ABSTRACT

According to estimates 40 million individuals are with limb amputations worldwide, about 36 million (90%) are lower-limb amputees, of whom an estimated 26% are transfemoral amputees (TFAs). Loss of somatosensory feedback after amputation inflicts a serious challenge for amputees to achieve postural stability. Despite a good understanding of kinematic and kinetic adaptation after lower limb amputation, the somatosensory consequences and cortical adaptations are not much studied. Specifically, an important research question is how the brain compensates for the loss of sensory input from a missing limb and how it processes the data due to this loss. In this context, the findings of this study might have an impact in the 'real world'. To this end, Electroencephalography (EEG) in synchronization with the center of pressure (CoP) signals was collected from eight transfemoral amputees during a balance task. Ten healthy volunteers were also recruited to provide a benchmark for the comparison. A pair of insoles consisting of force sensitive resistors were used to estimate the CoP. Participants were instructed to perform voluntary postural sway balance exercises in anterior-posterior and mediolateral directions. The postural stability of the participants was defined with the limit of stability (LOS) parameter. LOS refers to the maximum displacement of CoP under both the limbs (sound and prosthetic) during voluntary postural sway. In amputees, the sound limb's LOS was found to be significantly higher ($p<0.05$, Mixed repeated ANOVA) than at the prosthetic limb during the balance task. Using the independent components (ICs) from the three specified regions of the cortex i.e., left sensorimotor area (LSA), right sensorimotor area (RSA), and supplementary motor area (SMA), the results present a well-pronounced drop of alpha spectral power at sensorimotor area contralateral to sound limb of amputees (RSA) in comparison to SMA and the sensorimotor area contralateral to the prosthetic limb (LSA). Additionally, the correlation coefficient between resultant LOS and alpha spectral power at the sensorimotor area contralateral to the sound limb was found to be 0.86, showing a positive relationship between alpha spectral power and LOS. Therefore, the differences in the alpha spectral power at LSA, SMA, and RSA resulted in the differences in the LOS at the sound and prosthetic limb of amputees during voluntary postural sway. This phenomenon was taken as evidence of the reorganizations in the brain after amputation.

Improving motor skills by incorporating vibrotactile sensory feedback in the rehabilitation protocols for persons with lower limb amputation has been gaining traction over time. Consequently, a pair of customized foot insoles along with the vibratory feedback system was developed to examine the postural stability of amputees. The vibratory feedback was

delivered on the stump of the participants with the help of vibration tactors (Vibration Motor 310-113). These tactors were placed into the anterior and posterior surface of the amputee's socket at 2/3 the length of the stump from the greater trochanter. For feedback sessions, the vertical length of insoles was divided into three zones i.e., posterior zone (20%), mid zone (30%), and anterior zone (50%). If the CoP value crosses the threshold value outside the mid zone, the corresponding vibrating motor starts to vibrate. Therefore, by constantly mapping the CoP during voluntary sway, vibratory feedback was perceived by the participants. Accordingly, the LOS of the sound limb was found to be significantly higher with vibrotactile feedback in comparison to no feedback sessions in the present case.

To investigate the sensory mechanism responsible for improved stability with vibrotactile feedback, the time-frequency (wavelet transform) approach was applied. The method was utilized to capture the CoP dynamics in the time-frequency domain and the change in energy content at different frequencies/time-scales of CoP was examined. Vibrotactile feedback was found to be effective in controlling low-frequency postural sway in amputees. Results showed significantly higher energy ($p^* < 0.008$, T-test) at shorter time-scales ($j = 6,7$, freq. = 0.6–1.25 Hz) and lower energy at longer time-scale ($j = 10$, freq. = 0.078 Hz) in amputee's CoP time series with vibrotactile feedback in comparison to healthy individuals. This suggests that more than one sensory system is involved in controlling the body sway in amputees. However, due to the presence of vibrotactile feedback, the somatosensory receptors were contributing more to the postural control of amputees than visual and vestibular receptors. This demonstrates that, for the improvement in the LOS of transfemoral amputees, the central nervous system integrated the spatial location of the prosthesis with vibrotactile feedback by placing more weight on their somatosensory receptors.

To determine the involved cortical mechanisms which process the vibrotactile sensory feedback by placing more weight on somatosensory receptors and help to improve the LOS, independent components (ICs) from the secondary somatosensory cortex (S2) and fronto-central region were investigated. The results demonstrated that the improved LOS with vibrotactile feedback was in response to eliciting strong theta and gamma oscillations. S2 (contralateral to amputated side) processes the sensory information from vibrotactile feedback by significantly reducing ($p<0.05$, T-test) the theta spectral power, and the fronto-central region executed the motor response to improve the LOS by significantly increasing ($p<0.05$, T-test) the gamma power. The intra-regional functional connectivity at the S2 and the fronto-central region was significantly stronger ($p < 0.003$, T-test) in presence of vibrotactile feedback, and the two regions (S2 and fronto-central) were strongly connected while perceiving the

vibrotactile feedback in comparison to no feedback sessions. This suggests that the relevant sensory information is sent to the fronto-central region from the secondary somatosensory cortex which results in the improvement of LOS.

These findings provide fundamental insights into the cortical activity associated with the vibrotactile feedback and help in understanding the cortical mechanism of balance improvement in transfemoral amputees. By enhancing the flexibility of the highlighted cortical regions via targeted cognitive training or local stimulation techniques, neuroplasticity might be promoted which helps to reduce the training time for the efficient rehabilitation of amputees in the future. It could be of interest if some neurofeedback strategies might be developed that aim at improving the postural performance of amputees. Additionally, this new knowledge might benefit the designing and developing of innovative interventions to prevent falls due to lower limb amputation.