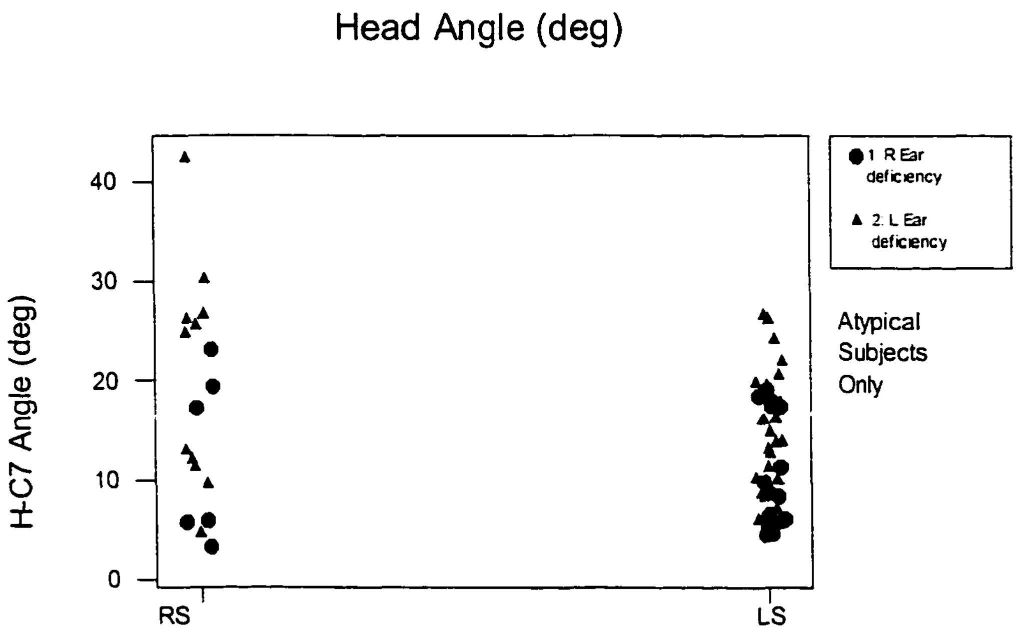


Figure 9.13 – H-C7 Angle for Group2 in LS vs. RS

9.13.3 Nod Angle Results

The results of the last section for H-C7 were shown to correlate with the second measured angle of head nod ("Nod"). As the head turned to the side, it was more difficult for the head to remain in a downward nod (See Figure 9.14).

In comparison to Figure 9.11, this effect is seen in Figure 9.14 as an increase in H-C7 and associated decrease in Nod for the straight-ahead portion of Case "Center Speaker vs. All Other Speakers". (Note: This combined case was not significant, but was presented here for illustration of the connection between Nod and H-C7).

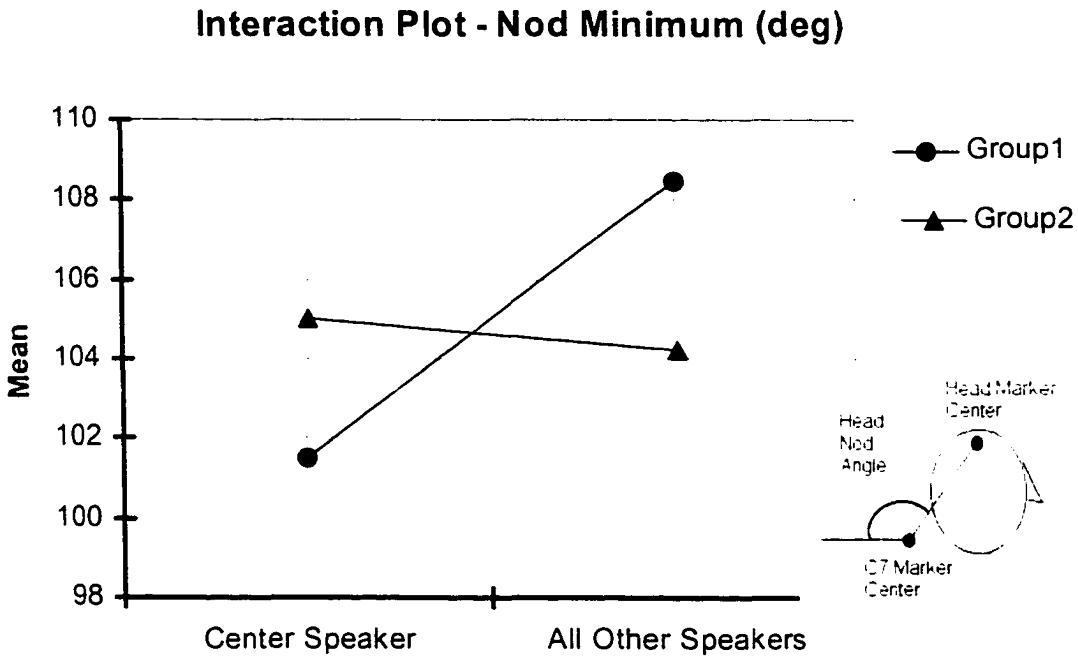


Figure 9.14 – Interaction Plot of Nod Min. for "Center Spkr vs. All Other Speakers"

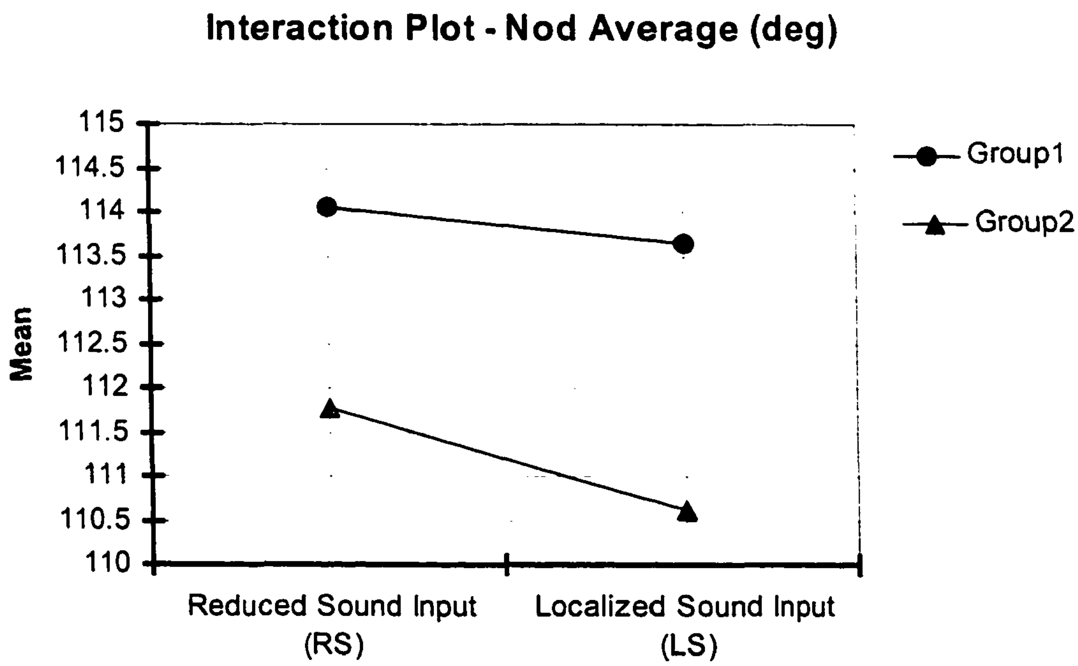


Figure 9.15 – Nod Average for "LS vs. RS"

In Figure 9.15, Nod demonstrates a difference in group-wise interactions for case "LS vs. RS" ($p = 0.043$). In the "RS" conditions, both Group1 and Group2 showed a group-wise significance in change in head nod from the heel strike to heel strike.

Both groups tended to lower their heads in "RS" more than in sound cases. In addition, Group1 tended to have a lower head position than Group2 (See Figure 9.15). A significant difference between groups was also demonstrated by Group2 tending to lower their heads more from heel strike to heel strike in "RS" than Group1 (See Figure 9.16).

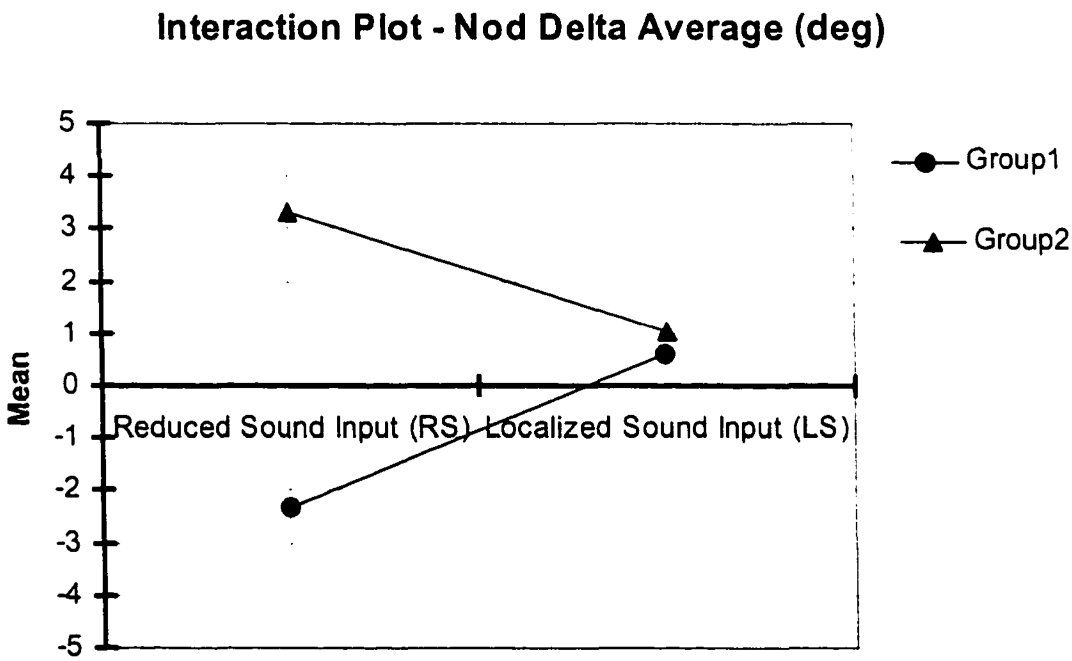


Figure 9.16 – Nod Delta Average for LS vs. RS

The difference in group interactions in Nod Delta from the heel strike to heel strike was highly significant for Case "Far Right & Left vs. Frontal

Speakers" (p = 0.01). Figure 9.17 shows that Group1 tended to raise their heads less when the side speakers (speakers one and five) are on, and raise them more when the frontal speakers are being used (speakers two through four).

The members of Group2 had the opposite reaction to Case "Far Right & Left vs. Frontal Speakers". They tended to raise their heads more for the side speakers and raise them less for the speakers in the frontal plane.

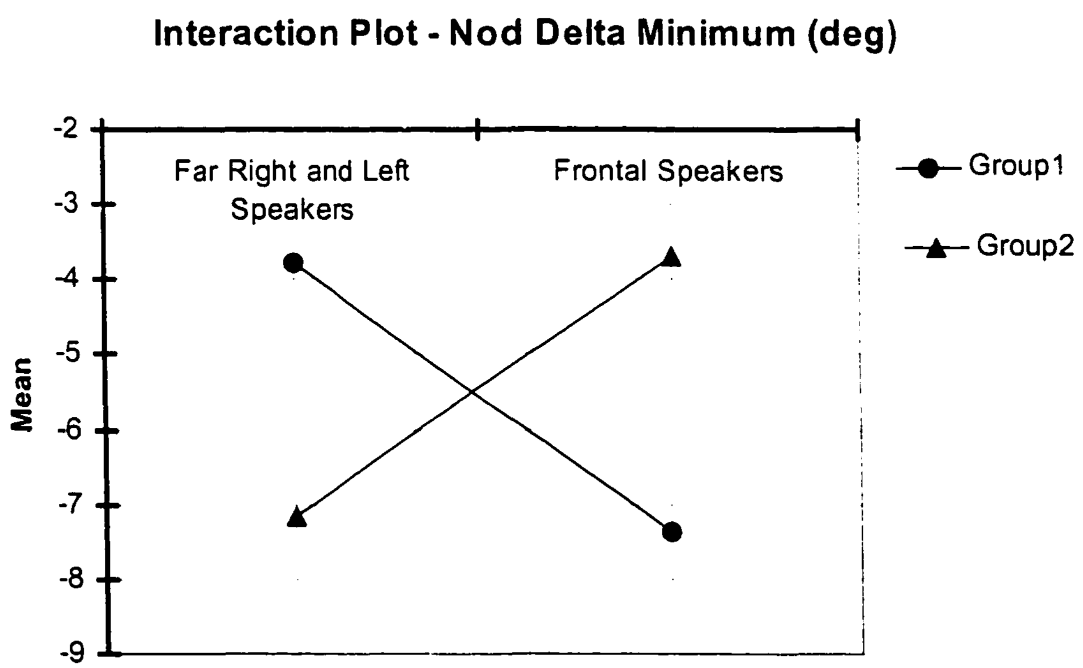


Figure 9.17 – Interaction Plot for Nod Delta Minimum for Case "Far Right & Left vs. Frontal Speakers"

9.13.4 Discussion of Nod Angle Results

The explanation of the effect of Case "Far Right & Left vs. Frontal Speakers" again goes back to the localization of sound. Group1 participants may have raised their heads as they passed a sound source but raised them more in order to localize the sound to the front. Group2 members may have had difficulty with sound sources to the side and consequently raised their heads less to avoid auditory stimuli to the side than for sources to the front.

The overall result for both groups having their heads lower in quiet correlated well with Pozzo et al. (1990, 1991). As mentioned before, Pozzo et al.'s subjects generally kept their heads lower during gait in darkness than in light. Perhaps this result of head lowering in quiet and darkness correlated with the "locking" of the head to the torso that Pozzo et al. was talking about in Section 1.6. When sensory input was reduced, both groups tried to gain stability in the gait by lowering the head (especially by Group2), narrowing the stride and reducing speed.

9.14 Gait Parameter Correlation Matrix

To explain the interaction parameters like H-C7 and Nod, a correlation matrix is presented in Table 9.17. This table demonstrates the close relationships presented earlier in this paper. The positive correlation of minimum stride width to walking speed was significant ($p = 0.001$). The correlation of H-C7 delta average and Nod delta average was highly significant ($p = 0.001$). Nod delta maximum was surprisingly significant and tended to show that the motion of the head is significant to the rest of the body.

The results of this study have shown that the effect of sound on a person's gait is significant. The correlation matrix will prove valuable to future research as a model for the performance of subjects with different auditory function.

In fact, a discriminate analysis using these parameters had a 79% success in diagnosing subjects in this study into their proper groups. Adding the parameters H-C7 minimum and maximum raised that success ratio to 94.4%. This discriminate analysis places subjects into groups dependent upon the variables given in the model. If the success ratio is high, it means the model predicted the same grouping of subjects as is modeled in the experiment. In other words, the discriminate analysis for this study correctly placed subjects into Group1 or Group2 based upon the gait parameters given in Table 9.16 – Group- wise Significant/Non-significant Gait Parameters. Consequently this analysis showed a high correlation between the measured gait data and the CAP test battery diagnosis.

Table 9.17 – Gait Parameter Correlation Matrix

	Walking Speed (%h)	*Min Stride Width (%h)*	*Max Stride Width (%h)*	*H-C7 Max Delta (deg)*	*H-C7 Min Delta (deg)*	*H-C7 Average Delta (deg)*	*Nod Max Delta (deg)*	*Nod Min Delta (deg)*
Minimum Stride Width (%h)	0.346							
p-value	0.001							
Maximum Stride Width (%h)	-0.009	-0.361						
p-value	0.920	0.001						
H-C7 Average Delta (deg)	-0.307	-0.050	0.162					
p-value	0.001	0.583	0.072					
Nod Maximum Delta (deg)	0.003	-0.165	0.309	0.471	0.105	0.334		
p-value	0.976	0.065	0.001	0.001	0.244	0.001		
Nod Minimum Delta (deg)	0.280	-0.017	0.352	-0.104	0.230	0.186		
p-value	0.002	0.848	0.001	0.248	0.010	0.038		
Nod Average Delta (deg)	0.158	-0.104	0.370	0.310	0.137	0.325	0.903	
p-value	0.078	0.248	0.001	0.001	0.127	0.001	0.001	
COM Position in Z	0.056	0.209	-0.495	-0.186	-0.402	-0.444	-0.054	-0.169
p-value	0.537	0.020	0.001	0.038	0.001	0.001	0.546	0.060
Pearson product moment correlation coefficient between each pair of variables.								

10. CONCLUSION

The motor function of people with an atypical central auditory nervous system was not well understood. No study has to this point been undertaken to investigate the influence of sound on the gait of this population. Furthermore, very little was known about the influence of sound on human gait, and this study is a large addition to the literature in this area.

Most importantly, it was found that the gait of people in both groups was influenced by sound. In addition, the measurement of gait under varying sound conditions was successful in showing group-wise differences in several gait parameters.

From the study data, the two subject groups are found statistically group-wise equivalent in height, gender, and age. Group1 (people with normal CANS function) was shown to be in line with literature normative data in all parameters except stride width and head vertical excursion. Stride width was found to be related to the localized sound (LS) conditions within the study, and the reactions of the two groups to these sound conditions. The variance of vertical head excursion from the literature norm was explained by the head angular position through the gait cycle. By the increased variance the head angular position over literature norms shown in this study, the head vertical excursion as measured by the H-C7 markers would also vary more than that in literature.

Overall, group-wise reactions were found to be highly significant. In general, Group1 reacted to reduced sound (RS) input by reducing speed, keeping the head low, and narrowing their stride width. Group2 (people with atypical CANS function) as a whole had the opposite reaction for walking speed and stride width. This group increased speed and stride width more in LS than in RS while keeping the head low during RS conditions. However, Group2 tended to lower their heads more than Group1 in RS and raise them more than Group1 in LS in terms of angular change from heel strike to heel strike. Additionally, Group1 tended to have a lower head Nod position overall than Group2.

Also it was found that the drifting of the center of mass (COM) in the lateral (Z) direction for Group2 changed significantly under the condition of sound. Interestingly, the two sub-groups had different COM movement dependent upon the diagnosis of weak-ear. For the people with a weak right-ear (Group2R), the lateral (Z) COM movement was large due to significant drifting. In contrast, the people with a weak left ear (Group2L), the movement of the COM in the lateral direction was smaller, indicating a lack of weight shift over the stance leg. However, Group2L did see an increase in lateral movement in LS, indicating that sound is a factor in both subgroups' gait. In addition, for the Case "LS vs. RS", both subgroups of Group2 tended to drift towards the side of their weak-ear diagnosis. This demonstrated an astounding correlation between CAP Test Battery diagnosis and motor function.

The movement of the head in the transverse plane, as measured by the H-C7 angle, was also significantly different between Group1 and Group2. Group1 tended to have a greater H-C7 angle for the center speaker than for the other speakers versus Group2, and vice-versa. This group-wise difference could indicate a difference in localization ability. It was additionally hypothesized that an inherent "offset" in the localization ability of Group2 would explain the greater H-C7 angle in Group2 versus Group1 for the speakers other than the center speaker.

In conclusion, this study demonstrated a significant influence of the effect of sound on human gait. It was the first study to explore this area. Significant correlations between the location of sound and walking speed, head angular position, and COM position were found.

10.1 Future Work

Future studies may want to expand upon this study to explore further the effect of auditory localization on gait. Some suggested changes would be to add one or two more synchronization pads to the gait walkway to measure the heel strike of both feet. This would allow for an effective step length and cadence calculation, both of which are measures of gait asymmetry.

In addition, a third marker should be added to the head to allow for planar angle calculations. By using planar calculations, an even more effective model of head movement could be accomplished and the true relationship between H-C7 and Nod could be explored. Additionally, the third marker distinguish between left and right head turns.

A marker should be added if possible to allow for pelvic angle calculations. This marker is not available in this study due to limitations in layout of the gait lab. Subjects should also be asked to use the same foot to start their gait every time. By doing so, it will help collect the same heel strike combination needed across gait trials for averaging.

If possible, the gait laboratory should be widened and lengthened to allow for a wider camera angle and consequently a better set of data due to improved calculation accuracy. The increased size of the room would allow the cameras to be moved permitting the addition of markers to the backside of the subject. The current study could not attach markers to the person's back since every marker must be seen in at least two camera views. The larger room would also allow two complete gait strides to be measured, which would then permit the assessment of gait asymmetry on the basis of COM movement and stride parameter differences.

A larger study group should be emphasized to include more gait runs per condition for fewer conditions. This would prevent the need for combining cases, as was done in this study, and allow the statistics to show truly what is influencing gait. In addition, with a larger population, the variance inherent in the data will not be an issue as it is for this study.

The suggestion for a larger population will require a significant reduction in the processing time to get the data from videotape to a computer file. The time requirement is a major hurdle since every set of subject data takes 10-15 hours to obtain. For this reason, an update to the Motus™ system is definitely needed before any significant improvements on the data acquisition can be obtained.

Besides the improvements to the room and statistical parameters, several new cases could be run to explore the findings of this study. To properly understand whether low lighting was truly a factor in the change of the gait of Group1, a study should be performed in normal lighting with varying sound conditions.

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12. APPENDICES

12.1 Regulation of Human Subject Selection

Subjects were recruited from the local communities of Colorado State University (CSU). Subjects were included without regard to gender or race. However, an effort was made to an equal distribution of males to females. The investigators obtained written informed consent from the subjects prior to entry into the research study. This was performed in accordance with the guidelines and under the supervision of the CSU Regulatory Compliance Office. All records were treated with strict confidentiality. The procedures involved in this study posed little to no risks to the subjects, including the gait study and auditory testing. All auditory testing was performed at normal hearing levels.

The study protocol was reviewed and approved by the human subject protocol committee at Colorado State University (Refer to Colorado State University Protocol # 98-150H). CSU required study review to prevent injury to study participants. Criteria for protocol approval appear on the CSU webpage.

12.2 Direct Linear Transformation (DLT) from Section 7.4

Using a set of known control points with an associated set of positional data (X,Y,Z) it was possible to transform the 2D coordinates of the acquired video to the 3D positional data of the gait study. The direct linear transformation used the orientation of each camera with respect to reference axes of a control calibration frame. At least six non-coplanar points with know separation distances were required to complete the transformation. Using the least squares method to determine the best fit, the parameters for the transformation to camera coordinates were acquired. These parameters were valid for as long as the conditions of camera position, focus, and focal length did not change (Peak Motus™, 1997).

12.3 Gait Laboratory Procedure Summary

(To help clarify the procedure, a short summary of the gait analysis protocol is given here.)

After the subject had undergone auditory testing, he or she participated in the gait lab portion of the study. The study was setup and run according to a checklist (See 0). The subject re-affirmed written consent and then answered the history questionnaire (See Appendix 12.6). The subject was asked to wear dark, tight clothing (preferably tank top and shorts) to minimize data error due to clothing movement. Reflective markers were placed on the pre-determined bony landmarks for consistency. Shoes were not worn in order to minimize any outside influence in the subject's gait. The subject was shown the gait lab in full light and the procedure was explained. The subject randomly drew for sequence of cases. Then the lights were dimmed, the subject took a few trial runs and then the gait testing was performed. Following this, the post-rotary nystagmus test was explained and offered. If the subject consented, then the test was performed. Female subjects received an escort to minimize any liability to the subject or the investigator.

12.4 Video Data Collection Methodology

	Description
SETUP	In Windows, create the subdirectories you need for all the subject runs.
	<M> Create base template with spatial model and desired data output in top directory.
	<M> Include Subject information in base model and save it.
	<M> Check the appropriate boxes in the calculations tab.
	<M> Save the base model as your subject base model (e.g., subject 5 base model).
	Connect the video cable from the back of VCR3 to the back of the computer.
SUBJECT	Load Camera #1 tape into VCR.
	<M> Capture the first calibration frame.
	Load Camera #2 tape into VCR.
	<M> Capture the second calibration frame.
	Load Camera #3 tape into VCR.
	<M> Capture the third calibration frame.
	<M> Digitize the three calibration frames.
	<M> Check the error of digitized calibration.

	<M> Save the subject base model.
	<M> Save the subject base model for each trial of each run in the subdirectory structure.
	Consult run sheet to see which of the cases appears first on the video tapes (e.g., Case 6).
TEST	Load Camera #1 tape into VCR.
	<M> Open the trial to be captured for the test (e.g., 5T6R1 for subject 5, trial 6, run 1) in the appropriate subdirectory according to directory protocol.
	<M> Capture the first run that is listed as a "go" on the trial run sheet by setting the time clip to an appropriate amount (e.g., 4 seconds) and hitting the red record button in Motus.
	<M> Crop the video clip 3 frames before the first EVCU signal begins and 3 frames after the second EVCU signal begins.
	<M> Save the test trial.
	Load Camera #2 tape into VCR.
	<M> Capture the run for camera 2 for the same run and trial take for camera 1.
	<M> Save the test trial.
	Load Camera #3 tape into VCR.
	<M> Capture the run for camera 3 for the same run and trial take for cameras 1 and 2.

	<M> Save the test trial.
	<M> Digitize each of the three camera views and save the test trial.
	<M> Set the data output button in the calculations tab to 30 Hz.
	<M> Click the calculate button.
	<M> In the data tab click on segment data – check the error of the several body segments, they should be stable.
	If data are stable, proceed to clipping and digitizing the rest of the trials. If not, check calibration frame, digitization process, and setup. As a last resort, run another test of a different trial.
CLIP	Load Camera #1 tape into VCR.
	<M> Open the trial to be captured (e.g., 5T6R2 for subject 5, trial 6, run 2) in the appropriate subdirectory according to directory protocol.
	<M> Capture the first run that is listed as a "go" on the trial run sheet by setting the time clip to an appropriate amount (e.g., 4 seconds) and hitting the red record button in Motus.
	<M> Crop the video clip 3 frames before the first EVCU signal begins and 3 frames after the second EVCU signal begins.
	<M> Save and close the current trial and open the next trial in the series (e.g., 5T6R2).
	Check the capture box on the digitization sheet for the appropriate camera for the appropriate trial.
	<M> Open the next trial to be captured (e.g., 5T6R3) in the appropriate subdirectory according to directory protocol.

	<M> Capture the run for that trial for the next video clip listed as a "go" on the trial run sheet.
	<M> Continue steps 35-40 until all of trials have camera one clipped for each run.
	Load Camera #2 tape into VCR.
	<M> Proceed as in steps 35-40 until each clip for camera 2 is saved in the appropriate trial.
	<M> Repeat 35-40 for camera #3.
DIGITIZE	<M> Open the current run of the appropriate trial.
	<M> Digitize each of the three camera views and save the trial.
	<M> Set the data output button in the calculations tab to 30 Hz.
	<M> Click the calculate button.
	<M> In the data tab click on segment data – check the error of the several body segments, they should be stable.
	<M> Repeat steps 46-50 until all of the runs are digitized.
AVERAGE	<M> Click on "Trial Averaging" under the tools menu.
	<M> Add the appropriate trials to the averaging box
	<M> Average the trials and save the trial with an appropriate name (e.g., 5T1average)
REPORT	<M> Open a report with the "open from layout" box checked. Change the trial for the report to the appropriate trial average.
	<M> Check the stick figures in the report for abnormality.

EXPORT	<M> Click on the data export button.
	<M> Select the appropriate trial to export and give it a new DOS name (e.g., 5T1average)
IMPORT	Open the appropriate file inside Excel and run macro to port the data.
	Graph the data by macro.
STATS	Open the Excel data inside Minitab and run stats functions.
	Compile data for the individual's gait.

12.5 Gait Analysis Checklist

Data Form Name ______________________ Date ____________________

Item #	Description	Data
	Have subject information	
	Fan turned off, room lights off, camera lights on	
	You've got the headphones, babble tape	
	Cameras setup and adjusted	
	Cameras – manual iris adjusted, manual focus	
	EVCU set to 60 Hz and both switches down	
	Video out cord from VCR to EVCU set	
	VCRs set to A1	
	Third VCR set up	

	Tapes numbered & loaded, calibration mats ready	
	Record test run and check report	
	Subject clothing available	
	Adhesive tape cut and placed on markers	
	Date sign made up	
	Consent form read and signed	
	History questionnaire completed	
	Clothing changed/jewelry, watches removed	
	Cal. Frame filmed with #1 towards #3 camera and with date before filming	
	Subject walks backwards to set pad distance	
	Tape placed for subject's heel	
	Subject stands on both pads to check framing in all views.	
	Order of gait trials / Speaker / Setting Muffed / 1 / 2 Open / 2 / 3 1 / 3 / 3 2 / 4 / 2 3 / 5 / 2	Localization

	ROM tests given (see ROM Form)	
	Reflective markers applied (INCLUDING HAT AND C7 MARKERS)	
	Sound localization test given	
	Practice gait run(s) given with sound	
	Record buttons hit on all machines	
	Gait trials given in random order returning to home in between each trial: a) all speakers off b) heel tape set c) markers checked d) tape stopped/ record paused e) every fifth trial, check camera views f) room closed, sound partition in place g) head markers OK h) Volume set	a) ________ b) ________ c) ________
	Post rotary nystagmus test given in both directions a) Time for clockwise spin b) Time for counter clockwise spin	a) _______ b) _______
	Recordings checked (BY UG)	

	Cal. frame filmed w/ #1 to #3 camera (BY UG) DO NOT ADJUST CAMERAS	
	Tapes labeled with subject # and date (BY UG)	

12.6 History Questionnaire (With parts from Morton (1993)

Name: ______________________________ Date ___________________.

	YES	NO	REMARKS
Is your general health status good?			
Do you have a history of fractures or bone problems?			
Have you hurt yourself or had an accident in the last 2 weeks (e.g., minor burns, scrapes, etc.)			
Do you have muscle cramping, twitching, pain, or weakness?			
Do you have limitations on physical activity?			
Do you have joint swelling, redness, or pain?			
Do you have joint deformity?			
Do you have joint stiffness?			
Do you have spinal deformity?			
Do you have chronic back pain?			
Do you know or do you suspect that you have a vision problem?			

Is that a problem unable to be corrected with glasses?			
Do you know or do you suspect that you have a balance problem?			
Do you have a history of ear infections?			
Do you have a history of dizzy spells or vertigo?			
Have you ever had major surgery?			
Do you have restriction of movement in the head and neck region?			

12.7 Minitab® Example

The general linear model (GLM) example below is for motion of the head in the Y direction. The GLM includes the main terms of CANS function grouping (Group), the presence or absence of localized sound sources (Case12_3-7), and the interaction term of group and sound source location (Group*Case12_3-7).

The F-test result given in the ANOVA table below was determined by dividing the adjusted mean sum of squares of the Group variable by the adjusted mean sum of squares of the nested variable Subjects(Group) (See Section - 8.2). The given p-value was calculated by Minitab given the derived ratio of Group vs. Subjects(Group) and the degrees of freedom for each variable.

```
MTB > GLM  'Head_YDel' = Group subjects(Group) 'case12_3-7' Group* &
CONT>     'case12_3-7';
SUBC>   Brief 2 ;
SUBC>   Means Group 'case12_3-7'.
```

General Linear Model

```
Factor            Type Levels Values
Group             fixed      2 1 2
subjects(Group)   fixed     18   1   2   3   4   5   6   7   8 10 11 12 13 15 16
17 18
                                19 20
case12_3          fixed      2 1 2
```

Analysis of Variance for Head_YDe, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	ADJ F	P
Group	1	0.0031398	0.0030717	0.0030717	1.13	0.31
subjects(Group)	16	0.0444585	0.0445380	0.0027836		
case12_3	1	0.0000578	0.0000604	0.0000604	1.92	0.168
Group*case12_3	1	0.0000500	0.0000500	0.0000500	1.59	0.210
Error	105	0.0032947	0.0032947	0.0000314		
Total	124	0.0510007				

Unusual Observations for Head_YDe

Obs	Head_YDe	Fit	StDev Fit	Residual	St Resid
18	0.060151	0.072175	0.002406	-0.012025	-2.38R
20	0.037024	0.054531	0.002406	-0.017507	-3.46R
80	0.076192	0.057493	0.002166	0.018699	3.62R
105	0.052122	0.073906	0.002164	-0.021784	-4.22R

R denotes an observation with a large standardized residual.