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IMPACT OF MENTAL FATIGUE ON REGAINING MOTOR FUNCTIONALITY: A PRELIMINARY EEG STUDY ON STROKE SURVIVORS

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ABSTRACT: In the past few decades, research has demonstrated that brain-computer interface (BCI) based neurorehabilitation for stroke survivors can enhance the re-learning of lost motor functionality better than traditional physiotherapy involving professional physiotherapists. Though BCI-aided systems have several advantages over traditional rehabilitation methods, one of the major shortcomings of such intervention is its inability to recognize the relevant motor activity of the brain when the user gets mentally fatigued, which eventually causes the deterioration of the BCI performance. In this paper, a preliminary EEG study on stroke survivors has been reported on how mental fatigue can potentially hinder the enhancement of motor re-learning and elongate the rehab process. From the study, it has been inferred that objective measurement of mental fatigue is essential to prevent any subjective bias, and the rehabilitation paradigm should be adaptive to the participants' mental status to optimize the rehab outcomes.

INTRODUCTION

Stroke is a severe and potentially life-threatening medical condition that occurs when the blood flow to a specific brain area is interrupted. The majority of the survivors face minor to major motor disability depending upon the severity of stroke [1]. Hence, it has become necessary to develop efficient assistive neurotechnology for stroke survivors to regain the motor functionality of their impaired limb. A previous study reported that traditional physiotherapy involving professional physiotherapists has less impact on regaining motor functionality [2]. One possible reason for this observation could be that the patient is not actively engaged in relearning the lost motor functions during this type of motor rehabilitation program [3]. The participant's active engagement is crucial in BCI-aided intervention for stroke rehabilitation to restore motor function effectively and efficiently.

Brain-computer interface (BCI) is an emerging technology that is increasingly becoming important to establish effective communication pathways between the brain and computer-controlled devices (e.g., robotic exoskeleton) by using invasive (e.g., electrocorticography) or non-invasive (e.g., electroencephalography, magnetoencephalography) neuroimaging modalities [4, 5]. Combining motor imagery (MI) or the imagined movement of a limb with BCI for neurorehabilitation enables users to control an exoskeleton attached to their impaired limb [6, 7]. Existing studies show BCI-aided neurorehabilitation exhibits promising improvements in restoring motor functionality compared to traditional physiotherapy and other assistive technologies [8].

Though the BCI-aided neurorehabilitation framework shows promising results for the rehabilitation of stroke survivors, there is a need to develop a reliable and efficient assistive system for neurorehabilitation to account for the variability in brain activity over time because brain activity changes its characteristics due to changes in different mental states (e.g., mental fatigue, boredom, etc.) while carrying out the same activity. In previous studies [9, 10], it has been observed that a shift in mental state, especially the induction of mental fatigue, negatively impacts the performance of BCI-based rehabilitation. Slower motor movement during a mentally fatigued state has been reported in [11]. While the impact of mental fatigue on motor performance has been explored in the existing literature, the impact of fatigue on the enhancement of motor learning has been less studied. Branscheidt et al., in [12], reported a long-lasting detrimental impact of muscle fatigue on long-term motor skill learning. Still, the research did not include the possible effect of mental fatigue caused by the prolonged cognitive load imposed during the experiment. Persistence of mental fatigue on motor control has been reported for healthy individuals in [13]. Moghani et al. have reported that mental fatigue causes a loss of self-controlled feedback in motor learning for healthy people [14].

Though the existing research has explored the potential impact and persistence of mental fatigue on long-term motor learning, there is a significant knowledge gap that correlates the impact of mental fatigue with regaining lost motor functionality for actual patients with motor impairment.

The study of mental fatigue and its effect on motor learning is mainly limited to healthy individuals, and to the best of the authors' knowledge, no research has been

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done so far to study the impact of mental fatigue on the re-learning of motor activities in stroke survivors. In this present contribution, a novel EEG-based preliminary study on stroke survivors has been reported, aiming to establish a relationship between motor learning and mental fatigue.

MATERIALS AND METHODS

Dataset Description:
This contribution used an EEG dataset acquired in [8] during a stroke rehabilitation program. The original data contains EEG recordings from 5 chronic stroke (ischemic) patients suffering from hemiparesis. The mean time since the first occurrence of stroke was 21.8±4.49, within the range of 17 to 28 months. As revealed by the testimonials of the patients, their motor functionality stopped improving for the last one year [8]. The dataset contains 12 channel EEG recordings from F3, F4, FC3, FCz, FC4, C3, C4, CP3, CPz, CP4, P3, and P4 brain regions. The data were recorded with a g.USBamp (g.tec, Graz, Austria) biosignal amplifier, along with active ring electrodes (g.LADYbird having sintered Ag/AgCl crown) attached to the EEG cap (g.GAMMAcap). The signal was sampled at 512 Hz, and initially, a band-pass filter with cut-off frequencies of 0.1 Hz to 100 Hz was applied with a notch filter at 50 Hz to avoid the power-line noise.
The participants were instructed to perform grasping attempts with their left and right hands, as shown on a computer screen. The rehabilitation program consists of up to 12 BCI-controlled hand-exoskeleton therapy sessions for each participant, spanning over 5 weeks with 2-3 sessions per week. Each session consists of 5 runs (the first two for calibration of the BCI exoskeleton and the last three with real-time feedback). Each run consists of 40 trials (20 trials for the left hand and 20 trials for the right hand), and each trial lasts for 8 seconds with a random 2s to 3s interval as the inter-trial interval between the two consecutive trials, which makes one run roughly 7.5 minutes. Short inter-run breaks of around 5–6 minutes were provided for the participants to rest. From the 5 volunteers, only 3 patients who completed the entire rehabilitation program (with 12 sessions) were selected for the present analysis.
The rehabilitation outcomes were measured every week in terms of standard motor recovery measures: Action Research Arm Test (ARAT) and Grip Strength (GS) (in kg). The ARAT measures grasp (score: 0–18), grip (score: 0–12), pinch (score: 0–18), and gross movements (score: 0–9). Thus, the total range of ARAT is 0–57. In this paper, only the ARAT score has been used for analysis, as it already includes measurements related to grip.
Participants were instructed to report their own evaluation of fatigue and motivation level before and after each session using the visual analogue scale from 0 to 10.

Data Pre-processing:
At first, the continuous data were epoched based on the trigger information. Then, the ICA-based automated artefact rejection technique was applied to filter ocular and other common muscle artefacts (using the 'EEGLAB' extension 'IClabel' in MATLAB R2022b), and cleaned data were visually inspected to check the quality and manually rejected any remaining artefacts. A band-pass filter with cut-off frequencies of 0.1 and 50 Hz was applied, as high-frequency noise had been observed after artefact correction.
The epoched and pre-processed data had been decomposed into different EEG rhythms, namely, Delta (0.1-4 Hz), Theta (4-8 Hz), Alpha (8-13 Hz), Beta (13-30 Hz), and Gamma (30-50 Hz).

Methodology:
In the existing literature, it has been well established that event-related desynchronization/synchronization (ERD/S) [15], a relative power decrease/increase of EEG in a specific frequency band, is highly associated with physical motor execution and mental motor imagery [16]. The same study also reported that the ability to generate ERD/S is highly subjective and involves sufficient neurofeedback training [16].
In this present contribution, ERD/S have been calculated for each EEG rhythm separately for all trials from all sessions. As effective ERD/S generation involves rigorous neurofeedback training, the present hypothesis assumes the enhancement of ERD/S as a potential indication of the enhancement of lost motor functionality.
As the pre- and post-task subjective fatigue scores varied in every session, the amount of fatigue exclusively induced by the rehabilitation session has been calculated by subtracting the pre-task fatigue score from the post-task fatigue score.
Rhythm-wise band-power estimation was also calculated for inter-trial intervals to study brain activities during the short resting states between two consecutive trials. As the original data were recorded during a rehabilitation session, which was not primarily focused on studying the impact of mental fatigue on BCI performance, no EEG recordings are available during the inter-run resting periods.

RESULTS AND DISCUSSIONS

In this present contribution, we studied how behavioural change occurs in patients with gradual motor functionality improvement. In the BCI community, it has been established that learning motor skills enhances the ERD/S at the motor cortex region of the brain [17]. Hence, the present analysis has been primarily focused on the C3 and C4 EEG channels based on the impaired limb of the participant.

Inter-session behavioural data analysis:
The variation of fatigue levels across different sessions has been shown in Fig.1. It is to be noted that the stroke severity of the participants differed for each individual, and the final regain of motor functionality was also not at the same level after completing all 12 sessions. Hence, to identify the motor ability improvement trend, ARAT

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scores, which were initially rated between 0-57, have been normalized between 0 and 1 using the "min-max normalization" technique. Similarly, the induced fatigue level has also been normalized between 0 to 1.

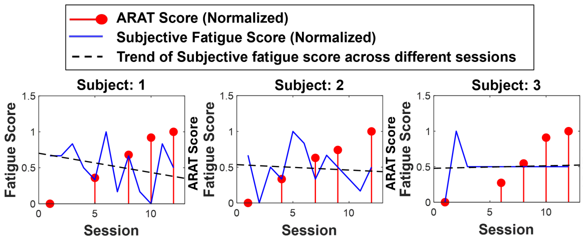

Figure 1: Trend of fatigue over 12 sessions. Trend line (dashed) fitted using linear regression

From Fig.1, it can be observed that subjective fatigue level is decreasing for two participants out of three over different sessions (trend based on linear regression has been shown by the dashed line in Fig.1) when ARAT score clearly demonstrates the improvement of motor functionality. The observation has been found to be statistically significant using Wilcoxon's two-tailed signed rank test with a 5% threshold for two participants (Subject 1 and 2). In contrast, no significant change has been observed for Subject 3.

Inter-session ERD/S analysis:
As reported earlier, ERD/S has been computed for all aforesaid EEG rhythms, and it has been found that the beta (13-30 Hz) band reflects the impact of mental fatigue on motor performance better than all other EEG rhythms. Such observation may be due to its rich content of information related to motor activity. Average ERD/S over different sessions for the motor cortex region is reported in Fig.2.

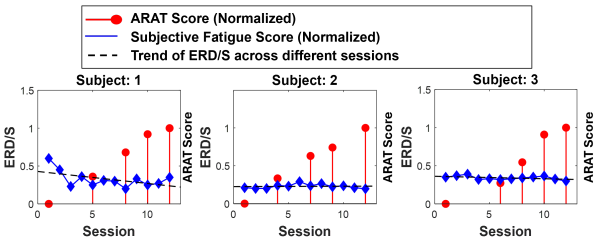

Figure 2: Trend of ERD/S across 12 sessions. Trend line (dashed) fitted using linear regression

From Fig.2, it can be observed that average ERD/S is decreased over different sessions for all three participants, indicating enhancement of ERD/S, which is a potential indication of motor function development for the impaired hand (statistical significance has been observed only for subject 1 while subject 2 and 3 did not exhibit any statistical significance). Hence, from Fig.1 and Fig.2, it can be inferred that subjective fatigue score and ERD/S have a positive correlation while it shows a negative correlation with ARAT score.

BCI classification performance across different sessions:
BCI classification accuracy averaged across 3 real-time feedback runs for every session, has been computed to understand how BCI performance changes across the 12 sessions with gradual improvement of motor functionality. The BCI performance for 3 participants has been reported in Fig3.

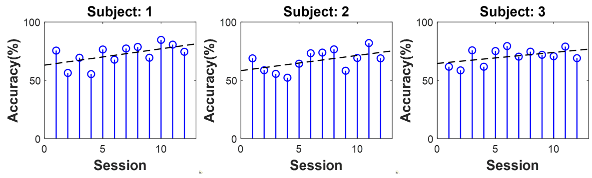

Figure 3: Average BCI classification accuracy during 3 feedback runs across 12 sessions. Trend line (dashed) fitted using linear regression

From Fig.3, it can clearly be observed that the performance of the BCI system was improving along with the improvement of motor functions of the impaired hand and exhibits a negative correlation with subjective fatigue level. It is interesting to observe that the BCI performance of Subject 1 was highest in the session in which the reported subjective fatigue score was observed to be the lowest (session 10). But for participants 2 and 3, no such observation can be made. One of the possible reasons for this may be the understanding of mental fatigue is highly subjective, and that can bias self-rating of mental fatigue. Previous literature indicates that volunteers participating in BCI or related experiments often confuse mental fatigue with other mental states, such as effortful attention (where the self-perceived effort of the participant is very high) or boredom [18]. Hence, it is necessary to evaluate mental fatigue objectively to quantify it without any subjective bias.

Intra-session analysis of ERD/S and beta bandpower:
Along with inter–session analysis, an intra–session study has also been done to obtain better insight into the underlying neural dynamics. For intra–session analysis, the first 10 trials and the last 10 trials from every run have been taken into consideration to calculate average ERD/S during the commencement and ending of each run. In Fig.4, intra-session analysis for three subjects for the beta band has been reported.
Based on the findings depicted in Fig.4, it is intriguing to note that there is a noticeable decline in the ERD/S enhancement following the completion of a run (group of trials without a significant resting period) on multiple occasions. This observation can be attributed to the potential induction of fatigue. Additionally, it is worth mentioning that in the majority of cases, the ERD/S improves at the beginning of the subsequent run compared to the ERD/S at the end of the previous run (statistically significant changes in ERD/S after short inter-run breaks have been marked in the figure with '$*$' when two-tailed Wilcoxon's signed-rank test has been done with 5% threshold). One plausible explanation for this trend is the restoration of the brain from a fatigued state, potentially facilitated by a short break between runs. In a few cases,

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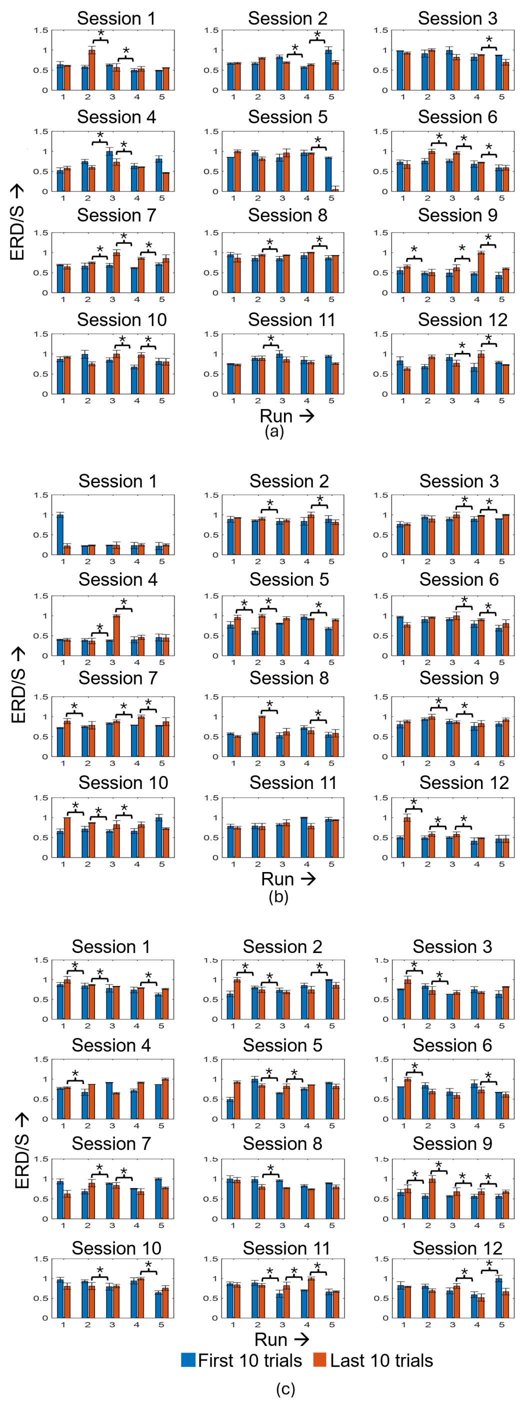

Figure 4: Intra–session ERD/S activities for different runs for (a) Subject 1, (b) Subject 2, and (c) Subject 3

for example, in Subject 3 session 2, it can be observed that there is a significant decline in ERD/S enhancement between run 4 and 5, which might indicate that the participant got too fatigued to recover during the small break between run 4 and 5.

Hence, the above analysis shows a possible relationship between fatigue and re-learning of motor functions by evaluating ERD/S, subjective fatigue score, and ARAT score.

Along with ERD/S, beta band power was also investigated for inter-trial intervals where participants were expected to have low or no motor activity. The analysis results are reported in Fig.5.

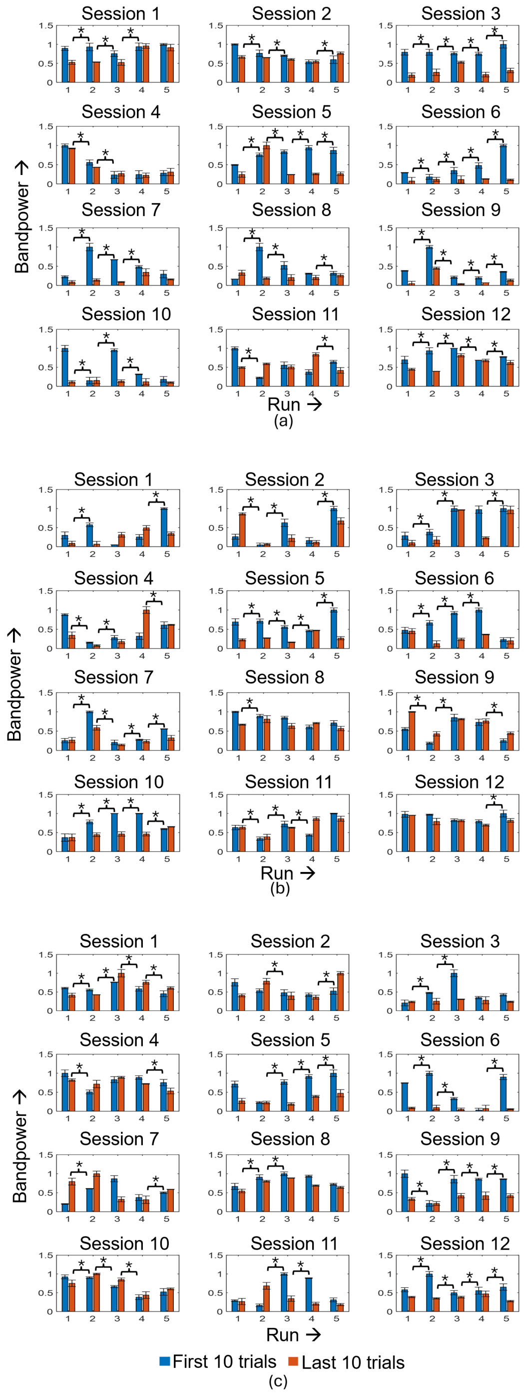

Figure 5: Intra–session beta band power activities for different runs for (a) Subject 1, (b) Subject 2, and (c) Subject 3

From Fig.5, it has been observed that, for the majority of the runs across different sessions, beta band power (which is also associated with focus and arousal [19]) has been reduced at the end of runs compared to the com-

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mencement of that run. Furthermore, this observation is found to be consistent across different subjects. The plausible explanation of this observation may be linked to the potential inclination of mental fatigue. Similar to Fig.4, improvement of brain arousal state (increase in beta band power) has also been identified after short inter–run breaks.

Intra-session BCI classification performance:
The average classification accuracy of the BCI system for the 3 feedback runs across all sessions has also been analyzed to obtain more insight into the relationship between motor re-learning and subjective mental fatigue. It is to be noted that the first two runs correspond to the calibration phase, and the classifier did not generate any output. The intra-session classification performance for all 3 participants has been reported in Fig.6.

From Fig.6 and Fig.4, it can be observed that classification accuracy exhibits an improvement compared to its previous run only in the cases where enhancement of ERD/S occurred after a short mid-task break, indicating the negative impact of mental fatigue on BCI performance which may hinder improvement of motor abilities.

A noteworthy observation is that Subject 3 consistently reported no subjective increase in fatigue levels during the rehabilitation sessions. However, the neural activity exhibited indications of possible fatigue induction. This reinforces the importance of establishing reliable, objective markers for fatigue.

From the psychological standpoint, mental fatigue manifests itself in terms of loss of attention and cognitive decline. Shift/loss of attention due to mental fatigue can disrupt participants' active engagement on task-related stimuli and can compromise the production of ERD/S. The intra-session analysis clearly indicates that BCI performance and regaining of motor functionalities are subject to the participant's active engagement in the rehabilitation exercise. This observation unfolds another vital aspect of BCI research. In existing BCI research, the majority of experimental paradigms related to motor imagery or motor execution tasks are designed as an open loop system where session length, number of trials per session, and mid-session breaks are fixed by the researchers and kept the same for all participants while the induction of mental fatigue is highly subjective and depends on the mood, emotional condition, and cognitive capacity of the participant at that moment. From this present contribution, it can be observed that adaptation and modulation of the experimental paradigm, based on participants' mental and cognitive states, are essential to ensuring participants' active engagement to optimize the enhancement of neurorehabilitation more quickly and effectively.

While the analysis mentioned above suggests that band power and ERD/S activity have the potential to serve as neuromarkers for monitoring fatigue objectively, further comprehensive investigations are required. A more detailed study is necessary to delve deeper into these measures and establish their effectiveness and reliability in fatigue monitoring. Moreover, previous studies on bore-

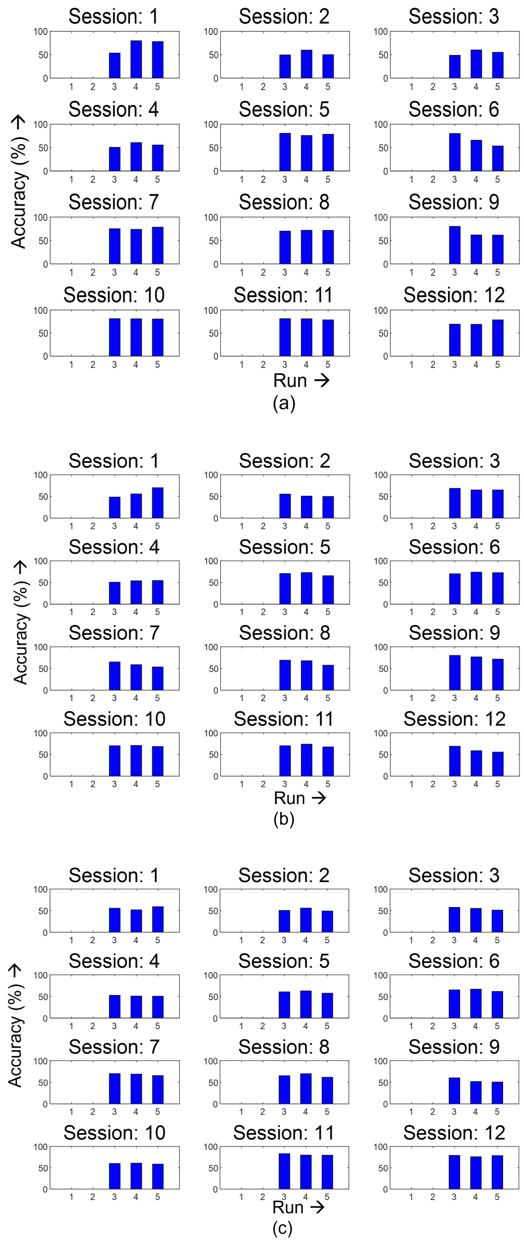

Figure 6: Intra–session classification accuracy of the BCI model for different runs for (a) Subject 1, (b) Subject 2, and (c) Subject 3

dom [20, 21] and mental fatigue [22] report similar types of decrement in vigilance and increased reaction time. This indicates a possible overlap between mental fatigue and boredom in terms of behavioural outcomes. Hence, it is necessary to identify relevant neuromarkers exclusively associated with mental fatigue while developing a passive BCI system to monitor mental fatigue.

CONCLUSION

In this present contribution, a preliminary study on the impact of mental fatigue on the improvement of motor functionality and BCI performance has been done on 3

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stroke survivors. The study exhibits the potential negative impact of mental fatigue on enhancing motor functions. This paper also highlights the necessity of objectively monitoring mental fatigue and designing an adaptive BCI rehabilitation paradigm for optimal enhancement outcomes. The future scope of this study includes consolidating current observations on a larger patient population and identifying neuromarkers explicitly associated with fatigue for developing a passive BCI-based status monitoring system that will assist an active BCI-based exoskeleton in adapting the rehab sessions based on patients' mental and cognitive conditions.

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