BRIEF REPORT

Brain–Computer Interface for Individuals After Spinal Cord Injury

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Purpose/Objective: To investigate the feasibility of brain–computer interface (BCI) with patients on an inpatient spinal cord injury (SCI) unit. Research Method/Design: This study included 25 participants aged 18–64 who sustained traumatic or nontraumatic SCI and did not have severe cognitive or psychiatric impairment. Participants completed a variety of screening measures related to cognition, psychological disposition, pain, and technology experience/interest. The Emotiv electroencephalography system was used in conjunction with a cube rotation and manipulation game presented on a laptop computer. Results: The majority of participants successfully completed the BCI game and reported enjoyment of the experience. Outside of a mild trend of lower performance among participants with a past or present head injury, there were no demographic variables, injury variables or screening measures significantly associated with BCI performance. Conclusions/Implications: The BCI paradigm demonstrated feasibility and safety across participant age range, educational and vocational background, and level of injury. Despite the rapid integration of technology into rehabilitation health care settings, there are few evidence-based studies regarding the feasibility of technology with specific inpatient populations. Clinical implications and challenges of using this technology in a rehabilitation setting are discussed.

Impact and Implications
Although brain–computer interface (BCI) technology has been studied for motor and communication augmentation, there is sparse literature exploring the use and tolerability of this technology with inpatient spinal cord populations. This study is one of very few attempting to clarify if BCI can be tolerated during inpatient rehabilitation. This work extends the literature supporting the use of BCI with spinal cord injury patients even with higher level injury, moderate pain complaints, and mild–moderate cognitive difficulties. BCI may soon be considered an option to enhance traditional rehabilitation after spinal cord injury. However, BCI paradigms need to be developed to demonstrate enhanced treatment effects beyond traditional care.

Keywords: virtual reality, disability, inpatient rehabilitation, technology

Introduction

The myriad electronic and computer assisted device to enhance daily functioning are continually expanding and gaining increased interest among individuals who have sustained a spinal cord injury (SCI). Brain–computer interface (BCI) is one such technology generating great promise to address both motor and communication barriers (Collinger et al., 2013; Ikegami, Takano, Saeki, & Kansaku, 2011; Mak & Wolpaw, 2009; Shih, Krusienski, & Wolpaw, 2012). BCI has been described as linking brain patterns to motor or mental intent in an effort to...
bypass the reliance upon peripheral nerves and muscles that may be compromised (Cincotti et al., 2008; Millan et al., 2010). Implications for promoting and/or monitoring neuroplasticity after central nervous system injury with repeat BCI use have also been postulated (Burns, Adeli, & Buford, 2014; Dobkin, 2007).

Case examples and a few small studies have highlighted how BCI can be applied to neurorehabilitation populations such as stroke, amyotrophic lateral sclerosis, locked-in syndrome, and SCI (Enzinger et al., 2008; Ikegami et al., 2011; Kaufmann, Holz, & Kubler, 2013; Kiper, Piron, Turolla, Stoeck, & Tonin, 2011; Schreuder et al., 2013). The use of BCI beyond motor and communication augmentation has received less attention despite the key role psychological factors play in perceived quality of life following SCI (Tate, Kalpakjian, & Forchheimer, 2002). Recommended avenues of further BCI exploration, which have direct relevance to SCI treatment targets, include pain management and psychological adjustment (Dobkin, 2007). These recommended areas closely align with research priorities voiced by individuals with SCI when surveyed (Hammell, 2010).

Intriguing findings from animal and human studies support the role of neuroplasticity and reorganization—particularly of the somatosensory cortex—in pain experience after SCI (Rao et al., 2013; Tidoni, Tieri, & Aghioti, 2015; Wrigley et al., 2009). The potential of repetitive BCI training to promote reorganization warrants additional exploration (Wrigley et al., 2009). BCI can be coupled with virtual reality (VR), which is appealing given the more recent development of promising VR paradigms for neuro-pathic pain and phantom limb pain (Alphonso et al., 2012; Murray, 2009). Studies using BCI for emotional recognition (e.g., participant electroencephalography [EEG] patterns for emotionally laden audiovisual stimuli) and psychological intervention highlight the potential for BCI to optimize psychological adjustment following injury (Dutta et al., 2013; Jatupaitoon, Pan-ngum, & Israsena, 2013). Theoretically, BCI may add an increased perception of control during pain modifying interventions. BCI could likewise serve as an adjunct to help interact with virtual environments already shown to be effective in treatment of anxiety disorders, which are seen at a higher rate among individuals after SCI (Motraghi, Seim, Meyer, & Morissette, 2014; Parsons & Rizzo, 2008).

Despite considerable promise, much of BCI technology is not ready for mainstream implementation and the various challenges inherent with such interventions—including how physical impairment may compromise BCI performance—have been well detailed (see Danziger, 2014; Hill, Hauser, & Schalk, 2014; Kübler & Birbaumer, 2008; Mak & Wolpaw, 2009; Millan et al., 2010; Shih et al., 2012, for more information). In a recent review of the use of BCI in persons with SCI, Rupp (2014) concluded that while BCI seems to be a promising assistive technology for individuals with SCI, systematic investigation is needed to obtain a realistic understanding of the feasibility of using BCI in a clinical setting. Rupp identified three potentially limiting factors related to feasibility that should be considered: (a) availability of technology for signal acquisition and processing, (b) individual differences in user characteristics, and (c) infrastructure and health care related constraints. Consequently, our exploratory study used an off-the-shelf BCI technology that is widely available to address Rupp’s initial concern and additional feasibility questions. Thus, the primary objective of this study was to assess feasibility of BCI usage including safety, technology suitability (e.g., reliability and usability), user characteristics (e.g., recruitment rates, age, gender, enjoyment), and potential health-care-related constraints (e.g., scheduling, participant tolerance). Secondary objectives included examination of associations between (a) participant demographic characteristics and BCI performance and (b) cognition, mood, and pain level with BCI performance. Although the current study is exploratory in nature, we hypothesized that greater cognitive impairment, higher endorsement of depression, higher reported pain, and limited familiarity with computers/technology could adversely affect BCI performance.

Method

Participants

Individuals with SCI between the ages of 18 and 64 and deemed medical stable were potential study candidates. The presence of significant visual impairment, significant cognitive impairment (based on multidisciplinary staff input, record review and screening clinician judgment), history of developmental disorders, or severe and poorly managed psychiatric illnesses precluded involvement in the study. Of 32 consecutive subjects meeting criteria who were approached, 25 agreed to participate in the study. The seven who declined to participate either cited no interest/aversion to technology or feeling too overwhelmed by their rehabilitation program to enter a research study. Participants were primarily Caucasian (76%), adult (age 45 ± 13.0), males (76%) who had vocational or educational achievement beyond high school (90%). Most had sustained a recent SCI (age at injury 44.5 ± 13.3) with the median time between injury and study participation of 50 days. The SCI was most frequently at cervical (48%) or thoracic (44%) levels and tetraplegia (52%) was common (see Table 1 below for American Spinal Injury Association Impairment Scale and injury details).

Procedure

The study was approved by the Institutional Review Board to ensure all procedures were considered ethical. All new admissions to the SCI unit were screened by a psychologist. Those patients who met the study criteria were approached to be part of the study. For interested patients, a psychologist or research team member explained the study and completed the consent process. All sub-

<table>
<thead>
<tr>
<th>Injury details</th>
<th>N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical</td>
<td>12</td>
<td>48</td>
</tr>
<tr>
<td>Thoracic</td>
<td>11</td>
<td>44</td>
</tr>
<tr>
<td>Lumbar</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Unknown</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>ASIA Impairment Scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Sensory complete</td>
<td>7</td>
<td>28</td>
</tr>
<tr>
<td>Motor complete</td>
<td>7</td>
<td>28</td>
</tr>
<tr>
<td>Motor complete</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Unknown</td>
<td>2</td>
<td>8</td>
</tr>
</tbody>
</table>
sequent contacts occurred in a private location (e.g., private room or designated hospital meeting room). Participants were either seen during the course of the rehabilitation therapies, in the late afternoon after therapies, or on the weekends. Depending on the participant’s preference and mobility level, all aspects of the study were completed in a wheelchair or hospital bed. A more extensive screening including all measures related to cognition, mood, and physical status was completed at initial contact. Select measures were repeated immediately before the BCI paradigm and at the final contact. The BCI game was displayed on a 12 in. laptop screen. After the relevant areas on the face and mastoids had been cleaned, the Emotiv EEG headset (see Figure 1) was positioned on the participant’s head. The examiner verified impedances in connections between each electrode and the participant’s scalp.

**Measures**

Participants completed a demographic questionnaire along with specific measures of cognition, mood, and physical status collected solely for the purpose of this study. Initially, individuals completed a brief cognitive screening to assess (a) current attention and processing speed abilities and (b) premorbid cognitive functioning. Attention and processing speed were measured using the Digit Span and Letter-Number Sequencing subtests of the Wechsler Adult Intelligence Scale–Third Edition (Wechsler, 1997) and the Oral Trail Making Test (Ricker, Houtler, & Axelrod, 1996). A single word reading test, the Wechsler Test of Adult Reading (Wechsler, 2001), was used to help estimate premorbid cognitive functioning. Mood was assessed using the Patient Health Questionnaire-9 (Kroenke, Spitzer, & Williams, 2001) and the State Mood Measure from the Profile of Mood States (McNair, Lorr, & Droppleman, 1971). The Pain Disability Index of the McGill Pain Questionnaire (Melzack, 1987) was used to assess perceived disability due to pain and average daily pain across contact points. The participants were also informally asked about pain during the BCI training to provide additional information about any discomfort in real time. The participant’s ability to become mentally absorbed in everyday activities was measured with the Tellegen Absorption Scale (Tellegen & Atkinson, 1974). Finally, semistructured qualitative questions developed specifically for this study inquired about participants’ prior recreation activities, prior video game experience/interest, and a subjective measure of the gaming experience within this study.

**Apparatus**

A BCI was used for acquiring brain-based information (e.g., via EEG-based device with scalp electrodes) that allowed for extraction of target information and identification of patterns linked to intent. This required analysis of signals by a system that aims to minimize nonessential physiological responses, movements and background noise (Lin et al., 2010). It is essential that the BCI system provides the user real time feedback and be flexible enough to meet the needs of its user (Mak & Wolpaw, 2009). One such device is the Emotiv EPOC headset, an inexpensive consumer-grade device, which was initially developed for the gaming industry but has recently been used in various research studies (Andujar, Ekandem, Alvarez, James, & Gilbert, 2011; Badcock et al., 2013; Dutta et al., 2013; Inventado, Legaspi, Suarez, & Numao, 2011; McMahan, Parberry, & Parsons, 2015a, 2015b; Pham & Tran, 2012). The Emotiv EPOC is a compact, wireless headset that requires comparatively little effort to set up and allows much greater flexibility and mobility than traditional EEG. The EPOC was aimed at the gaming market, and is not classified as a medical device, though several researchers have since adopted it for a variety of applications (Cinar & Sahin, 2013; Rosas-Cholula, Ramírez-Cortes, Martínez-Carballido, Alarcón-Aquino, & Gomez-Gil, 2010; Vi & Subramanian, 2012). Using the EPOC, researchers can detect facial movements, emotional states, and imagined motor movement.

![Figure 1. Emotiv electroencephalography and sensor placement](http://emotiv.com/media). See the online article for the color version of this figure.
This Emotiv EEG headset has 14 electrodes (saline sensors) locating at AF3, AF4, F3, F4, F7, F8, FC5, FC6, P7, P8, T7, T8, O1, O2 (see Figure 1) and two additional sensors that serve as Common Mode Sense (CMS)/Driven Right Leg (DRL) reference channels (one for the left and the other for the right hemisphere of the head). The Emotiv EEG’s 14 data channels are spatially organized using the International 10–20 system. The Emotiv EPOC headset does not require a moistened cap to improve conduction. The sampling rate is 128 Hz, the bandwidth is 0.2–45 Hz, and the digital notch filters are at 50 Hz and 60 Hz. The device yields less sophisticated EEG data than cost prohibitive traditional medical devices (Duvinage et al., 2013), but the ease of use and portability make it a preferred system within a hospital setting. Data transfer occurs wirelessly to a Windows based laptop via Bluetooth and USB dongle.

**Description of BCI Paradigm**

This study utilized a cube rotation game which begins with the participant initially being instructed to relax to create a “neutral condition” with no cube movement. Training progresses with an emphasis on imagining pushing or rolling the cube in a consistent fashion. Reminders to minimize facial or bodily movement are used as needed to minimize interference with the BCI analysis program. Following a training session for each movement (i.e., push, left, right, and cube disappearance), participants performed three trials, lasting 8 s each, focused on moving the cube in the trained direction. This paradigm was chosen due to the brevity and graduated complexity of the task in hopes that determining factors related to successful BCI completion could be explored. The task does require basic cognitive functions, such as attention to the visual stimuli and comprehension of directions, but was not considered to be heavily dependent on cognitive abilities or prior experience with computer interfaces.

**Data Analysis**

Participant characteristics along with measures developed for this study to understand computer use, interest in the study, competency ratings, and enjoyment of the BCI were summarized with means and standard deviations, medians, or counts and percentages. Means and standard deviations were used for the BCI trial results. To determine if participants’ cognitive testing scores were associated with BCI gaming results, Spearman and Pearson correlations were used, as appropriate. Comparison of patients with less than 10 completed trials versus 10 or more trials was performed with Wilcoxon’s rank sum tests for quantitative variables, and Fisher’s exact tests for categorical variables.

**Results**

The data speak encouragingly to the feasibility focus of the study. Participants across varying severities of SCI completed the BCI without adverse effects. Specifically, questions about headaches, nausea, vertigo, discomfort and other potential complication were queried. On three occasions, the BCI trial was rescheduled prior to onset due to participant complaints of intrusive pain or significant fatigue related to rehabilitation therapies. The participants were quite receptive to the BCI activity and the majority reported enjoying the experience (79.2 ± 23.9 on 1–100 scale with 100 indicating maximal enjoyment). Despite approximately half the participants indicating little to no experience with computers, participants generally felt competent during the BCI game (69.1 ± 28.4 on 1–100 scale with 100 indicating maximal competency). Furthermore, the collective data (see Table 2 below) support that participants were more successful than they perceived with the caveat that two participants did not have any successful trials.

A review of participant characteristics revealed no relationship between BCI performance and age, demographic variables, educational achievement, or vocation. Individuals who rated their computer competency higher at pretesting were slightly quicker to create movement across trials ($r = .45, p = .032$), yet the number of successful trials, average time to reach maximum movement, and mean power level accomplished were not significantly related to prior computer use or skill level ($p > .05$).

The inclusion of cognitive testing, screening of psychiatric distress and self-reported pain was based on the premise that such factors may impact BCI performance. Cognitive test scores were not generally correlated with BCI performance (see Table 3) and were quite similar across those who completed less than 10 trials versus those who completed 10–12 trials (see Table 4). There were also no significant relationships between cognitive testing outcomes and individual BCI tasks performance (i.e., push, left, right, and cube disappearance). Mood ratings were not significantly related to BCI performance. Furthermore, pain ratings were generally stable across the three contacts and higher pain ratings were actually correlated with better BCI performance ($r = .77, p \leq .001$).

A review of the demographics, injury related information, and test data did not reveal any specific trends for the two outliers unable to complete any trials. The possibility of technology failure could not be ruled out for these cases. Of the seven participants who completed less than 10 of the 12 trials, five had a history of head injury. In contrast, only two of the 18 participants completing 10 or more trials had such a history. Analysis of specific cognitive test measures did not show significant differences in scores among those who did versus did not report a head injury. This finding must be interpreted in light of the screening criteria which excluded individuals with moderate to severe deficits from recent head injury/medical complications or severe persistent deficits from remote events.

**Discussion**

This study adds to the cautious enthusiasm regarding the use of BCI technology with clinical populations. Our participants gener-

<table>
<thead>
<tr>
<th>Summary of Brain–Computer Interface (BCI) Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCI data</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>Number of successful trials*</td>
</tr>
<tr>
<td>Percentage of successful trials</td>
</tr>
<tr>
<td>Average time (seconds) to movement</td>
</tr>
<tr>
<td>Mean power accomplished</td>
</tr>
</tbody>
</table>

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* Two participants did not have any successful trials.
Table 3

Correlation Between Neuropsychological Evaluation and Combined BCI Results

<table>
<thead>
<tr>
<th>Item/Test</th>
<th>Number of successful trials</th>
<th>Average time to create any movement across all trials</th>
<th>Average time to reach maximum movement on all trials</th>
<th>Mean power level accomplished across all trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>I have avoided computers(^a)</td>
<td>−0.03 (.884)</td>
<td>.04 (.848)</td>
<td>.03 (.866)</td>
<td>.18 (.409)</td>
</tr>
<tr>
<td>Computer competency(^b)</td>
<td>−0.29 (.165)</td>
<td>.42 (.045)</td>
<td>.57 (.082)</td>
<td>−.16 (.458)</td>
</tr>
<tr>
<td>Wechsler Test of Adult Reasoning(^b)</td>
<td>−.15 (.485)</td>
<td>−.23 (.287)</td>
<td>.08 (.731)</td>
<td>.25 (.256)</td>
</tr>
<tr>
<td>WAIS Digit Span(^b)</td>
<td>−.03 (.883)</td>
<td>.05 (.817)</td>
<td>−.04 (.871)</td>
<td>.05 (.838)</td>
</tr>
<tr>
<td>WAIS Letter Number Sequencing(^b)</td>
<td>−.42 (.036)</td>
<td>.01 (.972)</td>
<td>.01 (.962)</td>
<td>−10.639</td>
</tr>
<tr>
<td>Oral Trails A(^b)</td>
<td>.09 (.667)</td>
<td>.11 (.609)</td>
<td>.31 (.156)</td>
<td>.13 (.557)</td>
</tr>
<tr>
<td>Oral Trails B(^b)</td>
<td>−.10 (.644)</td>
<td>−.28 (.201)</td>
<td>−.16 (.455)</td>
<td>.05 (.823)</td>
</tr>
<tr>
<td>Patient Health Questionnaire-9 score(^a)</td>
<td>.11 (.592)</td>
<td>−.31 (.146)</td>
<td>−.07 (.747)</td>
<td>.27 (.212)</td>
</tr>
<tr>
<td>Pain Disability Index score(^b)</td>
<td>−.30 (.139)</td>
<td>−.15 (.488)</td>
<td>.19 (.383)</td>
<td>.01 (.980)</td>
</tr>
<tr>
<td>Tellegen Absorption Scale(^b)</td>
<td>−.25 (.224)</td>
<td>.20 (.364)</td>
<td>.26 (.227)</td>
<td>−12.587</td>
</tr>
<tr>
<td>McGill Pain Questionnaire(^a)</td>
<td>.77 (&lt;.001)</td>
<td>−.51 (.013)</td>
<td>.17 (.440)</td>
<td>.53 (009)</td>
</tr>
<tr>
<td>Baseline gaming interest(^b)</td>
<td>.37 (.072)</td>
<td>−.24 (.274)</td>
<td>−.09 (.682)</td>
<td>.17 (.432)</td>
</tr>
</tbody>
</table>

Note. WAIS = Wechsler Adult Intelligence Scale. Bold face values indicate significant findings. 
\(^a\) Spearman rank correlation (p value). \(^b\) Pearson correlation (p value).

Table 4

Comparing Data Between Those Who Completed 10 or More Trials and Those Who Did Not, Excluding Two Patients With No Successful Trials

<table>
<thead>
<tr>
<th>Item/Test</th>
<th>&lt;10 Trials (N = 5)</th>
<th>10–12 Trials (N = 18)</th>
<th>p value(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoids computers</td>
<td>2 (18%)</td>
<td>4 (22%)</td>
<td>1.00</td>
</tr>
<tr>
<td>Inexperienced with computers</td>
<td>0 (0%)</td>
<td>3 (17%)</td>
<td>1.00</td>
</tr>
<tr>
<td>Wechsler Test of Adult Reasoning(^a)</td>
<td>45.2 ± 13.7</td>
<td>46.8 ± 11.1</td>
<td>.8536</td>
</tr>
<tr>
<td>WAIS Digit Span(^a)</td>
<td>47.2 ± 5.4</td>
<td>48.4 ± 7.4</td>
<td>.9092</td>
</tr>
<tr>
<td>WAIS Letter Number Sequencing(^a)</td>
<td>45.4 ± 12.1</td>
<td>46.4 ± 9.5</td>
<td>1.00</td>
</tr>
<tr>
<td>Oral Trails A(^a)</td>
<td>39.4 ± 15.9</td>
<td>40.5 ± 10.9</td>
<td>.8517</td>
</tr>
<tr>
<td>Oral Trails B(^b)</td>
<td>35.2 ± 19.3</td>
<td>42.9 ± 15</td>
<td>.3126</td>
</tr>
<tr>
<td>Patient Health Questionnaire-9 score(^a)</td>
<td>3.4 ± 4.0</td>
<td>4.3 ± 3.3</td>
<td>.5235</td>
</tr>
<tr>
<td>Pain Disability Index score(^a)</td>
<td>24.2 ± 17.7</td>
<td>21.5 ± 15.9</td>
<td>.7372</td>
</tr>
<tr>
<td>Tellegen Absorption Scale(^a)</td>
<td>43.2 ± 18.5</td>
<td>46.7 ± 26.6</td>
<td>.8521</td>
</tr>
<tr>
<td>McGill Pain Questionnaire(^a)</td>
<td>2 ± 4</td>
<td>4.1 ± 2.0</td>
<td>.0015</td>
</tr>
<tr>
<td>Gaming interest(^b)</td>
<td>74 ± 25.1</td>
<td>80 ± 13.9</td>
<td>.6493</td>
</tr>
</tbody>
</table>

Note. WAIS = Wechsler Adult Intelligence Scale. 
\(^a\) Mean and standard deviations are reported for all quantitative variables. \(^b\) Wilcoxon rank-sum tests used for quantitative variables and Fisher exact tests used for categorical variables.
adverse effects from prolonged and repeated BCI sessions. Furthermore, understanding participant strategies to increase mastery of more involved BCI exercises will be helpful in creating clinically relevant virtual environments which would undoubtedly be more elaborate and time intensive.

Even with this brief BCI paradigm, there were challenges with implementation due to the busy inpatient setting. The use of noise cancellation devices outside of the hospital room and doing BCI after typical therapy hours are worthy of consideration given the need to minimize distractions. Individual variables such as fatigue, pain, and medication effects may have likewise affected participant preference of morning or afternoon participation sessions, suggesting the need for flexible scheduling if possible.

While there are no comparison rates of recruitment, the consensus was that the BCI was well received by inpatients who often verbalized enthusiasm to trial the device. Those who declined tended to be females (five of seven) above 40 years of age. When queried, these potential subjects primarily verbalized limited interest in the technology. Future studies should further explore whether gender, age, and cultural factors are related to openness to using BCI.

Overall, there were minimal complications related to technology malfunction. On a few occasions, headset or sensor malfunctions prohibited running subjects. Considering the reasonable price of the technology, having multiple units would be preferable. This would also eliminate delays related to recharging the battery. Training for the administration of the paradigm was not time intensive and did not require extensive computer or medical technology expertise. As such, with more clinically relevant paradigms, it would be preferable to have a certified rehabilitation professional conduct the intervention. Our research group also had the advantage of access to multiple information technology specialists to address any headset or program complications. This luxury, which may not be available in most locations, minimized potential interruptions in patient care during the current study.

Ultimately, the utility and adoption of BCI in rehabilitation settings will be dependent upon more sophisticated programs that target measurable clinical goals. Future studies will then need to determine if BCI and advanced technologies show treatment gains as compared to traditional interventions. The potential for BCI remains intriguing yet much work needs to be done before this modality can be considered as a viable adjunct to current rehabilitation programs. The current study provides preliminary but essential support for the feasibility and safety of this technology in the inpatient setting.

References
BRAIN–COMPUTER INTERFACE AND SPINAL CORD INJURY


Received March 24, 2015
Revision received June 16, 2016
Accepted June 17, 2016

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