Brain Activity in People with Spinal Cord Injury, with Applications to Brain-Computer Interfaces for Neuroprosthetic Control

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CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Publications

Publications arising from this thesis

Discrimination of Left and Right Hip Motor Imagery for Neuroprosthetic Brain-Computer Interfaces

Boord P, Craig A, Tran Y, Nguyen H.

Submitted to *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18 April 2005

Brain-Computer Interface – FES Integration: Towards a hands-free neuroprosthesis command system

Boord P, Barriskill A, Craig A, Nguyen H.

Published in *Neuromodulation*, 7(4):267-276 (2004)

Levels of brain wave activity (8-13 Hz) in persons with spinal cord injury

Tran Y, Boord P, Middleton J, Craig A.

Published in *Spinal Cord* 42:73-79 (2003)

Alpha band activity during eye-closure in people with spinal cord injury

Boord, P., Tran, Y., Middleton, J., Craig, A., & Barriskill, A.

Published in *Proceedings of the 8th International Functional Electrical Stimulation Society Conference*, pp. 265-268 (2003)

Developing a "hands-free" neuroprosthesis command system

Boord P, Craig A, Barriskill A, Nguyen H.

Published in *Proceedings of the 8th International Functional Electrical Stimulation Society Conference,* pp.7-10 (2003)

Other related publications

Altered brain wave activity in persons with chronic spinal cord injury

Herbert D, Tran Y, Craig A, Boord P, Middleton J, Siddall P.

Submitted to *International Journal of Neuroscience* 2005

The efficacy and benefits of environmental control systems for the severely disabled

Craig A, Tran Y, McIsaac P, Boord P.

Published in Medical Science Monitor 11(1):RA32-9 (2005)

Using independent component analysis to remove artefact from EEG measured during stuttered speech

Tran Y, Craig A, Boord P, Craig D.

Published in Medical & Biological Engineering & Computing 42(5):627-33 (2004)

The Mind Switch Environmental Control System: Remote Hands Free Control for the Profoundly Disabled

McIsaac P, Craig A, Tran Y, Boord P.

Published in Technology and Disability 14:15-20 (2002)

Abstracts

Evidence of reduced intracortical inhibition as a mechanism of neuropathic pain in spinal cord injury

Boord PR, Siddall P, Tran Y, Herbert D, Middleton J, Craig A.

Published in *Proceedings of the International Association for the Study of Pain 11th World Congress on Pain* (2005)

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Thesis abstract

The aim of this thesis was to investigate brain activity changes in people with spinal cord injury (SCI), the possible basis for such changes, and the impact these changes are likely to have on signals used by brain-computer interfaces (BCI). BCI monitor brain activity and issue commands to operate electrical devices upon detection of specific changes in brain activity under a users control. BCI development is usually conducted with able-bodied people (for the sake of convenience), with the general assumption that the BCI developed will also be suitable for people with disabilities. This assumption may be flawed because the disability may be associated with significant changes in the brain activity signals used by BCI. Due to the paucity of BCI research in SCI, it is important to assess brain activity in people with SCI to determine if BCI are a suitable means of hands-free control in this population.

BCI could have significant potential for the operation of neuroprostheses in SCI. Neuroprostheses restore lost motor function to people with SCI through the patterned electrical stimulation of paralysed muscles, and have been used to restore hand grasp and release in people with tetraplegia, and standing and stepping in people with paraplegia. Restoring lost motor function brings with it the problem of how the restored function is to be operated by the user. SCI, by its very nature, reduces the capacity to voluntarily control the musculature, and therefore limits the ability of a user to issue commands to a neuroprosthesis. Chapter 1 critically reviewed the command interface requirements of neuroprostheses, and the ability of various BCI to meet those requirements. The review highlighted the potential of two BCI types potentially suited to neuroprosthetic control: 1) BCI based on the detection of eye-closure, and 2) BCI based on the detection of imagined movement of the lower extremities; referred to as eye-closure based BCI (EC-based BCI), and mental motor imagery based BCI (MMI-based BCI) respectively.

The studies in this thesis focused on brain activity in SCI during rest, movement and mental motor imagery (MMI). Chapter 2 examined brain activity in SCI and able-bodied groups during rest with the eyes-open (EO) and eyes-closed (EC). Studies were conducted to compare differences in brain activity with lesion level (paraplegia or tetraplegia), and with the presence/absence of neuropathic pain. Neuropathic pain is an

intractable disease that occurs in about 50% of people with SCI, and whose aetiology is largely unknown. There is evidence to suggest, however, that central mechanisms are involved in the genesis of neuropathic pain, so a separate study was conducted to identify brain activity changes with SCI neuropathic pain and the potential effect of these changes on BCI performance. Brain activity was measured with the electroencephalogram (EEG), which uses sensors to record small signals on the scalp reflecting underlying neuronal activity in the brain. The EEG was spectrally analysed to obtain measures of signal power in the delta, theta, alpha, beta, and gamma frequency bands. This allowed comparison of the results with the wide body of EEG literature, and helped to elucidate the changes in the brain associated with SCI. A notable finding in this thesis was of brain activity changes in people with tetraplegia that were similar to changes associated with neuronal atrophy, suggesting that people with tetraplegia may be more likely to suffer cognitive impairments and be at greater risk of developing dementia of the Alzheimer's type. Brain activity changes were also observed in people with SCI neuropathic pain, supporting and extending the view of how central processes may be involved in the genesis of this disease.

For sophisticated neuroprosthetic control, BCI need to be developed beyond the single-command capability of the EC-based BCI. To identify additional BCI signals, the study in Chapter 3 focused on brain activity in able-bodied people reactive to imagined movement of the lower extremities. BCI signals have previously been obtained by imagination of the feet, but it has not been possible to detect differences in the EEG between the left and right foot, due to the location of the cortical foot representation in the brain. To counter this difficulty the study in Chapter 3 investigated imagined movement of the left and right hip and found that they could be distinguished in the EEG. This finding gave support to the proposal that lower extremity motor imagery could be used for the operation of neuroprostheses in SCI.

A difficulty in detecting brain reactivity to imagined movement arises because the exact moment of movement imagination cannot be measured. This is in contrast to executed movement, where the precise moment of movement can be detected from sensors attached to the limb being moved. Brain activity reactive to imagined movement has been demonstrated as a potential BCI signal, but it has been suggested that it may not be detected among all people. The study in Chapter 3 employed a novel approach for the detection of brain activity reactive to imagined movement, and demonstrated that BCI signals reactive to motor imagery are widely prevalent in able-bodied people.

After finding significant changes in brain activity during rest in people with SCI compared with able-bodied controls in Chapter 2, it was necessary in Chapter 4 to examine and confirm if left and right hip motor imagery could be distinguished in people with SCI. The study found that left and right hip motor imagery could be distinguished in people with paraplegia, though with a diminished capacity compared with able-bodied controls. The ability to distinguish between left and right hip motor imagery was further diminished in people with tetraplegia. The study, however, found little difference in brain activity reactive to imagined movement in the beta frequency band. These signals have been successfully used as a BCI signal in a single-case study of a person with tetraplegia, but with a lack of replication, it has remained unknown whether these signals can be detected widely in people with SCI. The findings in Chapter 4 show that beta frequency band signals reactive to motor imagery are widely prevalent among people with SCI, suggesting that these signals have potential for use in BCI for neuroprosthetic control.

Abbreviations

Abbreviation	Phrase
ASIA	American Spinal Injury Association
BCI	Brain-Computer Interface
CMS	Common Mode Sense
DRL	Driven Right Leg
EC	Eyes-Closed
ECS	Environmental Control System
EEG	Electroencephalogram
EMG	Electromyogram
EO	Eyes-Open
EOG	Electrooculogram
ERD	Event Related Desynchronisation
ERS	Event Related Synchronisation
ICA	Independent Component Analysis
LE	Lower Extremity
MEG	Magnetoencephalogram
MMI	Mental Motor Imagery
MRI	Magnetic Resonance Imaging
PAF	Peak Alpha Frequency
PIBS	Post-Imagination Beta Synchronisation
PMBS	Post-Movement Beta Synchronisation
PSD	Power Spectral Density
PTAF	Peak Theta-Alpha Frequency

SCI	Spinal Cord Injury
SSC	Somatosensory Cortex
TBI	Traumatic Brain Injury
TCD	Thalamocortical Dysrhythmia
TMS	Transcranial Magnetic Stimulation