Postural Sway and Motor Control in Trans-Tibial Amputees as Assessed by Electroencephalography during Eight Balance Training Tasks

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
Literature Search F
Funds Collection G

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Background: The purpose of this study was to investigate the changes in the Power Spectral Density (PSD) of the electroencephalogram (EEG) during 8 common sensorimotor balance training tasks of varying difficulty in single-limb trans-tibial amputees.

Material/Methods: Eight sensorimotor balance exercises, including alteration in vision, base of support, and surface compliance, were used to test postural control and how it related to the electroencephalogram (EEG). A control group was compared to a group of people with trans-tibial amputation of 1 leg to see how the brain responds to loss of a single limb during progressively harder balance testing. Postural sway and EEG changes of the alpha, beta, and sigma wave bands were measured in 20 participants (10 controls, 10 amputees) during 8 balance tasks of varying difficulty with eyes open and closed, feet in tandem or apart, and on a foam or a firm surface.

Results: The power of alpha, beta, and sigma bands increased significantly in most tests when comparing the amputees to the control subjects. Balance was significantly worse in the amputees even when standing on both legs. In amputees, balance required more cortical activity than in the controls.

Conclusions: This study demonstrated that amputees have considerably more difficulty in motor control for the brain during balance tasks. Balance was impaired even when standing feet apart on 2 legs and EEG showed more spectral power in all areas of the brain in the amputees.

MeSH Keywords: Amputation • Neurofeedback • Postural Balance

Abbreviations: **C3** – left cortical electrode position; **C4** – right side cortical electrode position; **CV** – coefficient of variation; **CZ** – cortical center electrode position; **EEG** – electroencephalogram; **ERP** – event-related potential; **F3** – frontal lobe left side electrode position; **F4** – frontal lobe right side electrode position; **FAEO** – feet apart eyes open; **FIRM** – firm standing platform; **fMRI** – functional magnetic resonance position; **FNIRS** – function near-infrared spectroscopy; **FOAM** – foam flexible balance platform; **MRCP** – movement-related cortical potentials; **P3** – parietal lobe left electrode position; **P4** – parietal lobe right electrode position; **PET** – positron emission tomography; **POZ** – parietal lobe center electrode position; **PSD** – power spectral density; **TEC** – tandem eyes closed; **TEO** – tandem eyes closed; **TEO** – tandem eyes open

Full-text PDF: http://www.medscimonit.com/abstract/index/idArt/891361

Background

Amputations of the lower limb are common due to war-related injuries, accidents, and disease [1]. Diabetes is the most common cause of lower limb amputation but usually involves amputation of the foot and not the whole lower leg below the knee (trans-tibial) [2]. Vascular disease is another cause of trans-tibial amputations [3]. Mortality rates are as high as 40% 1 year after surgery and the survivors have numerous associated problems [3]. It is generally known that balance is poorer in people with lower leg amputations, and balance impairment and gait impairments have been extensively studied in trans-tibial amputations [4,5].

Maintaining an upright posture (balance) is a complex motor skill based on the integration of the visual, sensory, and vestibular systems [6]. The central nervous system plays an integral role in integrating the afferent information from these systems [7,8]. It was assumed that postural regulation is under the control of subcortical structures of the cerebrum and reflexes in the spinal cord [9]. The cerebellum and prefrontal cortex have been shown to be significantly involved in postural control [10]. The prefrontal cortex was shown to be activated after an external balance challenge [11]. Numerous investigators have shown cortical involvement in various balance tasks [12–14]. Goble et al. demonstrated central processing of proprioceptive signals from the foot during balance control [15]. With amputations, even with a prosthetic appliance, the sensory receptors in the lost limb and joints reduce feedback to the brain for decision making during balance and gait. Furthermore, spinal reflexes are impaired, theoretically shifting more control to the brain [16]. For example, in trans-tibial amputees on 1 limb, the EMG activation patterns are different and delayed on the amputated limb [16]. With muscles amputated in the lower leg, reorganization of the plantar flexors takes place, since 80% of the power during gait is through the plantar flexors [17]. This loss results in reorganization of the motor centers in the brain and spinal cord to shift, on the effected leg, to hip flexors as the mode of forward propulsion during gait [18].

While there is some central and spinal adaptation when a limb is amputated, the lack of sensory input from the missing limb segment does not allow for normal reflex and motor control to take place from the brain [19,20].

Most of the studies that investigated the neural response associated with balance training used electrophysiological and imaging techniques. Positron emission tomography (PET), a nuclear medicine imaging technique used to study the functioning of the brain by detecting the signal from a delivered radioactive material in the body, has been used to study the brain activation during maintenance of standing postures [10].

Functional near-infrared spectroscopy (fNIRS), a non-invasive and affordable neuroimaging technique used to monitor the blood hemoglobin concentrations and tissue oxygenation associated with neural activity by measuring the changes in near-infrared light in the brain, has been used to study the role of prefrontal cortex in balance control [11]. Functional magnetic resonance imaging (fMRI), a neuroimaging technique used to detect the changes in blood flow and oxygenation in response to neural activity, has been selected to investigate cortical involvement in shaping postural responses [12]. While these imaging techniques have excellent spatial resolution and provide excellent access to subcortical areas, they only measure the cerebral blood flow or metabolic activity during the performance of the tasks. Electroencephalogram (EEG) is the only electrophysiological recording technique that provides a more accurate temporal resolution of the brain activity in a millisecond time frame. EEG is traditionally used in the evaluation of neurological conditions, but it has often been used to quantify cortical response in relation to event-related changes.

Previous studies have investigated the EEG changes associated with postural control examining the activity in response from perturbation to postural stability [21–23]. Some studies have examined the movement-related cortical potentials (MRCP) preceding the onset of postural adjustment [24,25]. MRCP, a type of ERP (event-related potential) with low-frequency negative potential, is recorded in the motor cortex preceding voluntary movement [24]. It was interpreted as a reflection of the cortical processes in planning and preparation of voluntary movement [26].

Power spectral density (PSD) analysis is a common type of EEG analysis, reflecting the distribution of signal power over frequency. It has been used widely to assess changes in cortical activity during cognitive and motor tasks [27–29]. A recent study has shown that EEG power increases with increasing complexity of balance tasks. Further, in people with diabetes, EEG activity was higher than in age-matched controls with increasing balance tasks. The same may be true in people with a single trans-tibial amputation. In diabetes, there is also a loss in peripheral sensory feedback [30–32], which alters balance and gait patterns in people with diabetes. The question that arises is, when standing on 2 legs, does it take increased cortical activity for balance in a single-limb trans-tibial amputee? Is balance and EEG different than controls during balance tasks? For controls, when balance becomes more difficult, motor control is shifted to spinal reflexes with less cortical control. Does this happen in amputees or is there so much sensory loss that it cannot occur [13]. To answer these questions, a standard balance test involving 8 different tests was performed on single-limb trans-tibial amputees compared to controls.

Table 1. General characteristics of subjects.

	Age	Height	Weight	BMI
Controls	25.5±3.24	170.7±10.9	68.7±11.1	23.34±11.2
Prosthetics	42.7±13.1	171.3±12.2	71.3±22.3	25.3±4.1

Material and Methods

Overall design

This study was a 2×2×2 repeated-measures design with 3 independent variables. There were 2 levels for each repeated factor: vision (eyes open or closed), surface compliance (foam or firm surface), and base of support (feet apart or tandem stand). Each participant was exposed to 8 test conditions with 4 tasks on the firm surface and 4 tasks on foam. All participants were first tested in the control task, FAEO-FIRM, by standing with feet apart, eyes open on the firm balance platform. To control the order effects, each participant was then randomized to the 3 remaining balance tasks on the firm surface and then randomized to the 4 balance tasks on the foam. The tests were feet apart eyes open, feet apart eyes closed, feet tandem eyes open, and feet tandem eyes closed. They were done on the platform (firm support) and on the foam. We recorded the postural sway and the PSD of the alpha, beta, and sigma wavebands at the EEG electrode sites Fz, F3, F4, Cz, C3, C4 and electrode positions POz, P3, and P4 during the 8 balance tasks. The response of each variable in each task was compared to that in the control task for each participant to generate the relative response. The average relative response of each variable from the 3 trials of each task of all the participants was then used for statistical analysis.

Subjects

Twenty young healthy volunteers were recruited from the Inland Empire area in Southern California. To ensure the external validity of the study, equal numbers (n=10) of males and females were recruited. The participants were free of headaches, diabetes mellitus, and orthopedic or neurological conditions. To control the extraneous variables, a homogeneous group of sedentary individuals who did not participate in any regular balance exercises was recruited. Participants were instructed not to take any medication or central nervous stimulants that might affect their balance the day before the study. The general characteristics of the participants are shown in Table 1. The experimental protocol, approved by the Institutional Review Board of Loma Linda University, was explained to each participant and they gave their written informed consent for the study.
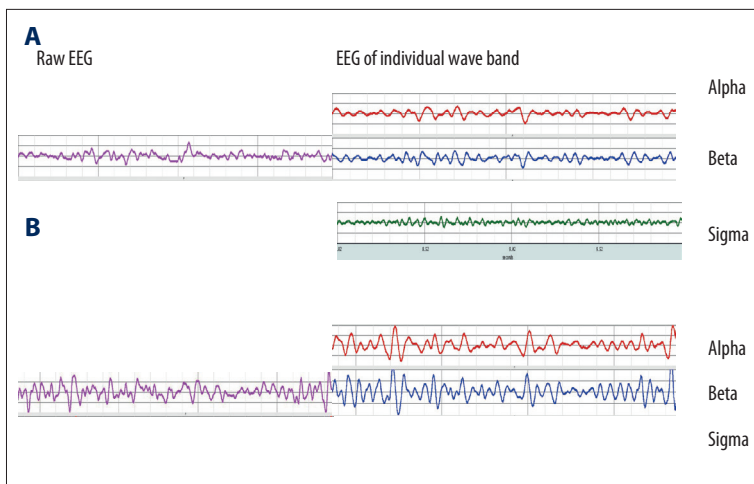
Balance tasks

Eight quiet standing balance tasks each lasting for 6 seconds were included in this study [33]. Sensory variables such as the vision, base of support, and surface compliance were altered individually or simultaneously in the balance tasks. To alter the visual input, 2 levels of vision (eyes open & closed) were used in the balance tasks. To alter the somatosensory input, 2 different surface compliances (firm surface & foam) were used. For foam, an Aeromat balance block, a PVC/NBR foam with size 16×19×2.5 inches and density of 0.04–0.06 g/cm^3 (AGM Group, Aeromat Fitness Product, Fremont, CA), was placed on top of the balance platform. Participants were asked to stand in 2 different stance positions with feet apart (centers of the calcaneus in the same distance as the 2 anterior superior iliac spine) or in tandem (feet in a heel-toe position with non-dominant foot in front).

In a previous study, Tse et al. categorized the difficulty of the 8 balance tasks based on the postural sway and reported that task difficulty was affected by the number of sensory variables altered [33]. Participants were randomized to the balance tasks. Details of randomization were explained in the overall design.

Measurement of postural sway

The displacement of the subject's center of pressure was measured using a valid and reliable balance platform of 1 m by 1 m in size and 0.1 m in height [34]. Four stainless steel bars, each with 4 strain gauges, were mounted at the 4 corners under the platform (TML Strain Gauge FLA-6, 350-17, Tokyo, Japan). The output of the 4 Wheatstone strain bridges made of 4 strain gages each was amplified with BioPac 100C low-level bio-potential amplifiers and recorded on a BioPac MP-150 system through a 24-bit A/D converter (Figure 1). The sampling rate was 2000 samples per second [34].

To calculate the load and the center of the pressure of the force on the platform, the output of the 4 sensors was used to measure the X and Y coordinates of the center of gravity of the subject. This data was converted to a movement vector giving magnitude and angular displacement. By averaging the vector magnitude over 6 seconds, mean and standard deviation (SD) were obtained for this measure. From this, the

Figure 1. EEG activity in a control subject at POz during the least difficult task, FAEO-FIRM (**A**) and the most difficult balance task, TEC-FOAM (**B**). Raw EEG is shown on the left side of the Figure and EEG of individual wave bands (alpha, beta and sigma bands) are shown on the right side of the Figure.
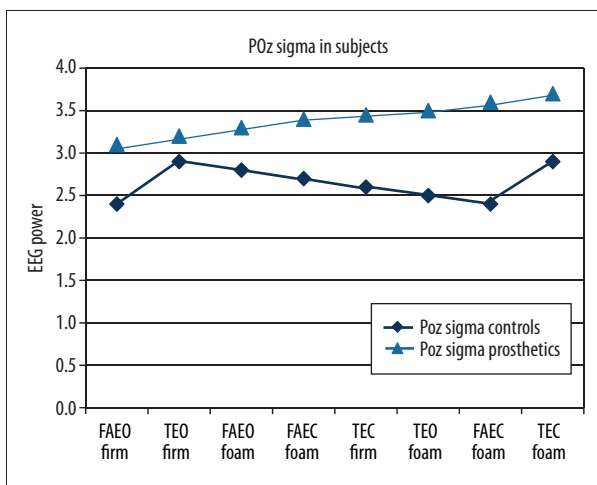
Figure 2. The EEG power in the sigma frequency range from the POZ (parietal) sampling area comparing the average data in 10 controls (diamonds) to 10 trans-tibial patients (triangles) for 8 balance testing positions.
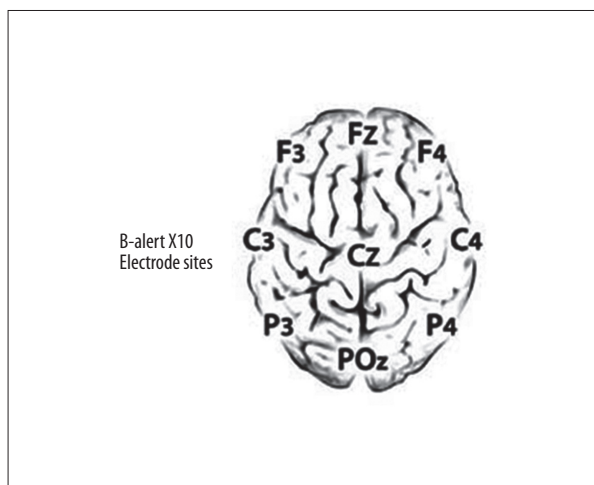

Figure 3. EEG electrode positions.

coefficient of variation (CV) was calculated (SD ÷ Mean ×100%) as a measure of the postural sway [34].

Measurement of cortical response

A 10-20 system, B-Alert X10 wireless EEG 9 channels headset (Advanced Brain Monitoring Inc., Carlsbad, CA, USA), integrated with the AcqKnowledge MP-150 acquisition software (BioPac systems, Inc., Goleta, CA) was used to acquire the EEG data from 9 channels in a monopolar configuration referenced to the linked mastoids (Figure 2). Data from 9 channels (sites Fz, F3, F4, Cz, C3, C4, POz, P3, and P4) were used for analysis (Figure 3). The impedance of each electrode was kept below 40 kΩ. Bandpass filters 0.1 Hz and 65 Hz at 3 dB attenuation were used to remove environmental artifacts. The data were sampled at a frequency of 256 samples per second and analyzed using signal processing techniques to identify and

decontaminate biological and environmental artifacts, including eye blinks, EMG, excursions, saturations, and spikes [35]. Details of the artifact decontamination process were described in a previous study [28].

All uncontaminated EEG data for each task were epoched into 1-second blocks with the B-Alert Software version 2.90 (Advanced Brain Monitoring Inc., Carlsbad, CA, USA). The power spectral densities (PSD) of alpha (8–12 Hz), beta (13–19 Hz), and sigma (30–40 Hz) frequency bands were computed for each task in each electrode site using a Fast-Fourier transform with a 50% overlapping window (see Figure 3 for sites). Three of the 1-second overlays were used to obtain the average PSD for an epoch. The PSD of a specific frequency band in each of the balance tasks was then divided by the PSD of the corresponding frequency band in the control task at the same electrode site for each participant. This provides the percentage of the PSD of each frequency band relative to the control task in each individual task at a specific electrode site (Figure 4). The average relative PSD was then computed using the 3 relative
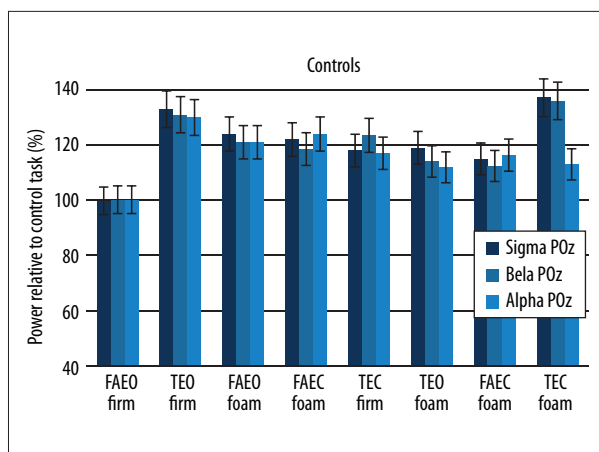
Figure 4. EEG activity in the 10 control subjects at POz during the 8 tasks by increasing order of difficulty.
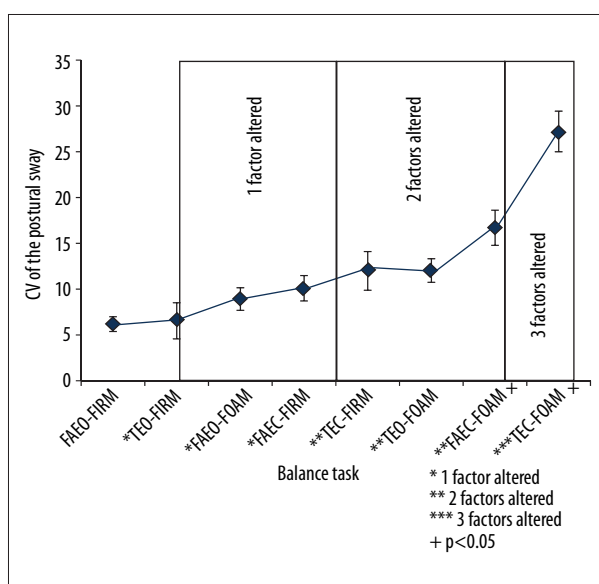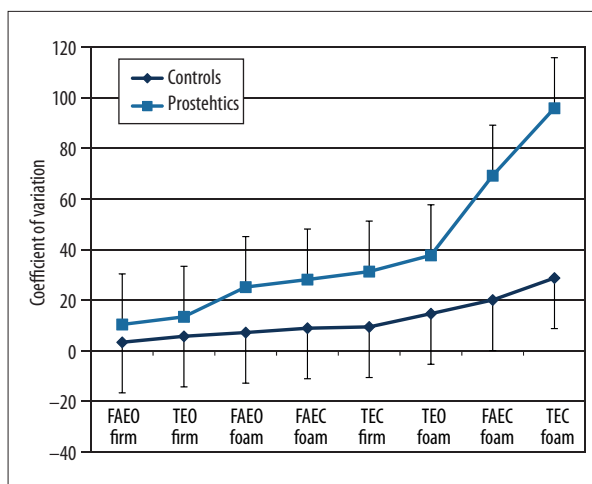

Figure 5. Mean ±SEM of postural sway (Coefficient of Variation of the postural sway) in 8 balance tasks on a typical subject with 3 repetitions.

PSD from the 3 trials. The same process was done on all the wave bands at all the electrode sites in the 7 balance tasks for each participant. All the average relative PSDs calculated were then analyzed using SPSS.

Experimental procedures

Baseline demographic data including age, height, weight, and side of dominance were collected from each subject at the beginning of the study. The B-Alert X10 wireless EEG 9 channels headset was placed on the skull. Bilateral mastoids were linked as reference. Electrode impedance was then checked. All the participants started with the control task, in which they stood with feet apart on the balance platform for 6 seconds. Their

Figure 6. Mean ±SEM of postural sway (Coefficient of Variation of the postural sway) in 8 balance tasks in all control subjects (diamonds) compared to prosthetics subjects (squares). For all 8 tests, balance was significantly worse in the prosthetics subjects (p<0.01) ANOVA.

feet were aligned with the centers of the calcaneus the same distance as that of the 2 anterior superior iliac spines. They were instructed to fix their eyes on a target on the wall 10 feet away from the balance platform with arms crossed in front of their chests to minimize the artifacts generated by any eye movement or excessive trunk and arm movements. To minimize fatigue, participants were instructed to hold onto a chair to rest standing for 10 seconds between the tasks. Thereafter, the subject was randomized to the rest of the balance tasks on the firm surface. Then an Aeromat balance block was placed on top of the balance platform and data were collected during the randomized balance tasks on the foam.

Data analysis

Statistical analysis was performed using SPSS for Windows version 20.0 [36]. The significance level was set at 0.05.

Results

Balance

A typical balance record on a single subject in the control group is shown in Figure 5. This figure shows the increased complexity of balance tasks, going from standing on a solid platform with eyes open and feet apart to the most complex task, standing on foam, tandem feet eyes closed. The increased challenge starts with 1 factor altered (e.g., going to foam or closing eyes), to 2 factors altered (e.g., tandem standing on foam), to 3 factors altered (e.g., eyes closed on foam). Using this progression as a means of examining all of the data, the

Table 2. Comparison of the prosthetic and control groups for all EEG analysis in all areas of the brain under 8 different balance tests.

|	Feet apart eyes open	Tandem eyes open	Foam feet eyes open	Feet apart eyes closed	Tandem eyes open	Foam tandem eyes open	Foam feet apart eyes closed	Foam tandem eyes closed
POz alpha		0.05	0.05	0.05	0.05	0.05	0.05	0.05
POz beta	0.05	0.05	0.01	0.05	0.05	0.01	0.01	0.01
POz sigma	0.05	0.01	0.01	0.05	0.01	0.01	0.01	0.01
FZ alpha		0.05	0.05		0.05	0.05	0.05	
FZ beta		0.01	0.01		0.01	0.05	0.05	0.01
FZ sigma		0.05	0.05		0.05	0.05	0.05	0.05
Cz alpha		0.01	0.05		0.01	0.05	0.05	0.05
Cz beta		0.05	0.05		0.05	0.05	0.05	0.05
Cz sigma	0.01	0.01	0.01		0.01	0.05	0.05	0.01
C3 alpha		0.05	0.05		0.05	0.05	0.05	0.05
C3 beta	0.05	0.01	0.01		0.01	0.05	0.05	0.01
C3 sigma	0.05	0.05	0.01		0.05	0.05	0.05	0.01
C4 alpha	0.05	0.05	0.05		0.05	0.05	0.05	0.05
C4 beta		0.01	0.01		0.01	0.05	0.05	0.01
C4 sigma			0.01			0.05	0.05	0.01
F3 alpha		0.05			0.05	0.05	0.05	
F3 beta	0.05	0.05	0.05	0.05	0.05		0.05	0.05
F3 sigma			0.01		0.05		0.05	0.05
F4 alpha		0.01	0.05		0.01			0.01
F4 beta		0.01	0.01		0.01	0.05	0.05	0.01
F4 sigma		0.01	0.01		0.01	0.05	0.05	0.01
P3 alpha			0.05			0.05	0.05	0.05
P3 beta			0.05			0.05	0.05	0.01
P3 sigma		0.05	0.01		0.05	0.05	0.05	0.01
P4 alpha		0.01	0.05		0.01	0.05	0.05	
P4 beta			0.01			0.05	0.05	0.01
P4 sigma		0.05	0.01		0.05	0.05	0.05	0.01

group data on the controls and prosthetic users are shown in the rest of the analysis.

As shown for the group data in Figure 6, the sway was much worse in the prosthetic users compared to the controls. For the most difficult task, the sway was 4 times greater. The sway, comparing the controls to the prosthetic users was not statistically different comparing FAEO firm and TEO firm (p>0.05), but the next 4 tests were significantly different comparing the 2 groups (p<0.05) and for the 2 hardest balance tests (p<0.01).

EEG

Typical EEG traces are shown in Figure 1. As shown in this figure, the raw EEG on a typical control subject is shown and the processed EEG broken into the 3 frequency bands of interest
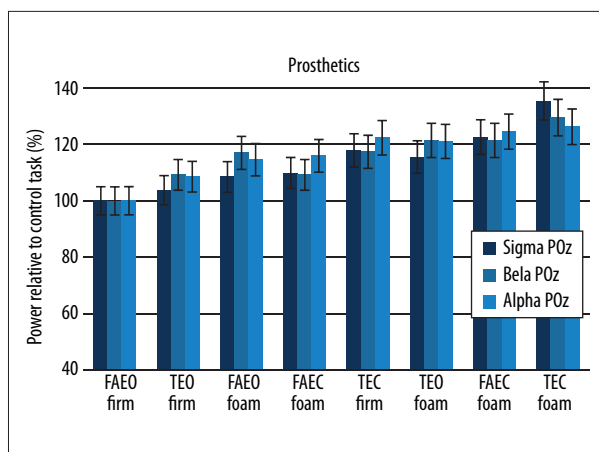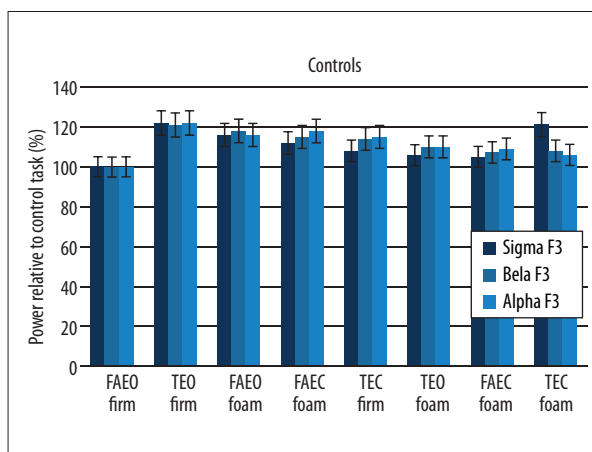
Figure 7. EEG activity in the 10 prosthetic subjects at POz during the 8 tasks by increasing order of difficulty.
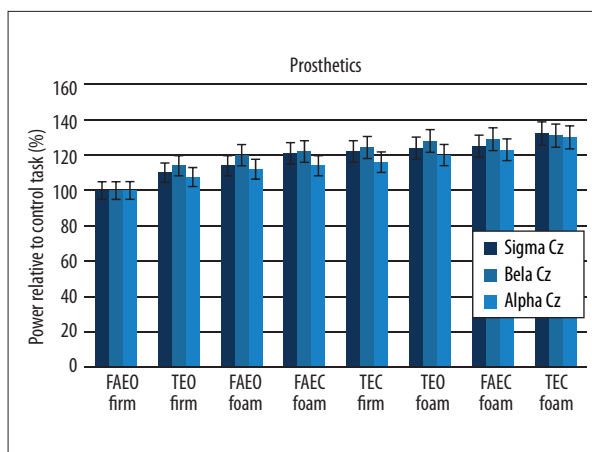
Figure 9. EEG activity in the 10 prosthetic subjects at the center of the cortex during the 8 tasks by increasing order of difficulty.
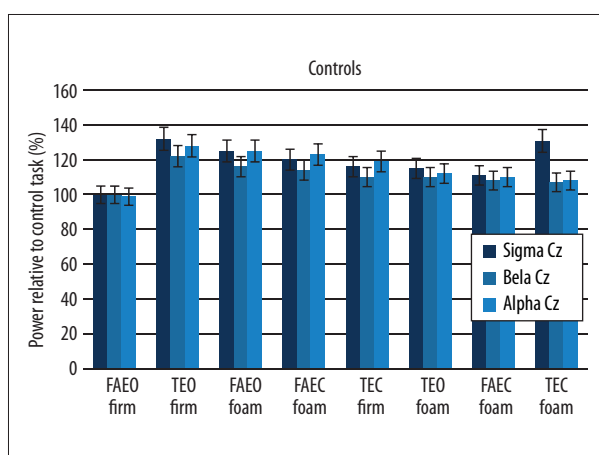
Figure 8. EEG activity in the 10 control subjects at the center of the cortex during the 8 tasks by increasing order of difficulty.
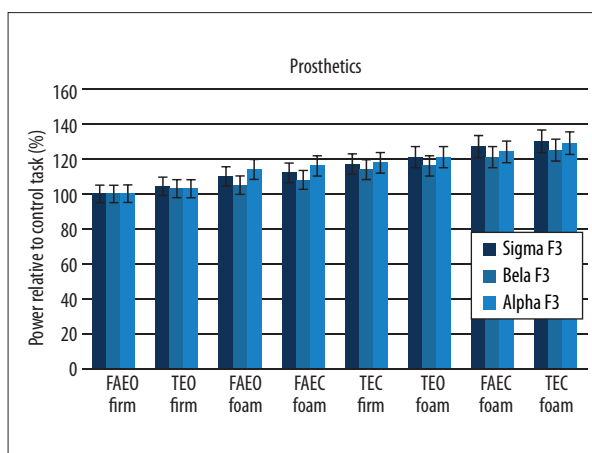

Figure 10. EEG activity in the 10 control subjects at the center of the cortex during the 8 tasks by increasing order of difficulty.

with digital filters. For the most difficult tasks, there is a clear increase in EEG amplitude as well as amplitude of the alpha, beta, and sigma frequency bands. The average power in the 3 bands is then presented under all conditions in the reminder of the paper as a single number, the spectral power of this waveform.

For all areas of the brain, the power of the EMG spectra was higher in the prosthetic users group (Figure 2). The pattern was also different with, for example, EEG sigma power increasing with the complexity of the balance tasks in the prosthetic group but in the control group increasing in the second task and then decreasing with increasing complexity of the tasks except for the most difficult task where it increased again.

Because of differences in the amplitude of the 2 groups, which was significant in most of the tests for all 3 spectra examined (Table 2), the power was normalized in terms of the power

Figure 11. EEG activity in the 10 control subjects at the center of the cortex during the 8 tasks by increasing order of difficulty.

seen during quiet standing in Figures 2, 4, 7–10 as a better means of comparing the EEG. Also, while 9 areas of the brain were examined, graphs shown here are for only 3 areas. The other areas of the brain in both groups of subjects had similar patterns.

Figures 4 and 7 illustrate the average EEG power in the POZ position during the 8 balance tasks in increasing order of complexity for the control (Figure 2) and prosthetic group (Figure 4).

For the control group, with the exception of the alpha waveform, which decreased continuously as the task complexity increased, the EEG power decreased with balance complexity until the most difficult task where it increased again. But in the prosthetic group, EEG power in all bands increased with the task complexity. This increase was significant (ANOVA p<0.05). The same pattern occurred in the cortex as shown in Figures 8 and 9 and Frontal region as shown in Figures 10 and 11.

Over the cortex (Figures 7 and 8) there was a peak in all 3 bands of EEG activity with the eyes closed. This was not seen over the parietal area of the brain (Figures 2 and 4). Further, in the prosthetic group, the increase with eyes closed was nearly double that seen in the control subjects. This same pattern was seen on the frontal area of the brain.

Discussion

Balance is an important part of rehabilitation [37] because falls are a major predisposing factor for fractures and death in the elderly [38,39]. It is well known that the loss of a foot or leg can reduce balance and impair gait [18,40]. This has the effect of increasing falls and reducing the quality of life [5]. What is not known is how the brain compensates for the loss of sensory input from a lost leg or how balance data processing is altered by this loss.

Our results on control subjects support other studies that show cortical spectral power during normal unperturbed quiet standing [41] and an increase of the corticospinal excitability during unstable stance [25,42,43].

When the tasks became more difficult with vision and somatosensory information was altered, the postural sway increased and the EEG band power decreased relative to the less difficult tasks. Studies have shown that H-reflexes are diminished when eyes are closed, suggesting that there was an increase in the supraspinal excitability in the postural control when vision was compromised [44,45]. In our study, the reduced power in the EEG with eyes closed may be due to a shift of the postural control from the cortex to the subcortical structures such as the motor centers in the spinal cord [13,14]. These

findings are consistent with previous studies suggesting the importance of subcortical structures in postural control [46,47] and an increase in the subcortical activity when postural demand increases [10].

During the most difficult task with vision, base of support and surface compliance altered, postural sway became the highest among all the tasks, and the band power of beta and sigma increased significantly at the central and parietal area of the brain relative to the control task. Although there may have been an increase in the subcortical activity as the tasks became more difficult, the increase in the EEG power in the most difficult task suggests that increased cortical activity was required in these more challenging tasks. Previous studies have suggested that the cerebral cortex contributes to postural control by sensorimotor processing of postural instability [21,25] or modification of postural responses through cortical response loops [12,48]. It has been suggested that more cognitive processing was required when the postural task became more difficult [49]. It is possible that when a balance task becomes extremely challenging with both visual and somatosensory information altered, the demand for cortical processing increases.

However, the results were different in the prosthetic user group. Here the loss of a foot and the lower leg certainly reduced sensory input from the leg during balance tasks. In that leg, there would also be no reflex activity to help with balance and provide input to the brain. Therefore, data processing for balance, without half of the sensory input from the somatosensory system, would rely more on the brain. As cited above, studies have been published showing that when balance tasks increase in complexity, cortical control is reduced and spinal processing takes over. Here, the only intact processing was the cortex. Making matters worse, sensory input from one leg but not the other may confuse data processing in the brain, resulting in adaptive control using more cortical processing. This would explain the continuous increase in cortical processing with the increased severity of balance tasks seen here.

Conclusions

Further investigation is needed. Other unanswered questions include examining people with single foot amputations as well as higher amputations to see how the brain adopts to these changes in sensory input. Certainly here, without some of the sensory input, balance was worse even during quiet standing. But how much sensory loss must there be to inhibit balance and increase reliability on the brain? Due to the length of the sensory neurons from the leg to the brain and the length of the motor neurons, a built-in time delay of at least 0.25 ms exists [50,51] to slow the motor control process. Therefore, it

is no surprise that reflexes are preferred in complex balance tasks to reduce delays and increase motor control. Here, the long delay in central balance processing to activate leg muscles is certainly a major contributor to the poor balance seen here. With a growing elderly population, balance testing and training and the use of EEG to understand central data processing [13,14] is important to many different health sciences [52], especially neuropsychology, sleep, and diabetes [14].

Other neural disorders are also being related to EEG, such as workload stress [53].

Acknowledgements

References:

1. Dua A, Patel B, Desai SS et al: Comparison of military and civilian popliteal artery trauma outcomes. J Vasc Surg, 2014; 59(6): 1628–32

2. Martins-Mendes D, Monteiro-Soares M, Boyko EJ et al: The independent contribution of diabetic foot ulcer on lower extremity amputation and mortality risk. J Diabetes Complications, 2014; 28(5): 632–38

3. Kristensen MT, Holm G, Kirketerp-Moller K et al: Very low survival rates after non-traumatic lower limb amputation in a consecutive series: what to do? Interact Cardiovasc Thorac Surg, 2012; 14(5): 543–47

4. Parker K, Hanada E, Adderson J: Gait variability and regularity of people with transtibial amputations. Gait Posture, 2013; 37(2): 269–73

5. Matjacic Z, Burger H: Dynamic balance training during standing in people with trans-tibial amputation: a pilot study. Prosthet Orthot Int, 2003; 27(3): 214–20

6. Horak FB: Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing, 2006; 35(Suppl.2): ii7–ii11

7. Peterka RJ: Sensorimotor integration in human postural control. J Neurophysiol, 2002; 88(3): 1097–118

8. Horak FB, Shupert C: Role of the vestibular system in postural control. Second ed. Vestibular rehabilitation: F. A. Davis, 2000

9. Keck ME, Pijnappels M, Schubert M et al: Stumbling reactions in man: influence of corticospinal input. Electroencephalogr Clin Neurophysiol, 1998; 109(3): 215–23

10. Ouchi Y, Okada H, Yoshikawa E et al: Brain activation during maintenance of standing postures in humans. Brain, 1999; 122(Pt 2): 329–38

11. Mihara M, Miyai I, Hatakenaka M et al: Role of the prefrontal cortex in human balance control. Neuroimage, 2008; 43(2): 329–36

12. Jacobs JV, Horak FB: Cortical control of postural responses. J Neural Transm, 2007; 114(10): 1339–48

13. Tse YY, Petrofsky JS, Berk L et al: Postural sway and rhythmic electroencephalography analysis of cortical activation during eight balance training tasks. Med Sci Monit, 2013; 19: 175–86

14. Petrofsky JS, Alshammari F, Lee H et al: Electroencephalography to assess motor control during balance tasks in people with diabetes. Diabetes Technol Ther, 2012; 14(11): 1068–76

15. Goble DJ, Coxon JP, Van Impe A et al: Brain activity during ankle proprioceptive stimulation predicts balance performance in young and older adults. J Neurosci, 2011; 31(45): 16344–52

16. Lee Childers W, Prilutsky BI, Gregor RJ: Motor adaptation to prosthetic cycling in people with trans-tibial amputation. J Biomech, 2014; 47(10): 2306–13

17. Winter DA, Sienko SE: Biomechanics of below-knee amputee gait. J Biomech, 1988; 21(5): 361–67

18. Soares AS, Yamaguti EY, Mochizuki L et al: Biomechanical parameters of gait among transtibial amputees: a review. Sao Paulo Med J, 2009; 127(5): 302–9

19. Childers WL, Kistenberg RS, Gregor RJ: Pedaling asymmetries in cyclists with unilateral transtibial amputation: effect of prosthetic foot stiffness. J Appl Biomech, 2011; 27(4): 314–21

20. Fey NP, Silverman AK, Neptune RR: The influence of increasing steady-state walking speed on muscle activity in below-knee amputees. J Electromyogr Kinesiol, 2010; 20(1): 155–61

21. Adkin AL, Quant S, Maki BE, McIlroy WE: Cortical responses associated with predictable and unpredictable compensatory balance reactions. Exp Brain Res, 2006; 172(1): 85–93

22. Mochizuki G, Sibley KM, Esposito JG et al: Cortical responses associated with the preparation and reaction to full-body perturbations to upright stability. Clin Neurophysiol, 2008; 119(7): 1626–37

23. Jacobs JV, Fujiwara K, Tomita H et al: Changes in the activity of the cerebral cortex relate to postural response modification when warned of a perturbation. Clin Neurophysiol, 2008; 119(6): 1431–42

24. Saitou K, Washimi Y, Koike Y et al: Slow negative cortical potential preceding the onset of postural adjustment. Electroencephalogr Clin Neurophysiol, 1996; 98(6): 449–55

25. Slobounov S, Hallett M, Stanhope S, Shibasaki H: Role of cerebral cortex in human postural control: an EEG study. Clin Neurophysiol, 2005; 116(2): 315–23

26. Shibasaki H, Hallett M: What is the Bereitschaftspotential? Clin Neurophysiol, 2006; 117(11): 2341–56

27. Dorneich MC, Whitlow SD, Mathan S et al: Supporting real-time cognitive state classification one mobile individual. Journal of Cognitive Engineering and Decision Making, 2007; 1(3): 2240–70

28. Berka C, Levendowski DJ, Lumicao MN et al: EEG correlates of task engagement and mental workload in vigilance, learning, and memory tasks. Aviat Space Environ Med, 2007; 78(5 Suppl.): B231–44

29. Stevens RH, Galloway TL, Wang P, Berka C: Cognitive neurophysiologic synchronies: what can they contribute to the study of teamwork? Hum Factors, 2012; 54(4): 489–502

30. Petrofsky JS, Cuneo M, Lee S et al: Correlation between gait and balance in people with and without Type 2 diabetes in normal and subdued light. Med Sci Monit, 2006; 12(7): CR273–81

31. Petrofsky J, Lee S, Cuneo ML: Gait characteristics in patients with type 2 diabetes; improvement after administration of rosiglitazone. Med Sci Monit, 2005; 11(6): PI43–51

32. Petrofsky J, Lee S, Bweir S: Gait characteristics in people with type 2 diabetes mellitus. Eur J Appl Physiol, 2005; 93(5–6): 640–47

33. Tse YYF, Petrofsky JS, Lee B et al: Postural sway and EMG analysis of hip and ankle muscles during eight balance training tasks. Int J Ther Rehabilitation, 2012 [submitted]

34. Petrofsky JS, Lohman E, Lohman T: A device to evaluate motor and autonomic impairment. Med Eng Phys, 2009; 31(6): 705–12

35. Kimura T, Kouzaki M, Masani K, Moritani T: Unperceivable noise to active light touch effects on fast postural sway. Neurosci Lett, 2012; 506(1): 100–3

36. Kouzaki M, Masani K: Postural sway during quiet standing is related to physiological tremor and muscle volume in young and elderly adults. Gait Posture, 2012; 35(1): 11–17

37. Gorgas AM, Widener GL, Gibson-Horn C, Allen DD: Gait Changes with Balance-Based Torso-Weighting in People with Multiple Sclerosis. Physiother Res Int, 2014 [Epub ahead of print]

38. Menant JC, Schoene D, Lord SR: Single and dual task tests of gait speed are equivalent in the prediction of falls in older people: A systematic review and meta-analysis. Ageing Res Rev, 2014; 16: 83–104

39. Hocking DR, Menant JC, Kirk HE et al: Gait profiles as indicators of domain-specific impairments in executive control across neurodevelopmental disorders. Res Dev Disabil, 2014; 35(1): 203–14

40. Sturdy J, Gates DH, Darter BJ, Wilken JM: Assessing preparative gait adaptations in persons with transtibial amputation in response to repeated medial-lateral perturbations. Gait Posture, 2014; 39(3): 995–98

41. Qiu F, Cole MH, Davids KW et al: Enhanced somatosensory information decreases postural sway in older people. Gait Posture, 2012; 35(4): 630–35

42. Solopova IA, Kazennikov OV, Deniskina NB et al: Postural instability enhances motor responses to transcranial magnetic stimulation in humans. Neurosci Lett, 2003; 337(1): 25–28

43. Lavoie BA, Cody FW, Capaday C: Cortical control of human soleus muscle during volitional and postural activities studied using focal magnetic stimulation. Exp Brain Res, 1995; 103(1): 97–107

44. Hoffman MA, Koceja DM: The effects of vision and task complexity on Hoffmann reflex gain. Brain Res, 1995; 700(1–2): 303–7

45. Earles DR, Koceja DM, Shively CW: Environmental changes in soleus H-reflex excitability in young and elderly subjects. Int J Neurosci, 2000; 105(1–4): 1–13

46. Doyon J, Gaudreau D, Laforce R Jr et al: Role of the striatum, cerebellum, and frontal lobes in the learning of a visuomotor sequence. Brain Cogn, 1997; 34(2): 218–45

47. Prentice SD, Drew T: Contributions of the reticulospinal system to the postural adjustments occurring during voluntary gait modifications. J Neurophysiol, 2001; 85(2): 679–98

48. Maki BE, McIlroy WE: Cognitive demands and cortical control of human balance-recovery reactions. J Neural Transm, 2007; 114(10): 1279–96

49. Teasdale N, Simoneau M: Attentional demands for postural control: the effects of aging and sensory reintegration. Gait Posture, 2001; 14(3): 203–10

50. Dalpozzo F, Gerard P, De Pasqua V et al: Single motor axon conduction velocities of human upper and lower limb motor units. A study with transcranial electrical stimulation. Clin Neurophysiol, 2002; 113(2): 284–91

51. Mrachacz-Kersting N, Grey MJ, Sinkjaer T: Evidence for a supraspinal contribution to the human quadriceps long-latency stretch reflex. Exp Brain Res, 2006; 168(4): 529–40

52. Kropotov JD, Mueller A: What can Event Related Potentials contribute to neuropsychology. Acta Neuropsychologica, 2009; 7(3): 169–81

53. Muhl C, Jeunet C, Lotte F: EEG-based workload estimation across affective contexts. Front Neurosci, 2014; 8: 114