The Mechanisms of Postural Control in the Coronal Plane During Perturbed Standing

by

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Abstract

The Mechanisms of Postural Control in the Coronal Plane During Perturbed Standing

Postural stability can be defined as a measure of the body's ability to remain upright in the presence of the frequently occurring small perturbations experienced throughout the course of daily activity. The ability to maintain balance is dependent upon the successful integration of afferent inputs from a number of sensory systems – the vestibular, vision, proprioceptive, and somatosensory systems. One method of studying the balance system is to perturb one sensory system in isolation and then measure the response. Galvanic vestibular stimulation was the method used to challenge postural control. It places a novel signal on the vestibular nerve that is transmitted along the normal vestibular pathways to both peripheral and central areas, and presents a sensory conflict with the vision and proprioception systems that must be resolved for successful balance recovery. The aim of the study was to describe the response movement, determine the control mechanisms behind the recovery movement, and speculate on the role of the vestibular system. Independent variables included the presence or absence of vision, direction of stimulus current, and duration of stimulus. The outcome measures used to describe the response include kinematic variables (linear and angular displacement of body segments – magnitude, duration and onset latencies), kinetic variables (GRF, CofP, resultant joint moments – magnitude and onset latencies), and EMG of selected postural muscles of the lower leg (gluteus medius, adductor magnus, tibialis anterior, and peroneus longus). Eighteen subjects took part in two separate experiments.

The perturbation caused the head, trunk and pelvis to move in a medial/lateral direction in the manner of an inverted pendulum rotating about

the pelvis centre of mass. This response was consistent across subjects and all conditions. Kinetic results show a four phase response for the longer duration perturbation and a three phase response for the short perturbation. Analysis of the joint moments confirmed kinematic results, showing most of the control of the movement focussed on the hip abductors/adductors. EMG analysis revealed the use of two strategies for movement: a 'hip dominant' and a 'hip/ankle combination' strategy. The foot placement adopted in the experimental protocol is thought to preclude the use of any possible 'ankle' strategy.

The type of perturbation used in the study does not trigger early postural responses through reflex activity. Its role is to aid in the determination of the orientation of the head and body in space – a role shared with the proprioceptive and vision systems. The vestibular system may have more influence than the proprioception system under the conditions tested. Because of possible VOR involvement, a comparison of the relative importance of vision and the vestibular system could not be performed.

Acknowledgements

When I was at the two-year mark of my doctoral work, I read that the dropout rate among Ph.D candidates was approximately fifty percent. I was amazed at the statistic at the time. I understand the reasons now.

This thesis could not have been finished without the support of many people. I want to thank my supervisor, Dr. Jim Frank, for his efforts. He had the unenviable task of taking over supervision halfway through and after most the major decisions had been made, not to mention the difficulties involved in supervising someone on the other side of the world.

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Chapter 1 Introduction

Postural stability can be defined as a measure of the body's ability to remain upright in the presence of the frequently occurring small perturbations experienced throughout the course of daily activities. Being able to maintain one's balance is a crucial element of a physically active and healthy lifestyle. Conversely, an inability to maintain balance can result in serious injury from slips, trips and falls. Besides the personal cost and suffering of the injured person, these injuries put an enormous strain on health care facilities, and increase industrial costs. Recent insurance reports have estimated that compensation payments made due to the consequences of injuries sustained from loss of balance either at home or at work exceed hundreds of millions of dollars per year (ACC, 1997). Falls account for over thirteen percent of all injury deaths (S. Bordeaux and J. Harrison, 1995). While many of these accidents may be due to external factors such as the slipperiness of floor surfaces and types of shoes worn, there may be other factors, which are intrinsic to the person.

The ability to maintain balance is thought to be dependent upon the successful integration of a number of sensory and cognitive systems. Previous studies have focused upon the impact of vision, proprioception, and the vestibular system upon balance and posture. Others have studied the role of some central processes and reflex activity. Loss of balance could result from trauma or disease effecting any of the above systems or processes. As well, degeneration of balance may occur with the aging process. Understanding the basis of postural stability is key to finding possible solutions to these health problems.

One method of studying the balance system is to apply a perturbation to one sensory system and then monitor the body's response. This thesis will study how the body attempts to recover from a challenge to the vestibular system. Specifically, a perturbation, galvanic stimulation, will be applied to the

vestibular system and the resulting motion and muscular activity recorded and analysed, taking into account the complex interactions with other sensory systems and processes. To that end, a review of the neurophysiology of the vestibular system will precede a summary of literature that focuses on its role in the control of balance. Additionally, there is a review of the research involving galvanic vestibular stimulation, focussing on the reliability and validity of the technique as well as its clinical use.

Neurophysiology of the Vestibular System

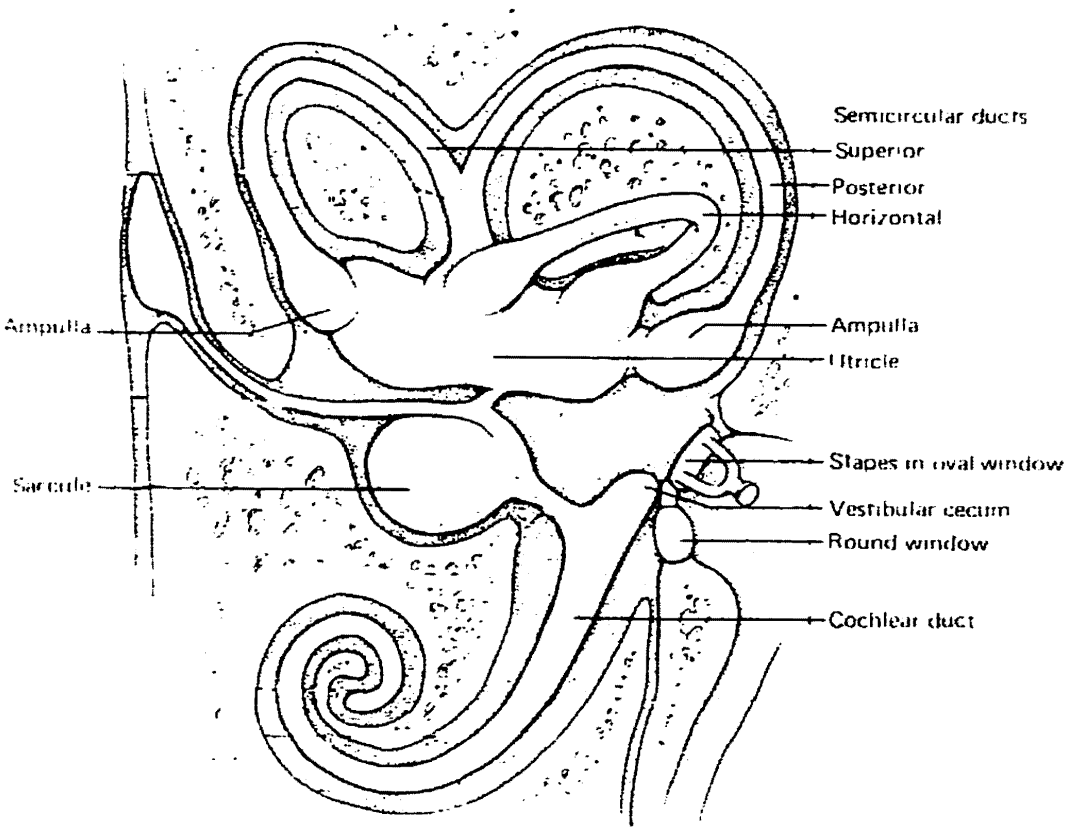
The sensory organs of the vestibular system are located in the inner ear and consist of the otoliths and the semicircular ducts. The main function of these organs is the detection of linear accelerations (otoliths) and angular accelerations (semicircular ducts) of the head. This information, when integrated with other sensory information, is used to determine the position of the head, both in absolute terms and relative to the body, and may moderate the activity of postural muscles. Since galvanic stimulation is thought to more readily effect the otoliths than the semicircular ducts at the magnitude used in this study, the discussion of the neurophysiology will be limited to that of the otoliths, pathways and connected processes.

The Otoliths

The otolith organs consist of a pair of sac like swellings called the utricle and the saccule (see Figure 1.1). Portions of the floor of these organs, called the maculae, are thickened and contain hair cell receptors. The maculae are covered with a gelatinous substance in which calcium carbonate crystals, called otoliths, are embedded. If the head undergoes linear acceleration, the otoliths deform the gelatinous mass, which acts to bend the hairs of the receptor cells. Bending the hair in one direction causes a depolarisation which results in an excitation of the afferent nerve while bending the hair in the other direction causes hyperpolarisation, resulting in an inhibition of the afferent nerve. Both the orientations of the utricle and the individual hair cells aid in responding to

tilts or acceleration in different directions. The macula of the utricle lies in the horizontal plane when the head is in a normal, upright anatomical position and responds to horizontal linear acceleration. The maculae of the saccule are oriented in the vertical position and responds to vertical linear acceleration of the head (J.P. Kelly, 1985). As well, the axes of the hair cells in the macula are arranged so that they do not face in a single direction but point towards a single curving landmark called the striola. A tilt in any direction would cause some hair cells to depolarise while others would hyperpolarize. Presumably the resulting pattern of excitation and inhibition of the afferent nerves is recognised by some central processing mechanism to provide an accurate measure of head position.

Figure 1.1 Schematic drawing of the inner ear, showing the sensory organs of the vestibular system (adapted from Kandel and Schwartz, 1985).



Projections

The main function of the otoliths is the detection of linear acceleration of the head -- information used in the maintenance of tone in gravity-opposing or extensor muscles. Three areas and corresponding pathways contribute to this function: the reticular formation in the brainstem and the reticulospinal tract: the vestibular nuclear complex and vestibulospinal tract; and the cerebellum. Signals from the hair cells ascend the 8th cranial nerve (vestibular nerve) to the ipsilateral vestibular nuclei (lateral and medial areas) in the brainstem as well as the flacculonodular lobe of the cerebellum. The afferent fibres of the vestibular system have their cell bodies in the vestibular ganglion, which consists of two parts. The superior division innervates the macula of the utricle, the anterior part of the macula of the saccule, and the cristae of the horizontal and anterior semicircular canals. The inferior division innervates the posterior part of the macula of the saccule and the cristae of the posterior duct. These axons join with others from the spiral ganglion in the cochlea to form the vestibulocochlear nerve, which runs near the internal auditory meatus and onto the vestibular nuclei in the brainstem (Kelly, 1985).

Reticular Formation and Reticulospinal Pathway

Two areas in the reticular formation have a modulating effect on reflex activity. The *lateral reticular extensor facilatory area* receives inputs from ascending pathways and facilitates extensor reflex activity when stimulated. The *medial reticular extensor inhibitory area* receives input mainly from the cortex and inhibits extensor activity when stimulated. Both areas influence the activity of alpha and gamma motor neurones to the extensor muscles. Thus, when both reticular areas are intact, the normal state is a constant balance of descending facilitation and inhibition on the segmental motor neurones.

Vestibulonuclear Complex and Vestibulospinal Influences

The vestibular nuclei are comprised of four distinct nuclei: the lateral vestibular nucleus (or Dieter's nucleus); the medial vestibular nucleus; the superior vestibular nucleus; and the inferior vestibular nucleus.

Each of the nuclei has distinct projections to specific regions in the central nervous system. Dieter's nucleus receives primary input from fibres innervating the macula and also input from the vermis of the cerebellum and the spinal cord. The cells of the nuclei project to the lateral vestibulospinal tract, which terminates ipsilaterally in the ventral horn of the spinal cord at the cervical, thoracic and lumbar levels. Dieter's nucleus has an excitatory influence on alpha and gamma motor neurones of the extensor muscles of the limbs. This tonic excitation enables the body to remain upright (T.J. Carew, 1985).

Cells of the medial and superior vestibular nuclei receive input from primary fibres of the ampullae of the semicircular canals and project to the medial vestibulospinal tract, which terminates bilaterally in the cervical region of the spinal cord. Monosynaptic connections are made with motor neurones that innervate the neck muscles. Central projections of the nuclei are made via the medial longitudinal fasciculus to participate in vestibulo-ocular reflexes (VOR) which act to co-ordinate eye and head movement.

The inferior vestibular nucleus receives primary fibres from the semicircular canals and from the utricle and saccule, as well as information from the vermis of the cerebellum. It projects fibres to the vestibulospinal tract, the vestibulorecticular tract, and the cerebellum. It appears that this nucleus is responsible for the integration of information from the vestibular sensory organs and the cerebellum and affects the activities of centres at higher levels in the brainstem. Some fibres terminate directly in the flucculonodular lobe of the cerebellum and may be important for the cerebellar control of posture (Kelly, 1985).

Cerebellar Influences

The influence of the cerebellum on maintenance of posture is at least two-fold. Projections from the vestibular nuclei lead to the vermis of the cerebellum, which acts to integrate inconsistencies in vestibular, visual, proprioceptive, and auditory inputs. As well, the anterior lobe of the cerebellum has projections to both the fastigial nuclei (part of the cerebellum) and Dieter's nuclei. These projections have an inhibitory effect on both the nuclei. The fastigial nuclei, in turn, also contribute to the excitation of Dieter's nuclei.

The previous sections have briefly outlined the complex interactions of the vestibular sensory organs with the various vestibular nuclei, brain stem, cerebellum, and spinal cord. The complex pattern of information from the hair cells is used to modulate the activity of the extensor muscles of the limbs via reflexes in the vestibulospinal tract and also moves 'higher' into the cerebellum to integrate possible inconsistencies with other sensory inputs. The following section will focus on the results of previous research that attempts to explain more fully the role of the vestibular system on the maintenance of balance and posture.

Literature Review of the Role of the Vestibular System in Postural Responses to Perturbation

An analysis of the neurophysiology indicates that the neural pathways exist for the vestibular system to exert a role in the maintenance of balance. The question to be answered involves the nature and extent of that role within the framework of the other systems also involved. Various researchers have postulated a number of possible roles. Does it have a dominant role in triggering responses to perturbations to posture? Is its influence context dependent (ie dependent upon the type and location of the perturbation)? Does it provide information only to resolve any inconsistencies in the sensory data? The following review of previous work will provide some insight into both the

mechanisms responsible for triggering responses and the patterns of muscular activity that comprise the response.

Because of the integrated nature of the various systems in the maintenance of balance, it is necessary to use different methods to perturb balance as well as to mask the influence of specific sensory systems in order to provide an estimate of the respective roles. One method uses patients with known vestibular deficits under conditions that will challenge their ability to maintain balance. Other methods use special types of apparatus that attempt to separately challenge the individual sensory inputs. In general, responses to the perturbations were measured by analysing the latency and magnitude of the electromyography (EMG) of selected postural muscles.

One apparatus that has been widely used to deliver a perturbation to the body was developed by Nashner (L.M. Nashner, 1971) in his attempt to separate the influences from visual, vestibular and proprioceptive inputs to the postural control system. A platform was built which could present an anterior/posterior directed perturbation. The platform could also be rotated about a medial-lateral axis in a way that matched the angle of body sway. This minimised any stretch of muscles across the ankle, thereby reducing possible proprioceptive information from those muscles to central or other peripheral areas. Absence of visual input was achieved by using a blindfold on the subject. Conflicting visual inputs were achieved by using a visual surround whose movement was linked to the rotational movement of the platform. The experimental paradigm consisted of various combinations of either absent or conflicted sensory inputs (proprioception, vision) in an attempt to isolate the effect of certain systems.

The results of some early work suggested that the functional stretch reflexes (FSR) of the muscles about the ankles were responsible for triggering postural responses to a perturbation. Nashner (L.M. Nashner, 1976) looked at the stabilising role of the functional stretch reflexes in the medial

gastrocnemius muscle (MG), a plantarflexor, in normals and cerebellar patients during perturbed standing balance. Normals were able to show adaptation of the FSR when the experimental protocol was changed so that the MG activation was an inappropriate response that tended to further destabilise the subject. While patients with cerebellar deficits showed normal latency and amplitude, their ability to adapt the FSR to differing stability conditions was effected, inferring some central mechanism for mediating postural responses. Further supporting the existence of a central mechanism is the authors' acknowledgement that 'postural set' of a task or its degree of uncertainty could effect stabilisation. While the FSR may be one method of maintaining standing balance, it is not the only method as it was utilised by less than half of the normal subject pool. Unfortunately, the authors did not describe the responses of the entire subject group. Later, Nashner (L.M. Nashner, 1977) observed a decreasing muscular response to perturbations when the 'normal' response acted to further destabilise the subject. He suggested that this adaptation of response was due to a change in the gain of stretch reflexes. Results from both bilateral and unilateral vestibular deficit patients showed that although there was decreased activity in ankle and neck muscles and a corresponding decrease in torque production compared to normal subjects, both processes of functional coactivation and habituation were present. Attenuation of response occurred in muscle pairs. This suggests that attenuation of response is not dependent upon an intact vestibulo-spinal reflex system and is most likely centrally influenced. Using the same experimental protocol, Nashner (Nashner, 1977) studied the hypothesis that functionally related postural muscles in the legs (gastrocnemius, hamstrings, tibialis anterior and quadriceps) activate according to a fixed pattern. They showed a distal to proximal activation pattern of functional muscle pairs and attributed this activation to the peripheral mechanism of the FSR and proprioception at the ankle. However, they chose not to discuss the response patterns of forty percent of the subject group who did not use the FSR to maintain balance. As in their previous work, the authors consider that any possible vestibular effect on stabilisation occurs much later on at latencies of

greater than 200 ms. although theoretical neural transmission times are much less.

Another group of researchers suggested that vestibular mechanisms were responsible for triggering initial responses to perturbations at the neck or at the ankle. Allum (J.H.J. Allum, 1983) looked at the stabilising responses of the tibialis anterior muscle to a dorsiflexion rotation of the platform in normal subjects during both standing and sitting conditions. It was hypothesised that any difference in response between the two conditions would be due to the presence or absence (in the sitting condition) of vestibular influence. In the standing condition, head movement occured 20 ms after onset of the perturbation and the resulting head acceleration exceeded vestibular sensory thresholds. As well, the tibialis anterior muscle was active at short and medial latency after the perturbation. During the sitting condition, there was no short latency tibialis anterior activity, suggesting that this muscle activity was either a vestibulospinal reflex resulting from head movement or a stretch reflex only present during standing. However, more recent work by Fitzpatrick, Burke and Gandevia (R. Fitzpatrick, D. Burke, et al., 1994), suggested an alternate conclusion. Their study concluded that vestibular effects on lower-limb muscles depended on whether vestibular cues were required for postural stability. Since platform rotation during sitting is not a postural task, a vestibular-evoked response would not be necessary. Allum and Pfaltz (J.H.J. Allum and C.R. Pfaltz, 1983) studied the postural control of unilateral peripheral vestibular deficit patients to platform rotations. There were two important findings of the study. Firstly, the responses of the tibialis anterior muscle differed between the contralateral and ipsilateral sides. The short latency response on the contralateral side was 70 percent larger in area compared to normal responses. In contrast, little difference was observed between the short latency responses of the ipsilateral side and those of normals. Secondly, the excessive muscle activity about the ankles produced large forward pitching head acceleration. Head stability was difficult to maintain for the vestibular patients because co-ordination between neck and ankle muscles

was altered. The authors suggest that these findings are evidence for the existence of two motor systems for controlling early postural responses. The vestibulospinal reflex corrects sudden deviation from upright stance and a centrally regulated system ensures that the head is stabilised as the body rotates about the hips and ankles. In a later study (J.H. Allum and C.R. Pfaltz, 1985), they attempted to quantify the visual and vestibular contributions to sway stabilisation of the neck and lower leg after a dorsiflexion rotation perturbation. Both normal and bilateral vestibular deficient subjects participated under conditions of visual influence (eyes open vs eyes closed) and vestibular influence (standing vs sitting, presence vs absence of intact vestibular apparatus). The normal response when standing with eyes closed was a short latency activation of the soleus muscles (50-80 ms), followed by short and medial latency responses of the tibialis anterior (80 and 125 ms respectively). The trapezius muscle acted to co-ordinate backward rotation of the head with forward rotation of the body by the tibialis anterior muscle. Slight increases in medial latency tibialis anterior activity was observed with visual input. When seated (with, presumably, no vestibular input), the tibialis anterior did not act in a burst, but increased gradually from 150 msec. after onset. When standing with eyes closed, differences were seen with patients in which the short latency tibialis anterior activity was reduced and had a delayed onset of 20 msec. As well, neck muscle activity did not act to co-ordinate with the ankle muscle activity. No differences were observed in the eyes open condition. While no differences were observed in ankle muscle activity when seated, there were differences in the activity of the trapezius to control head movement. From these results, the authors conclude that there is a coordinated pattern of ankle and neck activity with ankle muscle activity correcting for body sway and neck muscle activity stabilising the head. As well, there is evidence of vestibular influence in the activity of the short and medial latency tibialis anterior. Through correlation and regression analysis the authors quantified this influence and suggested that 80 % of short latency activity and 60 % of medial latency activity of the tibialis anterior was produced by vestibulospinal

influences. Another group found that vestibulospinal reflexes might be responsible for triggering some specific responses about the hip joint. Allum and Keshner (J.H.J. Allum and E.A. Keshner, 1986) compared the postural responses in the neck and lower leg of thirty-six normals and seven bilateral vestibular deficit patients in an attempt to determine the relative contribution of vestibular versus proprioceptive influence on balance control. They found that short latency tibialis anterior responses were delayed in the patient group and that medium and long latency ankle muscle responses and corresponding ankle torque were smaller for the patients compared to normal responses. They concluded that peripheral vestibular signals effect the size and initiation of adequate responses to perturbations in opposing ankle muscles but not the relation between the each muscle action. By expressing the difference between normal and patient EMG and torque responses as a percentage of normal responses, they were able to estimate the relative contribution to balance stabilisation. According to their data, 82% of soleus muscle response, 57% of tibialis anterior medium latency response and 48% of ankle torque were provided by vestibulo-spinal signal. This conclusion assumes that the central area that controls posture does not compensate for a vestibular deficit by enhancing the influence of the other sensory systems. Further, the authors found no significant difference between normal and patient neck muscle activity. They suggested that the cervico-collic reflexes might replace the action of the vestibulo-spinal reflexes. Shupert, Black, Horak and Nashner (C.L. Shupert, F.O. Black, et al., 1988) studied the effect of vestibular deficit on balance stabilisation by repeating the previous experimental protocol but introducing an additional support surface. Both normals and bilaterally effected patients were tested on a flat surface and on a beam. As well, head acceleration and EMG from two neck muscles (trapezius and sterno-cleido mastoid) were measured. Results under the flat surface condition were similar to previous experiments with both normals and patients, showing a distal to proximal muscle activation pattern and rotation occurring about the ankle (called the 'ankle strategy'). However, during the translation of the beam the normal

subjects used a different activation pattern where rotation occurred about the hip (called the 'hip strategy'). All vestibular patients fell during the translation of the beam, showing no discernible pattern of muscle activation. The authors conclude that the role of the vestibular system in postural control changes as a function of the postural control strategy. However, they do not produce sufficient evidence to prove that the vestibular system does not influence postural control during the translation of the flat surface. Black, Shupert, Horak and Nashner (F.O. Black, C.L. Shupert, et al., 1988) further studied the postural control of three groups of patients with peripheral vestibular disorders. They found that those patients with absent vestibular function were unable to use a hip response strategy to maintain balance on a perturbed beam. It is unclear whether this is a learned response to a situation in which use of a strategy, which produces large head accelerations, is avoided because the subject cannot stabilise the head. Those subjects with a distorted vestibular function did rely on hip movements to restore balance. Recent work by Runge, Shupert, Horak and Zajak (C.F. Runge, C.L. Shupert, et al., 1998) also demonstrated that patients with bilateral vestibular loss could use a hip strategy during rapid platform translation. They suggested that the lack of a hip strategy observed in other studies was due to a change in the task which altered the sensorimotor characteristics of the balance control system (ie type of surface, initial body posture, change in limits of stability, or availability of lower-leg sensory input). Any observed deficits in maintaining balance may be due to an inability to properly modify the mapping between perturbation and response. Allum, Honegger and Schicks (J.H. Allum, F. Honegger, et al., 1994), in their study of postural response in bilateral vestibular deficit patients, found that muscle activation latencies and timing patterns did not vary from those measured in normals, but that magnitude of muscular response did vary. They concluded that during a perturbation caused by a translating/rotating platform, vestibular signals did not trigger lower leg postural responses (lower leg proprioceptive signals were responsible for triggering the initial response), but enhanced the amplitude of appropriate lower leg muscle activation and inhibited the

responses of paraspinal muscles. They further concluded the response pattern of a vestibular loss patient was essentially a two degrees-of-freedom response involving the ankle and knee instead of the three degrees-of-freedom response pattern of normals that involved ankle, knee, and hip.

Some research suggests that the main role of the vestibular system is to maintain an upright head position. Nashner, Shupert and Horak (L.M. Nashner, C.L. Shupert, et al., 1988) focussed on head - trunk movement co-ordination in three normal subjects. Postural sway about the ankles or hips were elicited in two ways: during free fall on two different support surfaces (flat vs beam) and translation of the different support surfaces at two speeds. Slow translations of the flat surface elicited EMG response patterns typical of the 'ankle strategy' while slow translations of the beam resulted in EMG patterns typical of the 'hip strategy' as discussed in previous work. Faster translation of the flat surface resulted in an EMG pattern that was a mixture of the two strategies. Activation of the sternocleido mastoid muscle was noted during fast support surface translation where the subject used a mixed or hip strategy. These strategies elicit significant head acceleration and the sternocleido mastoid muscle reacts in order to restore stabilisation of the head. A review by Allum, Gresty, Keshner and Shupert (J.H. Allum, M. Gresty, et al., 1997) concluded that head movement depended on the properties of the head-neck mass-viscoelastic system which could be altered by neck muscle activity. In experiments involving stance perturbations, neck muscle activity was triggered by trunk and leg proprioceptive signals. However, in experiments where the head was perturbed directly, the vestibular system modulated the stabilising responses of the neck musculature via the vestibulocollic reflexes.

Other studies suggest that afferent information from the vestibular system mediates the FSR triggered responses or is part of an integrated process of response. Nashner, Black and Wall (L.M. Nashner, F.O. Black, et al., 1982) looked at the effect of both bilateral and asymmetrical vestibular deficit on stabilisation. Using the same experimental protocol as in previous work, all

subjects performed well under normal sensory conditions. Normal subjects successfully stabilised balance during perturbations under conditions of both absent or conflicting sensory cues. Bilaterally effected vestibular patients did not perform well under conditions of absent or conflicted cues while asymmetrically effected patients were able to maintain balance under conditions of absent cues but not conflicting cues. Also, the more severely afflicted patients were not able to adapt the FSR to produce more functionally appropriate responses to perturbations. The vestibular system would seem to have more importance in stabilisation of balance than previous work had indicated. From these results, the authors suggest that the vestibular system has two roles in the maintenance of balance during standing posture:

- At a hierarchically low level, it is a part of a weighted set of orientation inputs that include the vestibular, visual and proprioception sensory systems.

- At a hierarchically higher level the vestibular inputs provide an orientation reference level against which conflicts in sensory inputs are measured.

The results of a study by Black and Nashner (F.O. Black and L.M. Nashner, 1984) also suggest that the vestibular system acts to resolve inconsistencies in sensory input. They looked at postural control in four classes of functional vestibular abnormalities including both unilaterally and bilaterally absent vestibular function, distorted vestibular function and fluctuating function. Experimental conditions were manipulated to provide situations in which visual and proprioceptive information from the ankle joint were either absent or conflicted with other available sensory information. The authors found that patients with vestibular deficits performed poorly in situations where visual and proprioceptive information were both missing or conflicting. In these situations, patients needed to rely on vestibular information alone or were forced to select among apparently accurate support surface and vestibular

spatial references. These results differ from those of an earlier study (Nashner, et al., 1982) where there was a difference in the responses between bilateral and unilateral deficient patients. Keshner and Allum (E.A. Keshner, J.H. Allum, et al., 1987) looked at the differences between two groups of vestibular patients (bilateral and unilateral vestibular deficit) to the processes of functional coactivation (significantly correlated muscle response patterns) and habituation of stabilising responses. In normal subjects, the soleus and tibialis anterior muscles act together to restabilise the body after a dorsiflexion perturbation. Short latency correlations between soleus and tibialis anterior were weak because of independent onset latencies and initiation by different means -- muscle spindle and semicircular canals, respectively. However, medial latency soleus and tibialis anterior responses were significantly correlated. Bilateral patients showed decreased short latency tibialis anterior and medial latency trapezius muscle activity while unilateral patients showed muscle activation responses that were similar to normal. They concluded that a total absence of vestibular function resulted in a strongly reduced dynamic response in the ankle muscles that could not be compensated through other pathways whereas unilateral deficits can be partially compensated. Allum and Pfaltz (J.H. Allum and C.R. Pfaltz, 1987) studied the processes of functional coactivation and adaptation/habituation of response in normal and bilateral vestibular deficient subjects. Bilateral deficient subjects showed a 30% decrease in muscular response at both the neck and ankle compared to normal subjects. The authors suggest that the results showed necessary but not sufficient evidence of vestibulogenic coactivation of stabilisation responses. An alternate hypothesis is that stabilisation responses are triggered by the proprioception system and modulated by the vestibular system. A correlation analysis of muscle activity between neck and ankle rejected the suggestion that a single coactivation signal existed for neck and ankle muscles. This suggests separate control pathways for head and ankle muscles. Both normal and bilateral vestibular deficient subjects showed an attenuation of muscular activity at medial and long latencies for both ankle and neck muscles, indicating that adaptation is a central process

which receives a number of afferent inputs without being wholly reliant on any one for its function. Allum, Keshner, Honegger and Pfaltz (J.H. Allum, E.A. Keshner, et al., 1988) attempted to establish a correlation between amplitude of some variables of the vestibulospinal reflex and a spectrum of vestibular deficit in the subjects. Four groups were studied: bilateral vestibular deficient patients, uncompensated and compensated unilateral vestibular patients, and normal subjects. Measured variables included the integrated EMG of the soleus, tibialis anterior and trapezius muscles, ankle torque, muscle latencies, and adaptation ratios. The authors used a stepwise discriminant analysis to determine which variables would best classify the four subject groups. Results indicated that mean values of the integrated EMG of the ankle muscles and medial latency ankle torque were significantly different across the three patient groups with the bilateral deficient group showing the greatest reduction in comparison with normal subjects, followed by uncompensated and then compensated unilateral deficient patients. Therefore, the stabilising actions following a dorsiflexion rotation were thought to be due to the activity of the vestibulospinal reflexes and are correlated with the degree of impairment. The result of the discriminant analysis indicated that, in the eyes closed testing condition, use of seven of the measured variables produced a tight clustering of three groups: normal, bilateral, and unilateral deficient with no errors. The analysis scheme was less successful in correctly discriminating between compensated and uncompensated unilateral patients. A lack of tight clustering in the eyes open condition showed that vision could be used to compensate for some of the deficiencies of the vestibular system. Keshner, Woollacott and Debu (E.A. Keshner, M.H. Woollacott, et al., 1988) observed the muscle activation patterns of flexor/extensor pairs at the ankle, hip, trunk and neck in order to test the hypothesis of an ascending order of muscle activation during platform translation and rotation. Their results did not support a strict ascending order of activation. Early activation of neck and upper trunk muscles was recorded at the same time as ankle muscle activation, possibly to maintain head stability. They concluded that a differential control of stability exists where there are

different directions of muscle response at various levels of the body. They also concluded that a lack of consistency in muscle response was a result of the differing demands for destabilisation of the body as a result of the type of perturbation experienced. For example, it is 'easier' for the body to restabilise when it is forced in an anterior direction than in a posterior direction because the centre of mass of the body is more likely to be within an area of stability when moved anteriorly. Allum and Honegger (J.H. Allum and F. Honegger, 1993) compared the muscle responses to translation and rotation perturbations that produced the same amount of ankle dorsiflexion, but very different head displacement and velocity, as well as different centre of pressure patterns. The results showed that, in normals, the perturbations caused different EMG patterns of response in spite of the apparently similar proprioceptive information in both cases. They found that predicted torque about the neck lead the ankle and hip torque, suggesting that the head is stabilised first in a separate role. They also found that vestibular patients could not correct their stance for either type of perturbation. Horak, Shupert, Dietz and Horstmann (F.B. Horak, C.L. Shupert, et al., 1994) devised another type of apparatus in an attempt to separate the contribution of vestibular and neck mechanisms from the lower body somatosensory mechanisms. Weights, suspended from a frame attached to the sides of the head and supported by the back and shoulders, delivered a mechanical perturbation that caused an acceleration to the head. The results showed that the trunk and leg muscle responses were absent in patients who suffered vestibular loss as adults but were present in patients who suffered vestibular loss as children. The authors suggest that the early loss patients had learned to use proprioceptive information from the neck muscles to appropriately respond to perturbations. These results tend to add weight to the theory that the balance control system is capable of integrating sensory information from many sources and reweighing the relative influence of each, depending upon the context.

Perturbation Technique: Galvanic Vestibular Stimulation

The stated goal of these experiments is to further study the role of the vestibular system in maintaining balance. The results of past studies suggest that maintenance of balance and posture is a highly integrative process involving vestibular, proprioceptive, visual, somatosensory and cerebellar influences. A difficulty exists in devising a method in which to perturb balance that can, ideally, selectively isolate the influence of a particular sensory system. A possible perturbation method is the use of an external force to mechanically induce a linear acceleration that is then detected by the otolith. Devices of this type include the translating/rotating platform developed by Nashner (Nashner, 1971) and the head acceleration device developed by Horak (Horak, et al., 1994). The major drawback to these types of techniques is that it is difficult to apply a force that does not directly involve the proprioceptive system. For example, external forces applied to the head would involve the neck proprioceptive sensors, which have been shown to exert opposing actions on the lower limbs with respect to the vestibulo-spinal reflexes. These signals would tend to cancel each other out, showing no apparent effect on activation of the lower limbs (J. Kasper, R.H. Schor, et al., 1989; S. Lund and C. Broberg, 1983; Wilson, 1988).

A method, which may overcome the problem of proprioception system involvement, is galvanic vestibular stimulation. This technique consists of placing a constant current across two stimulating electrodes located over the mastoids just behind the ears. In order to justify this as an appropriate technique, a number of issues must be addressed. Does this technique simulate the response of the otolith to a perturbation? Does it effect other afferent pathways, such as that of the canal system? Is it a repeatable, reliable method? How does a variation in the stimulation parameters effect the output measure? A survey of the relevant literature, including both animal and clinical work, provides insight.

The first issue to be resolved regarded the physical nature of the stimulation. The results of a number of studies suggest that vestibular stimulation directly effect the firing rate of the vestibular nerve. Goldberg, Smith and Fernandez (J.M. Goldberg, C.E. Smith, et al., 1984) studied the relation between vestibular nerve discharge and response to galvanic stimulation in the squirrel monkey. They suggest that the galvanic currents act directly on a post-synaptic spike encoder of the nerve with anodal (or positive) currents causing inhibition in the firing rate and cathodal (or negative) current causing excitation. In later work Goldberg, Desmadryl, Baird and Fernandez (J.M. Goldberg, G. Desmadryl, et al., 1990; J.M. Goldberg, G. Desmadryl, et al., 1990) used these results to develop a transfer function of the response dynamics of the vestibular nerve that innervates the ultricular macula. Courjon, Precht and Sirkin (J.H. Courjon, W. Precht, et al., 1987) studied the neural basis of habituation in the rat using galvanic stimulation. The stimulation was applied at a point external to the labyrinth and otolith, near the round window and the resulting nerve pulses were recorded at vestibular nerve units and at the vestibular nuclei. The resulting nerve impulses showed either an increase or decrease in tonic spike frequency depending on the direction of the stimulating current. Anodal current resulted in a decreased spike frequency while cathodal current resulted in an increasing spike frequency-- results that were noted at both the vestibular nerve and the vestibular nuclei. The authors suggest that galvanic stimulation bypasses the sensory organs of the labyrinth and directly effects the fibres of the vestibular nerve, supporting the conclusions of Goldberg et al. (Goldberg, et al., 1990; Goldberg, et al., 1990; Goldberg, et al., 1984).

Given that galvanic stimulation bypasses the sensory organs and effects the vestibular nerve, the next logical question regards the specific action of the stimulation on the ultricular afferents. Because the response of the vestibular canals also share the vestibular nerve, it is important that stimulation of the nerve does not involve further processing of any potential canal signal, resulting in a perception of angular acceleration and possible involvement of

the vestibular ocular reflex (VOR). Does galvanic stimulation affect these afferents as well as those of the otolith? Studies by Tokita, Miyata, Ito and Takagi (T. Tokita, H. Miyata, et al., 1987), Severac (A. Severac, 1991), Coats (A.C. Coats, 1973) and Masumitsu and Sekitani (Y. Masumitsu and T. Sekitani, 1991) report that the stimulus threshold for galvanic nystagmus (which is indicative of canal system involvement) is higher than the threshold for galvanically induced reaction of the otolith. Therefore, in order to isolate the response of the otolith from the responses due to the semicircular canals it is necessary to maintain the current intensity below the threshold recorded for nystagmus to occur. This threshold has been experimentally determined to be approximately 1 mA, dependent on the subject (Y. Watanabe, H. Ohi, et al., 1985). However, measurement of a small amount of nystagmus, which is a result of stimulation of the canal afferents, is difficult to measure accurately (R. Fitzpatrick, 1997). And recent work by Cauquil (A.S. Cauquil, K. Popov, et al., 1998) suggests that galvanic vestibular stimulation elicits torsional eye movements at much lower current intensities, comparable to those required to produce postural responses. Hence, it should not be assumed that galvanic stimulation effects the vestibular otiliths in isolation.

Results from a number of clinical studies show the same consistent response to a galvanic stimulation. When the two electrodes are placed as described previously, the response to a stimulation is a movement of the body in the medial/lateral direction. Typically, a graph of the movement of the body centre of mass shows a small initial response toward the negative electrode followed by a larger response, called the deviation response, away from the negative electrode and toward the positive electrode. Changing the polarity of the electrodes resulted in movement to the opposite side. The response waveform of the displacement of the centre of mass shows both transient and steady-state components that correspond to the transient and dc components of the stimulus (see Figure 2.1). This finding of a characteristic response to galvanic stimulation has been confirmed by Watanabe (Y. Watanabe, H. Ino, et al., 1987), Tokita (Tokita, et al., 1987) and Lund and Broberg (Lund and

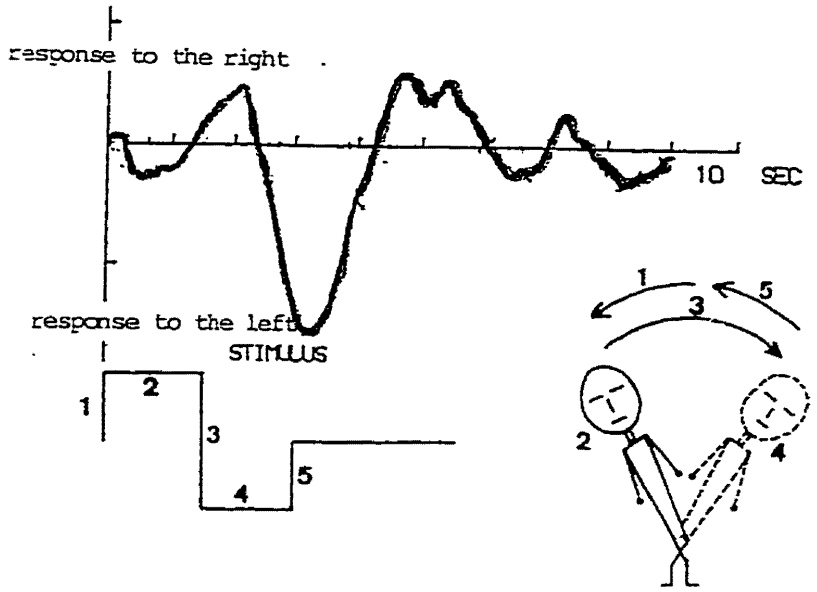
Broberg, 1983). Other electrode configurations may result in different responses. Magnusson (M. Magnusson. R. Johansson, et al., 1990) reported anterior-posterior body movement with a different configuration of electrode polarity. Therefore, this suggests that direction of movement can be determined by the electrode polarities.

Varying the stimulus parameters can have an effect on the resulting movement response. A.C. Coats studied these parameters in a series of experiments (A.C. Coats, 1973; A.C. Coats, 1972; A.C. Coats, 1972; Coats, 1973). They included the type of stimulus waveform (sinusoidal versus square wave), stimulus rise-time, current intensity and current direction. His output measure was body movement as determined by a potentiometer attached to the subject's chest. In response to different waveform stimuli, he reported that the body moved sinusoidally in response to a sinusoidal stimulus as long as the frequency was below 0.20 Hz. Response to a trapezoidal-shaped stimulus was similar to the typical waveform described previously. He found, however, that the test-retest variability of the sinusoidal stimulus was greater than that of the trapezoidal stimulus. Varying the rise-time of the trapezoidal stimulus effected the latency of response, with decreased rise-time resulting in a decreased latency. This is expected in a system that responds to rate of change as well as steady-state current. He also reported that increasing the stimulus current from 0 to 1.0 mA increased the response amplitude in an approximately linear manner. This linearity of response finding was later confirmed in studies by Watanabe (Watanabe, et al., 1985) and Iles and Pisini (J.F. Iles and J.V. Pisini, 1992). The animal studies of Goldberg (Goldberg, et al., 1984) also show a linearity of response between current magnitude and firing rate of the vestibular nerve.

It is highly unlikely that galvanic vestibular stimulation replicates or reproduces the type of vestibular signal that typically results when the head undergoes linear acceleration. As described earlier, the hair cells in the ultricle and saccule are oriented towards the striola in such a way that for any linear

acceleration experienced there is a particular pattern of excitation and inhibition of nerve fibers. However, under galvanic stimulation, with an anodal current presented at one mastoid and a cathodal current presented at the other, 'normal' patterns of nerve discharge do not occur. Given the placement of the electrodes, it is thought that the vestibular nerve on one side experiences a global excitation while the other side experiences a global inhibition, creating a novel pattern of afferent neural drive whose interpretation is left to more central

Figure 1.2 Movement response to galvanic vestibular stimulation, showing stimulus, body movement as recorded from a stabilometer, and stick figure representation of the movement (from Watanabe, 1987).



processing areas. This speculation is supported by Cauquil (A.S. Cauquil, M.C.C. Salon, et al., 1997) in a study that looked at the difference in postural response between monaural and binaural stimulation. They found that the response was comprised of the linear sum of two equivalent stimulations – one from the cathode excitation and the other from the anodal inhibitition.

In summary, previous studies have shown that the galvanic stimulation technique produces a signal on the vestibular nerve that results in a repeatable response. Current intensity has an approximately linear effect on response output, as determined by body movement. Response direction can be

determined by the configuration of positive and negative electrodes. Latency of response can be effected by the rise-time of the stimulus. Therefore, with these characteristics, this type of perturbation signal may meet the requirements of a signal needed to further study the balance control system during standing posture. The control of postural stability has been thought to encorporate both feedback and feedforward (or anticipatory) control systems. Because of the previously discussed properties of galvanic vestibular stimulation, it has been used to quantify postural response in terms of general transfer functions. Johansson and Magnusson (R. Johansson and M. Magnusson, 1991) and Johansson, Magnusson and Fransson (R. Johansson, M. Magnusson, et al., 1995) modelled the body as an inverse pendulum and determined the transfer function between the perturbation and the postural response as characterised by a stabilogram. Fitzpatrick (R. Fitzpatrick, D. Burke, et al., 1996) also determined the feedback loop characteristics of a transfer function and concluded that feedback control does not adequately explain the dynamics of postural response and some anticipatory control via vision must also be present. Although these studies have provided further information about the overall dynamic control of posture and stability, the use of transfer functions does not provide insight into the detailed mechanisms that cause the response movement.

Goal of Intended Research and Outline of Document

The results of the previous studies suggest that a response to a perturbation is context-dependent. More specifically, the response is probably dependent upon the site of the perturbation, the type of perturbation, and the sensory system that first detects a change. This supports the idea that the balance control system is highly integrative and depends upon seemingly redundant sensory information from a number of sources in order to respond in an appropriate manner. However, with this type of system it is difficult to devise a method of perturbation that will act to selectively challenge a specific sensory system.

Most of the studies reviewed have devised synergies of control from an analysis of the muscle activation patterns of selected postural muscles. Few (an exception is the study by Allum and Honegger (Allum and Honegger, 1993)) have attempted to study the biomechanics of the response by analysing both the kinematics and kinetics of the movement. Specifically, an analysis of the predicted joint torque which cause movement to occur, may provide more insight into the control synergies involved in maintaining balance.

The third issue to arise from the review of previous studies is the focus on movement in the anterior/posterior direction only. Little has been done to study the effect of perturbation effecting movement in the medial/lateral direction.

Therefore, taking these issues into account, the purpose of this series of experiments is to study the recovery response to a perturbation that causes movement in the frontal plane or medial/lateral direction. The recovery motion will be analysed with respect to movement displacement, joint torque responsible for the movement, and the electromyography of selected muscles. The method of perturbation used is galvanic vestibular stimulation.

Chapter 2 Methods

Introduction

The purpose of this chapter is to discuss the methods involved in acquiring and analysing the relevant data. The discussions includes details of the equipment designed and built to deliver the galvanic vestibular stimulation, followed by a description of the subjects involved in the studies; the kinematic, kinetic and electromyographical analyses; mathematical model; equipment used; and experimental protocol.

Galvanic Vestibular Stimulation

Based on the results of the previous research outlined in the last chapter, a battery-operated device capable of providing both short (500 ms) and long (3 sec.) trapezoidal-shaped constant current pulses was designed and built (see Figure 2.1). Other features of the device included adjustable current levels and remote triggering. The voltage output was also sent to the data acquisition board on the computer so that stimulation pulses were synchronised with other data. Disposable pellet electrodes (Medi-Trace Pellet Electrodes, part Number ECE 1801, Graphic Controls Ltd.) were used to conduct the pulses to the subject's mastoid.

Pilot trials were performed in order to resolve a number of logistical issues such as the best foot placement and electrode configuration. Foot placement was defined by width of stance and relative position of the feet. Both factors contribute to the size and shape of the base of support utilised in maintaining stability (B.L. Day, A. Severac Cauquil, et al., 1997). Best foot placement would allow a challenge to postural stability (ie reliable movement could be recorded) but not result in a subject 'losing balance' and be forced to make a corrective step.

Figure 2.1 Galvanic stimulator.



In making a corrective step, a subject would need to step off a forceplate and information required for subsequent analysis would be lost. Three different stance configurations were tested. These included normal stance (feet approximately shoulder distance apart), close stance (heels approximately 4.0 cm apart) and tandem stance (feet placed heel to toe with approximately 10 cm separation and displaced laterally about 12 cm). Each foot was placed on a separate forceplate and the centres of pressure were measured. Normal stance produced the most stable posture (little medial/lateral movement was observed), followed by close stance and, lastly, the tandem stance position. The close stance configuration resulted in the most consistent change in centre of pressure that could be measured. In normal stance, no consistent change in centre of pressure was observed with a stimulation that was below the subject's pain threshold, presumably because this stance provides a larger base of support resulting in a more stable position. In the tandem stance position, the subjects consistently lost their balance and had to take a step off the forceplates in order to recover balance. While this result was consistent, observance of

possible recovery mechanisms through kinetic analysis was impossible once one or both feet were off the forceplate. The decision was therefore made to use the close stance foot position in all other tests.

Results of previous literature suggest that electrode placement and direction of current can cause body movement in predictable directions. Electrodes placed over the mastoids with the head placed in a normal position will cause medial/lateral body movement dependent upon the direction of current. Magnusson (Magnusson, et al., 1990) reports anterior/posterior body movement with electrodes placed over the mastoids and a return electrode placed on the forehead. Pilot trials were performed to ascertain the reliability of the movement response, as determined through centre of pressure and ground reaction force measurements, to two different electrode placements -- over the mastoids (two electrodes) and over the mastoids and forehead (three electrodes).

Reliable responses from both configurations and, hence, body movement in both the medial/lateral and anterior/posterior directions would provide greater information in which to analyse possible postural response control mechanisms. Results of the trials showed that consistent results were observed with electrodes placed over the mastoids only. Direction of body movement was dependent upon current direction. The configuration described by Magnusson did not result in consistent anterior/posterior body movement. In fact, this configuration of electrodes caused pain during stimulation and was rejected.

Subjects

Eight subjects (four male, four female) ranging in age from 23 to 33 years of age participated in the study (see Table 2.1). There was no reported history of neurological, vestibular or balance problems from any of the subjects.

Table 2.1 Summary of Subject Information

Subject	Age	Mass (kg)	Height (cm)
WJ18	31	85.4	188
WJ19	26	84.1	181
WJ24	27	58.2	163
WK73	29	80.0	180
WJ26	27	66.0	166
WJ20	25	62.3	163
WK81	26	78.6	176
WJ27	27	66.4	150

Data Collection and Analysis

Kinematic, kinetic and electromyographical data were required for further analysis. Details of the various measurement systems as well as the methods used to collect data follows.

Kinematic System

The system used to acquire three-dimensional kinematic information was a two 'camera' OptoTrak ™(manufactured by Northern Digital, Waterloo). The system consists of a number of active infrared light-emitting (ired) markers that are placed on specific anatomical landmarks on the subject, and two columns of infrared detecting sensors placed several meters from the subject. Each column carried three one-dimensional CCD sensors. Although only one column of sensors is required to obtain three-dimensional information, two columns were used in order to obtain constant coverage of all markers during movement of the subject. The columns were placed at 120 degrees from each other with the first placed directly lateral to the right side of the subject. The system was calibrated to a global reference system before the start of data collection with the origin of the global system located just lateral to the subject.

The x-axis was defined as positive with reference to the anterior direction of the subject. The z-axis was defined as positive with reference to the right lateral side of the subject and the y-axis was defined as positive upwards (see Figure 2.2). Thirty-five markers were used to describe the various body segments. Description of marker placement is included in the section describing the model used in analysis. Data was sampled at 60 Hz, calibrated and stored on disk for further analysis.

Forceplate

Two AMTI forceplates were mounted in the floor, one placed several centimetres forward of the other. Forces along and moments about each axis were collected and sampled at 256 Hz. Centre of pressure at each forceplate was calculated.

Description of Mathematical Model

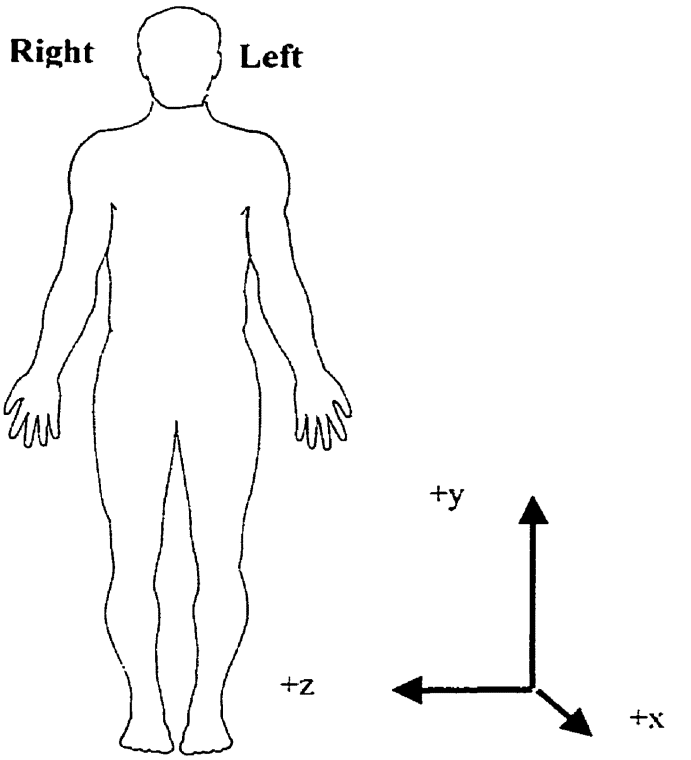
Joint force and moment information cannot be measured directly through experimentation but must be determined mathematically from other, more easily acquired, variables. Motion, however, can be measured directly and joint forces and moments, which are based on this kinematic data, can be calculated with the aid of an inverse dynamics model. This type of model is a mathematical model based on derived equations of motion which incorporate details of body anthropometrics, the number of relevant body segments, location of the centres of mass of these segments, location of joint centres of rotation, and orientation of local (segmental) coordinate axes.

The model used in this analysis incorporated nine segments comprising:

- left and right foot,
- left and right shank,
- left and right thigh,

- pelvis.
- trunk and arms.
- and head.

Figure 2.2 Orientation of axis system.



Anthropometric information for each of these segments was estimated using the regression formulae of Yeadon and Morlock (M.R. Yeadon and M. Morlock, 1989) for the mass moments of inertia and the regression formulae of Dempster via Miller and Nelson (N.R.C. Miller D.I., 1973) and via Plagenhoef (S.C. Plagenhoef, 1971) for segmental masses and location of centre of mass. At least three markers were placed on each segment in order to provide the necessary information required establishing local coordinate axes, which are

used to estimate the location of joint centres and segmental centres of mass from more easily identifiable body landmarks. A translation and rotation transformation matrix is required to describe the marker positions in terms of a local segmental coordinate axis system instead of the global axis system that the video collection system uses. To that end, each subject was recorded standing in a posture such that a local vertical axis defined in each segment was parallel to the global vertical axis in the frontal plane. This would define a mathematical relationship between the two axis systems.

Five markers were used in the foot segment to determine the local axis system and location of the segmental centre of mass. These markers were placed in the following positions:

- mid-way between the medial and lateral malleolus in the frontal plane (referred to as the 'ankle joint centre');
- the fifth metatarsal;
- across from the fifth metatarsal on the medial aspect of the foot;
- lateral malleolus;
- on the ground lining up with the ankle joint centre in the frontal plane.

The vertical axis was determined to be parallel to the line defined by the marker at the ankle joint centre and the ground marker in the frontal plane. The other axes were determined by the cross products of the vertical axis and vectors involving other markers of the foot segment. The centre of mass was located midway along the line defined by the markers at the fifth metatarsal and the lateral malleolus in the anterior/posterior plane and projected medially onto the midline (or vertical axis) in the frontal plane. The ankle joint was located midway between the malleoli in the frontal plane and one centimetre anterior to the lateral malleolus in the anterior/posterior plane.

Four markers were used in the lower leg segment. These include markers at:

- the lateral malleolus;
- at the head of the fibula;
- at a position distal to the lower leg.
- between the lateral malleolus and the head of the fibula in the anterior/posterior plane;
- and at a position in the mid lower leg in the frontal plane along the midline established by the foot markers.

The local vertical axis was defined by the markers placed at the lateral malleolus and at the head of the fibula in the anterior/posterior plane and projected onto the midline of the segment in the frontal plane. The other axes were determined by the cross products of the vertical axis and vectors involving other markers of the leg segment. The centre of mass was located on the vertical axis just described.

Three markers were used to define the thigh segment and were placed at:

- the greater trochanter,
- the lateral femoral condyle,
- and mid thigh on the midline of the segment in the frontal plane.

The local vertical axis is defined by a line joining the projection of the marker at the lateral femoral condyle onto the midline of the segment on the frontal plane and the hip joint center. Note that this axis, as defined, is not necessarily parallel to the global axis in the frontal or sagittal planes. The centre of mass is located on the line joining the markers at the greater

trochanter and lateral femoral condyle in the sagittal plane and projected onto the midline of the segment in the frontal plane. The position of the knee joint was defined as midway between the medial and lateral femoral condyles in the frontal plane and 2.5 centimetres distal to the lateral femoral condyle in the sagittal plane.

Three markers were used to define the pelvis segment and were placed at:

- the right iliac crest
- and right and left anterior superior iliac spines (ASIS).

The local axis system was assumed to be parallel to the global axis system with the centre of mass located between the left and right ASIS markers in the frontal plane and projected distally in the sagittal plane at the level of the marker at the iliac crest. The position of the hip joint centre was estimated as a percentage of the distance between the ASIS markers: 14% of the inter-ASIS distance medially, 30% distally and 19% posteriorly to the right ASIS (for the right hip joint centre) (A.L. Bell, D.R. Pedersen, et al., 1990).

The trunk segment was defined by markers placed at:

- the left glenohumeral joint,
- the left clavicle,
- the xiphoid,
- and the sternal notch.

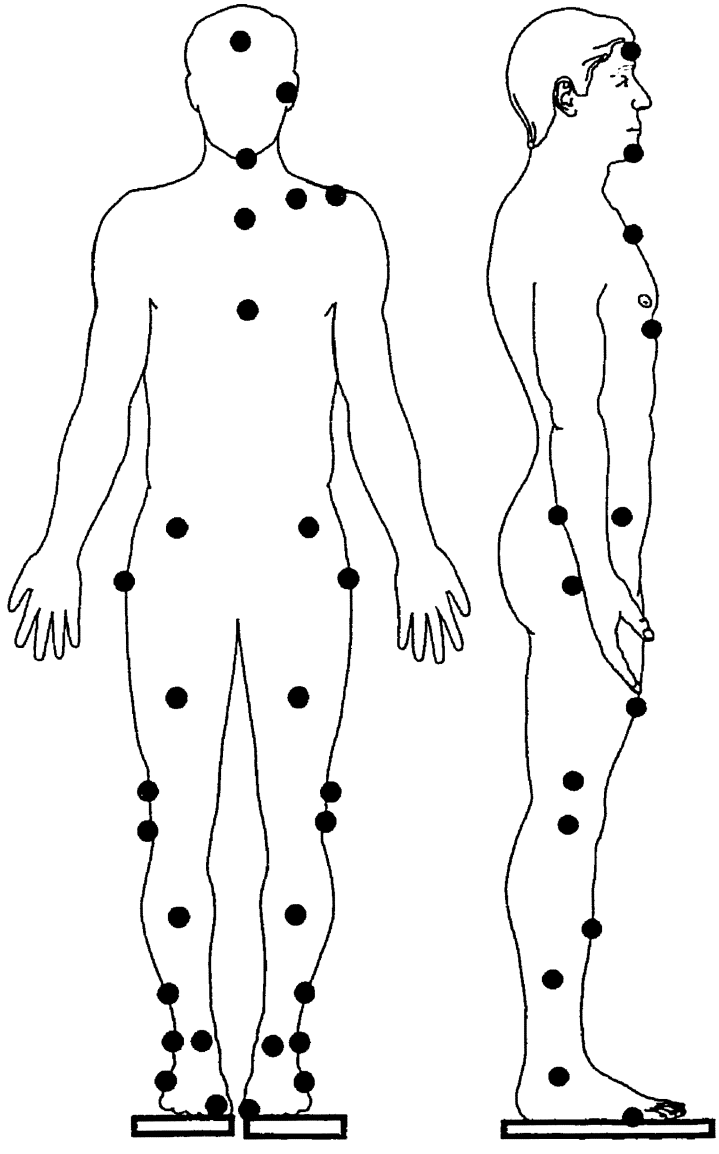
The local axis system was assumed to be parallel to the global axis system. The centre of mass was located on the line formed between the left ASIS marker and the glenohumeral joint in the sagittal plane and projected onto the midline of the segment in the frontal plane.

The head segment was defined by markers placed:

- in the middle of the forehead,
- on the chin,
- and on the left ear.

The local axis system was assumed to be parallel to the global axis system. The centre of mass was located at the level of the ear canal in the sagittal plane and on the midline of the segment in the frontal plane.

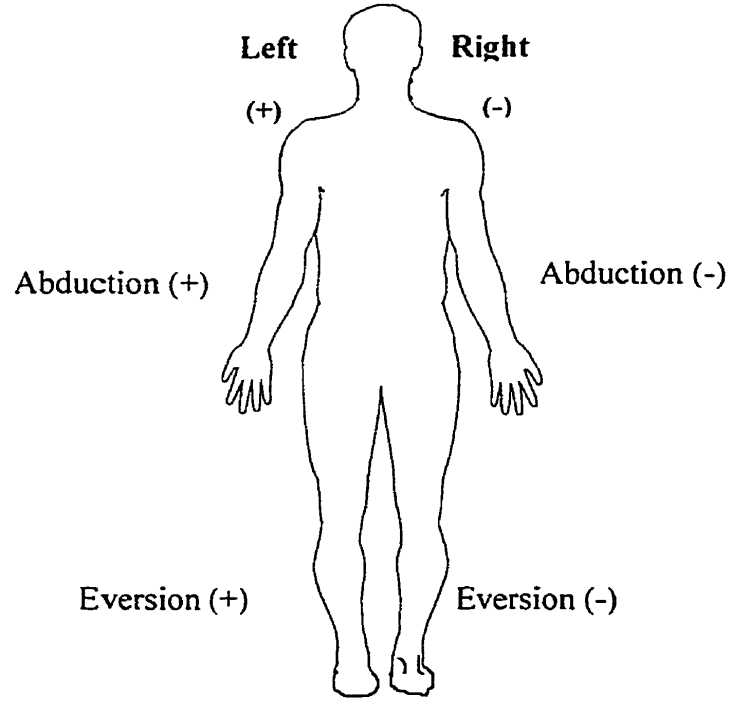
Figure 2.3 Placement of markers



Calculation of Joint Forces and Moments

A three dimensional inverse dynamics solution that incorporated external forces measured by the two forceplates, linear and angular segmental velocities and accelerations, and estimates of the segmental anthropometrics was used to calculate the joint forces and moments of each segment. Normally, use of this method assumes starting at the foot and calculating upwards through the segments. However, the error propagation that is implicit in the use of this method results in a large error in the joint moment calculated at the neck. Because the neck joint forces and moment are of interest in this study, it was necessary to start calculations at three places -- left and right foot segments, and head. Therefore, calculations proceeded downwards from the head and upwards from both feet, meeting at an imaginary or virtual joint in the pelvis. Figure 2.4 shows the relationship between the mathematical and anatomical descriptions of the moments at each segment. Note the difference in sign between left and

Figure 2.4 Anatomical descriptions. Figure shows posterior view of subject. A right-hand laboratory coordinate reference is used with positive X in the anterior direction, positive Y in the upwards direction and positive Z lateral to the right of the subject.



right sides of the body for the joint moments causing inversion and eversion.

Electromyography

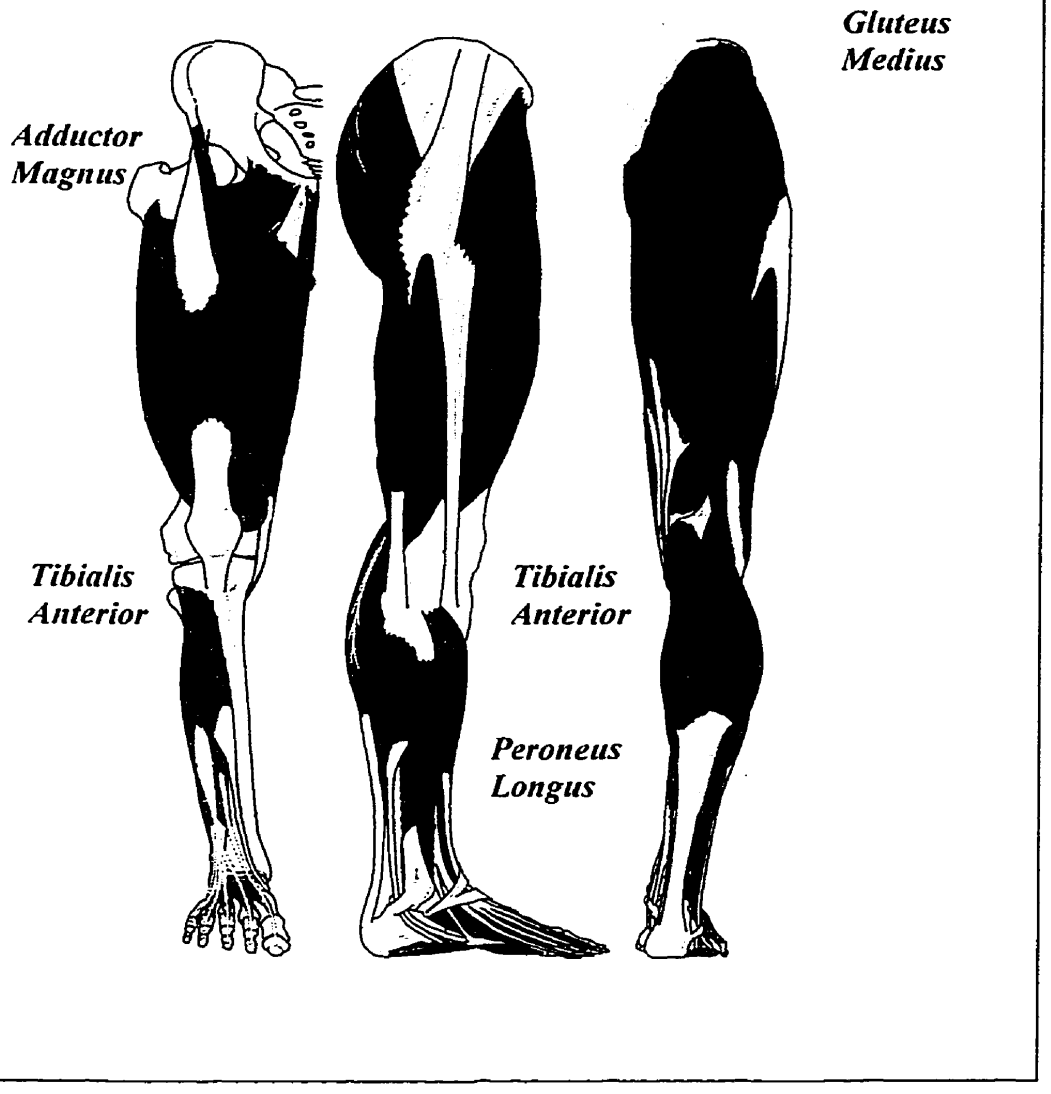
Because joint forces and moments are predicted from kinematic and ground reaction force data, it would be useful to have an alternative means of independently confirming the results. Although electromyographic signals do not give a direct measurement of joint forces and moments, an analysis of the latencies and activation patterns may confirm the joint moment predictions. For example, if the muscles about a joint do not initiate activation prior to that of the predicted joint moment one may conclude that significant errors exist in the calculation of the joint moment.

The equipment used to collect the EMG data was a commercial system called FlexComp/DSP, made by Thought Technology Ltd. The documented sensitivity of the sensors is less than 0.08uV RMS and the CMRR of the system is greater than 130 dB over the range 20 - 500 Hz. Eight channels of data signals were pre-amplified before being encoded and transmitted via fibre-optic cable to a specialised processing board on a computer. Silver-silver chloride disposable pellet electrodes (diameter: 1cm), manufactured by Graphic Controls, were used to record EMG signals. Seven channels of EMG were collected. The remaining data channel recorded the onset and cessation of the perturbation signal.

The activities of seven muscles were recorded and included:

- left and right gluteus medius,
- left and right adductor magnus,
- left tibialis anterior,
- and left and right peroneus longus.

Figure 2.5 Electrode Placement



Each muscle was chosen because of its role in maintaining the position of a segment across a joint in the medio-lateral plane (see Table 2.2).

The raw EMG signal was first filtered with a low-pass analogue filter with a cut-off frequency of 500 Hz to prevent aliasing. The data was sampled at 1000 Hz, rectified and subsequently synchronised with the forceplate data. Each muscle was normalised to the largest magnitude achieved over all trials on a per subject basis. This data was used to determine muscle onset latency. Onset latency was determined by calculating the mean of that portion of the data collected prior to the onset of the perturbation. Muscle activation onset

occurred when the magnitude of the signal exceeded three standard deviations of the earlier signal. Further processing provided the muscle activation pattern. The rectified signal was further filtered with a digital low-pass fourth-order dual-pass Butterworth filter. This was performed in order to remove the phase shift inherent in digital filtering and to provide a comparison with the moment data. A residual analysis procedure showed that a cut-off frequency of 3 Hz was adequate for filtering. The linear envelope data was used to determine muscle activation patterns.

Table 2.2 Summary of muscles studied and their role in maintaining balance during stance.

Muscle	Role
Gluteus Medius	Abducts the hip.
Adductor Magnus	Adducts the thigh.
Tibialis Anterior	Dorsiflexes and inverts the foot.
Peroneus Longus	Everts the foot.

Experimental Protocol

After the ired markers and surface electrodes were placed, the subject was requested to stand quietly with their feet placed correctly (as described previously) on the forceplate. The subject was told to keep their head upright and eyes facing forward toward a spot on the opposite wall, thereby ensuring a consistent head placement. This is important because of the effect of head position on the resulting movement direction.

Three independent variables were identified as possible contributing factors in the response movement to galvanic stimulation. They included the presence of visual feedback (eyes open vs eyes closed), the direction of stimulus current (left vs right), and the duration of the stimulus (500ms vs 3 sec). A full factorial experimental design was used. Each subject performed

five trials per condition, which resulted in a total of forty trials. These trials were presented in a randomised order in an attempt to avoid the occurrence of a possible learning effect. Although ten trials per combination would have been desirable from a statistical viewpoint, this was judged to be too fatiguing for the subjects. In order to avoid the occurrence of fatigue within the forty trials, the subject was given a five minute rest break at the end of every five trials.

Each trial had a recorded duration of eight seconds. This length of time was sufficient to record at least one second of normal unperturbed motion prior to the application of the stimulus, the response movement during the stimulus, and at least three seconds of any potential recovery movement after the cessation of the stimulus.

Chapter 3 Kinematic Analysis

Introduction

Galvanic stimulation of the vestibular nerve causes a perception of movement and imbalance to which the body reacts in order to apparently restore balance. The purpose of this chapter is to provide a description of this reaction movement of the subject in response to the perturbation. This description includes the linear and angular displacement of three segments: head, trunk, and pelvis. Displacement is described in terms of direction, magnitude, duration, and latency of the movement response. These measurements will be analyzed in order to describe the specific responses to differing conditions of vision, stimulus duration and direction of stimulus current. This analysis may provide insight into how sensory conflict is resolved during the maintenance of balance.

During quiet standing, the body does not remain completely still but tends to move in a random manner about the anterior/posterior and medial/lateral directions. Further analysis, such as determination of response latencies, requires that any response to a perturbation be differentiable from this background movement. Therefore, the experimental trials were designed so that at least one second of quiet standing occurred before a perturbation was applied. Using the onset of stimulation as a synchronization point, the kinematic data from the five trials collected per condition were ensemble averaged in order to remove the 'background' movement. The mean of the data occurring prior to stimulation onset was calculated and this value was subtracted from all the data. This process was successful in removing the background movement and enabled easier detection of the response to the stimulation (H. Noguchi, 1995).

A response was operationally defined as any deviation from the background level greater than two standard deviations in the linear and/or angular displacement of the segments occurring after the onset of the

stimulation. The maximum value of the magnitude, the duration, the direction, and the latency of this response were recorded and a statistical analysis, as described in the previous chapter, was performed on the data.

Responses are described in the medial/lateral direction only. Although there was also movement in the vertical and anterior/posterior directions, no consistent response to the perturbation was noted in terms of direction of movement or latency, confirming the results of previous studies (L.M. Nashner and P. Wolfson, 1974, Lund and Broberg, 1983). These results are a direct consequence of the electrode configuration described in the previous chapter. No further analysis was undertaken with the data in either the vertical or anterior/posterior directions.

Results

Direction of Response

The experiment was designed so that half of the forty trials per subject would consist of a stimulus current direction resulting in a movement to the right and the other half resulting in a movement to the left. Over ninety-five percent of the total trials resulted in movements in a direction consistent with the electrode configuration and current direction, supporting the results of previous studies. Of the 200 trials reported (40 trials by 5 subjects), a total of 192 trials showed movements of the pelvis, trunk and head towards the anode and 8 trials towards the cathode ($\chi^2 = 4423.69$, $p<0.01$).

Magnitude of Response

Response magnitude was defined as the difference in displacement between the onset of response and the maximum value attained. The differences in the linear displacements of the head, trunk and pelvis segments were measured and typical results show the head, pelvis and trunk moving in a medial/lateral direction, dependent upon the direction of the stimulus. Figure 3.1(a) shows a typical result to a long duration stimulus causing movement to

the right of the subject. Multivariate tests of significance performed on displacement magnitude showed that neither direction of stimulus ($F=0.04$, $p<0.846$), nor duration of stimulus ($F=3.16$, $p<0.150$), nor presence or absence of vision ($F=1.56$, $p<0.280$) had significant effects on the resulting displacement magnitude of the response of the segments. Further analysis of the segmental displacements reveals that the head moves a greater distance than the trunk and pelvis. These results were true over all trials, regardless of the conditions tested. Because the previous statistical analysis revealed no significant differences in displacement across the independent variables, measured displacements were averaged across all conditions. A contrast analysis was performed to determine if these differences in response magnitude between the head and trunk and pelvis segments were statistically significant. It showed a significant segment effect with the head displacement greater than the trunk and pelvis ($T=-2.695$, $p<0.05$). There was also a significant difference between the trunk and pelvis segments ($T=-2.62$, $p<0.06$). Table 3.1 shows the lateral displacement of the segments, averaged across all conditions and all subjects.

Table 3.1 Linear displacement (measured in mm).

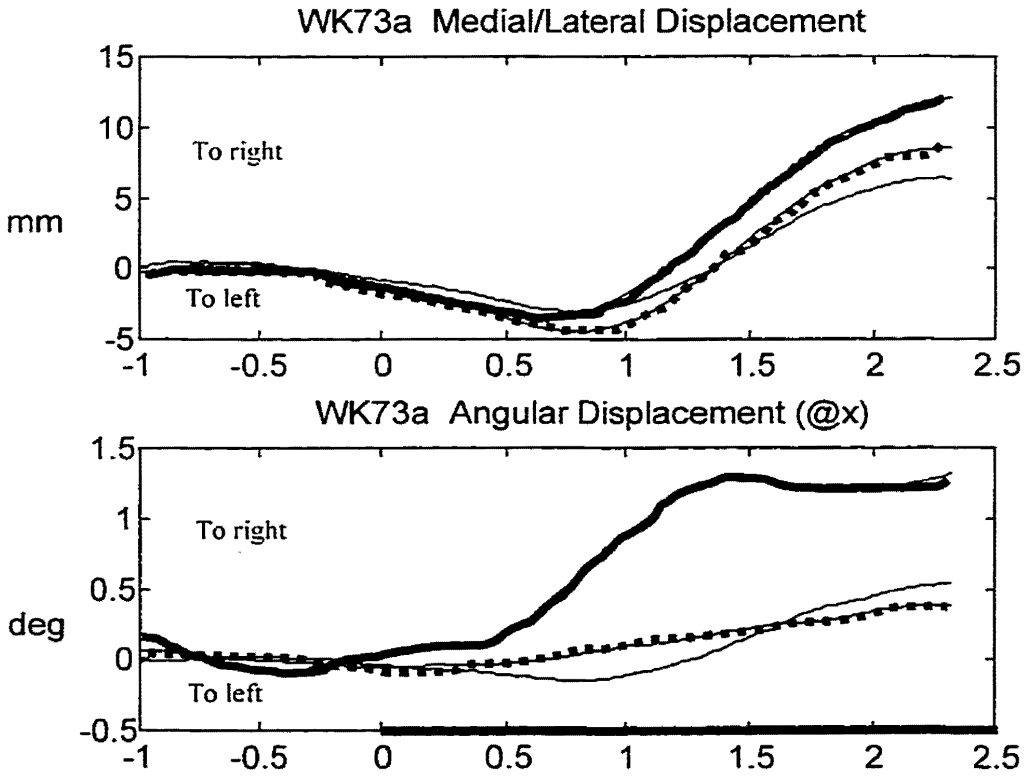
	Head	**Trunk**	**Pelvis**
Mean	6.15	5.6	3.8

The movement response, described by the linear displacement observed at the head, trunk and pelvis segments may be caused by some combination of lateral rotations about the joints between the segments. The most likely sites of these rotations are at the neck and pelvis. If the three segments were acting as an inverse pendulum rotating about the pelvis, the angular displacements of each segment would be similar. A comparison of the movements of the three segments show that the head segment undergoes a larger angular displacement

than the trunk and pelvis segments which tend to move together, as shown in Figure 3.1.

A multivariate analysis was undertaken to ascertain the effect of the various stimulus parameters on the magnitude of the linear and angular displacements measured at the head, trunk and pelvis. The results of the analysis did not show that presence or absence of vision of the subject, direction of the stimulus current or the duration of the stimulus had any significant effect on the magnitude of the response at these segments.

Figure 3.1 Typical response to a 3 second perturbation of the head, trunk and pelvis segments resulting in a movement to the right. The head segment is represented by a thick line, the trunk by a dashed line, and the pelvis by a thin black line. The duration of the stimulus is shown by the thick black line on the time scale.



Duration of Response

Duration of response was calculated as the difference between the time of the response onset and the time at which a change in the direction of movement

Table 3.2 Mean duration of linear movement response vs subject vision and stimulus duration (ms).

	Head		Trunk		Pelvis	
Conditions	**Length of Stimulus**		**Length of Stimulus**		**Length of Stimulus**	
	Short	**Long**	**Short**	**Long**	**Short**	**Long**
Eyes Open	953	1488	840	1370	800	1487
Eyes Closed	700	1374	678	1341	649	1350

occurred. This aspect of the movement response was analyzed with respect to three independent conditions: presence or absence of vision, duration of stimulus and direction of stimulus current. A multivariate ANOVA was performed in order to determine the effect of the variables on the duration of the response of the head, trunk, and pelvis segments. Of the three variables, only presence or absence of vision and duration of stimulus had any effect on the duration of the movement response shown by the segments. The analysis showed no significant differences between movements to the left and to the right (the direction of stimulus condition). Therefore, the observed duration results under this condition were combined.

The mean values of the duration responses under the vision and stimulus duration conditions are shown in Table 3.2, averaged across all subjects. The table shows that longer stimuli resulted in longer responses. This is also seen in Figure 3.3, which shows the linear and angular displacement of one subject. Each graph is represents the ensemble average of five repeat trials under the same condition. In the longer stimulus trials (WJ27b), the movement response continues throughout the duration of the stimulus. In the shorter stimulus trial

(WJ27d). The graphs show an attempt to recover the original position of the body after the cessation of the stimulus.

The table shows a difference in response duration between the eyes-open and eyes-closed conditions. Longer responses were observed in the eyes-open condition ($p<0.016$). Figure 3.2 shows the linear and angular displacement results of one subject under the vision condition with a short duration stimulus. Each graph represents the ensemble average of five repeat trials under an eyes open (WJ27c) or eyes closed (WJ27g) condition. Graphs of the linear displacement show a larger response displacement in the eyes-open trial. However, the opposite response is observed in the graphs of angular displacement where slightly greater angular displacement of the head is seen in the eyes closed condition.

Table 3.2 also shows a difference in response duration among the three segments. An analysis showed that the head segment recorded the longest linear displacement ($p<0.01$), followed by the pelvis ($p<0.02$), regardless of the condition tested. This result would be expected if the head, trunk and pelvis segments were acting like an inverse pendulum where the more distal segment to the fulcrum (head) would experience a greater linear displacement, hence a longer duration.

A difference among the angular displacement patterns of the segments was observed between the longer and shorter duration stimuli. However, this difference in response is due to the additional rotation of the head, apart from the movement of the trunk and pelvis as discussed earlier. Figure 3.3 (c) and (d) shows the angular displacement of the three segments under long (WJ27b) and short (WJ27d) stimulus duration conditions. Each graph represents the results of an ensemble average of five repeat trials. Both graphs show the additional angular movement undergone by the head. The longer stimulus causes a longer response.

Figure 3.2 Comparison of the linear and angular displacement of the head, trunk and pelvis segments in the eyes closed vs eyes open conditions. The head segment is represented by a thick line, the trunk by a dashed line, and pelvis by a thin line. The solid black line denotes the onset and duration of the stimulus.

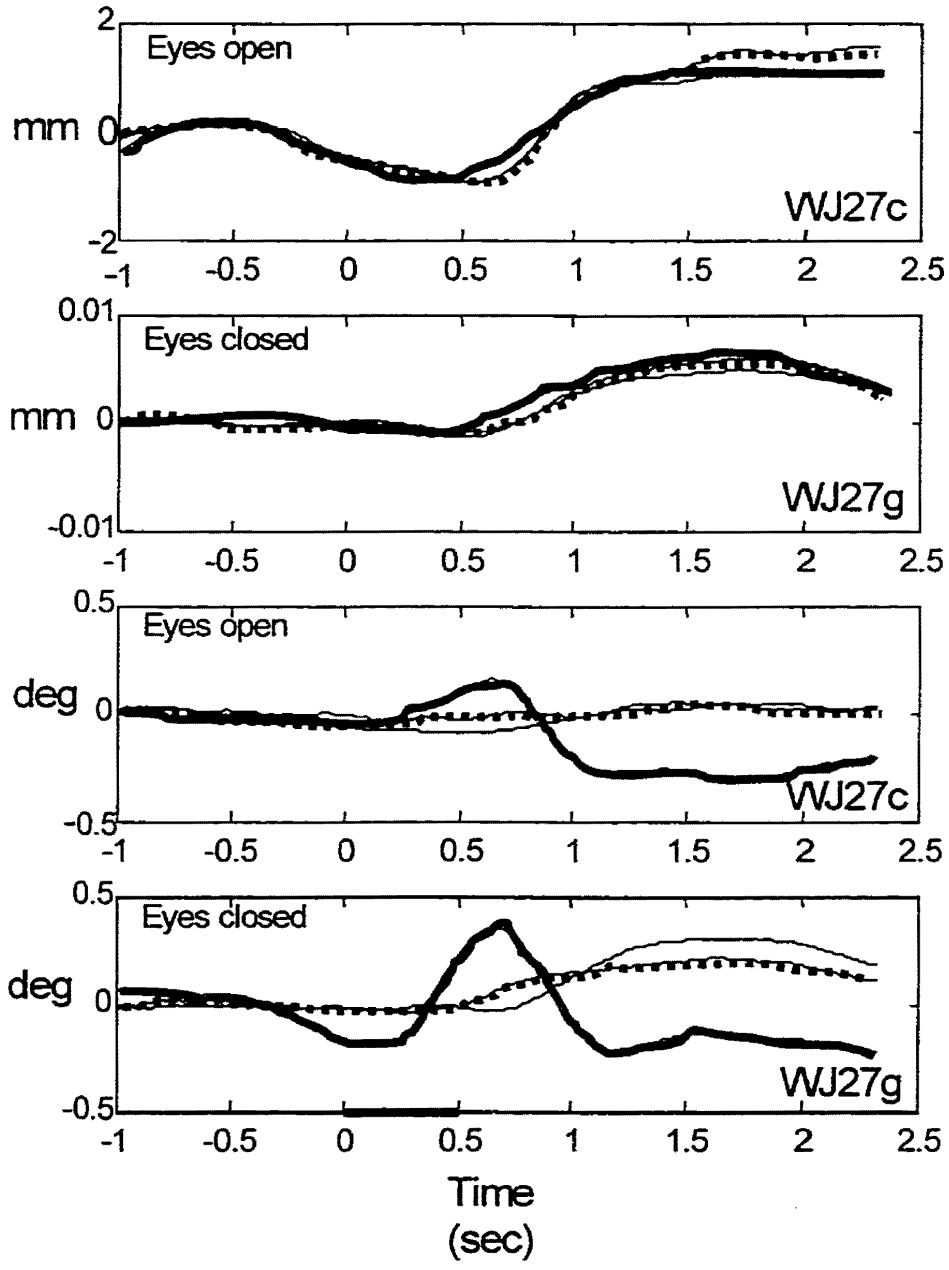
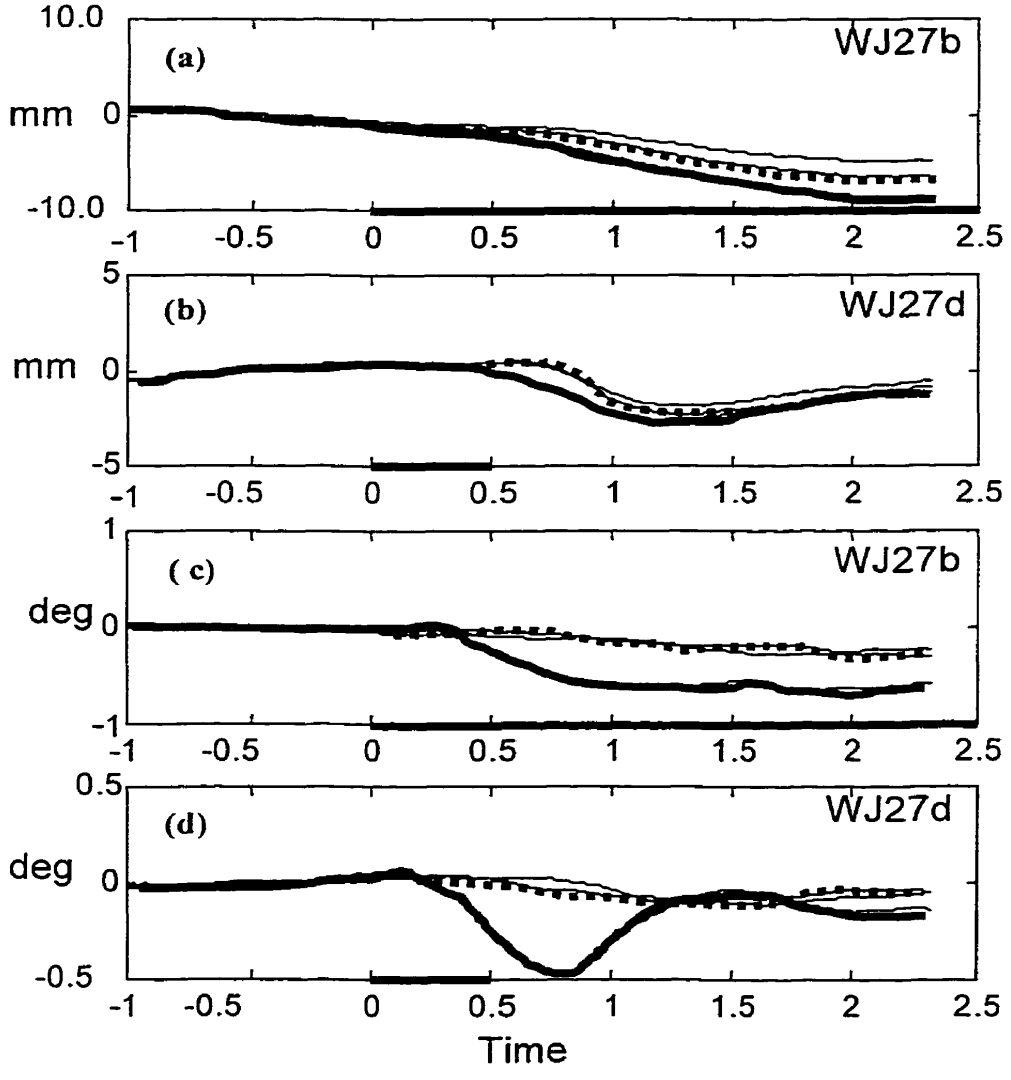


Figure 3.3 Linear (a,b) and angular (c,d) displacement of head, trunk and pelvis -- long vs short stimulus. The head is represented by the thick black line, the trunk by the dashed line and the pelvis by the thin black line.



Latency of Response

The latency of the response to the stimulus was calculated as the difference in time between the onset of the stimulus and the detection of the response. In general, the head segment initiated movement prior to the trunk and pelvis segments. As with the other parameters of the movement response, a multivariate ANOVA was performed on the measured latencies observed at the head, trunk and pelvis segments in order to determine any effect of the vision or stimulus parameters. The results of the analysis revealed no significant effect of subject vision, duration of stimulus or direction of stimulus current on the latencies measured at those segments. Latencies of response measured across all conditions for the segments are recorded in Table 3.3. Further analysis of the data revealed that the differences in latency observed among the segments was significant ($p<0.004$) with the head segment responding more quickly than the trunk and pelvis segments as illustrated in Figures 3.1, 3.2(a,b) and 3.3(a,b).

Table 3.3 Mean latency of response for the head, trunk and pelvis segments. Standard deviation of the mean is in brackets.

	Head	Trunk	Pelvis
Mean calculated over all conditions (msec)	340 (74)	503 (117)	619 (129)

Control of Pelvis Movement

The previous results have outlined the movements of the head, trunk and pelvis segments in response to galvanic perturbation. All three segments undergo lateral linear displacement, initially with the head segment and followed by, and in phase with, the trunk and pelvis segments. This movement may be likened to that of an inverse pendulum. As well, the head segment experiences some angular displacement, separate from the other two segments.

An obvious next question concerns the basis or cause of the pelvis movement. This segment is, of course, physically linked with the left and right thigh, shank and foot segments. Is the lateral movement observed at the pelvis caused by an angular movement about the ankle (where legs, pelvis, trunk and head act as an inverse pendulum)? Or is the movement a combination of more complicated movements involving active involvement of all of the segments. Further analysis of the movements of the left and right thigh, shank and foot segments follows.

If the body acted as an inverse pendulum rotating about the ankles, one would expect to observe similar angular displacements, bilaterally, at the ankles, shank, thigh, hip and trunk. Figure 3.4 shows the linear and angular displacement of both foot segments in response to a long perturbation causing a movement to the right. The graphs are the result of an ensemble average of five repeat trials. The right foot experiences a rotation of a magnitude capable of producing the movement observed at the hip. However, this rotation is seen only on the right side, the left foot is relatively motionless. Combined with the information that the centre of mass of the right foot also shifts towards the right, it can be observed that the right foot is inverting. Comparison of the movements of the foot, shank and thigh also show that the angular displacement is not transferred upwards. Figure 3.5 shows the medial/lateral linear and angular displacement of the right side foot, shank and thigh centres of mass in a typical response to a long perturbation causing a movement to the right. The graphs show a small angular and linear displacement of the right foot segment to the right, at an average latency of 250 ms. Relatively little movement is observed at the shank and thigh segments. This supports the conclusion that the rotation is confined to the foot segment and that the foot, leg and thigh segments do not act as an inverse pendulum to produce the observed movement in the upper body. This response was consistent across all conditions and subjects.

In more than half of the trials analyzed across all subjects a movement pattern shown in Figure 3.6 was observed. This figure is the result of an ensemble average of five repeat trials of a long duration perturbation resulting in a movement to the right. Concurrent with the medial/lateral displacement experienced by the thigh and pelvis segments, the pelvis segment underwent a small angular displacement and the thigh segments showed some vertical displacement. In the graph shown, overall movement was to the right side of the subject with the left thigh moving upward and the right thigh moving downwards. This vertical movement of the thigh segments is consistent with an angular displacement of the pelvis. This suggests that the pelvis moves independently of the ankles.

Figure 3.4 Linear and angular displacement of the right and left foot segments. Right foot is represented by solid black line, left foot by the dashed line.

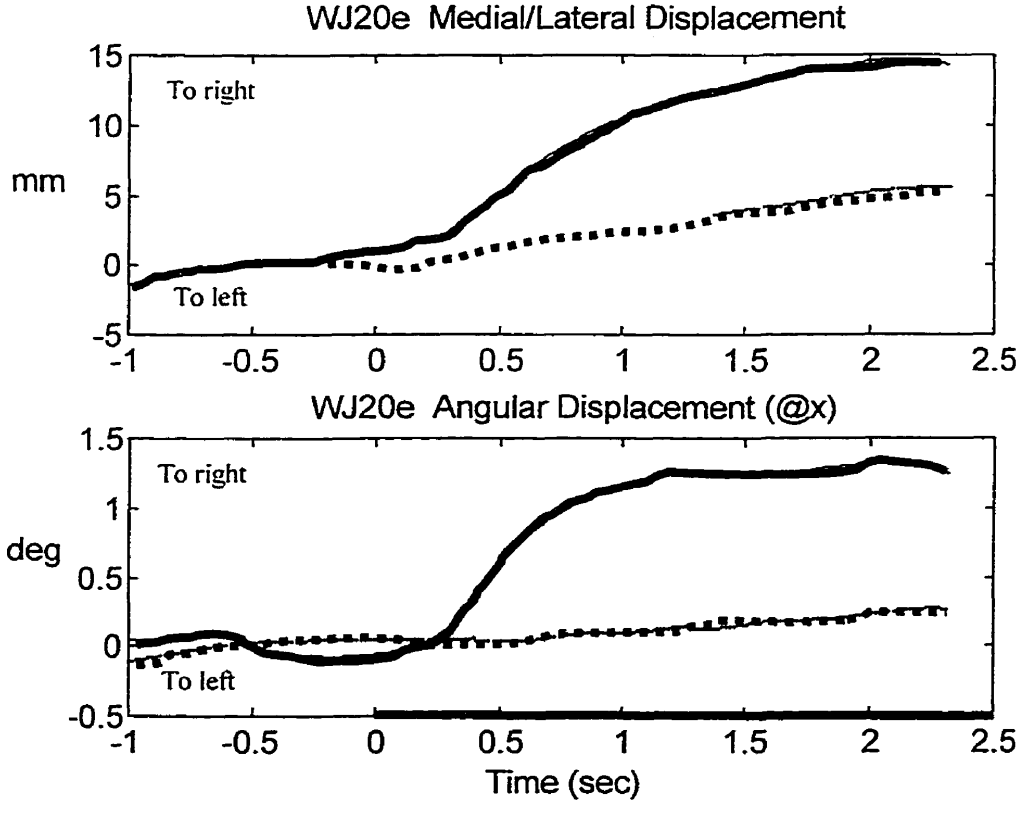


Figure 3.5 Linear and angular displacement of the right foot, shank and thigh segments in a movement to the right. The foot segment is represented by a thick line, the shank by a dashed line, and the thigh by a thin black line.

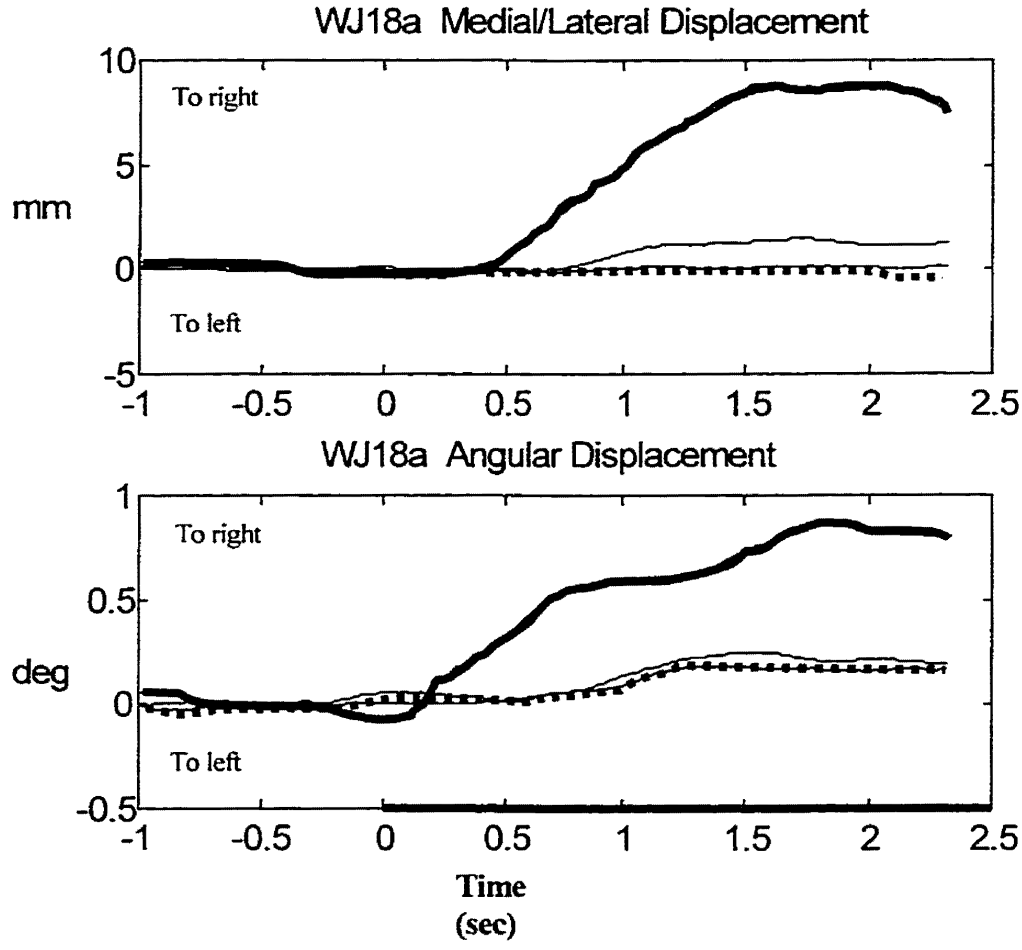
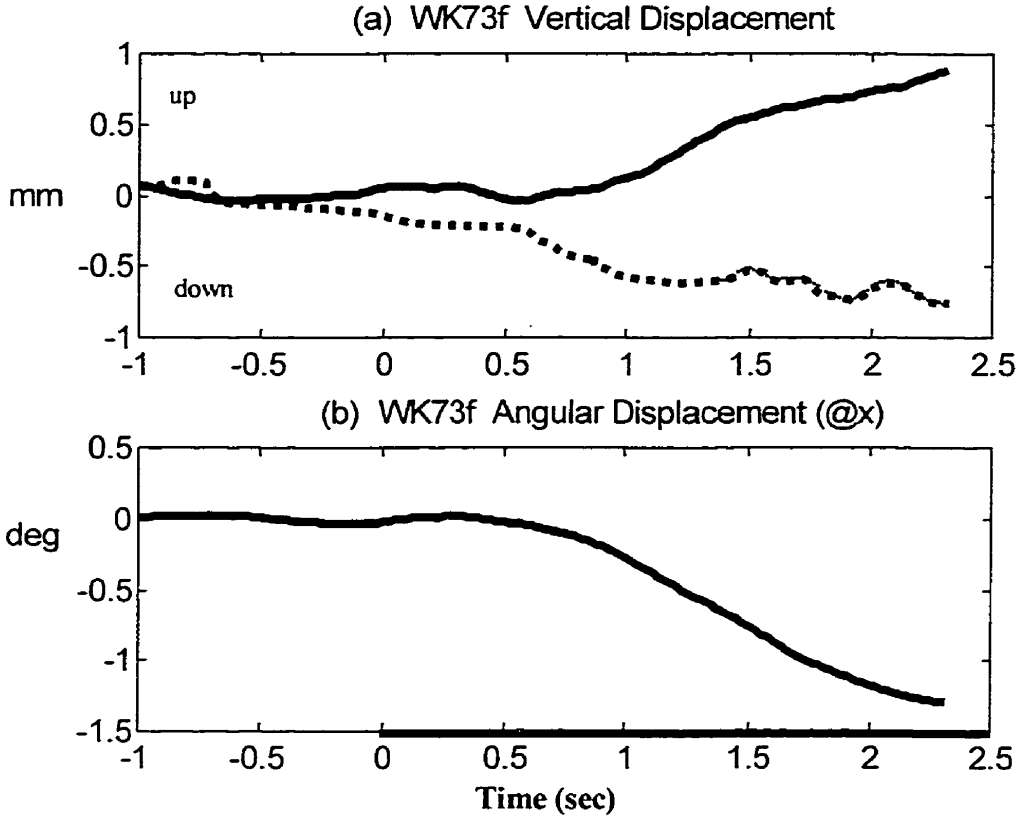


Figure 3.6 (a)Vertical displacement of thigh segments due to a long perturbation resulting in a movement to the right (right thigh ___ left thigh .....). (b) Angular displacement of pelvis



Discussion

Galvanic stimulation of the vestibular nerve may produce either a conflict in the perception of body movement or may more directly cause a movement to occur via the vestibulo-spinal reflexes. If the stimulus causes a perception of lateral movement, it will conflict with other (correct) sensory information from the proprioceptive, somatosensory and vision systems. The body then responds by moving to counter this fictitious movement. This chapter described this counter movement of the body in terms of displacement magnitude, duration and latency. Presence or absence of subject vision, duration of stimulus and direction (or polarity) of stimulus current were parameters that were varied in

order to study their effect on movement response. From this, some conclusions about the role of the vestibular system in balance control can be made. Body movement was described by the displacement of the head, trunk, pelvis, thigh and shank segments. The following attempts to explain the results in the context of the current understanding of the literature.

Direction of Displacement The results of the trials showed that consistent movement responses were in the medial/lateral direction only and that the direction of movement was dependent on the polarity of the stimulus current. An anodal current at the right mastoid would result in movement towards the right whereas a cathodal current would result with movement to the left. This is consistent with previous work (Watanabe, et al., 1987; Tokita, et al., 1987and Lund and Broberg, 1983) with a small exception. Most previous work showed a small movement towards the contralateral side just prior to the main movement. This smaller movement was not generally apparent in the responses observed in this study. There may be two reasons for this difference. Firstly, this difference may be due to the magnitude of the stimulus current used in this study which was generally lower (due to subjects comfort threshold) than employed in other studies. Results from previous work (Coats, 1972; (Watanabe, et al., 1985) suggest that the magnitude of response is a linear function of the stimulus current in which a larger current results in a larger displacement of the body. Hence, a smaller stimulus current would produce a smaller counter-movement, which may not be detectable. Secondly, the other studies cited measured either ground reaction forces or whole body centre of mass as the dependent variable. This smaller movement is more readily observed in the ground reaction force data that is presented in the next chapter.

No significant differences in magnitude or duration of movement response due to differing stimulus current were detected. This was not an unexpected result. Theories on the activity of the vestibular system postulate a bilateral symmetry between left and right side so that any differences in

magnitude may be more indicative of an asymmetry in electrode placement than in normal subject response.

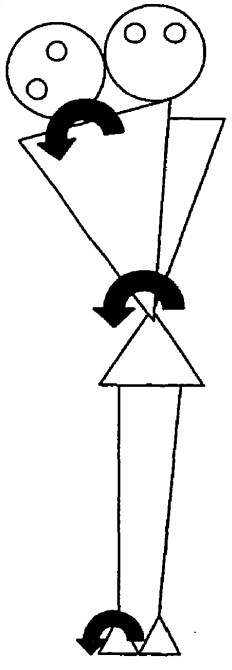
Response Coordination

The movement of the body in response to any of the tested conditions was consistent with regards to onset latency, direction and magnitude of displacement. The head underwent lateral movement first and showed the greatest displacement, followed by the trunk and then the pelvis segment. In order to ascertain whether the segments were moving in the manner of an inverse pendulum, the angular displacement of each segment was compared. The trunk and pelvis segments showed little angular displacement in comparison to the head and tended to move synchronously as was illustrated in Figure 3.1. Hence, the movement of the head, trunk and pelvis segments seems to be that of an inverse pendulum rotating about the pelvic centre of mass with some additional angular displacement of the head segment. The observation of the angular displacement of the head is not a surprising result when one considers the influence of the vestibular system on the cervical musculature. Nerve fibres from the otoliths project to the dorsal and ventral neck musculature via the lateral and medial vestibulo-spinal tracts and the reticulo-spinal tract. These pathways are the conduction routes for the vestibulo-collico reflexes (VCR) which act to stabilize head position (Allum, et al., 1997). The results from this study support the findings of head movement in other perturbation studies (Keshner, et al., 1988 in physical translation perturbations; T. Noda, S. Nakajima, et al., 1993 in galvanic stimulation perturbations).

In addition to the small lateral rotation experienced, the pelvis also showed some lateral translation the mechanism behind which could involve a combination of the activities of the pelvis, thigh, shank or foot segments. Figure 3.7 is an illustration of the relative angular and linear displacements undergone by the mass centres of the body segments. Of particular interest in explaining the movement of the pelvis, are the displacements sustained by the foot and

thigh segments. When the body movement is towards the right, the right foot inverts while the left foot is relatively motionless. The angular displacement observed at the right foot is not transferred upwards so that the foot, shank and thigh segments do not rotate about the ankles as in the action of an inverse pendulum. This suggests that the main mechanism for producing the rotation about the pelvis that moves the total body centre of mass involves the musculature about the hips and pelvis. Support for this mechanism was found in approximately half of the trials where vertical displacement about the thighs and hip joints was observed. In a response movement to the right, the right thigh and hip joint would move down while the left thigh and hip joint would move up causing a rotation about the pelvis.

Figure 3.7 Schematic diagram showing relative movement of body segments to the right side.



To summarize, the response mechanism of the body to a galvanic stimulation is to move the upper body laterally by a rotation about the pelvis. While some movement at the pelvis may be initiated at the ankles, the primary

mechanism seems to reside at the pelvis itself, a result supported by previous work by Day (Day, et al., 1997). In addition to the upper body rotation, the head segment underwent additional rotation about the neck, apparently in an attempt to maintain a level platform for the visual system. Kinetic analysis and study of the muscle activity will provide more detail regarding the cause of the movement at the segments.

The apparent predominant activity at the hips to adjust the position of the upper body is not surprising given the stance of the subject. In a 'feet together' stance, the abductor muscles at the hips are more likely to be used because they are already stretched, a situation which tends to increase proprioceptive sensitivity (B.L. Day, M.J. Steiger, et al., 1993). As well, because of the structure of the lower body, there is a mechanical coupling between the ankles and hips in the frontal plane (ie a change in ankle angle causes a change in hip angle and vice versa). The strength of this coupling increases with stance width (Day, et al., 1993; Day, et al., 1997). Therefore, given the narrow stance width of the subjects in this experiment, the strength of the coupling is weak. A consequence of this situation is that the only muscles able to prevent lateral rotation about the ankles are the ankle everters or inverters. This leaves the hip abductors and adductors free to adjust the position of the trunk without effecting the position of the ankles.

The unsymmetrical movement of the foot segments is more difficult to explain. In movements towards the right, the right foot inverts and the left foot is relatively motionless. In movements towards the left, the left foot undergoes a small inversion while the right foot shows some small eversion. This may be an attempt to widen the base of support in the frontal plane in the direction of motion. Alternatively, it may be a result of vestibulo-spinal reflex influences. The response to these influences would not necessarily be symmetrical because the original stimulus was not bilaterally symmetrical.

Effect of Stimulus Duration on Postural Response

This study employed stimuli of two duration -- shorter stimuli of 500 ms and longer stimuli of 3 seconds. The duration of stimulus had no significant effect on the magnitude of linear and angular displacement observed which confirms the results of earlier studies, which stated that magnitude of response was linearly related to the size of the stimulus current. Therefore, a longer stimulus would not result in a larger response, but would reach a magnitude determined by the stimulus current. However, the stimulus duration did have a significant effect on the duration of the displacement. Longer duration stimuli caused a longer duration of response movement. It appears that even with conflicting (although correct) sensory information from the vision, somatosensory and proprioceptive systems, information from the vestibular system controlled the movements in stabilizing the body. This suggests that informational cues from the vestibular system are weighted more heavily than cues from other sensory systems. There is also support for these conclusions from the results of the effect of vision on the response movement.

Effect of Vision on Postural Response

Use of vision by the subject did not have an effect on response magnitude of the head, trunk or pelvis segments. It was believed that the eyes-open condition would reduce the total conflict in the perception of movement. With absence of vision, there is a conflict between movement information from the vestibular nerve (body is moving in one direction) and the proprioception system (body is not moving). In the eyes-open condition, it was thought that the added information supporting the proprioception system would hasten the resolution of the conflict. A smaller displacement of shorter duration might have been indicative of this early resolution. However, no significant difference in magnitude of displacement was observed between the two vision conditions and the eyes-open condition actually resulted in movements of a longer duration. As noted previously, there is a linear relationship between

magnitude of stimulus current and resulting body movement. In other words, a certain level of stimulus will result in a corresponding magnitude of body movement and maintain this level until either the stimulus ceases or the perceptual conflict is resolved. The addition of information from the vision system in support of the proprioception system lengthened the time needed to resolve the sensory conflicts. This suggests that although vision and proprioception have important and necessary input in the maintenance of balance, vestibular input may be the primary source of information. This conclusion is partially supported by the results of Fitzpatrick, Burke and Gandevia (Fitzpatrick, et al., 1994) who found that lack of vision had no significant effect on a vestibular-evoked response when their subjects stood on a stable support. This behaviour suggests that vision cues are less important than the proprioceptive cues available. In more recent work involving the measurement of postural reflex feedback (Fitzpatrick, et al., 1996), they reported that eye closure had no effect on the loop gain. However, they speculate that the behaviour of the balance control system cannot be accounted for by a feedback system solely. Vision would be part of a feedforward or anticipatory system. However, it is debatable whether an anticipatory system would be triggered by the small lateral movements involved in the present study.

An alternative explanation involves the possible influence of the vestibular ocular reflex (VOR). Although most of the studies using galvanic vestibular stimulation maintain that only the otoliths are effected, there is the possibility that the vestibular canals are also stimulated, which could then involve the VOR (Cauquil, et al., 1998). This means that even in the 'eyes open' condition, there would be some torsion of the eyes signifying a rotation of the visual field. Although this information would be in conflict with the visual information, it would not conflict with the vestibular information. Hence, no appreciable difference may be seen in response magnitude.

Chapter 4 Kinetic Analysis

Introduction

The purpose of this chapter is to gain some understanding of the underlying causes of the movements resulting from galvanic stimulation of the vestibular system that were described in the previous chapter. The kinetic analysis involves a study of the ground reaction forces, centre of pressure of the ground reaction forces, joint moments about the neck, and joint moments about the left and right ankle and hip. The data presented in this chapter represents the results of two experiments involving a total of eighteen subjects. The first experiment used the protocol outlined in the second chapter and resulted in a full kinematic and kinetic analysis of eight subjects. The second experiment employed a reduced protocol that resulted in an analysis of the electromyography of selected leg muscles and ground reaction force data. This experiment involved ten subjects.

As in the previous chapter, individual trials in each of the eight combinations of the three independent conditions were synchronised to the onset of the perturbation and ensemble averaged. Coates (Coats, 1972) and Noguchi (Noguchi, 1995) used this method to maximise the dominant pattern of body sway and minimise the noise of the signal. Latency and direction of response were determined after both onset and cessation of the perturbation. In order to more easily compare results, the mean value of one second of data taken prior to the onset of the perturbation was calculated and subtracted from the averaged data. Therefore, the figures presented in this chapter reflect the changes in magnitude as a response to a perturbation.

Ground Reaction Forces

Changes observed in the ground reaction forces (GRF) represent the result of all movement activity undergone by the body. In general, as the kinematics reveal that the subject is moving in a medial/lateral direction, the

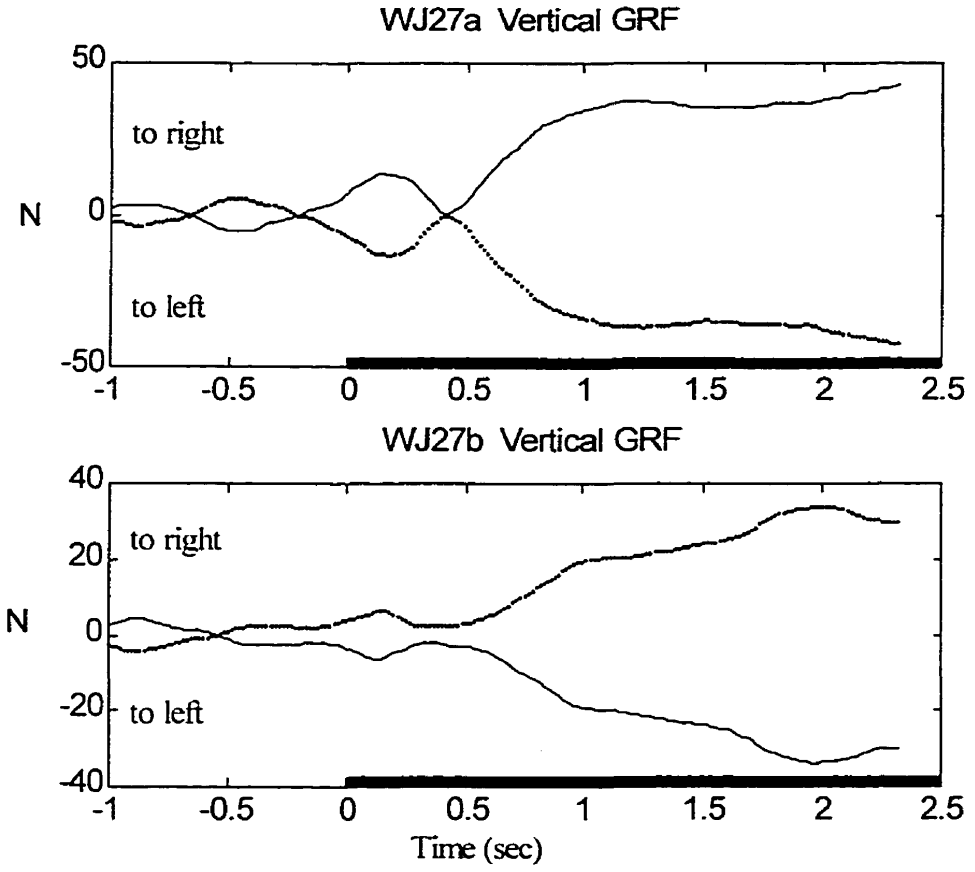
GRF's show a shift in body weight from one side to another. This is reflected by an increase in the vertical GRF on one force platform and a concurrent decrease in the vertical GRF on the other.

The ground reaction forces were analysed first in order to ascertain that a response to the galvanic stimulus occurred. A response was defined as occurring when the signal changed at least two standard deviations from the base signal taken prior to the onset of the perturbation.

Figure 4.1 shows the averaged data of one subject to two types of long perturbation -- one which resulted in a movement to the right of the subject and the other in a movement to the left of the subject. In the reaction that resulted in a movement to the right, the ground reaction force of the right side increases while that of the left side decreases, showing a shift in weight from the left to the right. The opposite pattern is noted in the reaction that resulted in a movement to the left. This loading/unloading pattern was consistent across all conditions and all subjects.

The perturbation response was divided into four phases: initial response, secondary response, recovery response, and cessation response. These phases are labeled in Figure 4.2 which shows the vertical ground reaction forces in typical responses to long and short perturbations resulting in movements to the left. The initial response is the first shift in body weight and is small, approximately the magnitude of two to four percent of body weight. This is followed by the secondary response, which is in the opposite direction to the initial response and is of greater magnitude, ranging from means of six to twenty percent of body weight across subjects. It is followed (in longer duration perturbations) by a recovery phase in which the vertical ground reaction forces reflect an increase or a shift in body weight back to the right side. There may be a number of small weight shifts during this phase. After termination of the perturbation, another reversal in weight shift occurs, characteristic of the cessation phase. In perturbations that result in a shift in

Figure 4.1 Vertical ground reaction forces (GRF) of five averaged trials of one subject. Top figure represents a movement to the right, bottom figure represents a movement towards the left. Right side GRF ____ Left side GRF ..... Solid line on time scale represents onset and duration of perturbation.



body weight to the left, there is a return shift in body weight to the right. Similarly, in perturbations that result in a shift in body weight to the right, there is a return shift in body weight to the left.

It should be noted that the responses to short perturbations do not show the recovery response phase -- only the initial, secondary and cessation phases. Table 4.1 summarises the response phases of the ground reaction forces and the major activities characterised in each phase.

Figure 4.2 Vertical GRF for a) 3 second and b) 500 msec perturbation, representing five averaged trials of one subject. The solid line on the x axis signifies the duration of the perturbation. The initial (1), secondary (2), recovery (3) and cessation (4) phases are labeled on each graph. Both graphs indicate a movement to the right.

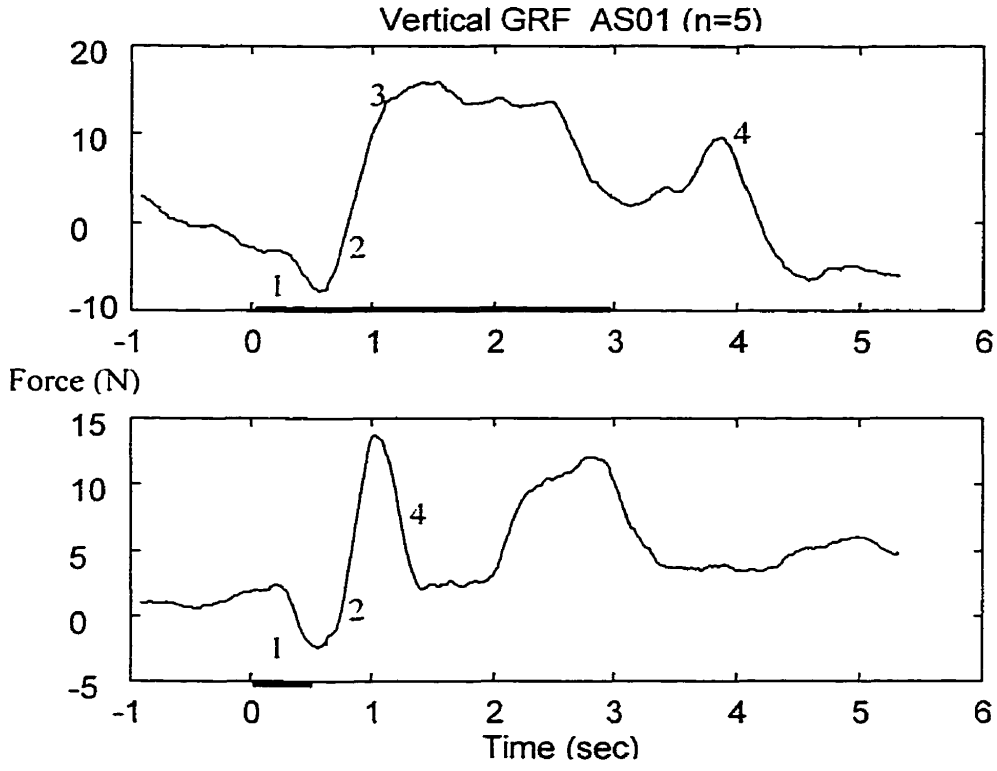


Table 4.1 Summary of GRF response phases.

Phase	Major Activity
1	small shift in body weight (2% - 4%) to the contralateral side 250 ms after perturbation onset
2	large shift in body weight (6% - 20%) in the opposite direction 560 ms after perturbation onset
3	recovery phase where there may be a number of fluctuations in direction. Latency is approximately 1455 ms after perturbation onset. This phase does not occur in responses to short duration perturbations.
4	cessation phase characterised by shift in direction of vertical GRF opposite to phase 2. Latency occurs approximately 810 ms after perturbation ceases.

Table 4.2 shows the mean latencies for these phases under long and short duration perturbations for each of the ten subjects of the second experiment. The mean latency (averaged across subjects) is listed at the bottom of the table. Latencies were measured manually by observing the change in direction of the GRF. Each change in direction that was greater than two standard deviations of the pre-stimulus movement activity was noted and latency calculated. In both movements to the right and to the left, the average onset latency of the initial response was 250 msec. for the entire population. A statistical analysis revealed no significant difference in latency in either direction or duration conditions. The average onset latency for the secondary response phase was 560 msec. As with the initial response, no significant difference in latency was found among the tested conditions. Average onset latencies for the recovery phase was 1455 msec. No significant difference was found between left and right-going stimulus perturbations. No analysis of latency with respect to duration differences was attempted because short duration perturbations did not result in a recovery phase (phase 3).

In order to compare the onset latencies of the cessation phase, the perturbation times (3 seconds for long duration stimulus and 500 msec for short duration) were subtracted from the measured latency. No significant differences in the average latencies were found between short and long duration stimuli or left or right-going stimuli direction. The average latency, pooling all subjects, was 810 msec.

A multivariate analysis of the results of the eight subjects of the first experiment was performed to determine any effect of the duration of the perturbation and presence/absence of subject vision on the magnitude and latency of the vertical ground reaction force. The results of the analysis showed no effect of vision on either the magnitude or latency of the ground reaction forces and only a small effect ($p<0.08$) of the duration of the perturbation on the magnitude of the ground reaction forces. When averaged across subjects and vision and direction conditions, the mean change in

magnitude of the vertical ground reaction force was 35 Newtons in response to a long perturbation and 18.5 Newtons in response to a short perturbation. The mean latency of the dominant (phase 2) response was 500 ms (sd=105 ms).

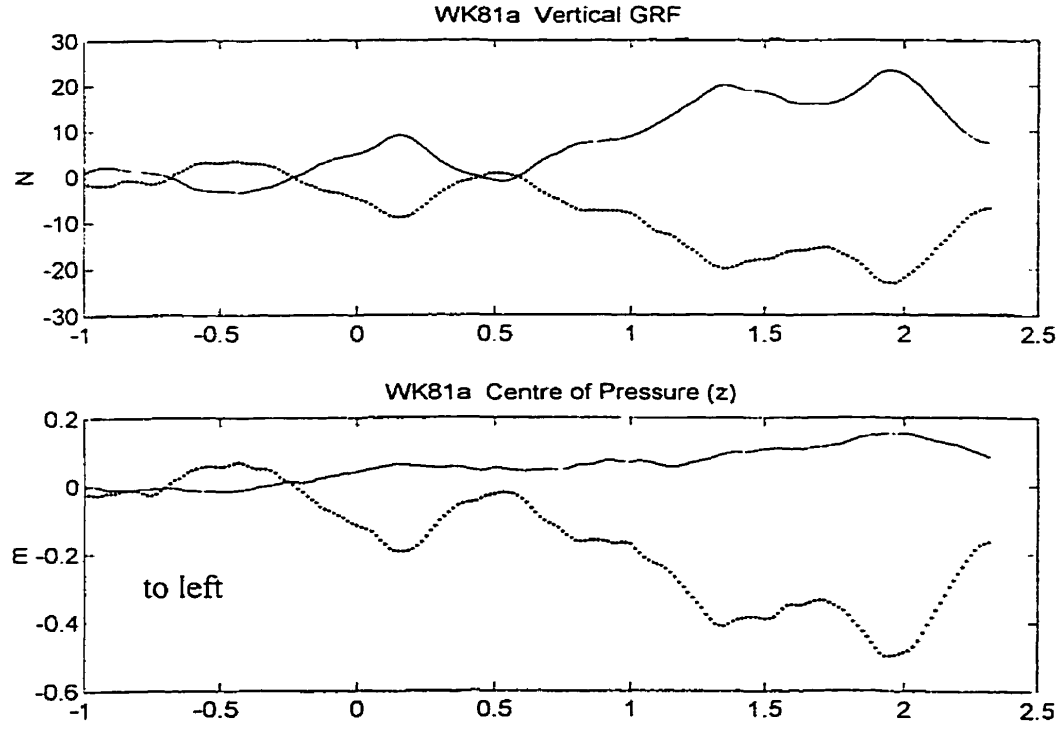
Table 4.2 Latencies (in msec) of the designated phases of the GRF. Phase 1 refers to the initial response, phase 2 to the secondary response, phase 3 to the recovery response and phase 4 to the cessation response. Average latencies across subjects and conditions are calculated, standard deviation given in brackets.

Subject	Trial Condition		Phase 1	Phase 2	Phase 3	Phase 4
AS01	Left	Long	200	500	1000	3500
		Short	250	600	--	1100
	Right	Long	250	550	1100	3800
		Short	250	500	--	1000
AS02	Left	Long	250	400	1100	3800
		Short	--	550	--	1000
	Right	Long	--	500	1200	3800
		Short	--	550	--	2500
AS03	Left	Long	200	450	2700	3900
		Short	200	550	--	1500
	Right	Long	200	800	1800	4000
		Short	200	600	--	1300
AS04	Left	Long	500	900	1800	3200
		Short	350	500	--	1400
	Right	Long	500	700	1300	3800
		Short	250	500	--	1300
AS05	Left	Long	200	500	1300	3700
		Short	200	500	--	1800
	Right	Long	200	500	1400	3800
		Short	--	500	--	1500
AS06	Left	Long	250	550	1600	4000
		Short	200	550	--	1300
	Right	Long	150	500	850	3800
		Short	200	500	--	1000
AS07	Left	Long	--	650	1500	4200
		Short	250	600	--	1600
	Right	Long	200	750	1800	4000
		Short	--	700	--	1600
AS08	Left	Long	--	400	750	3400
		Short	--	650	--	1500
	Right	Long	450	650	1200	3400
		Short	--	400	--	1100
AS11	Left	Long	200	450	1400	3500
		Short	--	600	--	1300
	Right	Long	200	550	2400	3500
		Short	200	500	--	1300
Mean			250 (94)	560 (110)	1455 (505)	810 (277) (adjusted)

Centre of Pressure

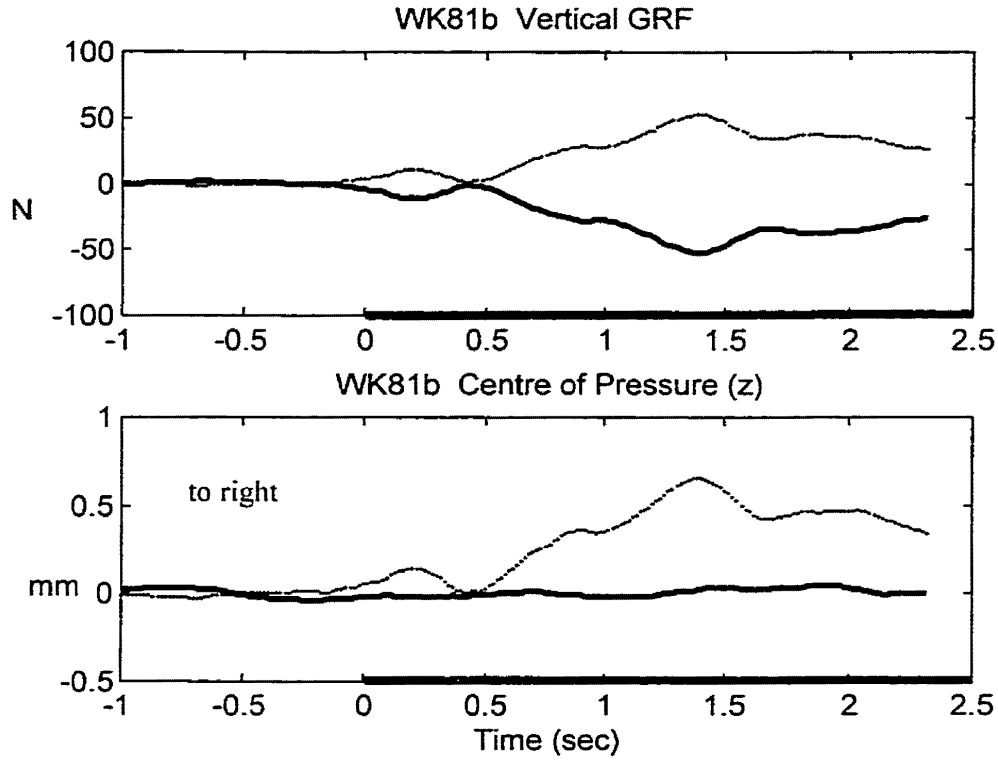
As with previous analyses, centre of pressure results were synchronised with respect to onset of perturbation and averaged across the eight combinations of conditions. As well, correlation analyses were performed between centre of pressure and ground reaction force data. Unlike the results observed with the ground reaction forces, the eight subjects showed no consistent pattern in the centre of pressures measured from each forceplate. The most common pattern of response was shown by five of the eight subjects and is illustrated in Figure 4.3 and Figure 4.4.

Figure 4.3 Vertical ground reaction forces and medial/lateral centre of pressure for a long perturbation resulting in a movement to the right (Right platform ___Left platform.....).



In perturbations which result in movements to the right (Figure 4.3), left ground reaction force and left side centre of pressure are positively correlated. Specifically, as the left side ground reaction force decreases, the left side centre

Figure 4.4 Vertical GRF and medial/lateral CofP for a perturbation resulting in a movement to the left. Right platform ____ Left platform .....



of pressure shifts towards the left of the subject. Three of these five subjects showed positive correlation between right side ground reaction forces and right side centre of pressure data. In other words, as the right side ground reaction force increased, the right side centre of pressure shifted towards the right of the subject. Other subjects showed either no discernible change in the centre of pressure or no consistent relationship between ground reaction force and centre of pressure.

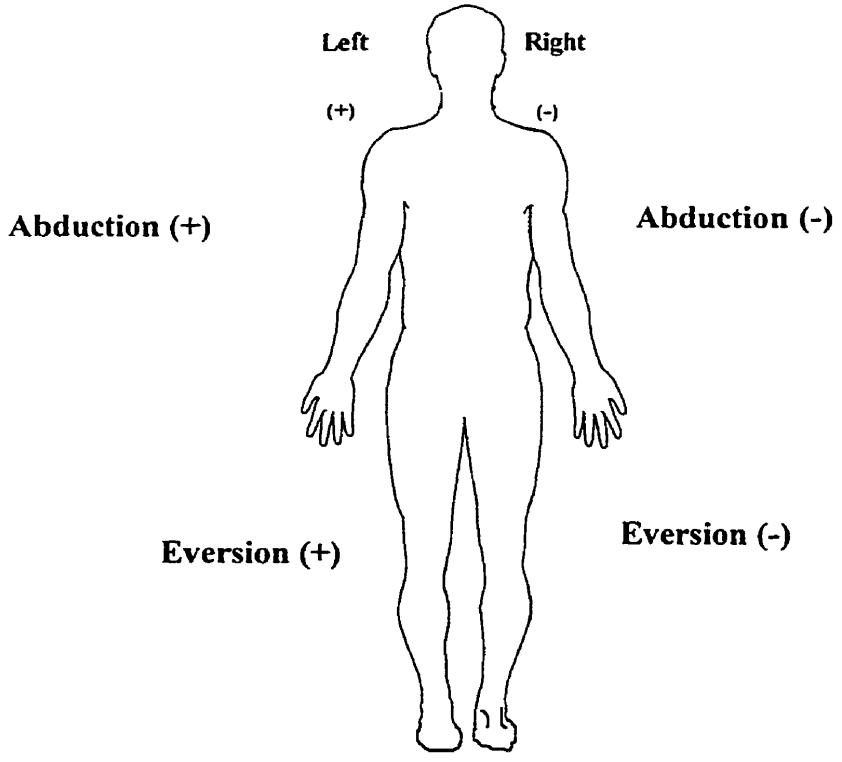
In a perturbation which resulted in a movement to the left (see Figure 4.4), five of the eight subjects showed a positive correlation between the left

side ground reaction force and left side centre of pressure. Specifically, the left ground reaction force would increase and the left side centre of pressure would shift towards the right. No consistent pattern of response was observed for the right side centre of pressure for these subjects. The remaining three subjects showed no consistent movement of either side centre of pressure and no significant correlation with either side ground reaction force.

Joint Moments

Data suitable for kinetic analysis was processed from five subjects. As before, individual trials were synchronised to the onset of perturbation and all trials under each of the eight experimental conditions were averaged. Joint moments are reported using the anatomical descriptors 'abduction' and 'adduction' at the hip, and 'eversion' and 'inversion' at the ankle. Figure 4.5 shows the relationship between these anatomical descriptors of movement and

Figure 4.5 Anatomical descriptors of the moment data. Illustration shows the posterior view with 'right' and 'left' referring to the right and left sides, respectively, of the subject.



that of the right-handed global coordinate system. Note that abduction of the hip is a negative moment on the right side of the subject but is a positive moment on the left side. This is also the case for adduction, and eversion and inversion at the ankle.

A statistical analysis (ANOVA) was performed to determine the effects of vision and stimulus duration on the onset latency and peak magnitudes of the right and left hip and ankle moments. No significant vision or duration effects were observed. The left and right hips moved synchronously with an average onset latency of 470 ms (sd.=190 ms). The average peak change in magnitude from the pre-stimulus baseline was 1.23 Nm (sd.=0.64) for the right hip and 1.41 Nm (sd.=1.29) for the left hip. The high variation may be due to the range in mass of the subjects. Analysis of the ankle moments revealed minimal activity at the right ankle. This pattern of activity was observed across subjects and across conditions. Activity at the left ankle occurred synchronously with the left and right hips. Average peak magnitude was 2.66 Nm (sd.=1.45).

Movements to the right Perturbations which caused movements to the right resulted in the hip and ankle moments illustrated in Figure 4.6, which shows the ensemble average of five trials in response to a long duration stimulus. The response at the hip is characterised by two events: one occurring at shorter latency at 0.25 to 0.30 seconds and the other at a longer latency response of 0.50 to 0.75 seconds after perturbation onset. The shorter latency event is characterised by an increase in abduction at the left hip and a concurrent decrease in abduction (or increasing adduction) at the right hip. The later event shows the reverse pattern with a decreased abduction at the left hip and an increased abduction (or increasing adduction) at the right hip. This pattern of response was consistently shown by all subjects over all experimental conditions with the exception of one subject not exhibiting the shorter latency event. The response pattern at the ankle shows no right ankle moment activity. Three of the five subjects showed a shorter latency event characterised by

increasing eversion at the left ankle. All subjects exhibited a longer latency event characterised by decreasing eversion at the ankle.

Movement to the left Figure 4.7 illustrates the typical response pattern at the hip and ankles to a perturbation resulting in a movement to the left. The shorter latency event is characterised by decreasing abduction at the left hip and increasing abduction at the right hip. No significant activity is observed at the right ankle but four of the five subjects exhibited decreasing eversion at the left ankle. The longer latency event shows increased abduction at the left hip and decreasing abduction at the right hip and an increase in eversion at the left ankle.

Figure 4.6 Hip (top graph) and ankle (bottom graph) moments characteristic of a movement to the right. This is an average of five trials in response to a long duration stimulus. Right side ____ Left side .....

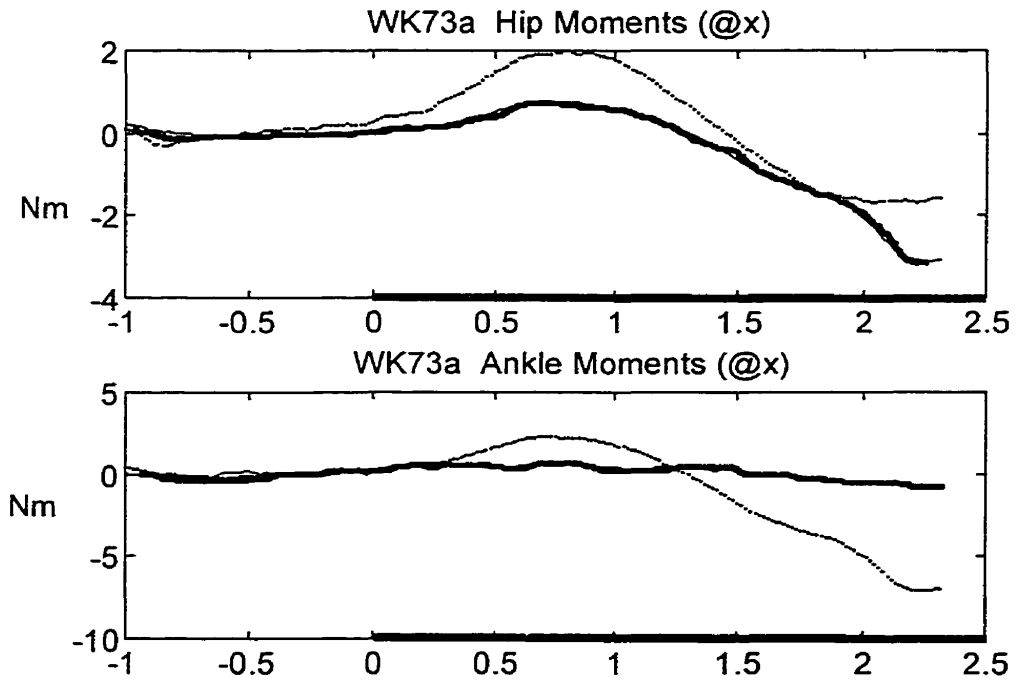
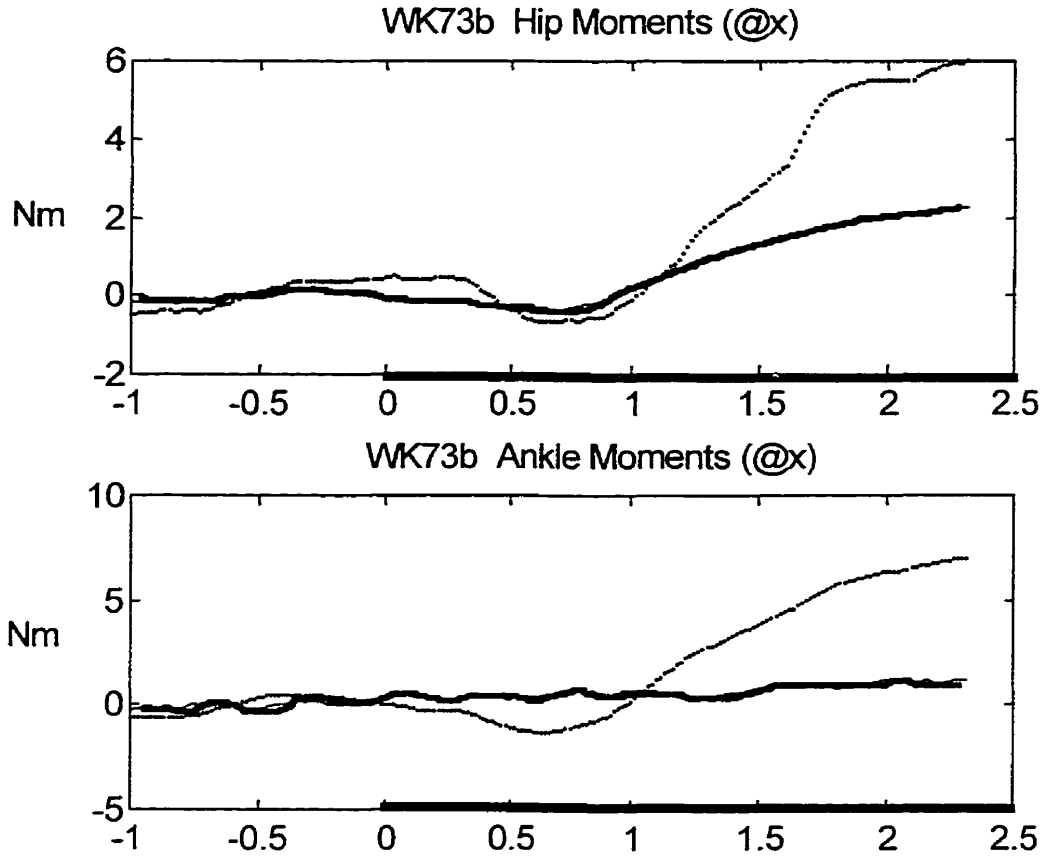


Figure 4.7 Hip (top graph) and ankle (bottom) moments characteristic of a movement to the left. This is an average of five trials in a response to a long duration stimulus. (___ right side ..... left side).



Neck Moments Results of the kinematic analysis revealed that the head experienced an angular rotation about the neck in a direction dependent upon the polarity of the stimulus. A kinetic analysis of this movement was performed in order to confirm that this head movement was independent of movements of the trunk and pelvis. Figures 4.8 and 4.9 illustrate the neck moments estimated from the kinetic analysis and the corresponding angular displacement. Figure 4.8 shows the moment about the neck from a stimulus resulting in a movement towards the left and Figure 4.9 shows the response in a movement to the right. An increasing positive moment caused an angular

rotation of the head to the left side while a negative-going moment caused an angular displacement of the head to the right side. This pattern of response was consistent across conditions and across subjects. The average latency of response was 350 ms (sd.=40 ms) after onset of the perturbation and average magnitude of response was 1.2 Nm (sd.=0.66). Neither the presence nor absence of vision, perturbation direction or duration had an observable effect on latency or magnitude of response. However, the duration of the response was dependent upon the duration of the perturbation with a longer stimulus causing a longer response.

Figure 4.8 Neck moment and angular displacement of the head segment, characteristic of a movement to the left (long stimulus).

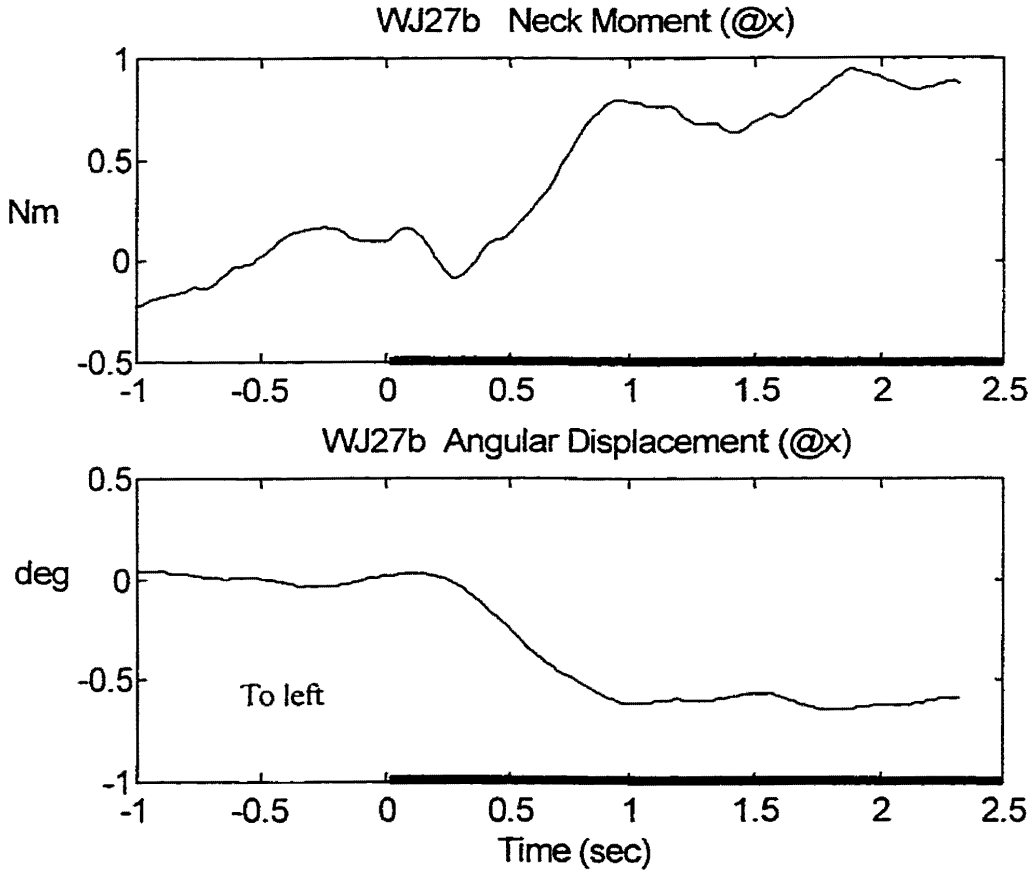
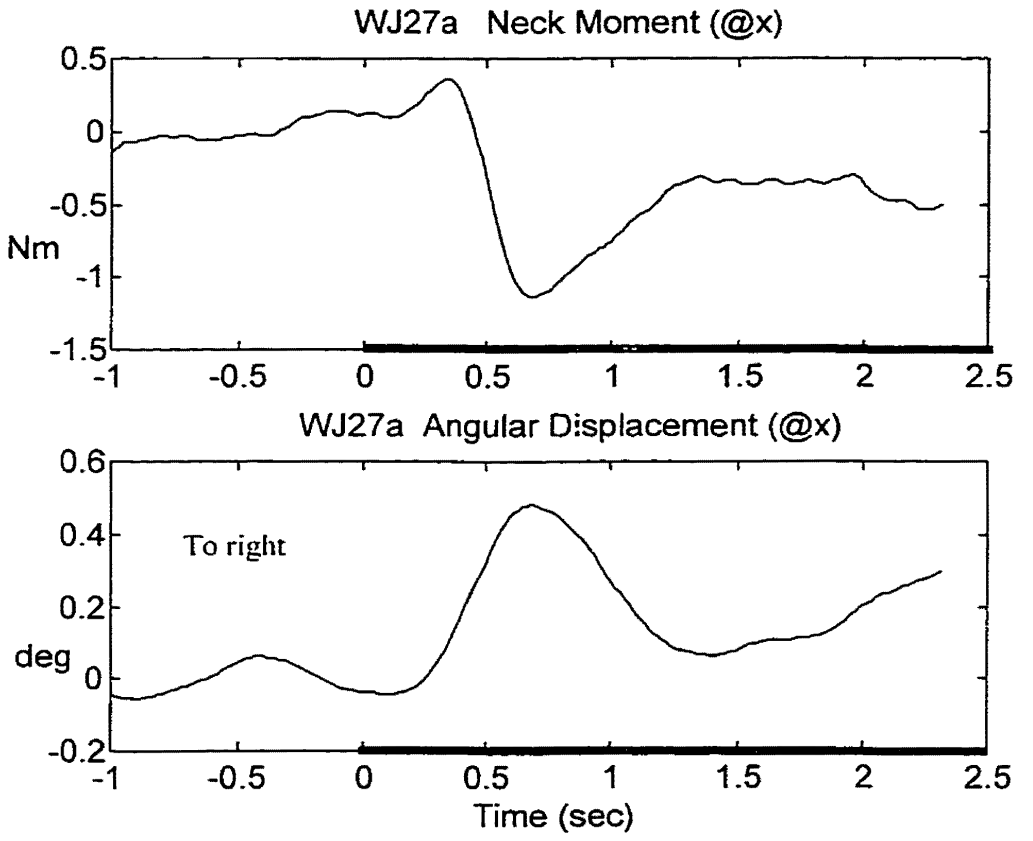


Figure 4.9 Neck moment and angular displacement of head segment, characteristic of a movement to the right (long stimulus).



Discussion

The results of the kinematic analysis of the previous chapter and the analysis of the ground reaction forces show that a galvanic stimulation of a specific polarity causes a postural change. Specifically, the body moves in a medial/lateral direction, with the trunk rotating about the pelvis causing a shift in body weight to one side. The question to be answered concerns the mechanisms responsible for this change in posture -- is it primarily the activity of the ankle or the activity of the hip or some combination of both? The analysis of the moments generated at the ankles and hips, in combination with the ground reaction forces, COP at each foot, and the segmental kinematics, provide some insight.

Ground Reaction Forces

Analysis of the vertical GRF provided a direct method of determining if the perturbation caused a shift in the whole body centre of mass and the extent of any recovery. When repeat trials were synchronised to the onset of the perturbation and ensemble averaged, four distinct phases were observed: the initial phase, dominant phase, recovery phase and cessation phase.

Phase 1, the initial response, is characterised by a small movement in the contralateral direction (average latency of 250 ms) that is generally apparent only when the signal to noise ratio is improved by averaging repeat trials. Because of the small magnitude, this phase is unlikely to be functional in the maintenance of postural control and may be an artifact of the type of stimulus. Possible explanations of an artifact concern the pattern of discharge created along the vestibular nerve, and/or the subsequent interpretation of this pattern at more central areas. This transient response was noted by Fitzpatrick (Fitzpatrick, et al., 1994) and by Britton (T.C. Britton, B.L. Day, et al., 1993) in their studies of anterior-posterior movement. Fitzpatrick suggests that it may reflect a compensatory reaction to an illusory movement in the opposite direction.

The small contralateral movement followed by the larger ipsilateral movement may occur through a change in polarity of afferent neural drive along the vestibular nerve. The state of excitation or inhibition is dependent upon the polarity of the stimulus and/or the site of the initial trigger along the nerve (citation). If the stimulus is triggered at the hair cell, the resulting wave will continue in one direction along the axon. However, because surface electrodes are used to produce the stimulus, a more global pattern of excitation/inhibition may occur and trigger at multiple points along the axon, resulting in a wave of excitation/inhibition that may not be monophasic. The subsequent change in firing rate would cause a change in the direction of movement, as seen between the initial phase and the dominant phase of the response. Goldberg, Smith and Fernandez (Goldberg, et al., 1984) studied the discharge rate of the vestibular nerve in squirrel monkeys under galvanic stimulation. Their results confirm the findings from previous studies that anodal currents (positive) inhibit the discharge rate and cathodal currents (negative) excite the discharge rate. In response to a five-second perturbation, their results further show that while the discharge rate along the nerve may diminish slightly due to an adaptation response, it does not change direction (from excitation to inhibition). These findings tend to support the view that the cause of the observed change in movement direction between the initial and dominant phases lies beyond the afferent drive of the stimulus. However, the method of stimulation used by Goldberg et al differed with a more direct implantation of electrodes in the inner ear, possibly resulting in a less global stimulation of surrounding tissue and reducing the number of potential multiple trigger sites along the vestibular nerve. Although this may be an unlikely cause of the change in movement direction, it emphasises the problem with this type of perturbation –without more invasive testing, a knowledge of the pattern of discharge of the stimulation is unknown.

An alternative explanation of the change in movement direction suggests that the initial response may be a result of the central processing or interpretation of the discharge pattern of the galvanic stimulus. As described

in an earlier chapter, the hair cells in the ultricle and saccule are oriented towards the striola in such a way that for any linear acceleration experienced there is a particular pattern of excitation and inhibition of nerve fibers. However, under galvanic stimulation, with an anodal current presented at one mastoid and a cathodal current presented at the other, 'normal' patterns of nerve discharge do not occur. Given the placement of the electrodes, it is thought that the vestibular nerve on one side experiences a global excitation while the other side experiences a global inhibition, creating a novel pattern of afferent neural drive whose interpretation is left to more central processing areas. The question of what is being interpreted arises. Suggestions include internal estimations of verticality and estimations of the position of the head and body in space. Inglis et al (J.T. Inglis, C.L. Shupert, et al., 1995) studied the effect of galvanic vestibular stimulation combined with a translating platform on the position of the whole body centre of mass(COM) and COP. They suggest that this type of vestibular signal sets an internal estimate of verticality to a new position and any subsequent movement is an attempt to realign the body with the new equilibrium position. If true, activity observed during the initial phase may reflect the 'resetting' of the internal position while the dominant phase may be an attempt of the body to realign itself. Their results show that the final position of the body COM and COP was significantly different from the initial positions when galvanic stimulation was paired with platform translation. However, the effect of galvanic stimulation alone on the final positions of both COM and COP was much smaller (0.8 cm with a variation of 0.6 cm) and may be within measurement error. This differs from the results of the current study, which found that the COP returned to pre-stimulus levels . As well, there is no indication of the length of time that the observed effect persisted after the cessation of the stimulus. This suggests that the effect may be due to a combination of sensory afferent information. This is supported by other studies (F. Hlavacka, T. Mergner, et al., 1996; F. Hlavacka, T. Mergner, et al., 1992; T. Mergner, F. Hlavacka, et al., 1993) suggesting that the internal estimation of the position of the head and body in space is dependent upon information from

both vestibular and proprioceptive sources. During the initial and dominant response phases, there is a sensory conflict -- the vestibular input is signifying that a movement of some kind is occurring while information from the other sensory systems (proprioception and tactile somatosensory) initially signifies the opposite. Therefore, activity during the initial phase may reflect a resolution of the conflicting information to provide an estimate of the position of the head and body in space, while activity during the dominant phase is the effort to recover postural equilibrium. It is speculated that the vestibular input is overriding any sensory information from the other systems. During this phase, the peak magnitude is reached – the value of which is determined by the level of the stimulus current (Coats, 1972, Coats, 1973). When the stimulus is prolonged for three seconds, a third phase -- the recovery phase – develops. In many cases, there are a number of small fluctuations in direction of weight bearing. During this period, there may be a re-evaluation of the relative importance of vestibular and proprioceptive input. This may occur because the proprioceptive and somatosensory inputs are signifying that a greater change in position is occurring. Approximately 800 ms after cessation of the stimulus, a movement is observed towards the pre-stimulus position. With the removal of the conflicting vestibular input, it is speculated that a re-evaluation of the relative importance of sensory input occurs with the subsequent movement to re-establish a normal standing posture. In summary, although there is no unambiguous evidence, the results suggest that the initial phase observed in the GRF may be a reflection of a re-organisation of relative importance of sensory afferent information in establishing the position head and body in space. The vestibular input seems to assume greater importance than the proprioceptive and tactile somatosensory inputs and this is reflected in the continued increase of the GRF until a peak is reached, the magnitude of which is determined by the level of stimulus current intensity. Fluctuations in the magnitude of the GRF are observed in the recovery phas, suggesting ongoing re-evaluation of sensory inputs as the somatosensory and proprioceptive inputs show more

change in position. Finally, during the cessation phase, there is no conflict in sensory afferent input and the body moves to recover its pre-stimulus posture.

Integration of the COP and joint moment data with the kinematic data may provide some insight into the mechanisms behind the observed movements. Figures 4.10 and 4.11 illustrate the hip moments, ankle moments and the corresponding pelvis displacement during movements to the right and left, respectively and will be referred to in the following discussion.

Movement to the right In a perturbation resulting in a movement to the right of the subject, the postural change results in a shift of some body weight from the left leg to the right. In five of the eight subjects, analysis of the relationship between the vertical ground reaction forces and COP show that there is a positive correlation between the left side ground reaction force and the left side COP. As the left side ground reaction force decreases (as in a movement to the right), the left side COP shifts left. No such consistent relationship was noted between the right side ground reaction force and COP, a result which confirms the findings of Cauquil (Cauquil, et al., 1997) who found that the whole body COP moved in the opposite direction of the lateral displacement of the body. Kinematic analysis shows that there is no significant change in linear or angular displacement at the left ankle at either the shorter or longer latency event -- any movement occurs well after the longer latency event. In contrast, the right foot inverts and this movement begins approximately 250 ms after perturbation onset (shorter latency event). An analysis of the moments generated during the movement of the left foot reveals that there is a small everter (or positive) moment generated at shorter latency followed by a larger inverter (or negative) moment at longer latency. However, since there is no movement measured about the left ankle at these time periods, this inverter moment must be acting to stabilise the ankle. The shift in COP must then be due to activity occurring higher up in the body, at the hip. The left hip undergoes some movement -- a small vertical and lateral displacement as the pelvis rotates to the right. An adductor moment is seen at the left hip that

corresponds with the displacement observed at the left hip. During this same time period, an abductor moment is generated at the right hip that corresponds to the observed movement. The right hip moves laterally and slightly downward as the pelvis rotates. A cross-correlation analysis revealed that the moments generated at the right and left hip are highly positively correlated. As the left side adducts, the right side abducts.

Movement to the left In a perturbation resulting in a movement to the left of the subject, the postural changes result in a shift of a proportion of the body weight from the right leg to the left. As in the movement to the right, there is a dominant relationship between the left foot COP and the left ground reaction forces in five of the eight subjects. As the left ground reaction force increases, the left foot COP shifts right. An analysis of the displacement of the foot segments reveals that the right foot everts with a corresponding decrease in the angular displacement between the foot and shank segments. The left foot experiences a slight inversion. The moments calculated at the ankles show little activity at the right and an everter moment at the left ankle, which is a reflection of the greater loading on the left due to the shift in weights from the right to the left side. Kinematic data of the pelvis and hips show a slight movement of the pelvis to the left, with a corresponding slight downward movement of the left hip and upward movement of the right hip. This pattern of movement produces a rotation a linear displacement of the pelvis as a result of adduction at the right hip and abduction at the left hip. Figure 4.11 shows the hip and ankle moments and the corresponding pelvis movement during a movement to the left.

A comparison of the moment activity about the ankles and hips resulting in movements towards the left or right shows a dominant pattern. Left and right hips act in a strongly correlated manner -- as one abducts, the other adducts. The pattern of activity is characterised by increasing abduction on one side and decreasing abduction on the other at a shorter latency of 250 milliseconds followed by a reversal of activity at the longer latency of 500

milliseconds. The shorter latency moment activity at the hips does not result in any apparent movement of the pelvis. The magnitude of the moment may not be great enough to produce a movement or the resulting movement may not be discernible in the natural background movement of the pelvis.

The moment activity at longer latency appears to be responsible for the pelvis movement. Although there is also ankle moment activity at longer latency, it is only discernible on the left side and is thought to act to stabilise the ankle. If there was apparent right ankle activity, a case could be made for the combined and coordinated action of ankles and hips to produce the required shift in body weight. However, no consistent pattern of right ankle moment activity was observed. A possible explanation concerns the mathematical model of the foot segment used to estimate the ankle moment. The foot was modeled as a single rigid body and is therefore unlikely to adequately account for the complexity of the movements of the foot during control of small postural adjustments.

Analysis of the moments generated about the neck reveals that some activity occurs that moves the head independently of the trunk, confirming the results of the kinematic analysis. The dominant moment activity resulting in medial-lateral head rotation occurs before the dominant activity at the hips at longer latency. Previous research has demonstrated that vestibular and cervical reflexes participate in the stabilisation of the head and neck. The vestibulo-collic response stabilises the head in space and the cervico-collic response is responsible for aligning the head with respect to the trunk. It is speculated that vestibular galvanic stimulation elicits head movement via the vestibulo-collic or vestibulo-spinal pathways.

Figure 4.10 Hip moments, ankle moments, and linear medial/lateral pelvis displacement in a movement to the right. Right side ____ Left side .....

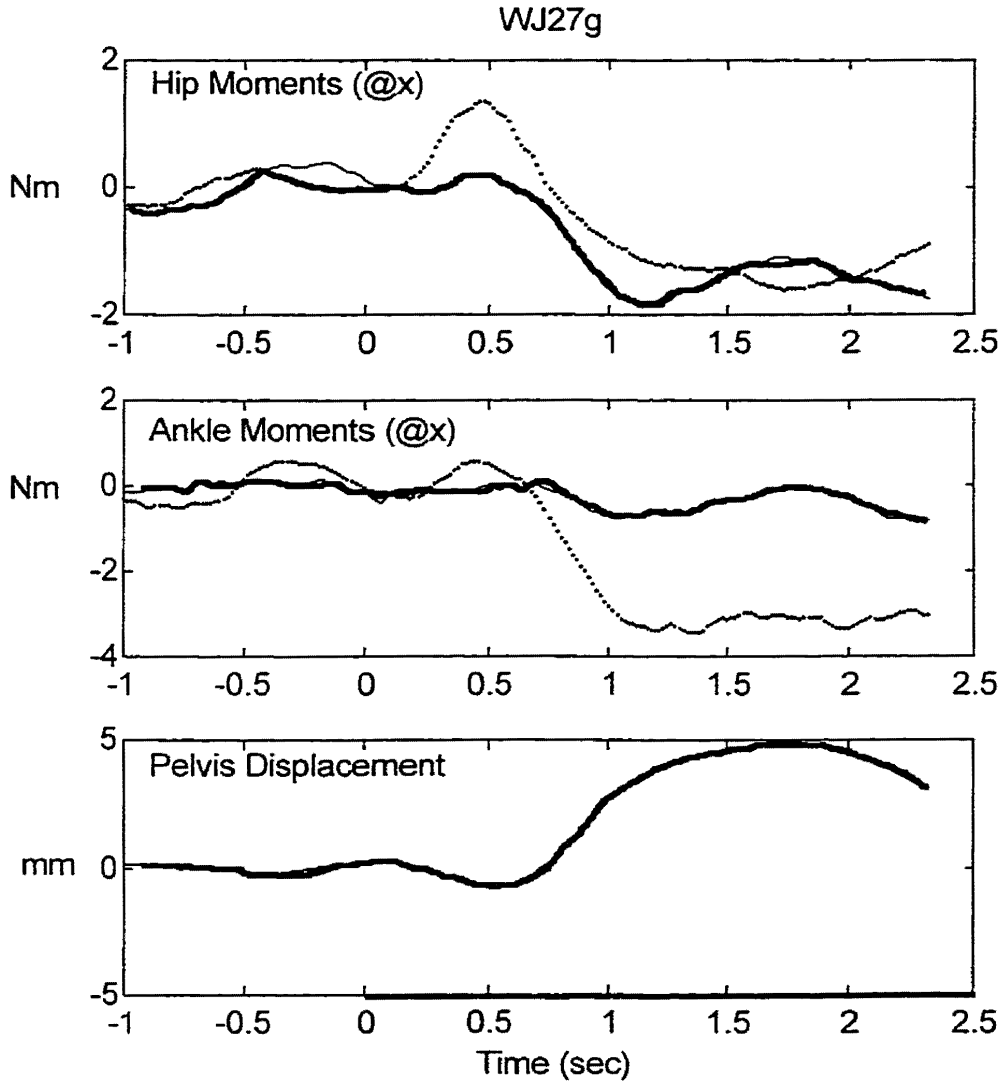
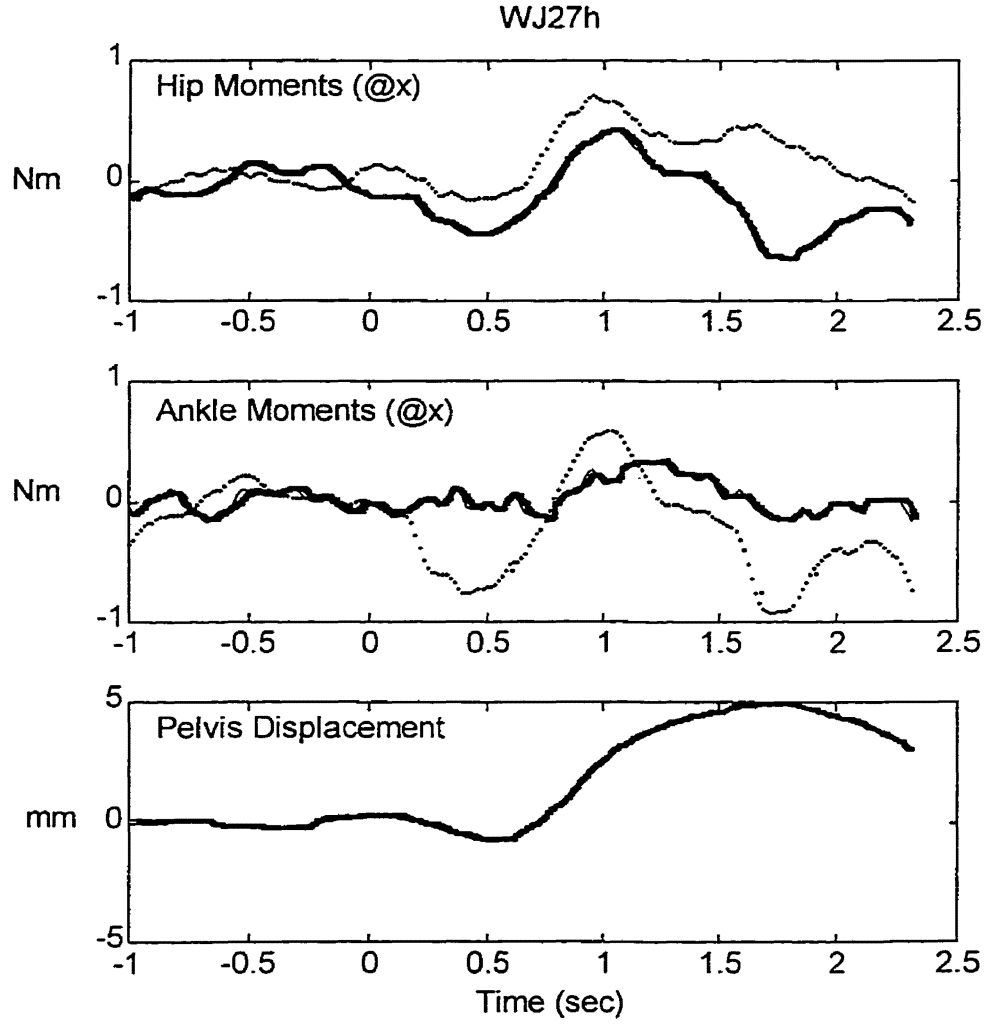


Figure 4.11 Hip moments, ankle moments, and linear medial/lateral pelvis displacement in a movement to the left. Right side _____ Left side .....



Chapter 5 Electromyography of Selected Postural Muscles During Perturbed Stance

Introduction

The results of the previous chapters show that galvanic vestibular perturbation produces a characteristic shift in body weight from one leg to the other, the direction of which was dependent upon the direction of the stimulus current. This shift in body weight is accomplished by a rotation of the trunk and upper body about the pelvis as in the manner of an inverted pendulum acting about the centre of mass of the pelvis. Kinetic analysis also reveals that abduction and adduction moments about the hips are correlated to the observed movement. Abduction of the right hip and/or adduction of the left hip is positively correlated to a movement towards the right of the subject whereas abduction of the left hip and/or adduction of the right hip is positively correlated with movement to the left of the subject. Also, in most of the subjects, some rotation is observed in the left foot that may also result in an adjustment of body weight.

To further investigate mechanisms of lateral postural stability provided by the vestibular system, this study examines muscle activity at the hips and ankles evoked by vestibular stimulation. Although a direct relationship between magnitude of electromyographic (EMG) activity and joint moments and corresponding displacements cannot be assumed due to the non-linear relationship between EMG and joint moments, an analysis of the existence of EMG activity within a realistic time frame of the corresponding moment provides confirmation of the kinetic results.

Although EMG data was collected during the original experiment, subsequent processing and analysis of this data revealed that it was unusable due to: electrical interference of the galvanic stimulation on the recordings; and a lack of sensitivity of the EMG collection system to the very small levels of

muscle contractions used for the fine postural adjustments observed in the response movement. The decision was made to repeat most of the experiment with a more sensitive EMG recording system.

Subjects

Ten subjects, ranging in age from 21 to 63, and with no history of vestibular, balance or neurological problems participated in this additional experiment. Table 5.1 summarises the subject data.

Table 5.1 Summary of Subject Data

Subject	Age	Height (cm)	Mass (kg)
AS01	27	172	56
AS02	27	178	67
AS03	29	180	66
AS04	23	152	45
AS05	20	180	60
AS06	63	165	70
AS07	42	178	73
AS08	24	150	46
AS09	29	153	47
AS10	30	168	75
AS11	25	155	51

Description of Experimental Paradigm

As in the first experiment, each subject was requested to stand relaxed, with feet adjacent and close together. Because only one forceplate was

available, the right foot was placed on the forceplate, the left foot placed just off the lateral edge of the forceplate. This configuration was used in order to measure the shift in body weight from one side to another as a result of body movement caused by the reaction to the perturbation.

Unlike the first experiment, there were only two independent variables tested -- direction of stimulus current (left vs. right) and duration of stimulus (3 seconds vs. 500 milliseconds), resulting in four different combinations of variables. Since the results of the original experiment showed no significant difference in dependent variables under the vision condition, it was not included and subjects were tested with their eyes closed. Five randomized repeat trials of each combination were presented, resulting in a total of twenty eight-second trials. Use of an eight-second trial allowed a randomised perturbation onset as well as at least a 500 ms initial baseline reading in each trial.

Dependent variables included the onset latencies and muscle activation patterns of specific hip and ankle muscles, specifically the left and right gluteus medius, left and right adductor magnus, left and right peroneus longus, and left tibialis anterior.

Analysis of dependent variables

The EMG signals were collected in a raw format at 2000 Hz and rectified. Two methods were used to further process the data. In the first method, the data was subsequently filtered with a fourth-order Butterworth low-pass filter with a cut-off filter of 250 Hz. Latencies of each muscle response were recorded after onset and cessation of the perturbation. In the second method, the data was subsequently filtered with a fourth-order Butterworth low-pass filter with a cut-off frequency of 3 Hz. The data of the five repeat trials under each condition were synchronised to the onset of the perturbation. This data was compared with the GRF data in an effort to determine the pattern of muscle activity responsible for the changes in GRF.

Results

Electromyography Response Patterns

The displacement of the body's centre of gravity in the medial/lateral directions can be achieved in a number of ways, which include combinations of abduction and/or adduction at the hips and inversion and/or eversion at the ankles. In order to determine the muscle activation patterns involved in the postural responses to the perturbation, onset latencies for each muscle were measured in each trial per subject and averaged. As well, cross-correlations between the individual muscle activation waveforms and vertical GRF waveforms were performed.

A number of different response patterns emerged from studies of the onset latencies and comparisons of EMG and corresponding vertical GRF patterns. Kinetic analysis of the original data revealed that both hips produced an abductor moment due to the stance that the subject was instructed to use (feet close together). Therefore, lateral movement could be achieved through combinations of activation reduction on one side and/or increases in activation on the other. As well, each abductor muscle is paired with an adductor. Agonist/antagonist pairs can act in seemingly infinite patterns involving various levels of activation and inhibition to achieve the desired result.

Tables 5.2 and 5.3 list the onset latencies for each of the muscles under the direction of perturbation (to the left, to the right) for long and short duration stimuli, respectively. Each tabulated onset latency is the result of averaging the results of the five individual repeat trials. If no consistent response was detected, an asterisk was placed in the relevant column. In general, the tables show that activation of the hip musculature, both the gluteal and adductor muscles, achieved the most consistent response.

Long duration perturbations The results listed in Table 5.2 show that, in movements to the left, the left gluteal muscles activated during phase two (corresponds to the dominant movement towards the left) of the response

period for six of the ten subjects. If the activation patterns of the right adductor muscle, an activation which may also cause movement to the left, are included, eight of the ten subjects show consistent activity of the hip musculature. Right gluteal and left adductor muscles activated during phase one and/or phase three for seven of the ten subjects. There was no consistent pattern of activity in the ankle muscles across subjects. In movements to the right, the right gluteal and/or left adductor muscles activated during the phase two (dominant movement) period in nine of the ten subjects. Left gluteal muscles and/or right adductor muscles activated during phase one or phase three latency periods in seven subjects. One subject (AS05) showed no consistent activity of the hip musculature during either left or right movements.

Short duration perturbations As in the long duration perturbation, the left gluteal and/or right adductor muscles activated during phase two of the response in movements to the left in eight of the ten subjects (see Table 5.3). Right gluteal and/or left adductor muscles activated during phase one or phase four of the response in six subjects. There was no consistent pattern of activity in the ankle muscles across subjects. In movements to the right, the activations of these muscles reversed, with eight of ten subjects showing right gluteal and/or left adductor muscle activation during phase two of the response and left gluteal and right adductor muscle activation during phase one and phase four of the response. As in movements to the left, there was no consistent pattern of ankle muscle activity across subjects.

It should be noted that averaging the latencies across the repeat trials tends to obscure any subtle variation in the combined actions of the hip and ankle muscles. Two subjects (AS05, AS08) show little consistent muscle activity in the latencies listed in both Tables 5.2 and 5.3. However, by studying the individual trials, patterns of response which combine either hip and/or ankle musculature emerges. This may be more readily apparent in Figure 5.1, which shows the frequency of the first onset of a specific muscle for phase 2, the dominant movement of the response. For each individual trial, the muscle that

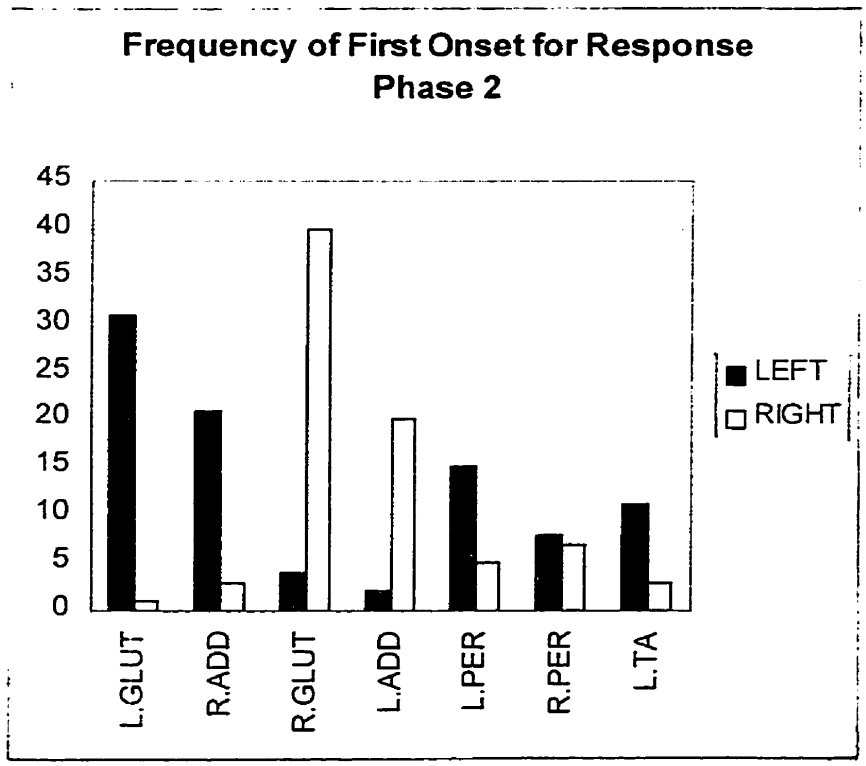
activated first just prior to the start of the dominant phase of the response was determined. The graph shows that the left gluteal and right adductor muscles tend to activate first in movements to the left while the right gluteal and left adductor muscles tend to activate first during movements to the right. However, the situation is not so clear for the peroneal and tibialis anterior muscles. Although the left tibialis anterior and left peroneus muscles show a tendency to activate first during movements to the left, the activity of the right peroneal muscle is split almost evenly between left and right movements. Based on this analysis, subjects who predominantly used the gluteal and adductor muscles where classified as being 'hip dominant' while those who used a combination of hip and ankle muscles were classified as being 'hip/ankle dominant'. Figures 5.2 and 5.4 are examples of a 'hip dominant' response to long and short duration perturbations, respectively. The bottom graph in the figures shows the vertical GRF of that particular trial. In Figure 5.2, the vertical GRF indicates a shift in body weight to the left side at an approximate latency of 500 ms. The EMG data shows that this movement is likely accomplished by the activation of the left gluteus muscle and later, by the right adductor. The vertical GRF shows a recovery movement (cessation phase) to the right side at a latency of 2500 ms. This is accomplished by the combined activation of the right gluteal and left adductor muscles, as well as by the decreased activation of both left gluteus and right adductor. There appears to be little correlation between the ankle muscle activity and GRF. In Figure 5.4, the vertical GRF graph shows a shift in body weight towards the left side at a latency of approximately 600 ms as a result of a short duration perturbation. As in Figure 5.2, this is a result of the activation of the left gluteal and right adductor muscles. This is followed by a movement towards the right side at a latency of approximately 1000 ms after cessation of the perturbation, corresponding to the activation of the right gluteal and left adductor muscles.

While the activation of the left and right peroneus muscles are not correlated with the GRF, there is a positive correlation between the left tibialis anterior muscle activity and the GRF.

Figures 5.3 and 5.5 are examples of a combination of hip and ankle muscle activity to produce movements to the left and right sides as responses to perturbation. In Figure 5.3, the vertical GRF indicates a movement towards the left at a latency of about 700 ms. This corresponds with a small increase in the activities of left gluteus, right adductor and left peroneus muscles and a small decrease in left adductor muscle activity.

Further movement to the left is correlated with increased activity of the left tibialis anterior. Movement to the right is correlated with the combined increased activity of the right gluteus and left adductor and decreased activity of the left tibialis anterior. Figure 5.5 is an example of the response pattern of short duration perturbation resulting in movement to the right. It shows a

Figure 5.1 Frequency of first latency onset of selected postural muscles during the dominant phase of the response.



gradual movement to the right beginning at a latency of 700 ms which is positively correlated with the increased activity of the right gluteus, left adductor and right peroneus muscles. The later movement to the left is correlated to the activity of the left gluteus, right adductor and left peroneus.

Table 5.3 Mean Muscle Onset Latencies for Short Duration Perturbations

Subject	Condition	L. Glut	R. Glut	L.Add	R.Add	L.Per	R.Per	L.TibAnt
AS01	**Left**	500	200	550	560	*	*	*
	Right	250	700	1750	250	*	*	*
AS02	**Left**	550	1600	1250	1300	*	*	*
	Right	250	500	1280	1350	*	*	*
AS03	**Left**	610	960	700	610	580	*	1290
	Right	1800	500	625	*	*	550	*
AS04	**Left**	550	1050	1110	*	250	*	450
	Right	*	500	1380	*	250	250	250
AS05	**Left**	*	*	*	*	*	690	*
	Right	*	*	*	*	*	250	*
AS06	**Left**	750	*	*	750	*	750	*
	Right	*	600	600	1100	*	*	*
AS07	**Left**	750	*	1350	*	*	*	*
	Right	2000	680	*	1350	*	*	*
AS08	**Left**	*	*	1460	*	*	*	*
	Right	*	*	680	670	*	*	*
AS09	**Left**	600	*	1830	*	*	*	570
	Right	*	580	*	*	600	*	*
AS11	**Left**	600	1510	1750	1560	2150	2160	800
	Right	1900	650	*	*	2175	1960	280

Table 5.2 Mean muscle onset latencies for long duration perturbations.

Subject	Condition	L. Glut	R. Glut	L.Add	R.Add	L.Per	R.Per	L.TibAnt
AS01	**Left**	750	3500	1800	1200	*	*	2600
	Right	1500	500	1750	1750	*	*	*
AS02	**Left**	600	*	1500	1050	*	*	*
	Right	1800	1600	300	1150	*	*	*
AS03	**Left**	840	3820	870	1100	1650	*	980
	Right	*	610	*	*	*	1075	*
AS04	**Left**	1670	300	400	450	*	*	*
	Right	1700	340	*	440	200	*	200
AS05	**Left**	*	*	830	*	*	1100	1100
	Right	*	*	*	*	*	*	I
AS06	**Left**	600	2000	3750	600	*	750	*
	Right	1250	500	500	1250	700	*	*
AS07	**Left**	1000	250	1400	600	*	*	*
	Right	*	820	1500	1500	*	*	*
AS08	**Left**	*	*	*	*	*	*	*
	Right	*	*	1050	1590	*	*	*
AS09	**Left**	670	*	*	*	*	*	*
	Right	*	600	*	*	*	*	200
AS11	**Left**	650	1750	*	1250	1130	700	440
	Right	1920	1720	*	1690	1225	1725	400

Figure 5.2 EMG activation patterns for a movement to the left as a result of a long duration perturbation. Perturbation onset and duration is characterized by a solid heavy line on the time scale. EMG magnitude is measured as a percentage of the greatest level recorded over all trials, per subject. GRF magnitude is measured in N.

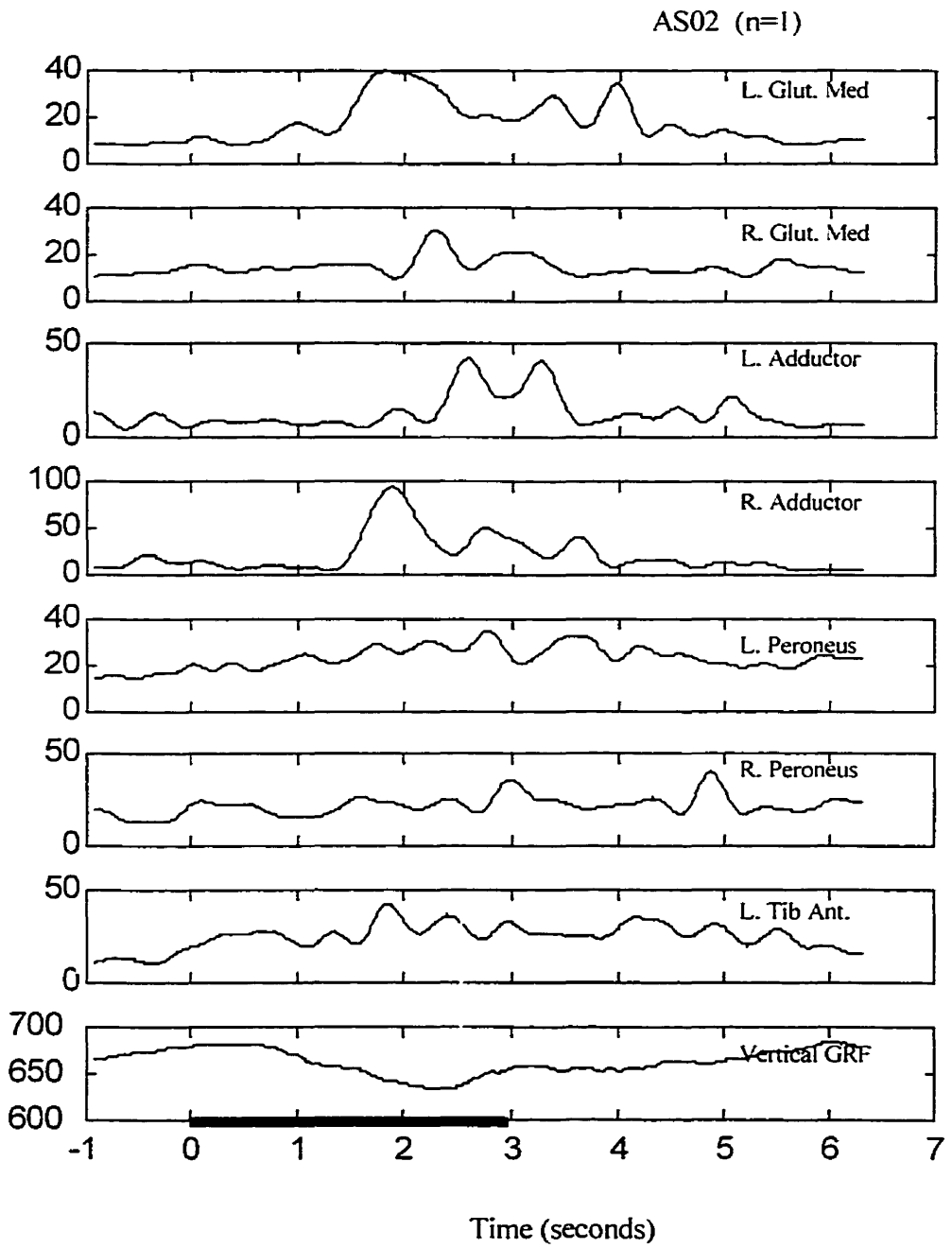


Figure 5.3 Combination Hip/Ankle EMG patterns of a movement to the left as a result of a longer perturbation. Onset and duration of the perturbation is shown as a heavy solid line. Magnitude of the EMG is a percentage of the greatest level recorded for each muscle over all trials, per subject.

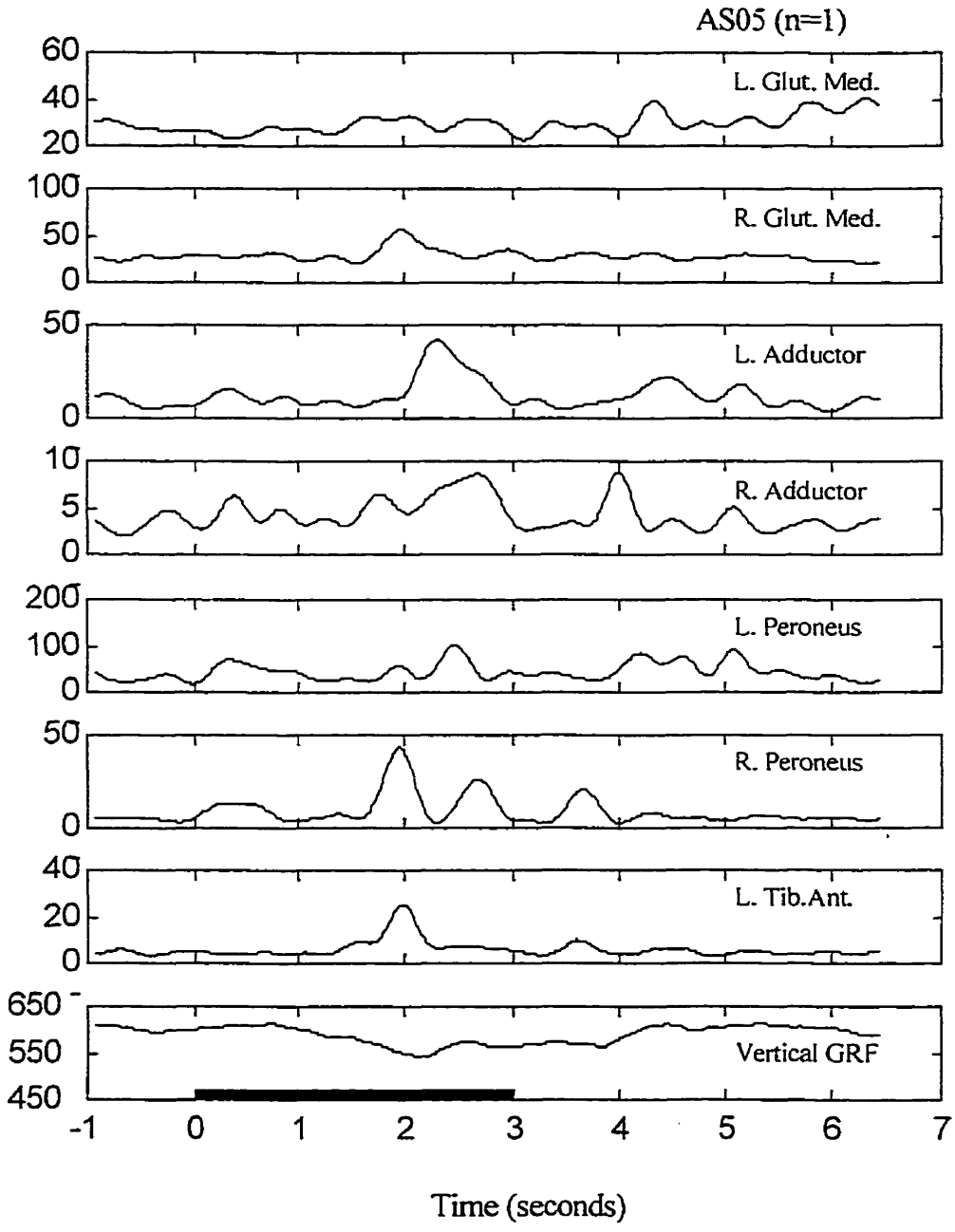


Figure 5.4 Hip muscle dominant pattern of a movement to the left as a result of a short duration perturbation. Onset and duration of the perturbation is shown as a heavy solid line. Magnitude of the EMG is a percentage of the greatest level recorded for each muscle over all trials, per subject. GRF magnitude is measured in newtons.

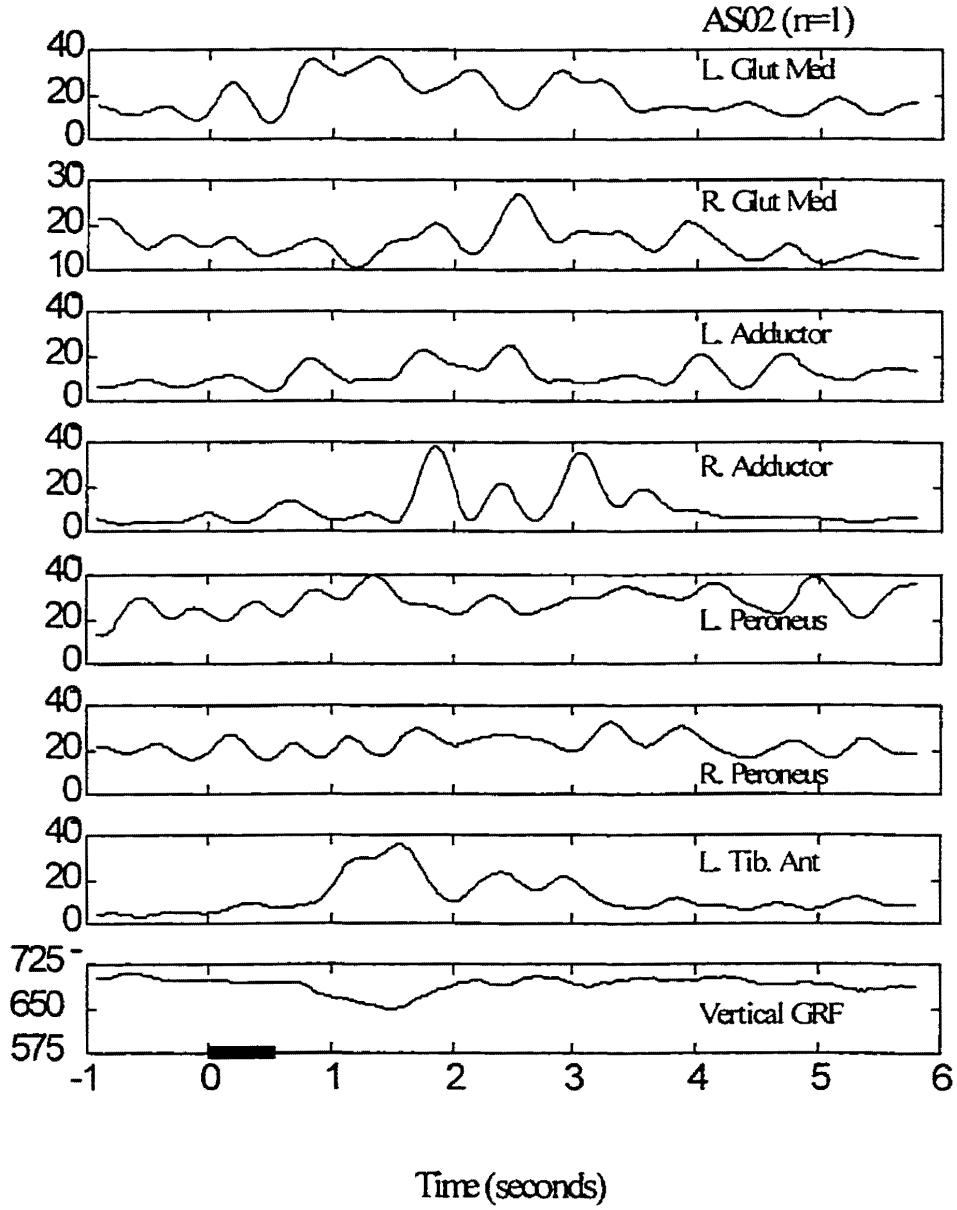
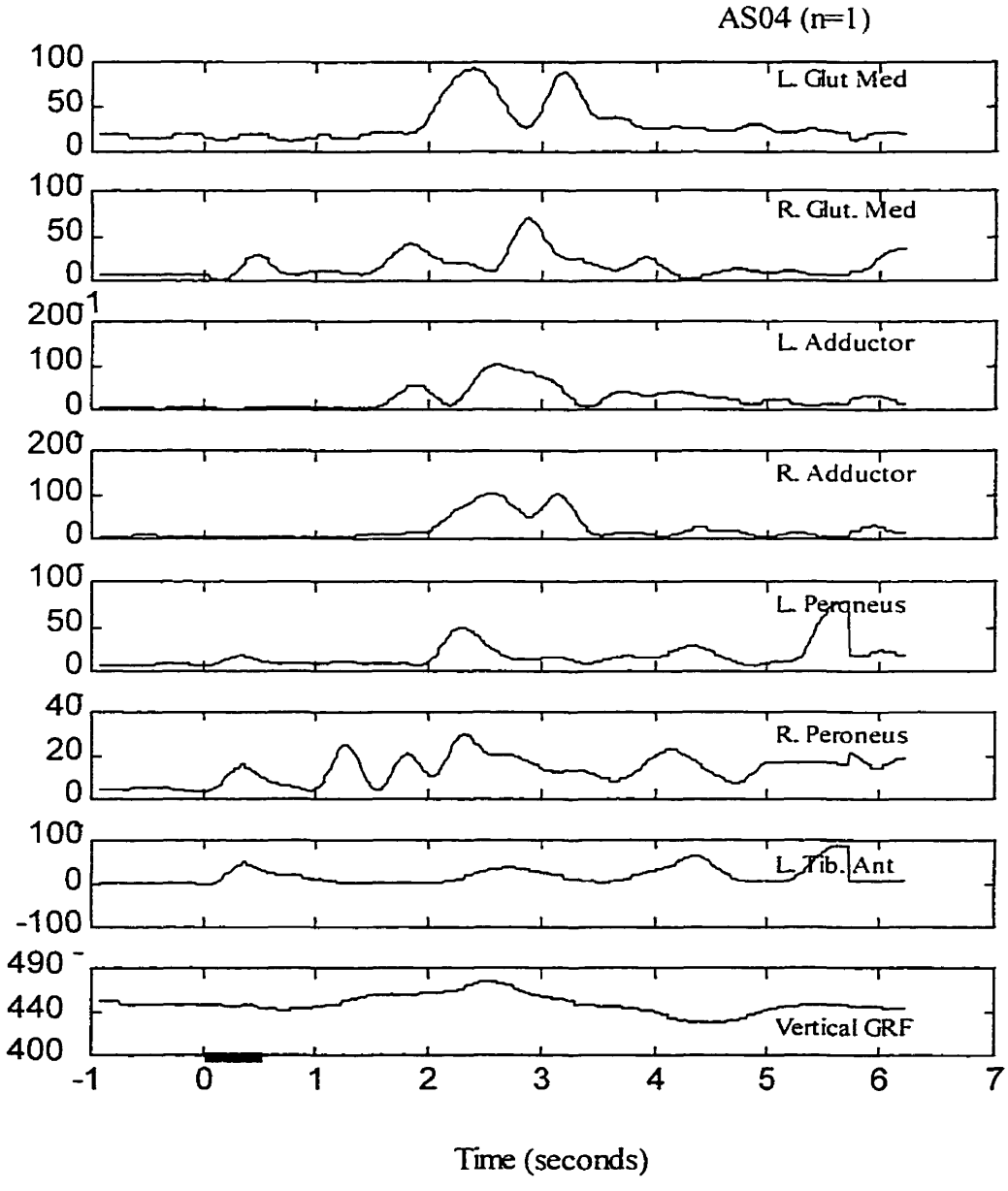


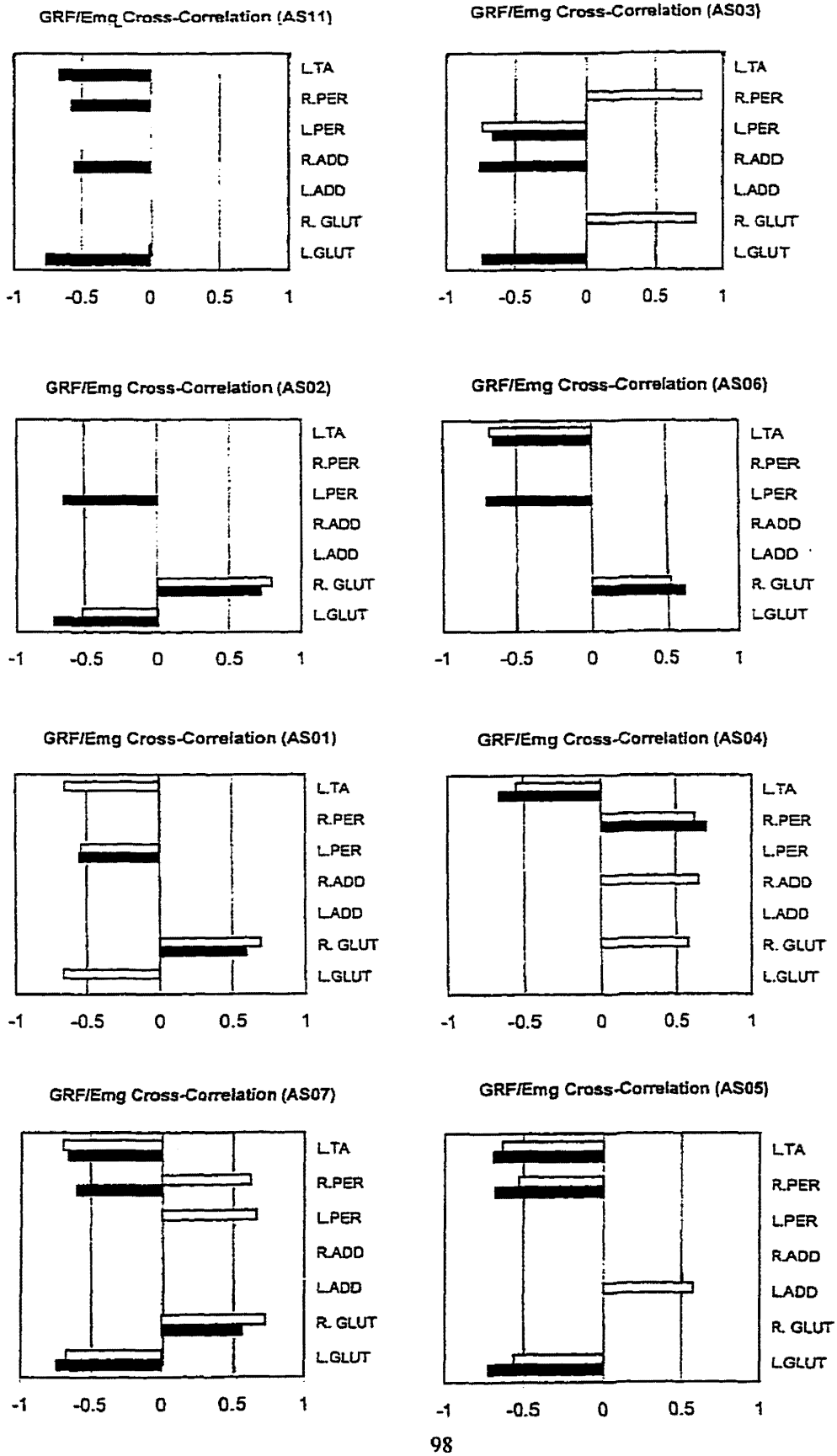
Figure 5.5 Combination Hip/Ankle EMG activation pattern in a movement to the right as a result of a short perturbation. Onset and duration of the perturbation is shown as a heavy solid line. Magnitude of the EMG is a percentage of the greatest level recorded for each muscle over all trials, per subject.



Cross-correlation analysis A cross-correlation analysis provides a measure of the contribution of a particular muscle activation pattern to the fluctuations in the GRF pattern. Certain muscles should activate to produce a movement towards the left or right regardless of the phase of the response.

The raw EMG patterns from each repeat trial were re-filtered (fourth order Butterworth lowpass with a cut-off frequency of 3 Hz) to produce a linear envelope of the original EMG signal. The bias was calculated from the pre-perturbation part of the linear envelope and subtracted. The resulting signal was cross-correlated with the vertical GRF from each individual trial. A correlation coefficient was considered significant if it had a greater magnitude than 0.50 and a functionally reasonable delay (the delay calculated with the coefficient had to be consistent with the EMG occurring prior to the GRF). The results for the long duration perturbation condition are graphed in Figure 5.6. The most common result across subjects showed a decrease in the GRF (signifying a movement to the left) associated with the increased activation of the left gluteus medius (negative correlation), and an increase in GRF (signifying a movement to the right) associated with the increased activation of the right gluteus medius. As well, the left tibialis anterior was associated with a movement to the left in the results of six of the eight subjects shown. Less consistency was shown with the activation patterns of the left and right peroneus muscles. Movement to the left was correlated with left peroneus activation in 4 subjects, and right peroneus activation in 2 subjects. In movements to the right, consistent responses in only 3 subjects showed right peroneus activation only. This confirms the analysis based on onset latency.

Figure 5.6 Cross-correlation values between GRF and linear envelope EMG muscle activation patterns (long duration perturbations).



Discussion

The results of the analysis of EMG data provide some insight into which muscles and muscle patterns are employed to maintain equilibrium in the medial/lateral plane. Two dominant muscle patterns emerged -- a hip dominant pattern and a hip/ankle combination pattern.

In the hip dominant activation pattern, the gluteus medius and adductor longus muscles combine in various ways to achieve the required net muscular moment about the joint which results in a shift in body weight (as a result of a rotation and lateral displacement of the pelvis). In shifts to the left, the left gluteus medius and/or the right adductor longus increase their activation levels. The right gluteus medius and left adductor magnus may also decrease their activation levels. This combination of excitation and inhibition achieve a net abduction on the left side and net adduction of the right side leading to the rotation and lateral displacement of the pelvis documented in previous chapters.

In a shift in weight to the right, the right gluteus medius and/or the left adductor longus increase activation while the left gluteus medius and right adductor longus may show some inhibition. As in movements to the left, this combination of excitation and inhibition would produce a net abductor moment about the right hip which would cause a rotation and displacement of the pelvis to the right.

The hip/ankle combination activation pattern that was observed in the responses of six subjects, is more complex. In this pattern, the above hip muscle patterns were observed with activation of the left and right peroneus longus and the left tibilias anterior muscles. The results of the cross-correlation analysis revealed that both the left tibilias anterior and left peroneus muscles were correlated with movements to the left with the excitation of the peroneus muscle occurring prior to the tibilias anterior. The main function of the peroneus muscle is eversion of the foot. During weight-bearing, this action would tend to pull the leg laterally with respect to the foot. The action of the

tibialis anterior is an antagonist to the peroneus longus -- its main function is the inversion of the foot or a medial displacement of the leg with respect to the foot during weight-bearing. In lateral movement, displacement can be achieved through the action about the pelvis and/or the ankle. In trials resulting in a shift in body weight to the left, the peroneus longus acts first to move the leg laterally. It is speculated that the tibialis anterior then acts to stabilise the leg. The activity of the right peroneus longus may also act as a stabiliser of the right leg to control whole body movement to the left. In trials resulting in a shift in body weight to the right, the right peroneus longus acted in a similar manner, presumably to move the right leg laterally. No consistent stabilising activity was observed in the left peroneus or left tibialis anterior muscles which would have lead to active medial movement of the left leg. However, inconsistency in the muscle activation patterns may also be due to the close proximity of the peroneus and tibialis anterior muscles and potential problems with cross-talk with the use of surface electrodes.

Chapter 6 Conclusions

The previous chapters have reported and discussed the results of the experiments in terms of the kinematics of the movement response, the predicted joint kinetics and the electromyography of selected postural muscles. Additionally, the effects of the independent variables (stimulus direction and duration, and vision) on the response movement were discussed. This chapter aims to summarize the conclusions regarding the effects of the given perturbation (galvanic vestibular stimulation) on recovery and maintenance of standing balance. The key results of these previous chapters will first be summarised. This will be followed by conclusions regarding the possible role of the vestibular system in maintenance of posture; mechanisms responsible for the movement response as described by the kinematic, kinetic, and EMG analyses; and the effects of vision and duration of the stimulus on the response. Lastly, the value of galvanic vestibular stimulation as an experimental tool will be discussed.

Response Movement

The following discussion will focus on the general 'whole-body' results of the movement as revealed by the GRF and CofP analyses.

The results of the GRF analysis have shown an increasing shift in vertical force (or weight) from the cathode side to the anode side of the body, corresponding to the direction of movement of the trunk and head segments. This suggests that the general response to the galvanic stimulus is an adjustment of the body's centre of mass towards the anode electrode.

A more detailed analysis of the GRF revealed a pattern of response consistent among all of the subjects. A stimulus of long duration resulted in a pattern consisting of four distinct phases: initial phase (mean latency of 250 ms) that showed a contralateral shift of weight; dominant phase (mean latency of 560 ms) that showed an ipsilateral shift in weight that correlated with the

observed lateral movement of the body; recovery phase (mean latency of 1455 ms) that showed a fluctuation in body weight: and cessation phase (mean latency of 810 ms after cessation of stimulus) that showed a return to pre-stimulus level of force on each forceplate. A stimulus of short duration consisted on three phases: initial response. secondary response. and cessation response.

The CofP patterns of response showed much less consistency than the kinematic and GRF analyses. However. five of eight subjects showed a similar pattern in which the left foot CofP moved to the left as the body moved to the right and moved to the right as the body moved to the left. This pattern of response may suggest an attempt to increase the base of support in order to optimize maintenance of balance. Alternatively. it may indicate an attempt to stabilize the ankles and therefore foot placement during a recovery of balance. It also suggests that the mechanism for the shift in weight from side to side exists higher up in the body. The following discussions provide a more detailed summary of the lateral movements. focussing on the mechanisms causing the observed sway.

Movement to the Left

A galvanic stimulus presented with the anode on the left side resulted in a lateral movement towards the left side of the subject. The kinematic analysis of both linear and angular displacement of the segments revealed that the movement occurred predominantly at the trunk and head. similar to that of an inverse pendulum (the trunk) rotating about the pelvis centre of mass. The kinetic analysis confirmed that the movement was caused by a combination of adductor and abductor moments at the hips. Specifically, at a mean latency of 250 ms. the left hip experienced a decreasing abduction (or increasing adduction) joint moment while the right hip experienced an increasing abduction moment. This was followed. at a latency of 500 ms. with increasing abduction at the left hip and decreasing abduction at the right hip. This latter

combination of moment activity corresponds to the dominant movement of the trunk and the second phase of the GRF. These results were confirmed with the EMG analysis which showed that, in general, the right gluteus medius (abductor) and left adductor longus were active during the early latency period (250 ms: initial GRF phase). The left gluteus medius and right adductor longus were active during the later latency period (500 ms: dominant GRF phase).

In the lower legs, the only significant movement occurred at the feet. The left foot showed some inversion and the right foot underwent a small eversion. Kinetic analysis revealed a decreasing eversion moment (or increasing inversion moment) at the left ankle at a mean latency of 250 ms, followed by an increasing eversion moment at the left ankle at a latency of 500 ms. No joint moment was estimated at the right ankle. EMG analysis revealed no consistent activity at the ankles, although some subjects showed an active left peroneus longus (everter) during the dominant phase of the response. These results are consistent with the results of the CofP analysis. If right ankle activity had been observed, it would suggest a combined and coordinated action of the ankles and hips to produce the required shift in posture. However, this lack of activity suggests that the hip abductors and adductors are responsible for movement of the upper body and that the ankle everters and inverters may be responsible for stabilization of the foot.

The head underwent angular rotation to the left at a mean latency of 340 ms. This rotation was independent of the rotation of the trunk about the pelvis. Kinetic analysis confirmed this by estimating a positive moment about the neck that corresponded to the observed movement.

Movement to the Right

A galvanic stimulus presented with the anode on the right side resulted in a lateral movement towards the right side of the subject. As with stimuli that resulted in movements to the left, the kinematic analysis of both linear and angular displacement of the segments revealed that the movement occurred

predominantly at the trunk and head, similar to that of an inverse pendulum (the trunk) rotating about the pelvis centre of mass. The kinetic analysis confirmed that the movement was caused by a combination of adductor and abductor moments at the hips. Specifically, at a mean latency of 250 ms, the right hip experienced a decreasing abduction (or increasing adduction) joint moment while the left hip experienced an increasing abduction moment. This was followed, at a latency of 500 ms, with increasing abduction at the right hip and decreasing abduction at the left hip. This latter combination of moment activity corresponds to the dominant movement of the trunk and the second phase of the GRF. These results were confirmed with the EMG analysis which showed that, in general, the left gluteus medius (abductor) and right adductor longus were active during the early latency period (250 ms: initial GRF phase). The right gluteus medius and left adductor longus were active during the later latency period (500 ms: dominant GRF phase).

In the lower legs, the right foot showed some inversion and the left foot was generally motionless. Kinetic analysis revealed a small increasing eversion moment (or decreasing inversion moment) at the left ankle during the initial phase followed by an decreasing eversion moment at the left ankle during the dominant phase (at a latency of 500 ms). There was no estimated joint moment at the right ankle. As in induced movements to the left, the EMG analysis revealed no consistent activity at the ankles.

The head underwent angular rotation to the right at a mean latency of 340 ms. As in the previously described movement to the left, this rotation was independent of the rotation of the trunk about the pelvis. Kinetic analysis confirmed this by estimating a negative moment about the neck that corresponded to the observed movement.

Effect of Independent Variables

Three independent variables were introduced as part of the study: presence or absence of vision; direction of stimulus current; and duration of

stimulus. Current direction was studied in order to ascertain bilateral symmetry of response. Short and long duration stimuli were included in order to study the differences between transient and tonic stimuli, as well as the effect of conflicting afferent information on balance recovery. Vision was studied in order to gain some insight into the relative importance of various afferent information.

Analysis of the kinematic data revealed no significant vision, stimulus direction, or stimulus duration effects on the magnitude of either the linear or angular displacement of the head, trunk, and pelvis segments. This is not a surprising result, given that previous research (Coats, 1973; Coats, 1972; Coats, 1972; Coats, 1973) has shown a linear relationship between current strength and magnitude of response. Since the current was maintained at a constant level throughout the study, it would be expected that the response magnitude would not vary significantly. Analysis of the effect of stimulus duration revealed that longer stimuli resulted in longer responses. Analysis revealed that vision had an effect on the duration of segmental displacement. The linear displacements of the head, trunk and pelvis segments were longer during the 'eyes open' condition. However, the angular displacement of the head was longer in the 'eyes closed' condition.

Role of the Vestibular System in Maintenance of Posture

Suggested roles for the vestibular system in the control of posture include the following:

- Initial trigger for postural response (Horak, et al., 1994).
- Possible contributor to the establishment of an internal representation of the orientation of the head and body in space (Hlavacka, et al., 1996; Mergner, et al., 1993).
- Responsible for re-weighting the importance of sensory information during conflict resolution (Nashner, et al., 1982; Allum, et al., 1994).

In general, the review of past literature reveals that there is a differential control of stability dependent upon postural requirements and the type of perturbation used to challenge the balance control system. Experimental techniques that use translating or rotating platforms reveal that proprioceptive and/or somatosensory afferent information may be more important in triggering postural responses. Techniques that use more direct methods of perturbing the head (Horak, et al., 1994) reveal that the vestibular system may trigger the postural response.

The results of the present study did not confirm the findings of Horak (Horak, et al., 1994) regarding the possibility of the vestibular system triggering postural response, but this may be due to methodological differences. Their study used a device that mechanically moved the head and resulted in some short latency soleus activity. No movement with a short enough onset latency to be considered reflex activity was observed in the present study and the EMG analysis did not reveal short latency muscle activity. However, the muscle activation levels involved in postural control are low and the short latency responses may only be detected by ensemble averaging multiple trials. This was not done in this study due to the low number of repeat trials per condition. Additionally, it is possible that the reflex activity observed by Horak was the result of activity generated by the cervical muscles and not via the vestibular system. This would confirm the results of a study by Inglis (Inglis, et al., 1995) which suggested that the vestibular system may not play a significant role in initial postural response. However, some studies, which used galvanic stimulation as the perturbation, have shown reflex activity in lower limb muscles. Fitzpatrick (R. Fitzpatrick and D.I. McCloskey, 1994) used a similar square-wave constant level stimulus current and observed transient reflex activity in the soleus muscle that was not correlated with the observed movement. This suggests that although the pathways for vestibular-initiated reflex activity exist, the result may not be significant for movement.

A study by Mergner (Mergner, et al., 1993) used rotation of various body segments to alter the perception of head and body orientation in space. Their findings confirm that the perception of body orientation in space is dependent upon inputs from the vestibular system, and neck and leg proprioception. Later, Hlavacka (Hlavacka, et al., 1996) used varying levels of galvanic stimulation and proprioceptive inputs (via vibration of the tibialis anterior) to study upright posture. They found an almost linear summation of vestibular and proprioceptive input on body displacement and CofP. They concluded that the maintenance of upright posture was under the continuous control of both vestibular and proprioceptive sensory information. While the present study does not claim to quantify the respective contribution of vestibular and proprioceptive inputs, the results tend to support the issue of contributions from both sensory systems. In the recovery phase, as shown in the GRF graphs, the vertical forces may undergo a number of fluctuations and show the beginning of recovery towards the initial baseline value, despite the constant input of the galvanic stimulus. If the response was under the sole control of the vestibular signal, no recovery would be observed and the vertical force would be maintained at a constant level until cessation of the perturbation. This suggests that there is some proprioceptive input into control of posture.

Inglis (Inglis, et al., 1995), in their study combining galvanic stimulation and platform translation, suggest that the vestibular afferent signals not only establish an internal representation of head and body orientation but also set the internal representation for body vertical that other sensory information is measured against. They observed that the final equilibrium position of the CofP and centre of mass shifted after cessation of the perturbations. However, their reported shift in equilibrium position during quiet stance (no translating platform) was very small and may be within measurement error. They found more significant shifts in equilibrium during platform translation, which suggests that a re-setting of the reference for vertical may be dependent on proprioception information as well. This is confirmed by the results of the

present study, which found no significant shift in the equilibrium position of segmental displacements (whole body centre of mass was not calculated).

The major conclusions of this study regarding the role of the vestibular system are:

- Given the type of perturbation and postural requirements, the vestibular system appears to trigger a postural response.
- The vestibular system acts to maintain the position of the head, independently from the postural requirements of the rest of the body.

Effects of Sensory Conflict on the Response Movement

Two findings of the study involve the effects of vision and stimulus duration on the various outcome measures of the response movement. The following discussion will summarise the results and attempt to explain them in the context of the research literature.

A statistical analysis was performed to study the effect of vision on the magnitude of the linear and angular displacement, onset latency, and duration of response. It revealed that the presence of vision did not decrease the magnitude of the displacement or response latency observed at the pelvis, trunk or head segments. One could conclude that the vestibular information was weighted greater than vision in the integration of sensory information. Conversely, any differences due to the presence of vision may be too small to be detected with the outcome measures used. Day (Day, et al., 1993) reported similar results in displacement magnitude but also found that the presence of vision decreased the velocity of movement. Additionally, the results of this study revealed that vision increased the duration of the response. This is a curious observation because one would expect that the increase in correct sensory information (or decrease in conflicting sensory information) would override the influence of the vestibular information. However, this would only be correct if the assumption, which was based on the results of earlier studies,

that the stimulus effects only the afferent pathways of the otoliths and not those of the vestibular canals, is correct. The sensory organs of the canals sense angular acceleration and have a direct influence on the vestibulo-ocular reflex (VOR) which stabilises the eye against changes in head position. If the afferent pathways of the vestibular canals are stimulated, the eyes will experience some vestibular nystagmus activity that normally indicates movement of the field of view (Kelly, 1985). In the eyes-open condition, although the VOR is incorrect, it is in agreement with the vestibular signal and may result in overriding the correct sensory information received from the proprioception and somatosensory systems.

Other results of the analyses show that there is a difference between the short (500ms) and long (3 sec) perturbations on the segmental kinematics. Longer perturbations caused a longer response, as measured by the linear and angular displacement of the head, trunk and pelvis segments, but had no effect on the displacement magnitudes. This suggests that the final displacement position is dependent upon the magnitude of the stimulus current, a conclusion supported by previous research (Coats, 1972), which showed a positive linear relationship between body sway and stimulus current level. This also suggests that the perception of body orientation is created early, possibly in the initial phase of the response. Both long and short perturbations have a dominant response phase and the peak displacement is reached then. There is no recovery phase in short duration perturbations as the stimulus has ceased.

Based on the previous conclusions concerning the effects of galvanic vestibular stimulation on the response movement and the resolution of conflicting sensory information, a number of conclusions can be made regarding the overall role of the vestibular system in maintenance of posture.

Given the type of perturbation and the postural requirements of the study, afferent information from the vestibular system appears to be weighted more highly than the information from the proprioceptive and somatosensory

systems, at least initially within the first and second phases of response. However, due to the small movements involved, the sensory threshold for those systems may not have been met until the end of the second phase. No conclusions can be made regarding its relative importance with respect to the vision system because of the apparent stimulation of the vestibular canals – it was not possible to isolate the effect of vision as originally intended.

Mechanisms of Postural Response

Attempts to describe the response mechanisms to postural perturbations have varied from studies using a more global 'whole body' systems control viewpoint concentrating on feedback and/or anticipatory afferent inputs (Fitzpatrick, et al., 1996; Johansson and Magnusson, 1991; R. Johansson and M. Magnusson, 1991; Johansson, et al., 1995) to studies that described the response mechanisms through kinematic and/or EMG analyses of body segments. The strength of this study lies in the use of biomechanical techniques to investigate the control of balance. The response movement to a supplied perturbation was studied using kinematic, kinetic and EMG analyses. The kinematic analysis showed that the dominant response involved the rotation of the trunk about the pelvis. Use of an inverse dynamics model to estimate joint moments provided insight into the mechanisms of the response, with results showing that moments generated at the hips were responsible for the observed movement of the trunk about the pelvis. The EMG analysis of selected hip and ankle musculature provided independent confirmation of this mechanism.

The results of previous studies focussed on descriptions of 'hip', 'ankle', and 'mixed' strategies (Nashner, et al., 1988, Shupert, et al., 1988) that were used in controlling movement in the anterior/posterior directions. Research by Keshner (Keshner, et al., 1988) and Runge (Runge, et al., 1998) concluded that there is a differential control of stability dependent upon postural requirements and type of perturbation. A perturbation that initially causes movement of the

lower leg about the ankle (as in a platform translating in the anterior/posterior direction) will elicit functional stretch reflexes. More ankle activity will be observed (Nashner, 1977; L.M. Nashner, 1979) because the plantarflexors and dorsiflexors are physiologically strong enough to generate enough force to move the centre of mass of the body to a more stable position. In cases where the surface is either shortened or compliant, or a narrower or tandem stance is used, the ankle musculature is less effective in producing a large enough ankle moment and the hip musculature is involved ('hip strategy'). A 'mixed strategy' may occur with differing combinations of perturbation and postural requirements.

In perturbations resulting in movement in the medial/lateral direction, the involvement of the ankle musculature depends upon stance width. Because of the structure of the lower body, there is a mechanical coupling between the ankles and hips in the frontal plane, the strength of which increases with stance width (Day, et al., 1993. Therefore, in cases where the stance is narrow, the ankle musculature is not able to generate enough force to move the body centre of mass to a more stable position. In contrast, the hip musculature is in a pre-stretched situation due to the increased abduction involved in a narrow stance position and can generate the necessary force (Day, et al., 1997). As in movements in the anterior/posterior direction, the type of response will depend on a number of factors. In the present study, the perturbation did not elicit stretch reflexes and further, the close stance adopted by the subjects as part of the experimental protocol precluded much ankle involvement. By necessity, hip activity was required to control balance.

A number of previous studies suggest that vestibular galvanic stimulation effects the vestibulo-collico reflexes, which act to stabilize head position (Keshner, et al., 1988; Noda, et al., 1993). In this study, the head underwent additional lateral rotation with respect to the trunk. Although this rotation was initiated prior to movement of the trunk and pelvis, the onset latency is much later than one would expect for a reflex response. It seems likely that this

movement is part of the body's recovery mechanism in response to the (fictitious) information from the stimulus regarding head orientation. This suggests that the role of the vestibular system is to stabilize both the head and the body in space. This differs from the conclusions of Day et al (Day, et al., 1997) who observed no additional head tilt and concluded that the role of the vestibular system was to maintain the position of only the body in space. The difference may be due to the larger number of markers used in the present study, leading to a more complete mathematical model of the body.

Use of Galvanic Stimulation as an Experimental Tool

Galvanic stimulation cause a wave of depolarization along the vestibular nerve, that, regarded on the level of the individual axon, may be similar to the discharge caused by movement of the hair cell in the peripheral vestibular organs (Goldberg, et al., 1990; Goldberg, et al., 1990). However, based on the knowledge of the physiology of the utricles and saccules (Kelly, 1985), it is highly unlikely that galvanic stimulation causes natural discharge patterns. It presents a novel perturbation to which the body responds.

What is the nature of the resulting signal on the vestibular nerve? Many studies have reported EMG onset of the soleus muscles at short latencies of 50 to 100 ms (Fitzpatrick, et al., 1994, Britton, et al.,1992). This resulting EMG is of short duration (Fitzpatrick, et al., 1994) and is not correlated with the large body displacement typically reported with this type of perturbation. This leads to two theories of the nature of galvanic stimulation. The first suggests that the stimulus comprises both a transient and tonic effect. The transient effect is a consequence of the initial change in discharge along the vestibular nerve from the square-wave form of the stimulus, and may result in reflex activity (via the vestibulo-spinal tract) observed in lower limbs. The tonic effect of the stimulus is observed much later, and effects more central processes, specifically reflecting the orientation of the head and body in space (Hlavacka, et al., 1996; Inglis, et al., 1995). This lead to the second theory that the tonic aspect of the

stimulus creates an illusion of movement and that the observed body sway is the body's reaction to the perception of movement (Fitzpatrick and McCloskey, 1994) in an attempt to re-orient or regain upright stance.

One of the main reasons for using galvanic stimulation as the perturbation measure in this study was the apparent ability to separate the influences of the vestibular, visual and some of the proprioceptive influences on postural control. A perturbation could be applied without initially evoking functional stretch reflexes in the legs, and the effects of vision could be controlled by closing the eyes. Based on previous research, low level stimuli would not evoke a VOR. However, results of this study suggest that a VOR was probably involved, despite the low level of stimulus.

Therefore, the future use of vestibular galvanic stimulation in the study of the vestibular system may be limited. The type of current level used in the perturbation will determine the type of response observed. A constant level stimulus will emphasise the tonic aspects (possibly the perception of head and body orientation), while a randomly varying current level will evoke reflex activity. It is important to note that both present a novel signal on the vestibular nerve. This type of perturbation may be more useful in studying the mechanisms that a body uses to restore posture after a perturbation.

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Appendix A

Information and Consent Form

INFORMATION AND CONSENT FORM

Department of Kinesiology
University of Waterloo

Study Title: A Model of Vestibular Control of Human Stance and Walking Gait

Conducted by: D.A. Winter
S.E. Walt

Parts of the vestibular system of the human body, located in the inner ear, sense linear acceleration of the body at the head. It is believed that when the body's balance is disturbed as during a push or trip, that the vestibular system senses the resulting acceleration and, in combination with other information from the body, determines appropriate courses of action to recover from the disturbance.

The purpose of this study is to investigate the effect of the vestibular system in the control of balance during quiet standing and walking. The mechanism used to disturb the balance of the body is called galvanic-electrical stimulation. With this method a very low current runs across two electrodes placed on the surface of the skin behind the ears. Before the formal testing begins, several trials of preliminary stimulation will be done while you are sitting so that you will be familiar with the sensation produced by the electrical stimulation. The stimulation intensity will be no greater than 1 mA of current and will last no longer than 1 second. You may feel some disorientation as if your head was undergoing a movement. There is a small chance that you may experience some nausea. If that is the case, the experiment will go no further. Any effects from the stimulation are transient and will disappear when the stimulation ceases.

The formal testing protocol requires that you stand quietly for a number of trials. Reflective markers will be placed on the body during video-taping of the experiment. As well, electrodes will be placed on various muscles on the legs and trunk to record their activity levels during testing. You may experience a loss of balance during the testing. Spotters will be placed to ensure that you do not fall. Formal testing will also include a few trials of normal walking both with and without electrical stimulation. You may experience a loss of balance. Again, spotters will ensure that you do not fall.

After the data has been collected a full biomechanical analyses will be done to enable the researcher to determine how your body responded to the electrical stimulation which caused the imbalance. It is hoped that this information will allow the researchers to speculate on the possible effects of the vestibular system on the control of balance during quiet standing and walking.

This project has been reviewed and received ethics clearance through the Office of Human Research at the University of Waterloo. If you have any questions or concerns about your participation in this project, please contact the Office at 885-1211 Ext. 6005.

Consent of Subject

I have read and understood the information presented above about the procedures and risks involved in this study and have received satisfactory answers to my questions related to this study. The specific details of this study have been explained. I understand that my identity will be protected throughout my participation in this study. I am aware that I may withdraw from the study at any time. With full knowledge of all foregoing I agree, of my own free will, to participate as a subject in this study.

Print Name	Signature of Subject
Dated at Waterloo, Ontario	Witnessed