Muscle  CNS  Sensor

> 80 ms

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About the Rehabilitation Engineering Lab

History

The Rehabilitation Engineering Laboratory was established in 2001 at the Lyndhurst Centre of Toronto Rehab. In 2006, the laboratory underwent a major renovation, doubling the amount of space available for personnel and experiments.

What We Do

We develop advanced technologies for spinal cord injury (SCI) and stroke rehabilitation. These include brain/machine interfaces, assessment tools for determining an individual’s level of function, and rehabilitation techniques for restoring walking and grasping ability. We also design neuroprosthesis systems to assist individuals with tasks such as walking, grasping, and balance during standing and sitting.

Most of our work is based on functional electrical stimulation (FES), which uses electricity to cause muscles to contract. FES can be used to provide movement to paralyzed muscles or to re-train weak muscles or the central nervous system.

Accomplishments – 2006 to 2008

- Developed FES therapies for neuro-rehabilitation in stroke and SCI
- Provided FES therapy to more than 50 individuals with SCI or stroke
- Published more than 22 peer-reviewed journal papers
- Obtained more than $2,000,000 in funding for SCI and stroke research
- Trained 8 postdoctoral fellows, and 16 graduate students in SCI and stroke research, who obtained an additional $1,200,000 in funding

Want to Get Involved?

We’re always looking for participants for our studies, volunteers to help us with the experiments, students and research collaborators. If you’d like to join us, please feel free to contact us at 416-597-3422 ext. 6206, or via e-mail at milos.popovic@utoronto.ca.
Research at the Rehabilitation Engineering Laboratory

Neuroprosthesis for Reaching and Grasping

Our reaching and grasping neuroprosthesis is designed for individuals who cannot reach and/or grasp voluntarily. These individuals are able to use the system to pick up and manipulate objects, and can significantly improve their independence in activities of daily living. People who have SCI at C5-C7 level or stroke have used this system as a rehabilitation tool to assist in retraining reaching and grasping.

Neuroprosthesis for Walking

The purpose of the neuroprosthesis for walking program is to demonstrate the long-term benefits of FES therapy on walking function in patients with incomplete SCI and stroke. Our pilot study showed a significant improvement in walking speed and/or a reduction in the use of assistive devices for walking after using the neuroprosthesis. We are currently conducting a randomized treatment-vs-control study to verify that these benefits truly resulted from FES-assisted therapy.

Neuroprosthesis for Sitting

Trunk instability is a major problem for many people with SCI that affects their independence and ability to perform activities of daily living. The long-term objective of this project is to produce a new device that will improve sitting stability by stimulating paralyzed trunk muscles using FES. This sitting neuroprosthesis will improve the ability of people with SCI to perform such tasks as reaching and wheeling. We are currently studying the mechanisms of balance in the trunk and the consequences of muscle paralysis on these mechanisms. This analysis will form the basis for developing the FES system for balance during sitting.
Neuroprosthesis for Standing

The neuroprosthesis for standing and balancing is a device that will allow some neurologic patients to stand up, perform stable “hands-free” standing, and sit down again. At least two applications of this technology are envisioned: 1) this device will be used as an independent system to allow complete SCI patients to stand; and 2) to retrain standing function and balance control in incomplete SCI, stroke and elderly patients through active, repetitive, balance training sessions. Besides the obvious functional benefits, this neuroprosthesis would also help maintain bone density and prevent pressure sores by allowing people to stand for extended periods of time.

Human-Machine Interfaces

Understanding the relationship between an assistive device and its user is a fundamental step towards designing better systems. The human-machine interface project focuses on developing new communication strategies and methodologies to allow users to have more natural control over an assistive device. One aspect of this work is our research into brain-machine interfacing, which investigates the relationship between intended arm movement and electroencephalogram (EEG) signals from the motor cortex of the brain.

Equipment

The Rehabilitation Engineering Laboratory has a variety of research equipment including:

- Compex II stimulators
- Body weight support treadmill
- Force plates
- Polhemus motion capture system
- Optotrack dual camera motion capture systems
- Erigo tilt table with motorized leg movement
- Electromagnetically shielded room for EMG and EEG measurements
- Vibration platforms
- REL-PAPPS perturbation system
Our People

Principal Investigators

• Dr. Milos R. Popovic, Head of the Laboratory, Toronto Rehab Chair in Spinal Cord Injury Research, Senior Scientist, and Associate Professor
• Dr. Mary Nagai, Research Scientist and Assistant Professor
• Dr. Kei Masani, Research Scientist

Postdoctoral Fellows

• Dr. Judith Hunter (neuroscience), Postdoctoral Fellow
• Dr. Richard Preuss (physiotherapy), Postdoctoral Fellow
• Dr. Dimitry Sayenko (medical doctor), Postdoctoral Fellow
• Dr. Masae Miyatani (exercise physiology), Postdoctoral Fellow
• Dr. Dany Gagnon (physiotherapy), Postdoctoral Fellow

Graduate Students

• Cheryl Lynch, PhD student
• Cesar Marques Chin, PhD student
• Albert Vette, PhD student
• José Zariffa, PhD student
• Davide Agnello, MASc student
• Milad Alizadeh-Meghrazi, MASc student
• Rob Babona Pilipos, MASc student
• Steve McGie, MASc student
• Egor Sanin, MASc student
• John Tan, MASc student
• Massimo Tarulli, MASc student
• Takashi Yoshida, MASc student

Support Staff

• Shaghayegh Bagher, Research Engineer
• Zina Bezruk, Administrative Assistant
• Abdul Bulsen, Research Engineer
• Betty Chan, Grants & Accounts Coordinator
• Suzy Iafolla, Physiotherapist
• Naaz Kapadia, REL Manager, Research Coordinator and Physiotherapist
• Abdulazim Rashidi, Research Engineer
• Dr. Vera Zivanovic, Research Coordinator

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# Awards

**Dr. Milos R. Popovic**

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<tr>
<th>Year</th>
<th>Award Description</th>
<th>Institution</th>
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<tr>
<td>2008</td>
<td>Professional Engineers Research and Development Award</td>
<td>Professional Engineers of Ontario and Ontario Society of Professional Engineers</td>
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<td>2007</td>
<td>Toronto Rehab Chair in Spinal Cord Injury Research</td>
<td>Toronto Rehabilitation Institute</td>
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**Albert Vette**

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<td>2008</td>
<td>Norman F. Moody Award in recognition of academic excellence</td>
<td>Institute of Biomaterials and Biomedical Engineering, University of Toronto</td>
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<td>2008</td>
<td>Best Student Paper Award – Second Place</td>
<td>13th Annual Conference of the International FES Society, Freiburg, Germany, September 21-25, 2008</td>
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<td>2007</td>
<td>Engineering Postgraduate Prize for most Outstanding Doctoral Candidate</td>
<td>Natural Sciences and Engineering Research Council of Canada</td>
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**Jose Zariffa**

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<td>2007</td>
<td>Best Student Paper Award – Third Place</td>
<td>30th Canadian Medical and Biological Engineering Conference, FICCDAT, Toronto, Canada, June 16-19, 2007.</td>
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**Dr. Judith Hunter**

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<td>2007</td>
<td>Northrop Frye Award</td>
<td>University of Toronto</td>
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Recent Research Posters

Neuroprosthesis for Grasping

1. “Functional electrical therapy: Retraining reaching and grasping functions in severe hemiplegic patients”
3. “FES therapy: Restoring voluntary grasping function”

Neuroprosthesis for Walking

4. “Necessity of successive sensory feedback to update the internal model for walking”
5. “Oxygen uptake during FES treadmill walking: Case study”

Neuroprosthesis for Standing

6. “Frequency response of stimulated knee movement”
7. “Optimal combination of minimum degrees of freedom to be actuated for the facilitation of arm-free paraplegic standing”
8. “Step prediction during perturbed standing using center of pressure measurements”
9. “Control mechanism of ankle muscles during standing”
10. “Motor command of proportional and derivative (PD) controller can match ankle torque modulation during quiet stance”
11. “Stochastic modeling of knee response”

Neuroprosthesis for Sitting

12. “Muscle recruitment patterns in perturbed sitting”
13. “Center of pressure excursion during voluntary trunk movement in sitting”
14. “Posturography measures during quiet sitting”
Human-Machine Interfaces

15. “Identifying movements from cortical signals”
16. “Localizing active pathways in peripheral nerves”
17. “Control of multiple degree-of-freedom tasks using one-dimensional electroencephalographic signals”
18. “ECoG controlled neuroprosthesis for grasping: Preliminary study”
19. “Influence of the number and location of recording contacts on the selectivity of a nerve cuff electrode”

Other Projects

21. “A test-of-principle prototype for a new device to measure a specific pain mechanism: Translating pain neuroscience theory into a clinical/research tool”
22. “Cardiovascular response to FES and passive stepping to improve orthostatic tolerance”
24. “A new intramuscular electrode for functional electrical stimulation in the rat”
FUNCTIONAL ELECTRICAL THERAPY
M.R. Popovic, A.T. Thrasher and V. Zivanovic
Toronto Rehabilitation Institute and University of Toronto

Retraining Reaching and Grasping Functions in Severe Hemiplegic Patients

Materials and Methods

PARTICIPANTS:
- Stroke patients with severe unilateral upper extremity paralysis.
- Chedoke McMaster Stages of Motor Recovery scores 1 or 2 measured at least three weeks after onset of stroke.
- Participants unable to voluntarily:
  - flex, extend, abduct, adduct, or rotate the shoulder;
  - flex or extend the elbow;
  - pronate or supinate the forearm;
  - flex, extend, abduct or adduct the wrist;
  - move any fingers;
- Participants were acute (0 – 6 weeks post stroke) or long-term (12 months after stroke).

Group A - control group had standard physiotherapy and occupational therapy alone.
Group B - treatment group had functional electrical stimulation (FES) therapy administered in addition to conventional physiotherapy and occupational therapy.

FUNCTIONAL TESTS:
- Functional Independence Measure (FIM)
- Barthel Index (BI)
- Chedoke McMaster Stages of Motor Recovery (CMSMR)
- Fugl-Meyer Assessment (FMA)
- REL Hand Function Test (REL) [1]

FES THERAPY PROTOCOL:
- Participant was asked to execute a task with the impaired arm (e.g. reaching and grasping a pen) unassisted.
- The components of the task that the participant was unable to carry out him/herself were assisted by the neuroprosthesis.
- Compex Motion neuroprosthesis was used for FES therapy [1].
- In the early stages of the treatment, the arm/hand tasks were performed by the neuroprosthesis alone.
- As the patient improved, the neuroprosthesis assistance was reduced to the necessary minimum and eventually was removed from the treatment protocol.
- The patient had three treatment sessions per week, 45 minutes per session, up to 16 weeks.

CONTROL GROUP PROTOCOL:
- Standard physiotherapy and occupational therapy
- Control group sessions were equal in length and intensity to the FES therapy sessions.

STATISTICAL ANALYSIS:
- Wilcoxon rank-sum test

Results

SUMMARY:
- The study was conducted with 24 stroke patients (8 female, 16 male; average age 56):
  - 15 participated in FES therapy
  - 9 were controls
- The difference between mean scores obtained on discharge and admission for both Groups A and B are shown in Fig 2.
- Significant differences were found between Groups A and B in terms of change of the FMA and the torque, force and eccentric load components of the REL Hand Function Test.
- The statistical analysis suggests that the FES therapy gives rise to greater improvement in arm and hand functions, compared to traditional physiotherapy and occupational therapy alone.

Fig. 1: a) Finger extension performed with the help of neuroprosthesis
   b) Voluntary finger flexion

FUNCTIONAL TESTS:
- Functional Independence Measure (FIM)
- Barthel Index (BI)
- Chedoke McMaster Stages of Motor Recovery (CMSMR)
- Fugl-Meyer Assessment (FMA)
- REL Hand Function Test (REL) [1]

Fig. 2: Differences between the after and before mean scores for: 1-5) REL Test; 6) FIM; 7) BI; 8) FMA; and 9) CMSMR tests. Statistical significance of the difference is presented as follows: * p < 0.05, and ** p < 0.01.

References:
Effect of Intensive Functional Electrical Therapy on the Upper Limb Motor Recovery after Stroke

--- Single Case Study of a Chronic Stroke Patient ---

Noritaka Kawashima 1,2,3, Vera Zivanovic 1,2, Milos R. Popovic 1,2

1 Institute of Biomaterial and Biomedical Engineering, University of Toronto, Canada
2 Lyndhurst Centre, Toronto Rehabilitation Institute, Canada
3 Japanese Society for Promotion of Science, Japan

1. Background

- Stroke survivors experience significant deficit of sensorimotor functions and half of them are left with major functional problems in their hands and arms.
- If recovery occurs it is mostly during the first four weeks after stroke and it is very rare that improvements occur in chronic stroke patients.

Functional Electrical Therapy (FET)
FET is a treatment that integrates electrical stimulation of sensory motor systems and repetitive functional movement of the paretic arm in hemiplegic patients.

During FET:
1. the subject can feel the proper movement of the paralyzed limbs and has been accomplished following their appropriate effort
2. sensory signals might be generated by the excitation of afferent pathways in the stimulated peripheral nerves

Recent studies reported a significant effect of the FET on recovery of upper extremity functions in stroke patients.

However... a potential to restore their upper arm functions, specifically in chronic stroke patients, is still not fully understood.

Question: What extent of motor recovery can be delivered by FET for chronic stroke patients?

Purpose: To investigate the effects of an intensive FET on motor recovery of a chronic stroke patient.

2. Methods

- Subject
A 22-year-old woman who had suffered a hemorrhagic stroke 2 years earlier.
While tactile sensation was not severely impaired, motor function of the upper extremity showed the typical flexor synergy pattern. The patient demonstrated increased resistance to passive stretch in the distal flexor musculature, and did not use her paretic upper limb for functional activities.

- FET program
The therapy consisted of two components:
1. Pre-programmed, coordinate muscular stimulation that coincided with the phase and type of arm motions that patient is trying to move. Stimulus intensity was 2 times larger than motor threshold
2. Manual assisted (externally generated) passive motion in order to establish physiologically correct movement

FET was administered twice times per day (one hour in each session) and carried out for 12 weeks. The patient had completed all training sessions (in total 108 sessions).

- Outcome Measures
1. Motor function
   - CMSA and MVC test
2. Spasticity assessment
   - MAS and H-reflex
3. Kinematical measurements
   - Drawing test, Dynamic ROM

4. Discussion

At the end of training, the patient was capable of picking up a thin object and touched her nose which could not be done prior to the training.

Motor Function
Maximal voluntary contraction level of upper arm muscles did not show remarkable improvements. CMSA scores for arm and hand also showed no changes.

- Muscle activation level (stimulus intensity) which dealt with FET was not enough to increase muscle strength in chronic stroke

Spasticity Assessment
A remarkable reduction of the arm spasticity was observed as indicated by the decrease of MAS and the reduction of H-reflex in the wrist flexor muscle (82.09% to 45.04% in the Hmax/Mmax).

- FET has a potential to decrease abnormal spinal motoneural excitability

Kinematical measurements
The results of the drawing test demonstrated an improvement of shoulder and elbow joint coordination. The subject also showed that a remarkable improvement of dynamic ROM of shoulder and elbow joints.

While motor recovery scored by CMSA scale and MVC level of upper arm muscles did not show remarkable changes, the patient showed improvement of upper arm functional motion.

- The improvement of the upper arm functional motion revealed by kinematical tests can attribute not to the motor recovery itself, but to the reduction of muscle tone and/or spasticity.
- This finding supports the classical concept that muscle tone reduction represents simplistic solutions to the deficit in motor control after stroke.

The present results suggest that intensive FET has the capability to improve upper arm functional movement, specifically by the reduction of muscle tone for chronic stroke patients.
**FES Therapy: Restoring Voluntary Grasping Function**

M.R. Popovic, N. Kawashima, M.E. Adams, R. Yee and V. Zivanovic

Lyndhurst Centre, Toronto Rehab
Institute of Biomaterials and Biomedical Engineering, University of Toronto

**FES Therapy for Individuals with Complete and Incomplete SCI**

**Novelty**
- Programmable transcutaneous FES system used to deliver short-term therapy
- Goal was to restore voluntary grasping function
- Both individuals with complete and incomplete SCI participated
- FES was not used as a permanent assistive device to facilitate grasping

**Methods**

**Subjects:**
- 23 individuals with acute C4 to C7 SCI
  - 8 complete
    - 3 FES therapy and 5 controls
  - 15 incomplete
    - 7 FES therapy and 8 controls
- On admission no active movement in the wrists and/or fingers - up to less than half the normal active range

**Assessments:**
- Assessments performed before and after the treatment period
- Hand function assessed using the REL Hand Function Test
- ADL assessed using FIM and SCIM
- Assessments made without FES

**Therapy:**
- **Controls** received two “doses” of regular OT and PT (2h per day), which may have included electrical stimulation for muscle strengthening without the functional component
- **Treatment group** received one “dose” of conventional therapy (1h per day) plus one “dose” individualized FES programs (1h per day) in which the neuroprosthesis was used to help the patients complete only those movements they were unable to produce on their own
- Treatment was 5 times per week, for up to 8 weeks

**Results**

**FIM**

*Pre* vs *Post* FIM scores for complete and incomplete SCI individuals.

**REL Object**, **REL Blocks**, **REL Torque**, **REL Force** graphs showing comparisons between groups.

**Conclusions**
- Repetitive daily FES therapy facilitated the carryover in hand function in all SCI individuals
- ASIA A, B, C and D participants in the treatment group showed larger improvements as compared to controls
- Frequently small improvements in the hand function resulted in considerable gains as measured by FIM

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Rehabilitation Engineering Laboratory
Institute of Biomaterials and Biomedical Engineering, University of Toronto

Contact: milos.popovic@utoronto.ca

www.toronto-fes.ca
1. Background

Walking is a highly sophisticated movement in human behavior.

- Even when we walk on an unstable surface, we can unconsciously accomplish stable walking within a few steps.
- Some evidences for the involvement of an internal model in the control of gait were suggested (Hodgson et al. 1994, Timoszyk et al. 2002, Lam et al. 2006).
- Given the previous finding about the internal model, two major mechanisms have been hypothesized to underlie the above phenomenon of walking:
  1. A predictive process according to previous experiences (i.e., using the internal model).
  2. A modifying process that detects a mismatch between the planned and actual movement (i.e., updating the internal model).

(Kawato et al. 1987)

2. Gait Experiment

According to self-contemplation, H.O. strongly relies on visual information during walking. He told us the following interesting experiences:

- He cannot walk with his eyes closed and is scared to walk in darkness.
- Interestingly, he needs several tens of seconds after the beginning of walking until he feels “walking is stable.”

In order to evaluate such an interesting phenomenon quantitatively, we have conducted the following very easy and simple gait experiment.

Methods

Subjects

- 1. Patient H.O. (64yrs, Stroke patient who has complete sensory loss)
- 2. Patient S.N. (61yrs, Stroke patient who has lacks both sensory and motor function)
- 3. Subject M.A. (34yrs, Able-bodied person)

Experiments consisted of three consecutive sets of walking at their comfortable speed. Stride time interval was evaluated from the data obtained from accelerometer (AS-10G, Kyowa Inc., Japan) placed on the lumber portion of the subjects (see below picture). The data was digitized (1 kHz) and stored in the memory of the data logging system (EDS-400, Kyowa Inc., Japan).

Results

Stride interval had larger variability, but kept within a certain range. Averaged stride time interval of patient H.O. was longer (slower) than that of M.A., but shorter (faster) than that of S.N.

Patient H.O. (sensory loss)

1.72

Patient S.N. (hemiplegic stroke)

1.40

Normal M.A.

1.20

S.I. (sec)


cf. Similar description was partly provided by Rothwell et al. (1982)

3. Patient's Information

H.O. is a 64 year old stroke patient. While he has complete sensory loss in the right side of the body, his motor function is very well preserved.

Does H.O. have internal model for walking?

Because H.O. is six years post injury, his walking performance has already been well established. Therefore, H.O. could presumably plan and accomplish the task of walking by using the internal model.

- Such adaptive changes might reflect the process which compensates for the lack of sensory feedback using the visual information.
- Once H.O. stops walking and resumes walking after one minute of break, it takes much time again to reestablish stable walking.

Compensatory process accomplished by the visual information can be used only temporally. This process significantly differs from updating the internal model in able-bodied individuals.

3.1. A modifying process that detects a mismatch because of his loss of sensory feedback.

The differences between the predicted and actual sensory feedback can be used as an error signal to update a predictive model.

(Wolpert and Ghahramani 2000)

3.1.1. Compensatory process accomplished by the visual information cannot be preserved as an internal model.

As a result, H.O. needs visually induced compensation for the sensory loss in each walk initiation.

4. Discussion

Main Results and Discussion

H.O. can seemingly walk well, but it takes several tens of seconds after the beginning of walking until the subject’s stride reaches a steady level. (Such adaptive changes were not observed in S.N.)

The present results strongly suggest that successive sensory feedback is an essential factor for updating the internal model of walking.

References:

Introduction

- People with spinal cord injury (SCI) need to exercise on a regular basis to prevent secondary complications, such as cardiovascular diseases, osteoporosis and obesity.
- To achieve the required fitness level is a challenging task for SCI patients because they have difficulty increasing their exercise intensity by their own.
- Functional electrical stimulation (FES) can restore movements by artificially contracting paralyzed or paretic muscles. Our previous study suggests that FES-assisted gait training has a positive effect on SCI patients (Thrasher et al. 2005).
- It is likely that FES-assisted gait training can provide the required cardiopulmonary exercise in SCI patients by increasing their leg muscle activity and energy consumption.
- However, to date, the physiological intensity of FES-assisted gait training has not been investigated.

Purpose

To examine the oxygen uptake and exercise intensity of FES-assisted gait training in patients with the motor-incomplete SCI.

Methods

- Participants: Two adults with incomplete SCI (participants A and B) and two able-bodied individuals (participants C and D) participated. The individuals with SCI completed 4 months of FES-assisted gait training prior to this study.
- FES System
  - Equipment: Compex Motion stimulators (Compex SA, Switzerland). Biphasic asymmetrical pulses (frequency 35Hz and pulse duration 0-300μs) were delivered to the body via eight self-adhesive gel electrodes.
  - Target Muscle: quadriceps, hamstrings, gastrocnemius /soleus and tibialis anterior
  - Pulse Amplitude: Participant A, B: 75% of the maximum FES induced contraction, Participant C, D: 20-25mA
  - FES Program: Feed-forward stimulation pattern triggered using two pushbuttons. For more details consult (Thrasher et al. 2005).

Experimental Protocol

- Walking Speed : 2.1km/h (participant A, C, D) and 2.5km/h (participant B)
- Protocol

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<th>Subject</th>
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<td>75.7</td>
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- Measurements
  - Measured Parameters: Oxygen Uptake (VO₂), Telemetric breath respiration measurement system (K4b2, Cosmed, Italy)
  - Calculated Parameter: Metabolic Equivalent (Index of exercise intensity): METs (1MET = 3.5 ml/kg/m VO₂ )
  - Stride length: Two-dimensional motion-analysis, the distance of the toe marker between two consecutive gate cycle (only participant A)

Results and Discussion

Oxygen Uptake during Rest, Non-FES Walking and FES Walking

- VO₂ was increased during FES walking compared to the initial Non-FES walking, and then decreased again during the second Non-FES walking in all four participants. The VO₂ increments in FES walking from the initial Non-FES walking were 9.0, 5.0, 10.6 and 20.8% in participant A, B, C and D respectively.

- METs values increased in FES walking in all four participants. METs values in participants A and B during FES walking (4-5 METs) corresponded to the level of moderate walking, which is the recommended daily physical exercise intensity by American college of sports medicine.

- Stride length during FES walking was significantly larger than that of 1st Non-FES walking. Stride length during 2nd Non-FES Walking was smaller than that of FES Walking, but there was no significant difference between two sessions. This preliminary result might suggest that the VO₂ increment in FES walking is due to the increment of stride length.

Conclusion

Oxygen consumption was increased in FES walking in all four participants. The intensities of FES walking in the SCI participants were 4.0 and 5.3 METs. Thus, FES walking can be used to increase the exercise intensity for individuals with SCI who in general have difficulty increasing their exercise intensity on their own.
FREQUENCY RESPONSE OF STIMULATED KNEE MOVEMENT

C. L. Lynch¹,², L. Mourra¹ and M. R. Popovic¹,²

¹Institute of Biomaterials & Biomedical Engineering, University of Toronto
²Toronto Rehabilitation Institute

What can the Bode plot tell us about electrical stimulation in SCI individuals?

Introduction

• Functional electrical stimulation (FES) can be used to restore motor function to paralyzed muscles in individuals with spinal cord injuries (SCI). FES uses electricity to generate muscle contractions.
• New FES applications, such as balance while standing and torso control while sitting, require closed-loop control of stimulated muscle contractions.

• A system’s frequency response provides information about the system’s dynamics, and is useful when developing closed-loop control systems [1].
• We determined the frequency response of electrically stimulated knee movements in an individual with complete SCI:
  • Input sinusoid – amplitude of stimulation delivered to muscle,
  • Output sinusoid – resulting knee angle.

Hypotheses

• The magnitude and phase responses will decrease with increasing fatigue
• The phase response will decrease with increasing frequency.

Methods

• The quadriceps muscle was stimulated to contract (stim. frequency = 25 Hz, pulse width = 250 μs), and resulting knee angle was recorded (see Fig. 1).
• The knee angle was made to follow a sinusoid by varying the stimulation amplitude sinusoidally between x and y mA:
  • x – minimum amplitude at which knee began to extend,
  • y – amplitude corresponding to maximum knee extension.
• Trials were conducted at different frequencies of stimulation sinusoid.

Results

• The quantities calculated for each trial: average phase shift, attenuation between stimulation waveform and knee angle.
• Figures 2 and 3 show the Bode plot of the stimulated knee movements.

Discussion

• The magnitude and phase responses decreased with increasing fatigue.
• The phase response decreased with increasing frequency.
• Future work:
  • Investigate the phase decrease at higher frequencies.
  • Extend this study to multiple subjects, multiple sessions.
  • Use results to describe system, then design closed-loop FES controller.

References

Optimal Combination of Minimum Degrees of Freedom to be Actuated for the Facilitation of Arm-Free Paraplegic Standing

Joon-Young Kim1,2, Albert H. Vette2,3, and Milos R. Popovic2,3

1 Department of Mechanical and Industrial Engineering, University of Toronto
2 Lyndhurst Centre, Toronto Rehabilitation Institute
3 Institute of Biomaterials and Biomedical Engineering, University of Toronto

Introduction

Background
Arm-free paraplegic standing by means of functional electrical stimulation (FES) has the potential to allow individuals with paraplegia to stand and at the same time use both arms to perform activities of daily living such as cooking and ironing. In this context, we have recently shown that only six of the existing twelve degrees of freedom (DOF) in the lower limbs need to be actuated to facilitate stable standing in the presence of external perturbations [Kim et al., 2006].

Methods

3D Dynamic Model
The 3D dynamic model, which represents the human body during double-support stance, is shown in Fig. 1 [Kim et al., 2006].

Inverse Dynamics Solution
Application of a computationally efficient inverse dynamics method [Nakamura et al., 1989]:
• driven by kinematic data from four healthy subjects;
• torque estimation for eight perturbation directions (D1 to D8 in Fig. 1);
• torque estimation for six combinations of six active DOF (Cases I to VI in Fig. 2) as identified in [Kim et al., 2006].

Results and Discussion

The torque sums for each case (Case I to VI) and each perturbation direction (D1 to D8) are shown in Fig. 3. The torque sums were calculated for a duration of 5 s after the perturbation.

Conclusions
• Cases V and VI (Fig. 2) exhibited the smallest torque sums (Fig. 3) for all subjects and perturbations.
• Due to the symmetry of the legs, this results in four combinations of six active DOF that are optimal with respect to the joint torque sums.

Fig. 1: Dynamic model of quiet standing with twelve DOF and eight perturbation directions (D1 to D8).

Fig. 2: Six cases of six DOF that need to be actuated in order to facilitate stable standing when external perturbations are present.

Fig. 3: Torque sums of the joint torques (5 s) at all active DOF, shown for each of the six cases and all directions of perturbation (D1 to D8).

• Cases V and VI (Fig. 2) exhibited the smallest torque sums (Fig. 3) for all subjects and perturbations.
• Due to the symmetry of the legs, this results in four combinations of six active DOF that are optimal with respect to the joint torque sums.

Conclusions
• Cases V and VI of six active DOF can achieve paraplegic arm-free standing while requiring minimum joint torques.
• The required joint torques can be generated by contemporary FES technology.
• FES-assisted arm-free standing is feasible even in the case where only six DOF in the lower limbs of a paraplegic can be actuated.
Introduction
The development of a center of pressure (COP) based step-prediction model for perturbed standing has a number of clinically relevant applications. For instance, it would contribute significantly to the development of a neuroprosthesis for stance regulation. This study investigated the feasibility of using COP and COP velocity (COPv) measurements to predict stepping.

Experiment
A perturbation device was used to perturb a subject engaged in quiet standing. The perturbation was applied in the anterior-posterior and lateral directions. The subjects were perturbed by various amount of loads. By larger loads, the subjects had to make a step. Our purpose in this experiment was to develop a step predictor that predicts if a person makes a step or not by measuring the force plate data.

Step Predictor
Using the result in Fig. 2B, the possibility of developing a step prediction model based on the thresholds (COPvth) in the COPvmax - COPmax plane was investigated. Two distinct threshold, the horizontal and vertical threshold, and their combination were tested.

The Horizontal Threshold

\[ \text{True; } \text{False } = \text{COP}_\text{max} \geq N_{\text{COP}} \cdot \left( b_1 \cdot \frac{\text{COP}_\text{vth}}{N_{\text{COP}}} + b_0 \right) \]

Note that \( b_1 \) and \( b_0 \) indicate the coefficients of the linear fit in Fig. 2B.

The Vertical Threshold

\[ \text{True; } \text{False } = \text{COP}_{\text{vmax}} \geq \text{COP}_{\text{vth}} \]

A sensitivity test was performed for each step predictor with all the perturbation trials, to identify the optimal thresholds for each direction.

\[ \text{Sensitivity} = \frac{TP}{TP + FN} \]

\[ \text{Specificity} = \frac{TN}{TN + FP} \]

When plotted against increasing COPvth, sensitivity decreases from unity while specificity increases from zero. The optimal COPvth was chosen to be the point where the product of sensitivity and specificity was maximum.

Application
The identified step predictor was implemented in a real time system, and tested in the independent experiment to the first experiment.

Table: (A) Sensitivities and specificities of stepping algorithms and (B) Average prediction time. ** indicate that the step prediction was made after the occurrence of the step.

The sensitivity in the antero-posterior direction was sufficiently high but the specificity needs to be improved. The sensitivity and specificity were high in the lateral direction but the predictor failed to predict the step, which should be improved.

Conclusion
We developed a step predictor using the force plate measurement. It could be applied for a neuroprosthesis for stance regulation, though some more tune-up is required for its parameters at this stage.
Control Mechanism of Ankle Muscles during Standing

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Purpose
We investigated the control mechanism of the ankle joint during quiet stance in the elderly.

Oversizing/densifying ankle torque exertion in the elderly induces larger body acceleration during quiet standing.

- The CDM amplitude was similar, whereas COP showed a larger deviation from CDM in the elderly than in the young. Thus, COP/CDM and ACC were smaller in the elderly than in the young.
- COP is proportional to the ankle torque. Thus, COP/CDM represents an oversizing/densification of ankle torque to maintain stability. The range of ankle torque is independent of distance, and this excessive ankle torque is proportional to ACC.

A: SD of CDP
B: SD of COP
C: SD of ACC
D: SD of COP-COP
E: Time SHI
F: Time SI
G: High Noise Gain vs Low Noise Gain

The larger inaccuracy of ankle torque causes the larger body acceleration in the elderly compared to young for both eyes conditions. The result that ACC correlated with muscle activity suggests that the torque inaccuracy is generated neurally. Therefore, we conclude that neural instability to control the ankle torque accurately is a cause of the large body sway in the elderly.

High driving noise level characterizes unit spontaneous sway behavior in the elderly.

A: How to measure quasi-stiffness
B: Unit Sway Size vs Quasi-Stiffness
C: Simulation Result
D: Control Strategy affects sway size but not account for aging in balance

1. We simulated the spontaneous body sway using a model with a mechanical PD controller, a neural PD controller, and a neuro-muscular force generation process. Various gain combinations, which stabilized the entire system, were tested.
2. Changes in the driving noise gain did not alter the temporal relationship between the motor command and the body sway at all.
3. TS shows a strong correlation with the sway size (C, right). CC had no correlation with the sway size although it showed some tendency (C, left). The 2 results are similar to the experimental ones.

CONCLUSION
The aging effect on the control mechanism of the ankle joint during quiet standing is accounted for by a large driving noise rather than the control strategy. However, in these studies, we considered only the feedback control mechanism. Model analysis with a predictive or feed forward mechanism might give a different conclusion.
Introduction

Background of Study
Our simulation studies have demonstrated that a proportional and derivative (PD) feedback controller can compensate for the sensory-motor time delay (Fig. 1A) and stabilize the body during upright stance. The required phase advance is generated by a large derivative gain Kd (Fig. 1B), resulting in a physiological motor command that precedes body sway by 100 to 200 ms [Masani et al., 2006].

Materials and Methods

PD Controlled Feedback Model
The modeled PD controller utilizes experimental body angle data to generate a motor command that is translated into ankle torque by a 2nd order muscle model of the plantar flexors [Tani et al., 1996] (Fig. 2).

Closed-Loop Time Delay to be Considered (Fig. 1A):
- Feedback time delay (Ttau_f = 40 ms)
- Motor command time delay (Ttau_m = 40 ms)
- Torque generation delay (Ttau_e > 100 ms)

= closed-loop time delay of more than 180 ms that needs to be compensated for by the neural PD controller

Hypothesis: Despite the closed-loop time delay, the PD controlled ankle torque modulation (model output) can match the experimental ankle torque modulation during quiet standing.

Results

Quiet Standing Experiments (12 healthy subjects)
- Measurements:
  - Ground reaction forces (Kistler force plate)
  - Body angle (Keyence laser sensor)
- Tasks:
  - Quiet standing with eyes open (2 × 60 s)
  - Quiet standing with eyes closed (2 × 60 s)

Optimization Procedure (DIRECT algorithm)
- Optimized Parameters (gray boxes in Fig. 2):
  - PD gains: Kp [Nm/rad] and Kd [Nm s/rad]
  - Twitch contraction time T of muscle model [ms]
- For each trial: 30 s of optimization & 30 s of validation
- Analysis: Identification of error torque and matching percentage

Discussion and Conclusion

- PD controller can match ankle torque modulation during quiet standing – even for a large sensory-motor time delay (> 180 ms).
- Optimized PD gains agree with previous findings [Masani et al., 2006], and optimized twitch contraction time is physiologically valid.

The PD controller can not only regulate balance, but also mimic the sensory-motor control task during quiet stance. Future work will implement the PD control strategy as part of a closed-loop system to test the feasibility of developing a neuroprosthesis for standing.

The authors acknowledge the support of the Toronto Rehabilitation Institute which receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long-Term Care in Ontario. The views expressed do not necessarily reflect those of the Ministry.
A Model of Electrically Stimulated Knee Response for Use in FES Systems

Introduction

- Functional electrical stimulation (FES) is a promising rehabilitation modality for individuals with spinal cord injuries (SCI) that involves electrically stimulating the neuromuscular system to generate skeletal muscle contractions. FES has been used for gait training [1] and grasp rehabilitation [2], among other applications. Currently, such systems require a significant amount of intervention by the user or the therapist.

- We are developing FES rehabilitation systems that work semi-autonomously, freeing the therapist and patient to concentrate on the rehabilitation, instead of concentrating on the technology. Such FES systems require closed-loop control, which is not currently available for clinical FES systems.

- One of the reasons that closed-loop control is not currently used in clinical FES systems is the lack of a model of the body’s response to electrical stimulation that captures the variability of the response.

- We propose a new stochastic model that will capture the day-to-day variation in the body’s response to stimulation.

Hypotheses

- We hypothesize that a nonlinear model with a stochastic term will capture the day-to-day variation in response to electrical stimulation that is seen in individuals with SCI.

Methods

- We randomly stimulated the quadriceps and hamstrings of a seated individual with a complete SCI at T3, and recorded the resulting knee angle with an electrogoniometer.

- We collected data during 24 hour-long sessions over the course of 8 weeks. We processed the data to de-noise and normalize all trials to the same initial knee angle, and grouped the trials by stimulation level.

- For each set of quadriceps and hamstrings stimulation parameters, we found the best-fit stochastic model of the form

\[ f(t) = \sum_{i=1}^{M} a_i g_i(t) + X(t) \]

- The deterministic portion of the model was a linear combination of M nonlinear basis functions, \( g_i(t) \), which were chosen to represent parts of typical response curves. The coefficients, \( a_i \), were found by using singular value decomposition and were chosen to minimize a Chi-square metric.

- The stochastic portion of the model, \( X(t) \), is a function whose value at each time point is a normally distributed random variable. The standard deviation of the random variable is the same as the standard deviation of the recorded knee responses at that time point, for a particular set of stimulation parameters.

Results

- Fig 1 and 2 show the results of modeling the knee response to 86 mA quadriceps and 24 mA hamstrings stimulation. Fig 1 shows the mean of all trials at this stimulation level and the stochastic best-fit model. For this stimulation level, the best-fit model used 7 basis functions. Fig 2 shows the raw data as well as the envelope of 100 stochastic best-fit models.

Conclusions

- The raw data and stochastic best-fit models show similar statistical properties, and the stochastic model encompasses the variation seen in the knee response.

- This stochastic modeling method captures the day-to-day variation in response to electrical stimulation that can be seen in individuals with spinal cord injuries. Such models will facilitate the development of a closed-loop system that is sufficiently robust to be used in real-world FES rehabilitation applications.

References


Muscle Recruitment Patterns in Perturbed Sitting

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\textbf{Introduction}

- People with spinal cord injury (SCI) have trouble maintaining trunk stability during sitting
- Functional electrical stimulation (FES) applies bursts of short electric pulses to groups of muscles to generate functional muscle contractions
- FES could be used to increase trunk stability during sitting for people with SCI
- Information about which trunk muscles are essential during sitting, and how these muscles respond to external perturbations are needed to develop a practical neuroprosthesis for sitting

\textbf{Goals}

- To determine the directional dependencies of trunk muscle responses, and the amount of muscle activities to perturbations applied from different directions during sitting of able-bodied subjects

\textbf{Methods}

- Subjects: 12 healthy, right-handed male, age 21 to 39 years
- Protocol:
  - Surface electrodes were placed on trunk and neck muscles on both sides of the body to measure muscle activities (EMG)
  - Subject sat on a custom seating apparatus, with the arms crossed in front of their chest, eyes-closed in a relaxed and natural position. Subject wore headphones and listened to asynchronous nature sounds. He also counted numbers aloud to prevent anticipation.
  - 40 perturbation trials (8 directions, 5 trials each) were applied to the subject at chest level manually

\begin{itemize}
  \item Front: 1, 2, 7, 8
  \item Back: 3, 4, 5, 6
\end{itemize}

\begin{itemize}
  \item 1 - rectus abdominis (RA)
  \item 2 - external obliques (EO)
  \item 3 - internal obliques (IO)
  \item 4 - thoracic erector spinae (T9)
  \item 5 - lumbar erector spinae (L3)
  \item 6 - latissimus dorsi (LD)
  \item 7 - sternocleidomastoid (SM)
  \item 8 - splenius capitis (SC)
  \item 9 - reference
\end{itemize}

\textbf{Results}

- Directional dependencies could be seen for RA, EO, IO, T9 and L3 (Fig. A)
- No directional dependencies found for SM and SC
- EMG responses of RA, EO, IO, T9 and L3 were curve fitted using Gaussian (Fig. B):
  \[ y = c_0 + c_1 \exp \left( -\frac{(x-c_2)^2}{2c_3^2} \right) \]

\textbf{Conclusion}

- The present study was the first to characterize the muscle responses mathematically to loads from different perturbation directions
- The direction and range of activation in which each muscle was maximally activated could be identified using these formula
- These formulas could be used in implementing a FES system for trunk muscles to stabilize sitting posture for people with SCI

This project was funded by CIHR
Center of Pressure Excursion During Voluntary Trunk Movement in Sitting

Richard A. Preuss PhD PT and Milos R. Popovic PhD P.Eng.

1) Limits of Stability
Main Findings:
- a) Covers an area ~33% of the base of support
- b) Elliptical, with the major axis in the sagittal plane
- c) Centered (slightly left & anterior) in the base of support

Approach:
- a) Maximum voluntary lean in 8 directions (11 subjects)
- b) Least-square ellipse fit to maximum COP excursion

Results:
- Elliptical limits of stability - mean (sd)
  - Area: 32.7% (0.4%) BoS
  - Center: 54.9% (4.5%) BoS length
  - 45.6% (1.5%) BoS width
  - Major Axis: 35.7% (3.4%) BoS length
  - 28.6% (3.9%) BoS width
  - Eccentricity: 0.66
  - Orientation: -2.0° (5.3°)

2) Postural sway: quiet upright sitting
Main Findings:
- a) Covers area <0.02% of BoS
- b) Elliptical, with major axis offset from sagittal plane
- c) Centered (slightly left & anterior) in the base of support

Approach:
- a) COP position over 4 minutes of quiet sitting (9 subjects)
- b) Least square ellipse fit (axis length doubled)
- c) Ellipses fit to each 1 minute period (axis length doubled)

Results:
- Four Minutes:
  - Area: 0.0155% (0.0036%) BoS
  - Center: 53.3% (4.1%) BoS length
  - 48.1% (1.1%) BoS width
  - Major Axis: 1.02% (0.54%) BoS length
  - Minor Axis: 0.45% (0.19%) BoS length
  - Eccentricity: 0.90
  - Orientation: -6.7° (21.4°)

- One Minute Intervals:
  - Area: 0.0047% to 0.0092% BoS
  - Center: 52.5% to 52.1% BoS length
  - 48.3% to 48.0% BoS width
  - Major Axis: 0.66% to 0.42% BoS length
  - Minor Axis: 0.41% to 0.33% BoS length
  - Eccentricity: 0.42 to 0.78
  - Orientation: -11.2° to 6.7°

3) Target-directed trunk movement
Main Findings:
- Significant decrease in the margin of stability with:
  - a) Movement in the frontal plane vs. sagittal plane
  - b) Increased target distance
  - c) Increased speed of movement

Approach:
- a) COP position during target-directed trunk movements (11 subjects)
- b) Least square ellipse fit to maximum COP excursion

Results:
- The margin of stability significantly decreased with:
  - a) Movement in the frontal plane
  - b) Increased target distance
  - c) Increased movement speed

Significant interaction effects were found between:
- a) Target distance and movement speed
- b) Target distance and movement direction

Unifying Conclusion: These limits of stability provide a valid means to quantitatively interpret the challenge to stability posed by various tasks performed in sitting.
Posturography Measures during Quiet Sitting

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²Toronto Rehab, Lyndhurst Centre, ³University of Houston,
⁴Japan Society for the Promotion of Science

Introduction

- Sitting balance is an important factor for the activity of daily life of individuals with SCI
- Previous studies have shown that the centre of pressure (COP) displacement recorded during quiet standing reflects the overall postural control system
- Postural steadiness (posturography) is commonly used for balance assessment but has not been applied to the study of sitting balance

Purpose of study

- To investigate how posturography during quiet sitting in healthy young male individuals differs from that of quiet standing
- To provide a benchmark for evaluating balance capacity during quiet sitting within different patient populations

Methods

- Thirteen healthy male individuals with no history of neurological disorders participated
  • Age 21-39 years
  • Height 178.0 ± 4.7cm
  • Weight 70.3 ± 10.0kg
- Individuals were asked to sit quietly on a force plate for 140 seconds, as shown in Fig1
- The force plate data was used to calculate the net COP in the anterior-posterior (AP) and medio-lateral (ML) directions, and resultant distance (RD)
- Signals were collected using a 64-channel, 12-bit analog-to-digital converter at a sampling frequency of 2000Hz

Fig1 – (A) Experimental setup and (B) an example of COP time series (only 30 s of data presented) in a planar plot (left), and time series of AP (top) and ML (bottom)

Analysis

- Time-domain, frequency-domain and stabilogram diffusion analyses were applied to the COP time series as described in the study by Maurer et al. [1]
- Time-domain, frequency-domain results were compared to those described in the quiet standing study by Prieto et al. [2]
- Stabilogram diffusion analyses results were compared to those described in the quiet standing study by Collins and DeLuca [3]

Fig2 – Comparison of time-domain and frequency-domain measures

Results

- The time-domain measure values during quiet sitting were smaller than the corresponding values during quiet standing (Fig2)
- Mean frequency was two to three times higher for quiet sitting as compared to quiet standing (Fig2)
- Stabilogram diffusion analyses measures (Table 1): Hurst exponent for the short-term and long-term intervals for sitting were larger and shorter, respectively, as compared to standing. The critical time interval was shorter during sitting as compared to standing

Table 1: Stabilogram Diffusion Function Measures

<table>
<thead>
<tr>
<th></th>
<th>Quiet Sitting</th>
<th>Quiet Standing [2]</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD</td>
<td>0.45 ± 0.24</td>
<td>0.92 ± 0.29</td>
<td>0.49</td>
</tr>
<tr>
<td>AP</td>
<td>0.53 ± 0.36</td>
<td>0.97 ± 0.46</td>
<td>0.55</td>
</tr>
<tr>
<td>ML</td>
<td>0.49 ± 0.23</td>
<td>1.06 ± 0.42</td>
<td>0.47</td>
</tr>
<tr>
<td>RD</td>
<td>0.86 ± 0.03</td>
<td>0.76 ± 0.04</td>
<td>1.13</td>
</tr>
<tr>
<td>AP</td>
<td>0.86 ± 0.03</td>
<td>0.77 ± 0.04</td>
<td>1.12</td>
</tr>
<tr>
<td>ML</td>
<td>0.89 ± 0.05</td>
<td>0.74 ± 0.05</td>
<td>1.20</td>
</tr>
<tr>
<td>RD</td>
<td>0.12 ± 0.14</td>
<td>0.34 ± 0.08</td>
<td>0.31</td>
</tr>
<tr>
<td>AP</td>
<td>0.10 ± 0.18</td>
<td>0.38 ± 0.10</td>
<td>0.28</td>
</tr>
<tr>
<td>ML</td>
<td>0.20 ± 0.12</td>
<td>0.23 ± 0.05</td>
<td>0.89</td>
</tr>
</tbody>
</table>

*Ratio = quiet sitting / quiet standing

Conclusions

- Differences in time-domain measures, and frequency-domain measures between quiet sitting and quiet standing could be attributed to the differences in the size of the free moving part (i.e., the whole body versus trunk, arms and head)
- Quiet sitting utilizes open-loop and closed-loop postural control schemes similar to standing, but the exact control schemes are different between sitting and standing

References

Identifying Movements From Cortical Signals
César Márquez Chin and Milos R. Popovic
Institute of Biomaterials and Biomedical Engineering, University of Toronto
Toronto Rehabilitation Institute

Electrocorticographic Signals Reflect Specific Motor Tasks

Long –Term Goal
• To create a system that uses the electrical activity of the brain to control electronic devices: a brain-computer interface.

Purpose of the Study
• Explore the changes elicited by specific movements in the electrical activity of the primary motor cortex.
• Identify features in the electrocorticographic (ECoG) signals that show consistent behaviour in relationship to movement.

Background
• Different frequency bands in the electrical activity of the brain experience changes in amplitude during voluntary movement and/or preparation to perform such movement.
• These changes have been used to identify the occurrence of specific movements.
• The electrical activity of the brain can be recorded with intracranial electrodes (subdural electrodes) placed on the surface of the brain.
• The signals recorded with these electrodes are referred to as ECoG signals.

Materials and Methods

Participants
• Two individuals were implanted with subdural electrodes (four contacts) for the treatment of movement disorders: Parkinson’s disease (PD) and Essential Tremor (ET). (See Fig. 1 and Table I)
• The site of implantation corresponded to the arm area of the primary motor cortex, confirmed with electrical stimulation.

Experimental Procedure
• Participants performed specific movements (see Table I).
• ECoG signals and position (X, Y, Z coordinates) of the hand were recorded simultaneously.

Table 1. Participants of this study.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age / Gender</th>
<th>Diagnosis</th>
<th>Performed Movements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Male / 73</td>
<td>PD</td>
<td>•Elbow Flexion (EF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>•Reaching to the Right (RTR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>•Reaching to the Left (RTL)</td>
</tr>
<tr>
<td>2</td>
<td>Female / 65</td>
<td>ET</td>
<td>•Closing Hand (CH)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>•Reaching to the Right (RTR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>•Reaching to the Left (RTL)</td>
</tr>
</tbody>
</table>

Analysis
• ECoG signals were analyzed in different configurations including monopolar as well as the difference between adjacent and non-adjacent electrodes.
• The time-frequency distribution was estimated for each ECoG signal with a resolution of 1.5 Hz.
• The spectral components with the highest correlation values with each one of the kinematic dimensions were identified for each movement.
• These frequency components were then grouped in a histogram.
• The magnitude of each column represents the probability that a specific frequency band is correlated with a kinematic dimension of each movement.

Results
• The consistency of the distributions of correlated spectral components suggest that these features might be used to classify ECoG signals automatically.

Discussion
• The consistency of the distributions of correlated spectral components suggest that it might be possible to use it as features to automatically classify ECoG signals.
Localizing Active Pathways in Peripheral Nerves

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Introduction

- Localizing active pathways in peripheral nerves would help us to monitor control signals flowing between the central nervous system and a limb or an organ, and ultimately to control a neural prosthesis.
- Using a multi-contact nerve cuff electrode and solving a source localization inverse problem (similar to EEG source localization), we hope to observe information flow through a peripheral nerve.
- We tested the proposed methods on simulated measurements.

Methods

- The relationship between the measurements and bioelectric sources in the nerve can be expressed as a linear system.
  \[
  \mathbf{v} = \mathbf{L} \mathbf{j} + \mathbf{\varepsilon}
  \]
  \( \mathbf{v} \): measurements  \( \mathbf{L} \): leadfield  \( \mathbf{j} \): sources  \( \mathbf{\varepsilon} \): noise
- We want to recover \( \mathbf{j} \) from \( \mathbf{v} \), knowing \( \mathbf{L} \), but there are more unknown variables than measurements, resulting in an underdetermined problem. Many algorithms exist for this sort of situation, and rely on imposing constraints on the solution.
- We chose to use the sLORETA [1] algorithm, which was originally developed for localizing bioelectric sources in the brain. It uses a smoothness constraint, resulting in a blurred solution with well-localized peaks.
- Our choice of algorithm is based on three criteria:
  1. No assumption about the number of sources
  2. No assumption about stationarity
  3. Speed

Test Cases

- Action potentials propagating through the nerve were simulated using the Sweeney model for ion channel dynamics in myelinated mammalian nerve fibers [2]. The corresponding measurements were computed using Equation 1, for a 2.5ms time interval.
- First case: one active pathway at a random cross-sectional position (100 trials).
- Second case: three simultaneous active pathways at random cross-sectional positions and with small random time shifts (100 trials).

Results

- Fig. 2: Localization example for a single-pathway trial
- Fig. 3: Simulation results in terms of pathway localization error, missed pathways, and spurious pathways.

Conclusions

- Localization can be achieved within tolerable error in the one-pathway case, although the solution is blurred. The blurring is inherent to the sLORETA algorithm and therefore to be expected.
- The limited resolution is the biggest challenge to the localization of several pathways, because pathways close to each other cannot be adequately separated. Alternative algorithms should be explored to address this issue.
- The other issue to be addressed is the high number of spurious pathways at high noise levels.

References

Control of Multiple Degree-of-Freedom Tasks Using One-Dimensional Electroencephalographic Signals

Egor Sanin 1,2, César Márquez Chin 1,2, Jorge Silva 2, Tom Chau 2,3, Alex Mihailidis 2,4, and Milos R. Popovic 1,2.

1 Toronto Rehabilitation Institute, Toronto, Canada. 2 University of Toronto, Toronto, Canada. 3 Bloorview Kids Rehab, Toronto, Canada. 4 Intelligent Assistive Technology and Systems Laboratory, Toronto, Canada.

Background
What is a Brain-Machine Interface (BMI)?

Limitations
Binary Switch

Proposed Solution
Signal Processing → Binary Signal → Single-Switch Asynchronous Control Strategy → Real-time 2-D navigation

Implementation

Signal Processing
Band-pass filter: 8-13 Hz

Moving Average

< T

True

False

T = Threshold

Raw EEG signals are processed to realize a voluntary binary switch.

EEG binary switch used to drive an asynchronous control algorithm which iteratively converges on the desired outcome.

Results
System realized in software to navigate a cursor towards a target.

System realized in hardware to drive a remote-controlled car.

Conclusion
• We developed and implemented a brain-machine interface which allows a single EEG channel to be used for real-time two-dimensional navigation, an example of a multiple degree-of-freedom task.
ECoG Controlled Neuroprosthesis for Grasping: Preliminary Study

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Introduction

- Functional electrical stimulation (FES) is a reliable method to facilitate movement of paralyzed limbs after a spinal cord injury.
- Brain-machine interfaces (BMI) use brain signals to generate control commands.
- The convergence of the fields of motor neuroprosthetics and BMI appears to be a natural step for these two areas of research.
- We created a neuroprosthesis for grasping and controlled it using ECoG signals acquired previously.

Using BCI technology, a neuroprosthesis could detect the intention of performing a specific movement and deliver the electrical simulation pattern to produce the intended movement.

Method

Subjects

\textbf{Subject 1}

- 67 year old woman
- Implanted with a quadripolar subdural electrode to treat essential tremor
- Performed specific arm movements: wrist flexion (WF), reaching to the right (RTR), and reaching to the left (RTL).

\textbf{Subject 2}

- 35 year old man
- Motor complete cervical spinal cord injury (C6 level/ ASIA B)
- Received 4 weeks of FES therapy
- Fitted with a neuroprosthesis for grasping

ECoG Controlled Neuroprosthesis for Grasping

Subject 2 pressed one of three buttons to control the neuroprosthesis. Each button was associated with a dataset of ECoG signals recorded previously from subject 1. The system randomly extracted a single trial of the corresponding dataset which was classified by a nearest neighbor classifier. The classification result was used to trigger the stimulation sequence. Successful classification resulted in the correct stimulation sequence delivered to subject 2. Conversely an incorrect classification would result in an incorrect action taken by the neuroprosthesis.

Implementation Details

- Time-resolved ECoG spectral components correlated with each movement are grouped using histograms with bins representing frequency bands of 10 Hz.
- The histograms were used as features for classification of ECoG signals \cite{1}.

Results

- The system performed with 94.5\% accuracy

Discussion

- This work represents a true end-to-end system test on the use of ECoG signals to control a neuroprosthesis for grasping without intracranial surgery for the purpose of developing BMI technology.

Acknowledgements

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References

Influence of the Number and Location of Recording Contacts on the Selectivity of a Nerve Cuff Electrode

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Introduction

- Nerve cuff electrodes are used to record the electrical activity of peripheral nerves, but have difficulty discriminating between different nerve branches.
- Manufacturing advances have increased the number of recording contacts that can be placed on a nerve cuff.
- We investigate how a nerve cuff with 56 contacts (7 rings of 8 contacts each) can improve selectivity.

Experimental Methods

- Experiments were performed on six rats (old male Long-Evans breeders).
- The 56-contact (“matrix” configuration) recording cuff was placed on the sciatic nerve.
- 3 stimulating nerve cuffs were placed on the tibial, peroneal, and sural branches of the sciatic.
- Short pulses were used to stimulate each nerve branch in turn (100 trials per branch).

Classification of the Neural Activity

- We use the recordings from the cuff electrode on the sciatic nerve to determine which nerve branch was stimulated in a given trial (i.e. classify the activity).
- Our goal is to compare the classification performance of two contact configurations: the full matrix configuration vs. only the 8 contacts in the middle ring of the cuff (this second configuration is taken from the neuroprostheses literature). The two configurations are shown in Figure 1. In both cases a tripole reference is used (average of the contacts with a black outline).

Classification Accuracy as a Function of the Number of Contacts Added

- Classification is performed by building a feature vector for each trial, consisting of the peak amplitudes of every contact in the configuration being used. A training set is used to obtain a typical feature vector for each nerve branch. Each feature vector in the testing set is assigned to the nerve branch whose feature vector it most resembles. The classification accuracy is the percentage of trials in the testing set that are correctly classified.

Results

- The matrix configuration resulted in statistically significant improvements in classification accuracy in all rats.

Classification Accuracy (%)

Maximum Classification Accuracies of Matrix vs. Single-Ring Configurations

- By adding one contact at a time to the matrix configuration, from the most informative to the least informative, and evaluating the classification accuracy at each step, we found that high accuracies could be achieved with a small number of contacts.

Conclusions

- The recordings from the matrix cuff led to better classification accuracy than previously used configurations.
- The improvement was due to the possibility of selecting the most informative contacts, rather than to the sheer number of contacts.
- These results have implications for the design of future cuff electrodes.
Background and Purpose

Why do we focus on Arterial Stiffness?
- Stiffening in the cardiothoracic arteries is an emerging risk factor for coronary artery disease (CAD). Decreases in the elastic properties of arteries reduces the buffering capacity of the arteries, leading to increased pulse pressure, aortic impedance, and left ventricular wall tension, all of which increase CAD risk.

What is Pulse Wave Velocity (PWV)?
- PWV is the speed of the blood flow wave traveling through the arterial system. PWV is affected by the elasticity and distensibility of the artery. Higher velocity corresponds to higher arterial stiffness and lower distensibility.

Why do we need to know about PWV in SCI patients?
- Obesity is a common problem among individuals with spinal cord injury (SCI). Thus, it is hypothesized that individuals with SCI have high risk of CAD associated with above normal PWV values.

What are aims of the project?
- To test the hypothesis that SCI subjects have greater arterial stiffness (PWV) than age-gender matched non-SCI subjects.
- To investigate the association between adiposity and PWV in these subjects.

Methods

- Subjects (n=18)
  - SCI men (n=9) without CAD (Age: 51 ± 11 yrs; Height: 179 ± 6.6 cm; Body weight: 90.5 ± 22.5 kg; neurologic level: between C3 to L3; ASIA impairment scale A; Years postinjury: 25 ± 10.7 years) and n=9 age and gender matched Non-SCI controls (Age: 45 ± 10 yrs; Height: 175.1 ± 7.9 cm; Body weight: 75.6 ± 10.9 kg)

- Body composition Measurements
  - Adiposity (Trunk fat mass, total body fat mass) were assessed using Dual-energy X-ray absorptiometry (DXA).
  - Waist circumference was measured in supine position.

- PWV Measurement
  - Pulse wave at two vascular landmarks were simultaneously measured using two identical non-invasive transcutaneous doppler flow meters (Smartdop50, Hadeco, Inc., Kanagawa, Japan)
  - The pulse wave latency (PWL) (1) between the carotid artery (CA) and the femoral artery (FA); and (2) between FA and posterior tibial artery (PTA) were recorded (see diagram).
  - The distances (D) in centimeters traveled by the pulse wave were measured over the surface of the body using a metal tape measure.

Diagram of PWV measurement sites

- Calculation of PVW
  1. Aortic PWV (cm/sec) = D Aortic / PWL between CA and FA
  2. Leg PWV (cm/sec) = D Leg / PWL between FA and PTA

Results

PWV in SCI and Control

Aortic PWV in SCI were significantly higher than that of control (*One outlier in CON was excluded).
There were no significant difference between SCI and control in leg PWV.

Relationship between Aortic PWV and adiposity in SCI and Control

There were significant correlations between adiposity and aortic PWV in SCI subjects (*One outlier in CON was excluded).

Discussion and Conclusion

The higher trunk PWV in subjects with SCI than able-body population suggests their higher risk of CAD and potential need for aggressive risk factor modification. The correlation results imply that obesity is associated with stiff arteries in the SCI population and thus body composition, in particular adiposity, should be assessed in clinical practice and may be used to detect patients with SCI with stiff arteries.
A Test-of-Principle Prototype for a New Device to Measure a Specific Pain Mechanism

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Translating Pain Neuroscience Theory into a Clinical/Research Tool

Background
Central neuropathic pain (CNP) is a devastating, unrelenting pain that can occur after a disease or injury to the central nervous system such as stroke, multiple sclerosis, or spinal cord injury (SCI).

A roadblock to effective CNP treatment is the inability to identify, within an individual, the specific neurobiological “mechanism(s)” responsible for the pain.

One such mechanism is “thermosensory disinhibition”, or, the loss of cold-inhibition of pain within the central nervous system.

Prior research has shown that the thermal grill illusion (TGI) can be used to evaluate cold inhibition of pain.

Thermal Grill (TG) Apparatus
A TG allows the simultaneous application, to the skin, of spatially interlaced nonpainful warm (40°C) and cool (20°C) bars, causing the individual to experience a painful thermal percept, or TGI.

- There is no commercially available TG.
- The TGI has only been tested on the hand of able-bodied individuals; but CNP can occur in any body location.
- Translation of the TGI response, to a tool to evaluate individuals with SCI-related CNP requires a new TG, appropriate to evaluate the TGI in many anatomic regions.

Future Directions
- We plan to build the REL-TG with 64 contact-thermodes (8 x 8 matrix, Fig. 7).
- Design will allow a range of complex stimuli similar to those shown in Fig. 6.

Purpose
Our overall goal is to develop a new TG for multiple-body-site testing and develop an open platform for investigators and clinicians in the field as a psychophysical measure of alterations in cold inhibition of pain. Our plan for the current study was to evaluate the principles-of-design for new more portable and flexible TG apparatus.

Design Needs
1. Lightweight and portable system
2. Safe for use with patients
3. Six contact thermodes with:
   - individual & independent temperature control
   - adjustable spacing between thermodes
4. Physical capacity to:
   - heat or cool each thermode in range 0°C to 50°C
   - maintain each thermode at a stable temperature of 20°C or 40°C
   - achieve dynamic temperature ramp of 1.0°C/s
5. Individual continuous data logging of thermode temperature
6. Response system to record continuous subject response

Conclusions
Our TG design based on the use of Peltier elements, an air cooling system, and electronic response system has the level of control and system flexibility required for future clinical, large scale studies to identify the existence of a pain producing mechanism among individuals with CNP.

Based on prototype performance the following revisions are needed for the planned larger “Rehab Engineering Lab Thermal Grill” (REL-TG): 1. Separate PC screen for patient. 2. Improve system thermal dynamics by: revising the software, adding variable power supply; and optimizing the thermode unit. 3. Improve software usability by preprogramming for specific protocols.
Cardiovascular Response to FES and Passive Stepping to Improve Orthostatic Tolerance

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Background

- Orthostatic hypotension, a sudden drop in blood pressure, is prevalent following spinal cord injury. Over 70% of SCI patients experience sudden symptoms of dizziness, lightheadedness, and syncope upon postural change or following periods of prolonged sitting resulting from venous pooling.

- Orthostatic hypotension hinders the patient’s participation in rehabilitation activities which is necessary to promote neuronal placidity, prevent loss of muscle mass, mitigate osteoporosis, and maximize cardiovascular conditioning.

- Functional electrical stimulation (FES) and passive stepping movements have been shown to increase blood pressure and reduce venous pooling and thus have been proposed as potential therapies to counter the effects of orthostatic hypotension.

Research Question

- Can lower limb movements, either through active leg muscle contraction (FES) or passive leg walking (Stepping), be effective in preventing orthostatic hypotension in able bodied subjects undergoing tilt?

Method

- Orthostatic hypotension conditions were simulated in 10 able bodied subjects. Subjects were secured on a tilt table and their thighs were attached to robotic actuators which allowed passive stepping movements. All trials began with a 10 minutes rest phase in the supine position. During the test subjects experience 70° head-up tilt for 15 minutes or until syncope occurs.

- Four tilting conditions were performed in random order
  - Head Up Tilt (HUT)
  - HUT + FES
  - HUT + Passive Stepping
  - HUT + FES + Passive Stepping

- Electrical stimulation was applied to the gastrocnemius, quadriceps muscle group, and hamstring muscle group.

- Cardiovascular data (blood pressure, heart rate, venous return, cardiac output) were collected throughout the testing condition

- Data was analyzed using Student’s t-Test to determine the significance between various tilting conditions.

Results

- One subject experienced syncope during head-up tilt.
- No subjects experienced syncope during FES, Stepping or the combined modality.
- FES synchronized with passive stepping significantly increased venous return over 15 minutes of tilt.
- FES significantly increased heart rate over 15 minutes of tilt.
- Blood pressure did not change significantly over 15 minutes of tilting

![Fig 1](image1.png) Doppler ultrasound imaging of a subject’s inferior vena cava during (a) Tilt Condition and (b) FES w Stepping.

![Fig 2](image2.png) Cardiovascular data from a subject undergoing tilt in varying conditions. FES & Stepping were found to be effective in increasing venous return and heart rate over 15 minutes of tilt.

Conclusion

- The combination of FES with passive leg movements significantly increases venous return, thereby mitigates the effects of orthostatic hypotension over the long term.

- Active muscle contraction by FES are effective in increasing the heart rate over the duration of tilting.
Wave ® vs. Juvent ®: Whole-Body Vibration Assessment Feasibility & Usability for Patients with SCI

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Background

•Sublesional Osteoporosis (SO) is the decline of bone mineral density (BMD) in the hip and knee regions after SCI.

•25-45% of SCI patients experience fragility fractures as a result of SO.

•Lower extremity fragility fractures result in decreased mobility, delayed healing, and in extreme cases amputation.

•Current treatments for SO which include oral biphosphonates, and rehabilitation interventions (passive standing, tilt table, walking, muscular and functional electrical stimulation) have been largely ineffective in producing a significant or sustained increase in BMD.

•Whole-Body Vibration (WBV) is a new therapy used for improving muscular strength and BMD in animals, postmenopausal women, and children with neurological impairments.

Objective

•To compare the feasibility and usability of two vibration platforms Wave® and Juvent® for treatment of SO among patients with chronic SCI.

Methods

•Subjects: Healthy male volunteers 20-40 years old (n=4) and age matched traumatic SCI patients with motor complete paraplegia (n=4).

•Vibration parameters: Frequency 30-50 Hz, and amplitude <5 mm.

•Feasibility criteria: Vibration propagation through the body measured with 4 accelerometers located at the plate, lateral femoral condyle, iliac crest, and head (see diagram below).

•Usability criteria: Vibration perception, subject reactions (adverse effect/perceived benefits), skin breakdown, device accessibility, H-reflex, & lower extremity EMG.

Expected Results

•Acceleration propagation up the lower extremities is essential prior to determining what effects WBV has on the lower extremity bone microstructure.

•H-reflex will be used as indicator of spinal motor neuron excitability. A relationship between hyperexcitability of the spinal motor neurons in SCI patients and spasticity exists, such that reductions in H-reflex may inhibit spasticity of the soleus.

•Electromyography (EMG) will allow us to monitor lower extremity muscle activity pre, during and post vibration exposure. Increased EMG activity during vibration may be an indicator of muscle fiber activation.

Diagram of Accelerometer Locations
A NEW INTRAMUSCULAR ELECTRODE FOR FUNCTIONAL ELECTRICAL STIMULATION IN THE RAT

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INTRODUCTION

In the recent decade a number of Functional Electrical Stimulation (FES) devices have been developed to assist people with severe motor paralysis to improve grasping and walking function.

The potential role of FES therapy as an adjunct to traditional rehabilitation programs is beginning to be realized.

The goal of FES therapy is to increase function with a concomitant increase in independence and quality of life.

How FES works to improve motor function remains a mystery.

An understanding of how FES improves motor function is critical to the future development and use of FES in rehabilitation medicine

PEARSON et al (2005) successfully designed and implanted an EMG electrode into mice.

The sole purpose of Pearson’s implantable electrode was to record the movements of mice and measure EMG.

This electrode is difficult to fabricate and not suitable for FES therapy

PURPOSE

To fabricate an electrode which can be implanted into various extremity muscles in the rat which can be used to examine the pathophysiologic effects of FES.

RATIONALE

The electrode design must incorporate the following features:

- Use fine, flexible biologically inert wire which will not induce an inflammatory reaction in the muscle
- Cause minimal disturbance of the muscle tissue when implanted
- Have minimal interference with the normal gait pattern and activity behaviour of the rat
- Inexpensive
- Durable—to withstand the daily movements of the rat for at least one month
- Easy to fabricate
- User friendly—easy to implant and easy to attach to the Compex Motion FES system

REFERENCES
