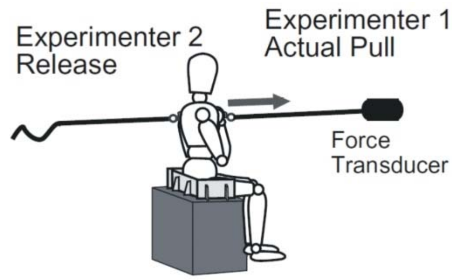
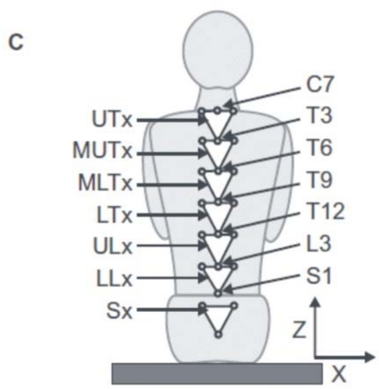
Rehabilitation Engineering Laboratory

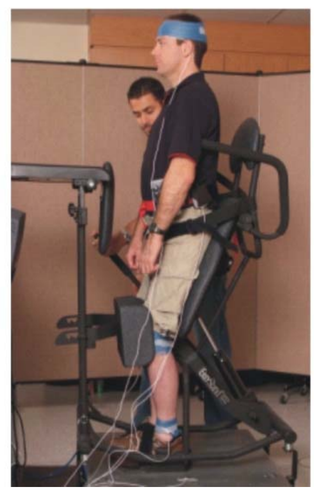
Institute of Biomaterials & Biomedical Engineering
UNIVERSITY OF TORONTO

Toronto Rehab
Everything Humanly Possible

# REL
RehabilitationEngineeringLaboratory



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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 and in 2009, the laboratory underwent two major renovations, quadrupling the amount of space and equipment 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, reaching, and grasping ability. We also design neuroprosthesis systems to assist individuals with tasks such as walking, reaching, 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 – 2008 to 2010

- Completed a number of randomized control trials with stroke and SCI individuals involving FES therapies
- Developed advanced communication and stimulation technologies for neuroimplants
- Provided FES therapy to more than 50 individuals with SCI or stroke
- Published more than 25 peer-reviewed journal papers
- Obtained more than $1.1M in direct funding and collaborated on grants which total funding exceeded $4.6M
- Trained 8 postdoctoral fellows, and 22 graduate students in SCI and stroke research, who obtained an additional $1M in funding

## Want to Get Involved?

We're always looking for participant for our studies, volunteers to help us with the experiments, and students and research collaborators. If you would like to join us, please feel free to contact us at 416-597-3422, Ext. 6206.

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# 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, significantly improving their independence in activities of daily living. People who have SCI at C3-C7 level or stroke have used this system as a rehabilitation tool to assist in retraining voluntary 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 studies showed a significant improvement in walking speed and/or a reduction in the use of assistive devices for walking after using the neuroprosthesis. In this application the neuroprosthesis for walking is used as a short-term intervention for improving voluntary walking function.

## Neuroprosthesis for Sitting

Trunk instability is a major problem for many people with SCI, affecting 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.

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## 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
- Biodex System 3

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## Our People

### Principal Investigators

- **Dr. Milos R. Popovic** (biomedical engineering), Head of the Laboratory, Toronto Rehab Chair in Spinal Cord Injury Research, Senior Scientist, and Professor
- **Dr. Kei Masani** (exercise physiology), Research Scientist
- **Dr. Mary Nagai** (surgery), Research Scientist and Assistant Professor

### Postdoctoral Fellows

- **Dr. Elias Daniel Guestrin** (biomedical engineering), Postdoctoral Fellow
- **Dr. Reza Javaheri** (electronics), Postdoctoral Fellow
- **Dr. Masae Miyatani** (exercise physiology), Postdoctoral Fellow
- **Dr. Santa Concepción Huerta Olivares** (electronics), Postdoctoral Fellow
- **Dr. Dimitry Sayenko** (space medicine), Postdoctoral Fellow

### Graduate Students

- **Rob Babona Pilipos**, PhD student
- **Cheryl Lynch**, PhD student
- **Andresa R. Marinho**, PhD student
- **Cesar Marquez Chin**, PhD student
- **Steve McGie**, PhD student
- **Mateja Milosevic**, PhD student
- **Albert Vette**, PhD student
- **José Zariffa**, PhD student
- **Davide Agnello**, MASc student
- **Milad Alizadeh-Meghrazi**, MASc student
- **Egor Sanin**, MASc student
- **John Tan**, MASc student
- **Massimo Tarulli**, MASc student
- **Miyuki Tsukimoto**, MASc student
- **Lev Vaisman**, MASc student
- **Noel Wu**, MASc student
- **Lorne Chi**, MHSc student
- **Diane Kostka**, MHSc studen
- **Takashi Yoshida**, MHSc student
- **Meredith Kuipers**, MSc student


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## Our People

### International Research Placements

- **Stefanie Buley** – University of Applied Science Senftenberg, Germany
- **Rodrigo Fernandez Vidal** – Universidad Iberoamericana, Mexico
- **Ubaldo Garcia** – Universidad Iberoamericana, Mexico
- **Dr. Noritaka Kawashima** – National Rehabilitation Center for Persons with Disabilities, Japan
- **Carmen Krewer** – Neurological Hospital BadAibling, Germany
- **Marisol Martinez** – Universidad Iberoamericana, Mexico
- **Rocio Prad Vega** – Universidad Iberoamericana, Mexico
- **Catalina Villa Saenz** –School of Engineering of Antioquia, Columbia

### Support Staff

- **Marlene Adams**, Occupational Therapist
- **Shaghayegh Bagher**, Research Engineer
- **Zina Bezruk**, Administrative Assistant
- **Betty Chan**, Grants & Accounts Coordinator
- **Chandy Green**, Occupational Therapist
- **Dr. Stephen Hill**, Kinesiologist
- **Jennifer Holmes**, Occupational Therapist
- **Anne Hu**, Physiotherapist
- **Suzy Iafolla**, Physiotherapist
- **Naaz Kapadia**, REL Manager, Research Coordinator and Physiotherapist
- **Abdulazim Rashidi**, Research Engineer
- **Mark Robinson**, Research Engineer Assistant
- **Egor Sanin**, Research Engineer
- **Dr. Vera Zivanovic**, Research Coordinator

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## Awards and Distinctions

### Davide Agnello

| | | |
|---|---|---|
| 2008 | Graduate Scholarship | Natural Sciences and Engineering Research Council of Canada |

### Milad Alizadeh-Meghrazi

| | | |
|---|---|---|
| 2009 | Best Poster Award | Toronto Rehabilitation Institute's 5th Annual Research Day |
| 2008 | Barbara and Frank Milligan Graduate Fellowship | University of Toronto |

### Robert Babona Pilipos

| | | |
|---|---|---|
| 2010 | Scientific Day 2010 Best "Lightning Round" Presentation | Institute of Biomaterials and Biomedical Engineering, University of Toronto |
| 2008 | John D. Schultz Science Scholarship | University of Toronto |

### Dr. Elias Daniel Guestrin

| | | |
|---|---|---|
| 2009 | Post-doctoral Fellowship in Spinal Cord Injury Research | Ontario Neurotrauma Foundation |

### Dr. Santa Concepción Huerta Olivares

| | | |
|---|---|---|
| 2009 | Clinical Research Fellowship | Canadian Paraplegic Association Ontario |

### Michael Jones

| | | |
|---|---|---|
| 2010 | Summer Student Scholarship | Natural Sciences and Engineering Research Council of Canada |
| 2009 | Summer Student Scholarship | Natural Sciences and Engineering Research Council of Canada |

### Meredith Kuipers

| | | |
|---|---|---|
| 2010 | Ontario Graduate Scholarships in Science and Technology | University of Toronto |
| 2010 | Student Travel Award, Young Investigators' Forum | Institute of Circulatory and Respiratory Health, Canadian Institute of Health Research |


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# Awards and Distinctions

## Meredith Kuipers - continued

| | | |
|---|---|---|
| 2009 | Graduate Scholarship | Natural Sciences and Engineering Research Council of Canada |
| 2009 | Ontario Graduate Scholarships in Science and Technology- (*declined*) | University of Toronto |

## Cheryl Lynch

| | | |
|---|---|---|
| 2010 | Best Student Paper Award – Third Place | International Functional Electrical Stimulation Society Conference |

## Andresa R. Marinho

| | | |
|---|---|---|
| 2009 | Doctoral Research Award Vanier Canada Graduate Scholarships | Canadian Institute of Health Research |

## Cesar Marquez Chin

| | | |
|---|---|---|
| 2008 | Best Poster Award | Toronto Rehabilitation Institute's 4th Annual Research Day |

## Steve McGie

| | | |
|---|---|---|
| 2010 | Barbara and Frank Milligan Graduate Fellowship | University of Toronto |
| 2009 | Student Scholarship – OSOTF Award | Toronto Rehabilitation Institute |
| 2009 | CREATE – CARE Graduate Scholarship | Natural Sciences and Engineering Research Council of Canada |

## Dr. Masae Miyatani

| | | |
|---|---|---|
| 2009 | Post-doctoral Fellowship in Spinal Cord Injury Research | Ontario Neurotrauma Foundation |

## Dr. Milos R. Popovic

| | | |
|---|---|---|
| 2009 | Top 20 Cited Authors in 2009 | Journal Neuromodulation |

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## Awards and Distinctions

### Egor Sanin

| | | |
|---|---|---|
| 2008 | Barbara and Frank Milligan Graduate Fellowship | University of Toronto |

### Dr. Dimitry Sayenko

| | | |
|---|---|---|
| 2008 | Post-doctoral Fellowship in Spinal Cord Injury Research | Canadian Paraplegic Association Ontario |

### Albert Vette

| | | |
|---|---|---|
| 2010 | CIHR Strategic Research Training Post-Doctoral Fellowship in Health Care, Technology & Place | Canadian Institute of Health Research |
| 2010 | MITACS Industrial Fellowship Award | MITACS |
| 2009 | Best Paper Award | Institute of Biomaterials and Biomedical Engineering, University of Toronto |
| 2009 | Institute of Musculoskeletal Health and Arthritis (IMHA) Travel Award | Canadian Institute of Health Research, Ottawa ON |
| 2009 | Musculoskeletal Fellowship | Ontario Rehabilitation Research Advisory Network |

### Noel Wu

| | | |
|---|---|---|
| 2010 | Student Scholarship – OSOTF Award | Toronto Rehabilitation Institute |
| 2010 | Barbara and Frank Milligan Graduate Fellowship | University of Toronto |

### Takashi Yoshida

| | | |
|---|---|---|
| 2010 | CREATE – CARE Graduate Scholarship | Natural Sciences and Engineering Research Council of Canada |

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## Recent Research Posters

### Neuroprosthesis for Grasping

1. Toronto Rehab Functional electrical stimulation therapy for grasping in traumatic incomplete spinal cord injury: Randomized control trial
2. Effect of intensive functional electrical stimulation therapy on the upper limb motor recovery after stroke: Single case study

### Neuroprosthesis for Standing

3. Inverted pendulum standing apparatus
4. Including non-ideal behaviour in FES simulations
5. Stochastic modeling of knee response
6. Video game-based training for calf muscles
7. Arm movements in dynamic postural stability

### Neuroprosthesis for Sitting

8. Posturography measures during quiet sitting
9. Posturography measures for healthy young adults during quiet sitting in comparison with quiet standing
10. Complex three-dimensional spine motions during target-directed movements of the trunk in sitting
11. Center of pressure excursion during voluntary trunk movement in sitting
12. A complete, universal, and verifiable set of upper body segment parameters for three-dimensional dynamic modeling
13. Muscle recruitment patterns in perturbed sitting

### Whole Body Vibration

14. Wave vs. Juvent: Whole-body vibration assessment \
15. Effect of whole-body vibration on H-reflex

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## Human-Machine Interfaces

16. ECoG controlled neuroprosthesis for grasping: Preliminary study
17. Identifying movements from cortical signals
18. Detection of movement onset: Brain-machine interfaces

## Human-Machine Interfaces

19. A new intramuscular electrode for functional electrical stimulation in the rat
20. Influence of the number and location of recording contacts on the selectivity of a nerve cuff electrode
21. Bioelectrci source localization in the rat sciatic nerve


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# TRI FES Therapy for grasping in incomplete SCI: Randomized Control Trial

Kapadia N[1], Zivanovic V[1], Furlan J[1], Craven B.C[1,3], McGillivray C[1], Popovic M.R[1,2]

[1] Toronto Rehabilitation Institute, [2] IBBME - University of Toronto,
[3] Departments of Medicine and Health Policy Management and Evaluation - University of Toronto

## Introduction

- There are about 350,000 SCI survivors in US and Canada and 50% of them are Quadriplegics.
- 50% of the Quadriplegics ranked return of arm hand function as their highest priority.

## Methods

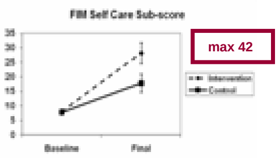
- N =21: 1) Control: n=12. 2) FES: n=9.
- Both groups received 40 sessions of therapy
- Control group received 2 hours of conventional occupational therapy (COT) and intervention group received 1 hour of COT plus 1 hour of FES therapy.
- Primary outcome measure was FIM Self Care Sub score and secondary outcome measures were SCIM Self Care Sub score and TRI-HFT.

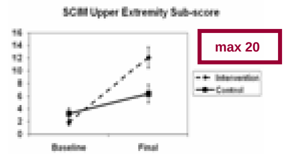
## Subject Demographics

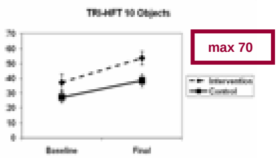
| Feature | Control Group | Intervention Group | p value |
|---|---|---|---|
| ***Age (years)*** | | | |
| Mean age ± SEM | 44.75 ± 4.72 | 43.2 ± 5.45 | 0.896 |
| Median age | 51.5 | 50 | |
| Age range | 20 to 65 | 18 to 66 | |
| ***Sex (n)*** | | | |
| Males | 9 | 8 | 1 |
| Females | 3 | 2 | |
| ***Cause of SCI (n)*** | | | |
| Motor vehicle accident | 7 | 2 | 0.009 |
| Fall | 2 | 8 | |
| Other causes | 3 | 0 | |
| ***Severity of SCI (n)*** | | | |
| AIS B | 4 | 4 | 0.517 |
| AIS C | 8 | 5 | |
| AIS D | 0 | 1 | |
| ***Level of SCI (n)*** | | | |
| C3 | 0 | 1 | 0.071 |
| C4 | 7 | 3 | |
| C5 | 4 | 1 | |
| C6 | 1 | 5 | |
| ***Time since SCI (days)*** | | | |
| Mean time ± SEM | 58.33 ± 6.55 | 69.9 ± 14.11 | 0.974 |
| Median time | 63.5 | 50 | |
| Age time | 22 to 102 | 33 to 164 | |

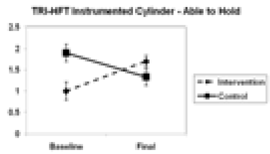
## Results

- FIM self care sub-score: 20 points improvement (FES therapy) as compared to 10 (COT) (p=0.015).
- SCIM self care sub-score: 10 points improvement (FES therapy) as compared to 3 (COT).
- TRI-HFT: TRI-HFT total score for manipulation of objects 1 to 10 also approached statistical significance (p 0.0538).




| Test | Control Group | | Intervention Group | | p values (both hands) |
|---|---|---|---|---|---|
| | *Before* | *After* | *Before* | *After* | |
| FIM Self Care Sub-scores | 7.8 | 17.8 | 8.1 | 28.2 | 0.015 |
| SCIM Self Care Sub-score | 3.3 | 6.4 | 1.9 | 12.1 | <0.0001 |
| TRI-HFT Components | | | | | |
| 10 Objects | 27.2 | 38.5 | 37.1 | 53.8 | 0.054 |
| Rectangular Blocks | 29.3 | 38.4 | 34.7 | 49.7 | 0.124 |
| Instrumented Cylinder *Able to Hold* | 1.90 | 1.33 | 1.0 | 1.7 | 0.033 |
| Instrumented Cylinder *Torque Values (Nm)* | 0.26 | 2.59 | 0.26 | 1.13 | 0.4247 |
| Credit Card *Able to Hold* | 1.33 | 1.41 | 1.0 | 1.7 | 0.035 |
| Credit Card *Force Values (N)* | 2.67 | 8.76 | 4.42 | 12.5 | 0.422 |
| Wooden Bar *Able to Hold* | 0.63 | 0.96 | 0.8 | 1.5 | 0.065 |
| Wooden Bar Thumb Direction *Length Values (cm)* | 2.88 | 10.5 | 1.67 | 10.94 | 0.622 |
| Wooden Bar Little Finger Direction *Length Values (cm)* | 3.17 | 11.85 | 5.56 | 12.78 | 0.767 |

## FES Therapy Participant

## Conclusion

•Restoration of voluntary hand function in incomplete SCI is possible using FES.

•Improvements in hand function and thereby increase in level of independence are significant with FES training.

## Recommendations

- Flexible and programmable FES system.
- Repetitive daily treatments.
- FES in combination with OT.

## References

1. Popovic MR, Keller T, Pappas IPI, Dietz V, Morari M. Surface-stimulation technology for grasping and walking neuroprostheses. IEEE Engineering in Medicine and Biology Magazine 2001; 20(1): 82-93.

2. Thrasher TA, Zivanovic V, McIlroy W, and Popovic MR, Rehabilitation of reaching and grasping function in severe hemiplegic patients using functional electrical stimulation therapy. Journal Neurorehabilitation and Neural Repair, 2008; 22(6):706-714.

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**Partners:**

The views expressed in this poster do not necessarily reflect those of any of the granting agencies.

*The authors acknowledge the support of Toronto Rehabilitation Institute who 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."*

# Effect of Intensive Functional Electrical Stimulation 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. University of Toronto, Canada, 2. Toronto Rehabilitation Institute, Canada, 3. Japanese Society for Promotion of Science, Japan

## 1. Background

- Stroke survivors experience significant deficit of sensorimotor functions and 85% of them are left with major functional problems in their hands and arms
- If recovery occures it is mostly during the first four weeks after stroke and it is very rare that improvements occur in chronic stroke patients

Functional Electrical Stumulation therapy (FES therapy)

FES therapy is a treatment that integrates electrical stimulation of sensory motor systems and repetitive functional movement of the paretic arm in hemiplegic patients.

*During FES therapy...*

1. the subject can feel that the proper movement of the paralyzed limbs and has been acomplished 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 FES therapy 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 FES therapy for chronic stroke patients?

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

## 2. Patient Information

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.

Acknowledgement:

The authors acknowledge the support of Toronto Rehabilitation Institute who receives funding under the Provincial Rehabilitation Research Program from the Ministry of Health and Long-Term Care in Ontario and The Physicians' Services Incorporated Foundation.

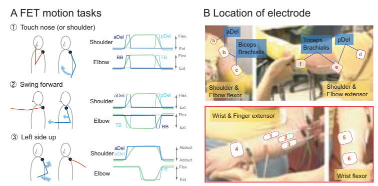
## 3. Methods

### FES therapy 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




FES therapy was administrated two times per day (one hour in each session) and carried out for 12 weeks. The patient had completed all training sessions (in total 108

Shoulder & Elbow motion

| *Task* | *Shoulder motion* | *(Electrode)* | *Elbow motion* | *(Electrode)* |
|---|---|---|---|---|
| Touch nose | Flexion | a-b | Flexion | b-c |
| Touch Shoulder | Flexion&Int.rotation | a-b | Flexion | b-c |
| Swing forward | Extension | d-e | Extension | e-f |
| Left side up | Abduction | a-b & d-e | Extension | e-f |

Wrist & Hand motion

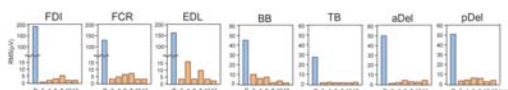
| *Task* | *Target motion* | *(Electrode)* |
|---|---|---|
| Bottle grasping | Wrist extension & full finger open | 1-4,2-4, & 3-4 |
| | Wrist flexion | 5-6 |
| Small object picking | Two finger (Thumb&Index) open | 1-4 |

### Outcome Measures

(1) Motor function *(CMSA and MVC test)*
(2) Spasticity assessment *(MAS and H-reflex)*
(3) Kinematical measurements *(Drawing test, Dynamic ROM)*

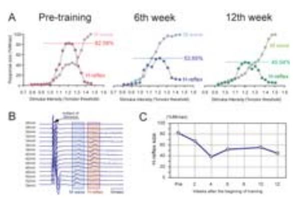
## 4. Results

### 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.

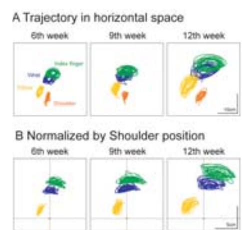
### Spasticity Assessment




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).

- FES therapy has a potential to decrease abnormal spinal motoneuronal 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.

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

## 5. Discussion

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 FES therapy has the capability to improve upper arm functional movement, specifically by the reduction of muscle tone for chronic stroke patients.

Partners:

# INVERTED PENDULUM STANDING APPARATUS

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## A novel apparatus for developing new FES methodologies

### Introduction

• We have developed an apparatus that uses an inverted pendulum to mimic quiet standing, as shown in Figures 1 and 2.
• This novel apparatus allows spinal cord injured (SCI) subjects to remain safely seated while participating in experiments on FES-based standing.
• The feet of the seated subject are strapped to foot plates, and electrical stimulation is used to flex or extend the ankles, balancing the pendulum.
• The results we obtain using this apparatus can be applied to many other FES applications that use electrical stimulation to actuate joints.

### Dynamic Equations of Quiet Standing

• The dynamics of quiet standing are analogous to the dynamics of a single-link inverted pendulum, which are given in Equation 1.
  • I is moment of inertia of the pendulum; $\tau_{plantarflexors}$ and $\tau_{dorsiflexors}$ are electrically stimulated torques about the ankle.

$$\ddot{\theta} = \frac{1}{I}\left(\tau_{plantarflexors} - \tau_{dorsiflexors} + \tau_{passive} - mg\ell \cdot \sin\theta\right)$$

**Equation 1** – Dynamics of quiet standing

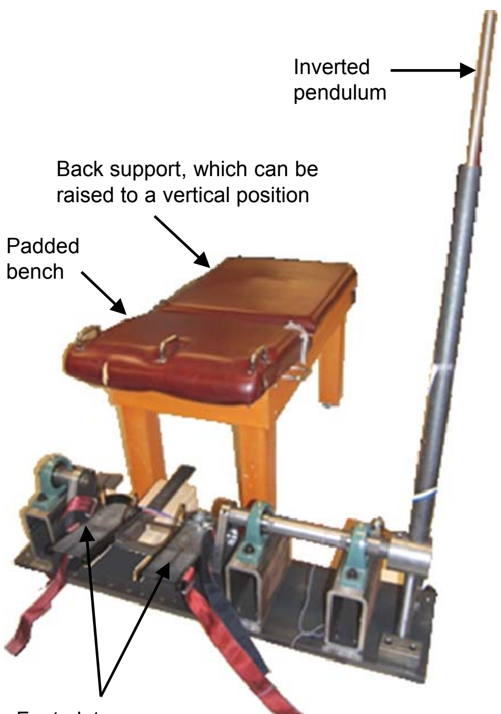


**Fig 1** – Inverted pendulum apparatus. Foreshortening of the image makes the bench appear somewhat smaller than its actual size.

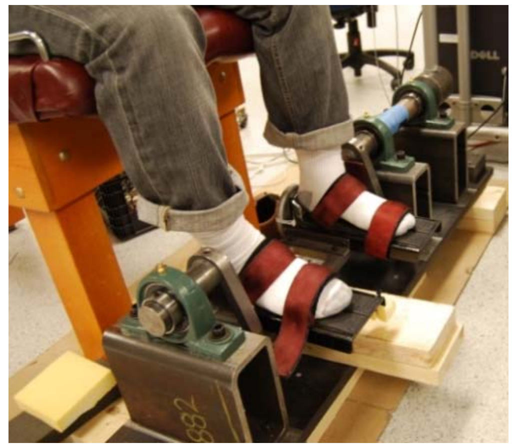

**Fig 2** – Detailed view of foot plates in use

### Applications of Apparatus

• Electrical stimulation-based muscle conditioning:
  • New protocols will maximize the work that muscles are able to do, for both FES rehabilitation and neuroprosthesis applications.
  • Game-like conditioning protocols may increase user compliance with training process.
• Closed-loop control systems for FES applications:
  • Novel control systems will minimize fatigue and compensate for changes in muscle response, which is necessary for FES applications such as walking and torso control.
  • These advanced control systems may lead to more FES systems for use in the home and community by SCI individuals.

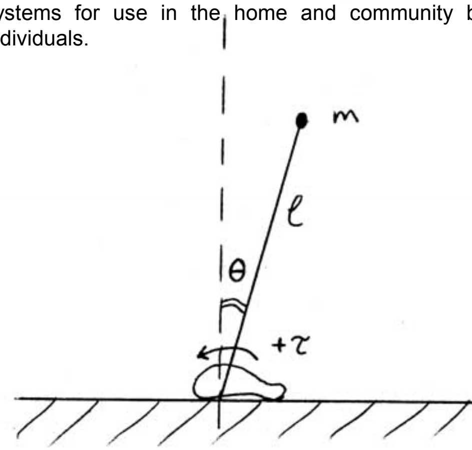


**Fig 3** – Inverted pendulum model of quiet standing

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The authors acknowledge the support of Toronto Rehabilitation Institute who 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.

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# INCLUDING NON-IDEAL BEHAVIOUR IN FES SIMULATIONS


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## Introduction

• Functional electrical stimulation (FES) can be used to restore or replace motor function in individuals with spinal cord injuries (SCI).
• New SCI applications must be thoroughly tested with SCI subjects – time-consuming and expensive, so simulations are used to refine design of FES applications prior to testing.
• FES simulations are often based on ideal stimulated muscle response, which may result in an overly optimistic assessment of FES system's likely real-world performance.

• We created a "non-idealities" block in Simulink with data from complete SCI subjects (injury levels C6 through T10).
  • Block modifies nominal stimulated muscle response to reflect undesirable behaviour seen in real world.
  • Represents the range of spasm, tremor, and fatigue behaviour exhibited by stimulated muscles.
  • Can be incorporated into existing simulations to analyze potential real-world performance of FES systems.

## Methods

• Spasm, tremor, and fatigue waveforms were extracted from stimulated knee movements of complete SCI subjects.
  • Fatigue waveforms were scaled between 0 and 1 [1].
  • Each non-ideality waveform was classified as mild, moderate, or severe.

• Non-idealities block was implemented in Simulink, and allows user to choose severity of non-idealities included in particular instance of block.
  • Actual waveform that is used for each non-ideality is chosen randomly from group of waveforms having desired classification.
• Eqn 1 gives output of block, where $\tau(t)$ is nominal stimulated muscle torque, $\nu(t)$ is modified torque, and *s(t)*, *m(t)*, and *fat(t)* are instances of spasm, tremor, and fatigue waveforms, respectively.

• Fig 1 shows example of implementation of non-idealities block in FES simulation.
  • PID controller is used to track desired knee angle.
  • Based on Ferrarin & Pedotti's model of seated, stimulated knee extension against gravity [2].

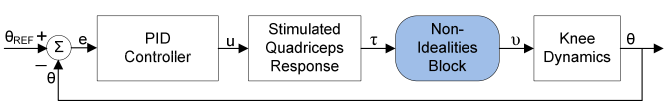


**Fig 1** – Diagram of knee control simulation (θ is knee angle)

## Results

• Fig 2 shows effect of non-idealities block. Dotted line is nominal knee torque at maximum stimulation. Solid line is modified torque for mild spasms, fatigue, and tremor.
• Fig 3 shows unit step tracking performance for PID controller. Dotted line is without non-idealities block, and solid line is with block (mild spasms, fatigue, and tremor).

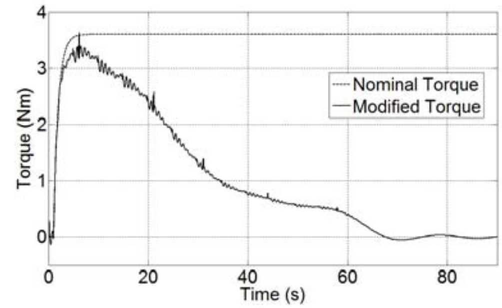


**Fig 2** – Nominal torque at maximum stimulation, and modified torque from non-idealities block (mild spasms, fatigue, and tremor)

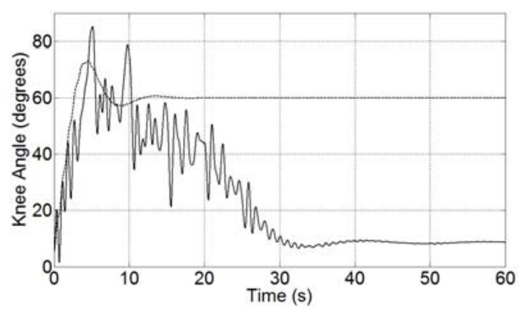


**Fig 3** – Sample implementation – unit step tracking with PID control (dotted line is nominal case, solid line is with non-idealities block).

$$\nu(t) = (\tau(t) + s(t) + m(t)) \cdot fat(t)$$

**Equation 1** – Output of non-idealities block

## Discussion

• Modified torque produced by non-idealities block clearly differs from nominal torque.
• Fatigue, tremors had a large effect on control performance.
• Real-world control performance may be modestly better than simulated results due to unmodeled muscle recovery.
• Isotonic contractions in trained muscles may have different fatigue profiles than those used in non-idealities block.
• Non-idealities block does not reflect all possible undesirable behaviour that can occur with real-world FES use.

## Conclusions

• Non-idealities block allows researchers to assess likely real-world performance of FES systems prior to subject testing.
• MatLab code for block will be freely available in early 2011 at www.toronto-fes.ca under Products.

## References


[1] Graham GM, Thrasher TA, Popovic MR. *IEEE Trans Neural Syst Rehabil Eng*, 14:38-45, 2006.
[2] Ferrarin M, Pedotti A. *IEEE Trans Rehabil Eng*, 8:342-352, 2000.





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# STOCHASTIC MODELING OF KNEE RESPONSE

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## 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.

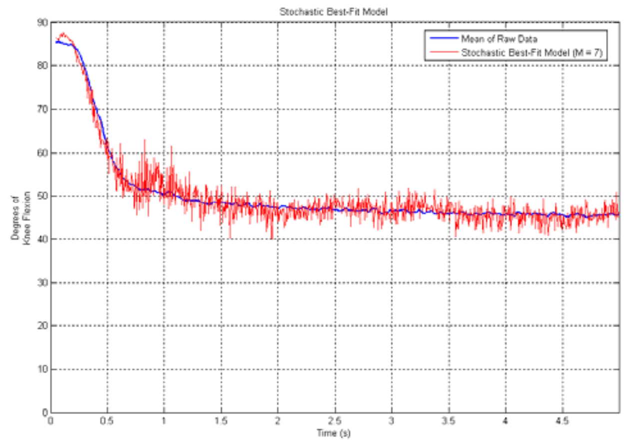


**Fig 1** – Stochastic Best-Fit Model

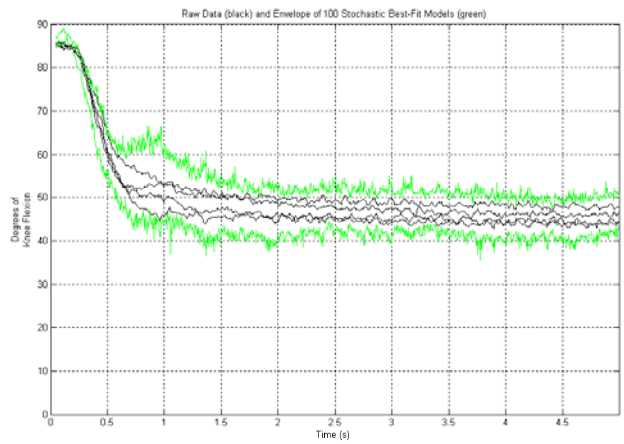


**Fig 2** – Raw Data and Envelope of 100 Stochastic Best-Fit Models

### 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

[1] TA Thrasher, HM Flett, & MR Popovic. Spinal Cord. 44(6):1-5. 2006.

[2] MR Popovic, TA Thrasher, ME Adams, V Takes, V Zivanovic, MI Tonack. Spinal Cord. 44(3):143-151. 2006.

[3] WH Press, BP Flannery, SA Teukolsky, WT Vetterling. Numerical Recipes in C, 2nd ed. Cambridge University Press, Cambridge, UK, 1999.

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The views expressed in this poster do not necessarily reflect those of any of the granting agencies.

# VIDEO GAME-BASED TRAINING FOR CALF MUSCLES

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KMV McConville* and MR Popovic

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## Introduction

**Secondary complications after spinal cord injury (SCI)**

- Pressure sores
- Bone demineralization
- Deep venous thromboses

**Musculoskeletal atrophy and disuse**

**Neuromuscular electrical simulation can counteract musculoskeletal atrophy and decrease the likelihood of secondary complications**

### *Objective*

**To evaluate the concept of the new training system**

## Hypothesis

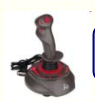
*Awareness*
*Motivation*
*Continuity*
*Overload*
*Progression*
*Specificity*
*Periodicity*

USER-SYSTEM INTERFACE: VIDEO GAME → USERS AWARENESS AND VOLITION → ELECTRICAL STIMULATION → MUSCLE CONTRACTION → JOINT POSITION

↑ strength
↑ endurance
↑ joint mobility

## Methods

**PARTICIPANT**
- 57-year-old man
- complete paraplegia (AIS A)
- 4 years after injury
- level T4



**JOYSTICK**

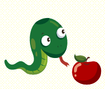
**Analogue joystick**
- 5V output

**STIMULATION**

**Compex Motion**
- pulse duration 300 µs
- frequency 40 Hz
- intensity from 20mA to 80 mA

**RESULTANT MOVEMENT**

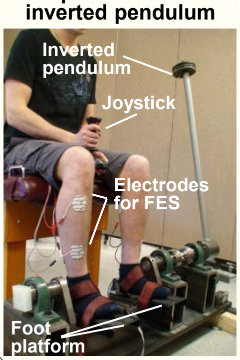
**3-axis accelerometer**
- LabVIEW 8.1 (National Instr., USA)



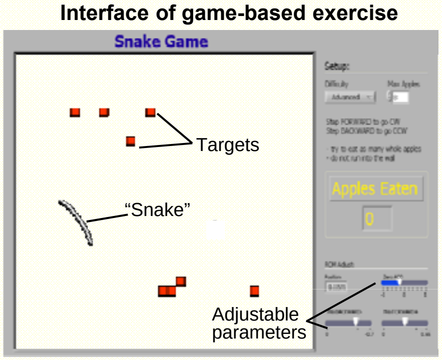
**VIDEO GAME**

**Adjustable parameters**
- speed of the snake
- number of targets
- neutral position of the foot plate
- range of motion

**Foot platform with the inverted pendulum**

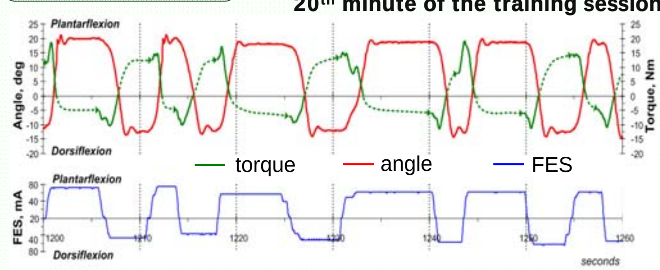



**Interface of game-based exercise**




## Results

**20th minute of the training session**




**Video game-based training provided:**
- **Simple control**
- **Challenge**
- **Optimal agonist-antagonist stimulation ratio**
- **Isotonic concentric plantarflexions and dorsiflexions**
- **Positive effect on muscle fatigue resistance**

## Conclusion

**Video game-based training may be clinically relevant as a tool to improve muscle performance in individuals with SCI, and/or to promote their participation in other rehabilitation programs**

## Acknowledgment

**The authors acknowledge the support of Toronto Rehabilitation Institute who 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.**

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The authors acknowledge the support of Toronto Rehabilitation Institute who 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.

Partners:

# ARM MOVEMENTS IN DYNAMIC POSTURAL STABILITY


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[2] Toronto Rehabilitation Institute
[3] Institute for Biomaterials and Biomedical Engineering, University of Toronto


## Introduction

- Falls are related to health quality of life and have big social impacts
- **Canadian Community Health Survey** (CCHS 2005):
  - injuries occur more frequently as a result of falls for elderly

- **Balance Strategies** (Horak, 2006; Maki & McIlroy, 2006; Maki, McIlroy & Fernie, 2003)

| | |
|---|---|
| **Leg and trunk strategies** | - Hip strategy / CoM |
| | - Ankle strategy |
| | - Change-of-support |
| **Arm strategies** | - Reaching-grasping |
| | - Protective movements |

- **Handedness in Balance**

Motor Lateralization of Balance VS. Dynamic Hand Dominance
dominant arm for balance — both arms important
(Perennou et al., 1999) — (Sainburg, 2007)

## Objectives

- Novel diagnostics method for balance using accelerometers
- Dynamic postural balance assessment
- Exploration of arm movements balance mechanism

## Methods

- Subjects: Four healthy middle-aged adults (mean age = 56 years); all participants were right handed

**Protocol:**
Maintaining balance on a balance board while simultaneously observing anterior-posterior and lateral balance

- **Dynamic Balance Board tests:**
  - **Complex (CP)**: balance board movements in all direction
  - **Anterior-posterior (AP)**: front-to-back balance board movements
  - **Lateral (LAT)**: balance board movements in lateral direction

- **Apparatus:**
  - Tri-axial accelerometers ±2.0g (Kionix Inc., KXM52-1050)
  - Data: 12-bit resolution (National Instruments, NI-USB6008)
  - Signal processing application (National Instruments, LabView 8.2)

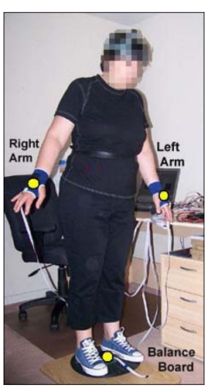



**Fig 1** – Experimental setup

- **Sensor Placement:**
  - Arms (Left and Right arm)
  - Balance board

- **Signal Processing:**
  - Vector Magnitude Unit (VMU):

magnitude of accelerations

$$a_{VMU} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

**Fig 2** – Balance board

- **Signal Analysis: Segmentation**
Regions of *Stable Balance* and *Balance Recovery* obtained to examine arm movements in the two balance regions

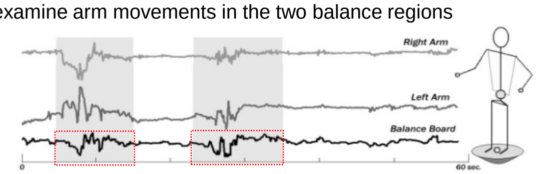
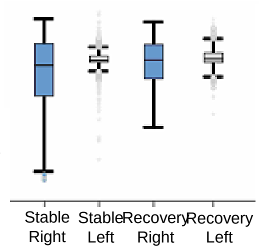



**Fig 3** – Segmentation algorithm

## Results

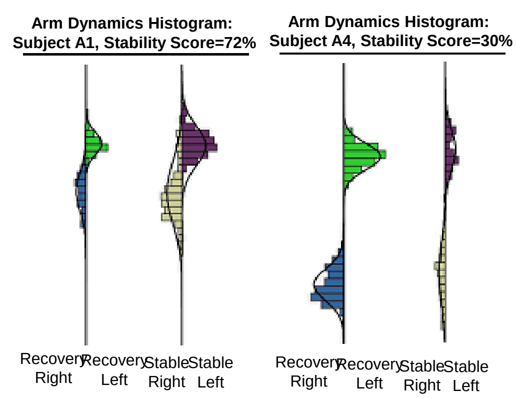



**Arm Movement Dynamics:**
**Lateral Balance test**
- Arms important for lateral balance
- LAT test → Counterbalancing strategy
- LAT test → Dominance in balance

**COM Test & Arm Movements**
- Coordinated arms use → better balance
- Correspondent use in both regions → better balance

**AP Test & Arm Movements**
- Low intensity of arm use during AP test → worse balance

**LAT Test & Arm Movements**
- Coordinated arms use → better balance
- Active arm movements → better balance




## Discussions

Results suggest important role of arms for dynamic postural balance

**Arm use:**
- associated with lateral balance (LAT test)

Results support *Dynamic Hand Dominance Model*:
- specific role of the dominant and non-dominant arm
- during both stable and recovery phases

**Arm strategies** for better balance performance:
- ***Active***, ***Counterbalancing*** and ***Coordinated*** arm movements

## References


Horak. Age Ageing, 2006
Maki et al. IEEE Eng Med Biol Mag, 2003.
Perennou et al. Rev Neurol (Paris), 1999
Sainburg. Exp Brain Res 2002



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The authors acknowledge the support of Toronto Rehabilitation Institute who 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.


**Partners:**

# Posturography Measures during Quiet Sitting


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[2]Toronto Rehab, Lyndhurst Centre, [3]University of Houston,
[4]Japan 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

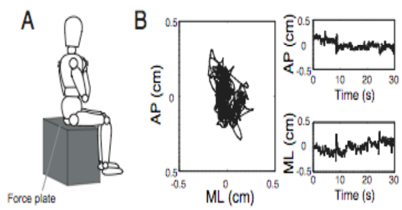


**Fig1** – (A) Experimental setup and (B) an example of COP time series (only 30 s of data presented) in a planar plot (left), and time series of AP (top) and ML (bottom)

## 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]

## 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

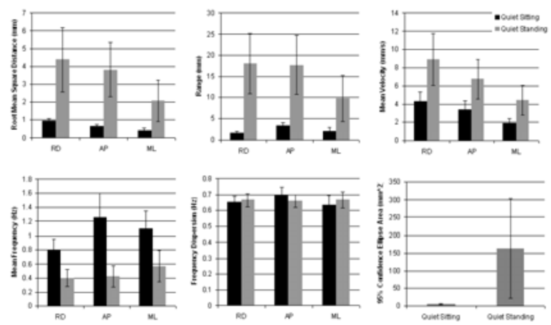


**Fig2** – Comparison of time-domain and frequency-domain measures

**Table 1:** Stabilogram Diffusion Function Measures

| | | Quiet Sitting | Quiet Standing [2] | Ratio* |
|---|---|---|---|---|
| $\Delta t_c$ (s) | RD | 0.45 ± 0.24 | 0.92 ± 0.29 | 0.49 |
| | AP | 0.53 ± 0.36 | 0.97 ± 0.46 | 0.55 |
| | ML | 0.49 ± 0.23 | 1.06 ± 0.42 | 0.47 |
| $H_S$ | RD | 0.86 ± 0.03 | 0.76 ± 0.04 | 1.13 |
| | AP | 0.86 ± 0.03 | 0.77 ± 0.04 | 1.12 |
| | ML | 0.89 ± 0.05 | 0.74 ± 0.05 | 1.20 |
| $H_L$ | RD | 0.12 ± 0.14 | 0.34 ± 0.08 | 0.31 |
| | AP | 0.10 ± 0.18 | 0.38 ± 0.10 | 0.28 |
| | ML | 0.20 ± 0.12 | 0.23 ± 0.05 | 0.89 |

*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


1. C. Maurer, R.J. Peterka, *Journal of Neurophysiology* 93 (2005) 189 - 200.
2. T.E. Prieto, et al., *IEEE Transactions on Biomedical Engineering* 43 (1996) 956-966.
3. J.J. Collins, C.J. de Luca, *Experimental Brain Research* 95 (1993) 308-318.


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# Posturography Measures for Healthy Young Adults during Quiet Sitting in Comparison with Quiet Standing

**Albert H. Vette, Kei Masani, Vivian Sin, and Milos R. Popovic**

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## Introduction

**Background**

Measures of postural steadiness – known as posturography – are commonly used for balance assessment during quiet standing [1-3]. Although quiet sitting balance may be studied via posturography as well, this has not been done to date. Similar to quiet standing, the posturography for quiet sitting could eventually be applied as a clinical assessment tool for sitting balance and for the development of novel balance rehabilitation techniques and assistive devices.

The purpose of this study was to characterize the posturography during quiet sitting in comparison with quiet standing and to provide a benchmark for future studies investigating differences in balance regulation and execution.

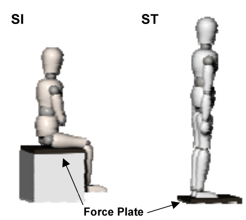
## Methods

**Subjects**

- 12 healthy and young individuals (10 male, 2 female)
- age 27.7 ± 6.6 years; height 176.2 ± 9.3 cm; weight 75.8 ± 13.6 kg
- no neurological or musculoskeletal disorder / no acute or chronic back pain

**Experimental Procedure and Recordings**

- quiet sitting (**SI**) and quiet standing (**ST**) for 2 minutes each [4]
- two conditions: eyes open (**EO**) and eyes closed (**EC**)
- force plate data (100 Hz) used to calculate center of pressure (COP):
  - anterior-posterior fluctuation (**AP**)
  - medial-lateral fluctuation (**ML**)
  - resultant distance fluctuation (**RD**)




**Analysis of AP, ML, and RD (SI and ST)**

- Time Domain Measures [1, 3]:
  - mean distance (**MD**)
  - mean velocity (**MV**)
- Frequency Domain Measures [1, 3]:
  - centroidal frequency (**CFREQ**)
  - frequency dispersion (**FREQD**)
- Stabilogram Diffusion Function (SDF) Measures [2, 3]:
  - short-term & long-term Hurst exponents (**$H_S$** and **$H_L$**)

## Results

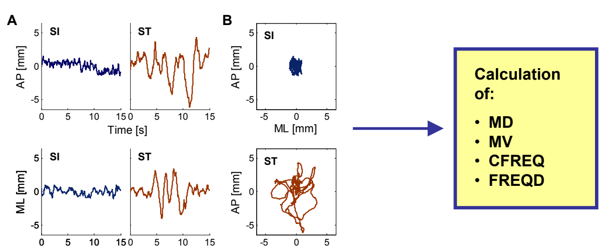



**Fig. 1:** COP fluctuation. A: AP (top) and ML (bottom) time series during SI (left) and ST (right); B: Phase plots during SI (top) and ST (bottom).

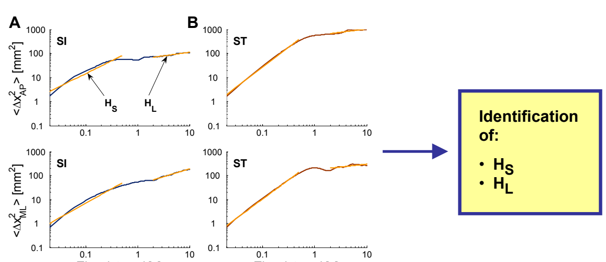



**Fig. 2:** Log-log SDF plots. A: SDF plots during SI (AP & ML); B: SDF plots during ST (AP & ML). Orange lines represent linear regression fits.

**Data Analysis – Main Findings**

- Body sway was ***smaller*** and ***slower*** during SI in comparison to ST (**Table I: MD & MV**)
- Body sway during SI was characterized by a ***higher*** centroidal frequency and a ***larger*** frequency variation in comparison to ST (**Table I: CFREQ & FREQD**)
- $H_S$ was consistently ***larger*** than 0.5 for both tasks → positive correlation of stochastic process; $H_L$ was consistently ***smaller*** than 0.5 for both tasks → negative correlation of stochastic process (**Table I: $H_S$ & $H_L$**)
- SI exhibited a less ***positively*** correlated stochastic activity in the short-term region and a less ***negatively*** correlated stochastic activity in the long-term region when compared to ST (**Table I: $H_S$ & $H_L$**)

**Table I:** Summary of posturographic and statistical analysis (* P<0.05; ** P<0.01; *** P<0.001)

| | | Ratio of SI/ST | | Posturographic Quantities | | | | Paired t-Test | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | SI | | ST | | Tasks | | Eye Cond. | |
| | | EO | EC | EO | EC | EO | EC | EO | EC | SI | ST |
| MD (mm) | AP | 0.66 | 0.33 | 1.66 | 1.40 | 2.53 | 4.26 | – | *** | – | *** |
| | ML | 0.75 | 0.53 | 0.93 | 1.00 | 1.25 | 1.89 | – | * | – | ** |
| | RD | 0.68 | 0.37 | 2.06 | 1.87 | 3.04 | 5.03 | * | *** | – | *** |
| MV (mm/s) | AP | 0.74 | 0.40 | 3.12 | 3.18 | 4.21 | 7.90 | *** | *** | – | *** |
| | ML | 0.81 | 0.60 | 2.46 | 2.37 | 3.04 | 3.92 | – | ** | – | *** |
| | RD | 0.77 | 0.46 | 4.43 | 4.40 | 5.78 | 9.61 | ** | *** | – | *** |
| CFREQ (Hz) | AP | 1.82 | 1.79 | 0.65 | 0.70 | 0.36 | 0.39 | ** | ** | – | – |
| | ML | 1.15 | 1.19 | 0.65 | 0.62 | 0.57 | 0.52 | – | – | – | – |
| | RD | 1.47 | 1.38 | 0.56 | 0.55 | 0.38 | 0.40 | * | – | – | – |
| FREQD (–) | AP | 1.08 | 1.11 | 0.86 | 0.85 | 0.80 | 0.77 | * | * | – | ** |
| | ML | 1.14 | 1.16 | 0.86 | 0.89 | 0.76 | 0.77 | ** | ** | – | – |
| | RD | 1.06 | 1.08 | 0.90 | 0.91 | 0.85 | 0.84 | *** | *** | – | – |
| $H_S$ (–) | AP | 0.78 | 0.78 | 0.68 | 0.68 | 0.86 | 0.86 | *** | *** | – | – |
| | ML | 0.82 | 0.79 | 0.68 | 0.66 | 0.83 | 0.83 | *** | *** | – | – |
| | RD | 0.80 | 0.79 | 0.66 | 0.65 | 0.82 | 0.83 | *** | *** | – | – |
| $H_L$ (–) | AP | 1.35 | 1.30 | 0.23 | 0.23 | 0.17 | 0.18 | – | – | – | – |
| | ML | 1.65 | 1.39 | 0.25 | 0.28 | 0.15 | 0.20 | * | – | – | – |
| | RD | 2.74 | 2.51 | 0.18 | 0.17 | 0.07 | 0.07 | * | * | – | – |

## Discussion

**Effects of Sitting versus Standing Posture**

Using an inverted pendulum model [5] and Winter's anthropometric approximations [6]:

- **biomechanical differences** between SI and ST can account for the smaller time-domain measures (MD & MV) during SI:

  **height of center of mass (SI) / height of center of mass (ST) = 0.50**

- **dynamic differences** between SI and ST must contribute to the larger frequency-domain measures (CFREQ & FREQD) during SI:

  **sway frequencies (SI) / sway frequencies (ST) > 2.00**

**Differences in Control Schemes**

- short-term, presumably open-loop postural control mechanism during SI (since **$H_S$ > 0.5** [2]) is less unstable (**smaller $H_S$**) → fewer drifts away from relative equilibrium point over short time intervals when compared to ST.
- long-term, presumably closed-loop postural control mechanism during SI (since **$H_L$ < 0.5** [2]) is less stable (**larger $H_L$**) → fewer controlled adjustments to bring the system back to equilibrium over the longer term when compared to ST.

  **→ two results above complement each other!**

## Conclusion

The posturographic differences between SI and ST can be partially explained by biomechanical and dynamic differences of the body portions that are in motion during quiet sitting and standing. The SDF analysis suggests, however, that also the balance control strategies are not identical. These findings may be especially useful for the clinical assessment of sitting balance and the development of novel balance rehabilitation techniques and assistive devices.

## References

[1] Prieto TE et al. IEEE Trans Biomed Eng 43(9):956-966, 1996.
[2] Collins JJ, De Luca CJ. Exp Brain Res 95:308-318, 1993.
[3] Maurer C, Peterka RJ. J Neurophysiol 93:189-200, 2005.
[4] Carpenter MG et al. Gait Posture 13:35-40, 2001.
[5] Gage WH et al. Gait Posture 19:124-132, 2004.
[6] Winter DA. Biomechanics and motor control of human movement. Wiley, New Jersey, 2005.

*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.*



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**Partners:**

# Complex three-dimensional spine motions during target-directed movements of the trunk in sitting

Richard A. Preuss & Milos R. Popovic

## Purpose

To assess segmental spine motion, in three dimensions, during multi-directional, target-directed trunk movements.

## Main Finding

Spine motion varied with target placement and was unevenly distributed between spine levels, often with complex interactions between task variables.

## Methods

***Subjects*** - Eleven healthy volunteers; 7 male, 4 female; mean age 28.5 (3.3) years

***Test Position*** - Sitting, feet unsupported.

***Experimental Task*** - Touch target with head; 5 target directions (Fig.1A); 3 subject-specific target distances (Fig. 1B)

**Kinematic Model** - 7 marker triads from sacrum to C7 (Fig. 1C). Data acquired with a 6-camera, Vicon 512 motion analysis system. Motions named for orientation of rostral triad relative to caudal triad.

***Statistical Analysis*** - 3-way ANOVA for each segmental motion (flexion, side-bending, axial rotation). Independent variables: trunk level (6), target distance (3) and target direction (5).

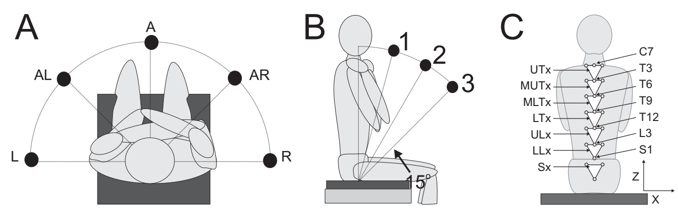


**Figure 1** - **A.** Target directions; 45° intervals. **B.** Target distances; 15° intervals based on subject's trunk height. **C.** Marker triads for kinematic model.

## Results

***Flexion***

*Main Effects:*

- Trunk Level
- Target Distance
- Target Direction

*Interaction Effects:*

- Level & Distance
- Level & Direction

***Side-Bending:***

*Main Effects:*

- Trunk Level
- Target Distance
- Target Direction

*Interaction Effects:*

- Level & Distance
- Level & Direction
- Distance & Direction

***Axial Rotation:***

*Main Effects:*

- Trunk Level
- Target Distance
- Target Direction

*Interaction Effects:*

- Level & Direction

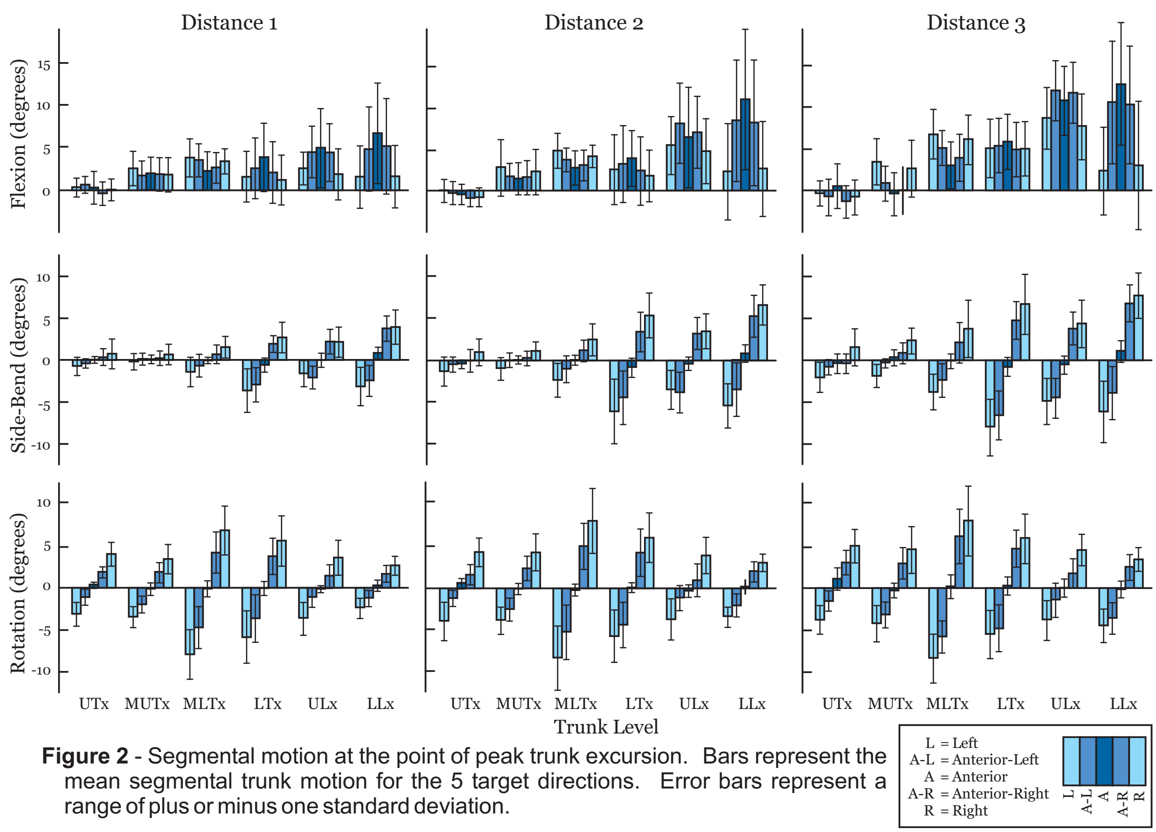


**Figure 2** - Segmental motion at the point of peak trunk excursion. Bars represent the mean segmental trunk motion for the 5 target directions. Error bars represent a range of plus or minus one standard deviation.

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Partners:

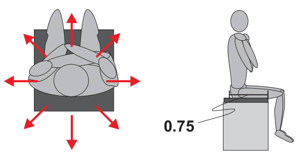
# CENTER OF PRESSURE EXCURSION DURING VOLUNTARY TRUNK MOVEMENT IN SITTING

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

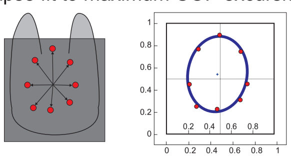
## 1) Limits of stability

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)

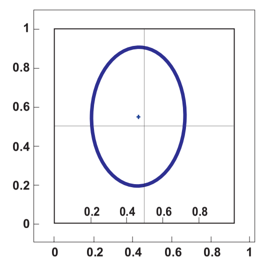
Area: 32.7% (0.4%) BoS

Center: 54.9% (4.5%) BoS length
45.5% (1.5%) BoS width

Major Axis: 35.7% (3.4%) BoS length
26.9% (3.9%) BoS width

Eccentricity: 0.66

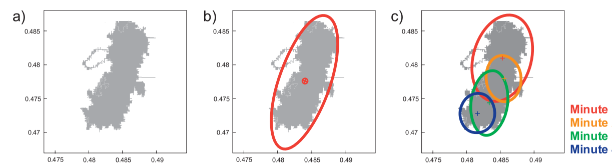
Orientation: -2.0° (5.3°)



## 2) Postural sway: quiet upright sitting

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

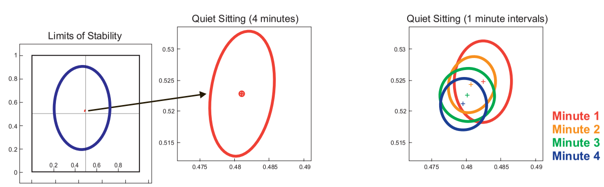
Approach:
a) COP position over 4 minutes of quiet sitting (9 subjects)
b) Least square ellipse fit (axis length doubled)
c) Ellipses fit to each 1 minute period (axis length doubled)




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°)

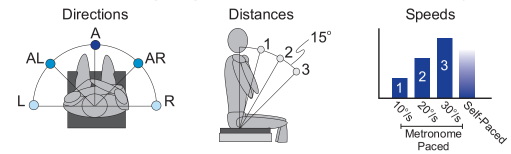
One Minute Intervals:
Area: 0.0047% to 0.0092% BoS
Center: 52.5% to 52.1% BoS length
48.3% to 48.0% BoS width
Major Axis: 0.66% to 0.42% BoS length
Minor Axis: 0.41% to 0.33% BoS length
Eccentricity: 0.42 to 0.78
Orientation: -11.2° to 6.7°




## 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

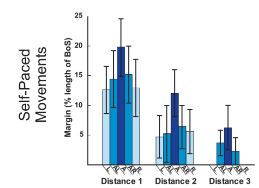
Approach:
a) COP position during target-directed trunk movements (11 subjects)



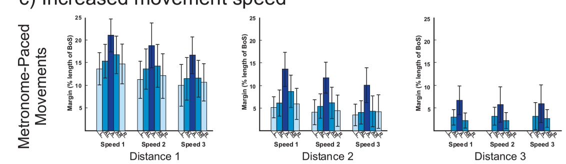

b) Margin of stability = minimum distance from COP to limits of stability

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.

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Partners:

We also thank Dr. Joyce Fung, and the JRH-CRIR, for the use of equipment and laboratory space for the acquisition of these data.

The views expressed in this poster do not necessarily reflect those of any of the granting agencies

# A Complete, Universal, and Verifiable Set of Upper Body Segment Parameters for Three-Dimensional Dynamic Modeling

**Albert H. Vette, Takashi Yoshida, T. Adam Thrasher, Kei Masani, and Milos R. Popovic**

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Center for Neuromotor and Biomechanics Research, University of Houston

## Introduction

**Background**

Dynamic models of the human trunk have been extensively used to investigate the biomechanics of lower back pain and postural instability in different populations. Despite their diverse applications, these models rely on intrinsic upper body segment parameters (UBSP), e.g., each segment's mass-inertia characteristics. However, a comprehensive UBSP set allowing state-of-the-art, three-dimensional (3D) dynamic modeling does not exist to date.

The purpose of this study was to establish a UBSP database that is accurate, complete, and universal, i.e., independent of pre-defined (lumped) trunk portions such as 'upper trunk' and 'lower trunk' (**PART I**). To demonstrate the practicality of the UBSP, they were finally implemented in a 3D dynamic model of the upper body to predict lumbar joint torques from experimental kinematics during perturbed sitting (**PART II**).

## Methods – Geometric Models and UBSP

**Data Source:**

- High-resolution, transverse color images from the **Male Visible Human** (MVH) [1]
- MVH anthropometrics: age 38; height 180 cm; weight 90 kg [1]
- Image resolution: 0.144 mm x 0.144 mm x 1 mm [1]

**Body Segmentation:**

- 24 vertebral trunk and head segments:
  - 5 lumbar segments (**L1 to L5**)
  - 12 thoracic segments (**T1 to T12**)
  - 6 cervical segments and head (**C2 to C7 and HD**)
- 2 x 2 upper limb segments:
  - left and right upper arm (**lUA and rUA**)
  - left and right forearm-hand complex (**lFA-H and rFA-H**)

**3D Geometric Models of:**

- MVH spinal vertebrae, spinal discs, and pelvis (PV)
- MVH body shell

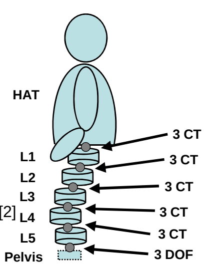
**Identified Parameters:**

- Spinal joint centers
- Segment masses
- Location of segment center-of-masses
- 3 x 3 moment of inertia tensor of segments

## Methods – Inverse Dynamics

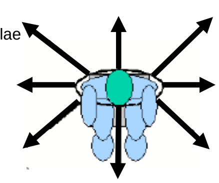
**Model:**

- Focuses on the action of the lumbar spine [2]
  - AP: flexion-extension
  - ML: lateral bending
  - RT: axial rotation
- Six rigid bodies [2]:
  - L1 to L5
  - Head-Arms-Thorax complex (HAT)
- 3 degrees-of-freedom (DOF) between at L5-PV joint [2]
- 3 x 5 constraints (CT) at the remaining 5 joints [2]




**Experiments:**

- 1 subject with MVH anthropometrics
- Horizontal perturbations during upright sitting
- 8 perturbation directions, 5 trials each
- Impulse force of ~200 N max, applied inferior to axillae

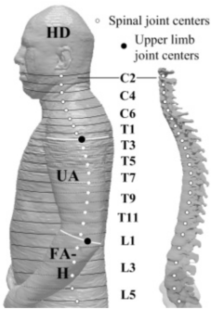


**Joint Torque Estimation:**

- Inverse dynamics from kinematics to joint torques
- 3 different dynamic implementations:
  - Newton-Euler formulation
  - Lagrange formulation
  - Simulink & SimMechanics (Mathworks Inc.)

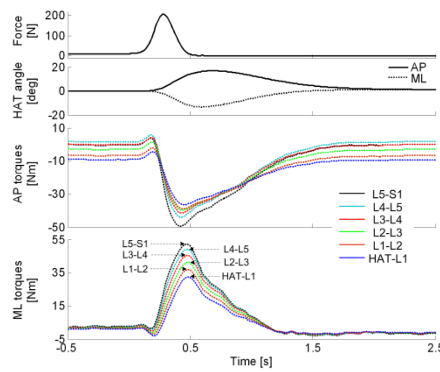
## Results

**Geometric Models and UBSP:**




Surface models of the MVH body shell and spine. The identified joint centers were used to define the vertebral trunk segments and upper limb segments for which respective mass-inertia characteristics were calculated using the geometric method.

**Inverse Dynamics:**




Results of the inverse dynamics using the identified UBSP set. Shown are the AP and ML trunk angles and joint torques for an anterior-left diagonal perturbation during sitting. A visual inspection suggests that the torque outputs of the three different inverse dynamics implementations match very well (plotted on top of each other; $R^2$ = 99.9999 %). It can also be seen that the AP torque traces are affected by the AP curvature of the spine.

## Discussion

**Identified UBSP Set:**

- **Complete** with respect to 3D dynamic modeling (all required parameters identified)
- Based on **highly accurate** 3D geometric models (1000 higher than existing sets)
- **Universal** with respect to model definitions (parameters can be lumped together)
- Uniquely **verifiable and expandable** (MVH dataset is freely accessible)

## Conclusion

A comprehensive UBSP database has been obtained that can be implemented in 3D dynamic models to: (1) systemize thinking in postural control studies; (2) quantify the effect of impact forces on the head and trunk (e.g., during whiplash); (3) suggest population-specific experiments based on theoretical insights into trunk dynamics (e.g., regarding lower back pain); or (4) assess the feasibility of new surgical techniques (e.g., spinal fusion) and neuroprostheses (e.g., after spinal cord injury [3]).

## References

[1] Spitzer V et al, *J Am Med Inform Assn* **3**, 118-130, 1996.
[2] Wilkenfeld AJ et al, *J Rehabil Res Dev* **43**, 139-152, 2006.
[3] Masani K et al, *Clin Biomech* **24**, 176-182, 2009.

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**Partners:**

# Muscle Recruitment Patterns in Perturbed Sitting


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[1]Institute of Biomaterials and Biomedical Engineering, University of Toronto
[2]Toronto Rehab, Lyndhurst Centre, [3]University of Houston


## 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

## Goals

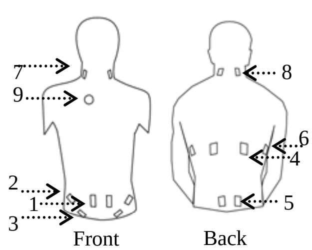
• To determine the directional dependencies of trunk muscle responses, and the amount of muscle activities to perturbations applied from different directions during sitting of able-bodied subjects

## Methods

• Subjects: 12 healthy, right-handed male, age 21 to 39 years

• Protocol:

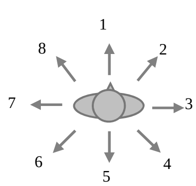
  • Surface electrodes were placed on trunk and neck muscles on both sides of the body to measure muscle activities (EMG)

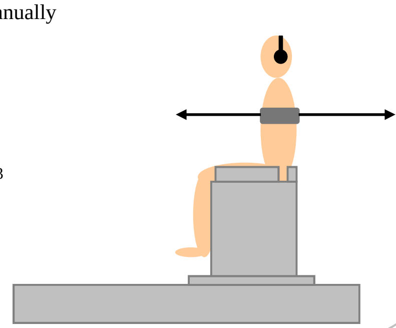



1 - rectus abdominis (RA)
2 - external obliques (EO)
3 – internal obliques (IO)
4 – thoracic erector spinae (T9)
5 – lumbar erector spinae (L3)
6 – latissimus dorsi (LD)
7 – sternocleidomastoid (SM)
8 – splenius capitis (SC)
9 - reference

  • 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



## 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):

$$y = c_0 + c_1 \exp^{(-((x-c_2)/c_3)^2)}$$

Fig. A

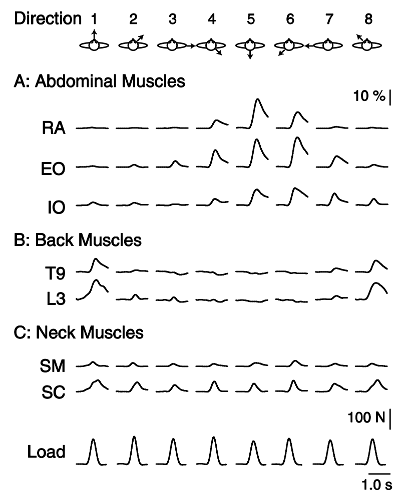
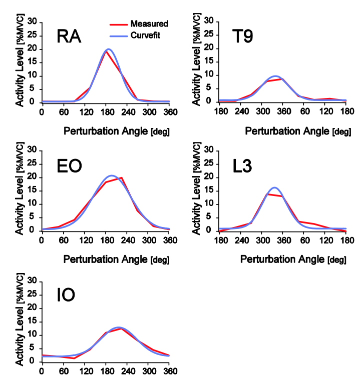



Fig. B




## 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



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**Partners:**

# Wave® vs. Juvent™ : Whole-Body Vibration Assessment


**M Alizadeh-Meghrazi[1,2], J Totosy De Zepetenek[1,3], M Miyatani[1], LM Giangregorio[3], A Morris[1], L You[2], MR Popovic[1,2], BC Craven[1,2]**

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**[2]University of Toronto**
**[3]University of Waterloo**


## Background

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

•25-46% of SCI patients experience lower extremity fragility fractures due to SO.

•Current SO treatments include: oral bisphosphonates, and rehabilitation have been largely ineffective in producing a significant or sustained increase in knee region BMD.

•Whole-Body Vibration (WBV) is a new therapy used for improving muscular strength and BMD in animals, post-menopausal 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.

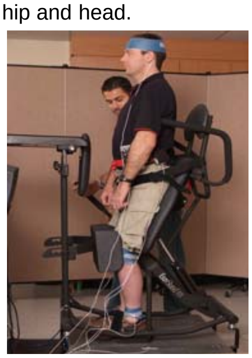
## Methods

•Subjects: Healthy male volunteers (AB), 20-50 years old (n=7) and age matched traumatic SCI patients with motor complete paraplegia (n = 5).

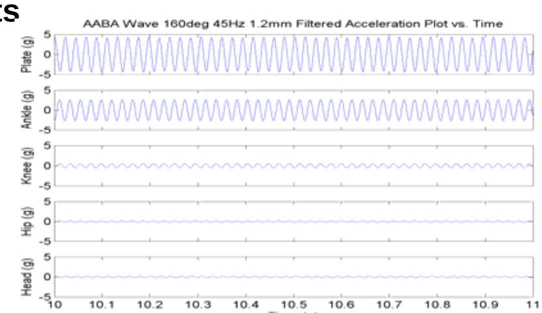
•Controlled parameters:

1) Vibration Frequency : (25, 35 & 45 Hz)
2) Vibration Amplitude : (0.6 & 1.2 mm)
3) Posture, Knee Angle : (140º, 160º &180º)

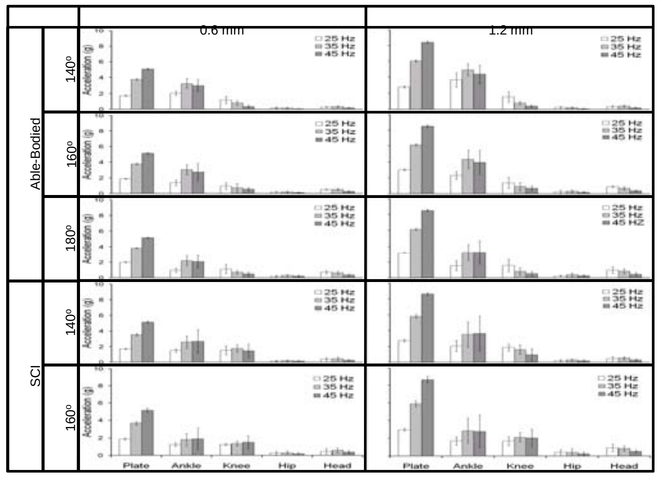
•Quantitative analysis: Degree of vibration propagation, measured with accelerometers located at the plate, ankle, knee, hip and head.



## Results




**Wave® Peak to Peak Acceleration Amplitude vs. Location**




## Discussion

•Effect of Frequency:

1) Strong relationship with peak to peak acceleration and transmissibility.
2) Resonance at the ankle at 25 Hz.
3) Reduction in transmissibility with increase in frequency.

•Effect of Amplitude:

1) Strong relationship with peak to peak acceleration and weak relationship with transmissibility.
2) Enhanced effect on peak to peak acceleration with increase in frequency and/or posture.

•Effect of Posture:

1) Strong relationship with peak to peak acceleration in AB subjects (not with SCI); and strong relationship with transmissibility in both subject groups.
2) Reduction in its effect on peak to peak acceleration when frequency is increased; and increase in its effect on peak to peak acceleration with increase in amplitude.
3) Reduced effect on transmissibility with increase in frequency and/or amplitude.

•Vibration propagates through the body at the frequency output from the platform, with phase shift.

•The two platforms created similar propagation characteristics.

•Intensity of vibration output from the Wave® platform is close to one order of magnitude higher than the Juvent™.

## Conclusion

•The optimal parameters for highest vibration absorption while transmitting the lowest vibration to the head is:

45 Hz - 0.6 mm -160º

•Due to the higher intensity of vibration the Wave® is suggested to have stronger osteogenic effects compared to the Juvent™.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The authors acknowledge the support of Toronto Rehabilitation Institute who 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.

**Partners:**

# EFFECT OF WHOLE BODY VIBRATION ON H-REFLEX

DG Sayenko, K Masani, M Alizadeh-Meghrazi,
MR Popovic, and BC Craven

Institute of Biomaterials & Biomedical Engineering UNIVERSITY OF TORONTO

Toronto Rehab

## Introduction

- Whole-body vibration (WBV) is being extensively used in sport training, and has been shown to enhance muscle force-velocity, power, and strength. This suggests that WBV could be implemented in rehabilitation of individuals with neuromuscular disorders such as spinal cord injury (SCI).
- The neuromuscular effects of WBV in sport training have been reported after vibration with voluntary lower extremity muscle contraction. For example, 1 min WBV in a squatting posture causes a significant inhibition of the soleus H-reflex. However, application of WBV during voluntary muscle activity is difficult or unattainable following neurological impairment. Acute changes in motorneuronal excitability during WBV in passive standing would suggest that WBV has positive implications for utilization among individuals with neurological impairment.

## Purpose

To examine and compare the acute effect of WBV during passive standing on the soleus H-reflex among able-bodied participants and individuals with SCI.

## Methods

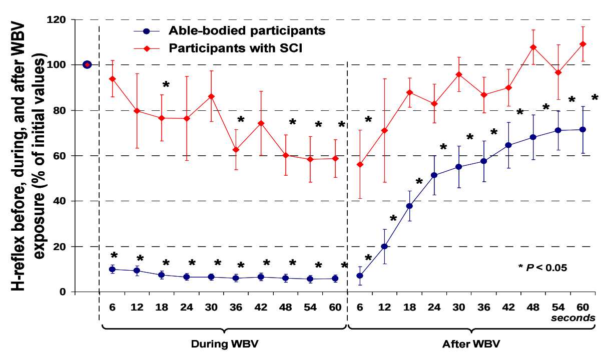
**PARTICIPANTS**: Able-bodied male volunteers, 20-50 years old (n=7) and age matched males with incomplete SCI (C6-T12 AIS B-D).

**CONDITION**: WBV at a frequency of 35Hz with a peak-to-peak amplitude of 1.2mm via a vertical oscillation plate (WAVE Inc, Windsor ON, Canada).

**POSITION**: Passive standing in "EasyStand 5000" (Altimate Medical, Inc., USA).

**H-REFLEX**: Ten soleus H-reflexes with an amplitude equivalent to 30% of maximum M-response were elicited pre-, post-, and during 1 min of WBV.


Raw soleus H-reflexes obtained for able-bodied participant and participant with SCI before, during, and after WBV




Pooled data showing the effect of WBV on the soleus H-reflex

## Results

**In able-bodied participants**:

- WBV caused significant inhibition of the H-reflex as early as 6 s post vibration onset (9.9 ± 1.6 % (p<0.001).
- The magnitude of the H-reflex gradually recovered after WBV, but remained below initial values for 1 minute post WBV (57.5 ± 7.8 % (p<0.001).

**In participants with SCI**:

- Inhibition of the H-reflex was less pronounced.
- The magnitude of the H-reflex recovered within 1 min following WBV exposure.

## Conclusion

- WBV during passive standing caused significant inhibition of the soleus H-reflex similar to WBV exposure while squatting, suggesting that modulation of spinal motoneuronal excitability during WBV can be achieved without voluntary contraction.
- Less pronounced inhibition of the H-reflex among participants with SCI during WBV may be due to interruption of descending pathways which help maintain a tonic level of presynaptic inhibition of Ia terminals in the intact spinal cord.
- Passive standing during WBV among participants with SCI may modulate spinal motoneuronal excitability.

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The authors acknowledge the support of Toronto Rehabilitation Institute who 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.

**Partners:**

# ECoG Controlled Neuroprosthesis for Grasping: Preliminary Study


César Márquez-Chin[1], Dr. Tracy Cameron[2], Dr. Andres M Lozano[2], Dr. Robert Chen[2], and Dr. Milos R Popovic[1]

[1]Rehabilitation Engineering Laboratory, Toronto, Canada

[2]Toronto Western Research Institute, Toronto, Canada


## 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 neurprosthetics 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.

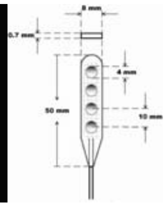
**Using BCI technology, a neuroprosthesis could detect the intention of performing a specific movement and deliver the electrical simulation pattern to produce the intended movement.**

## Method

### Subjects

**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).

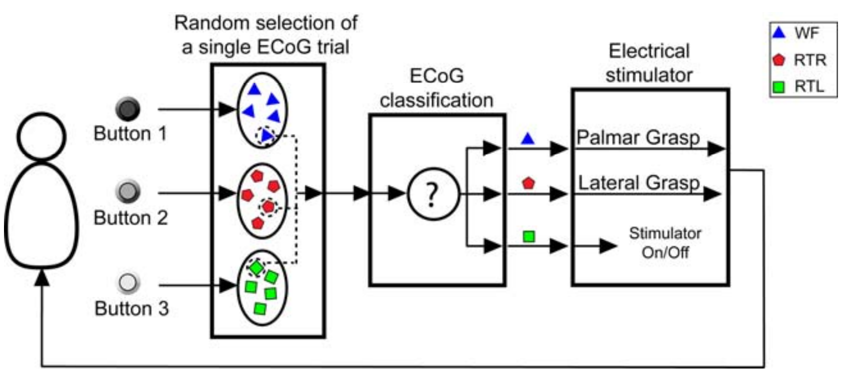



**Subject 2**

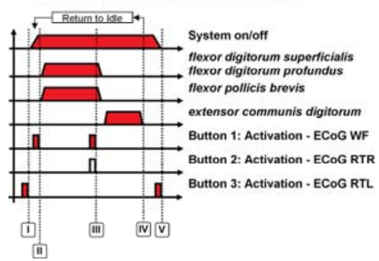
- 35 year old man
- Motor complete cervical spinal cord injury (C6 level/ ASIA B)
- Received 4 weeks of FES therapy
- Fitted with a neuroprosthesis for grasping

### ECoG Controlled Neuroprosthesis for Grasping

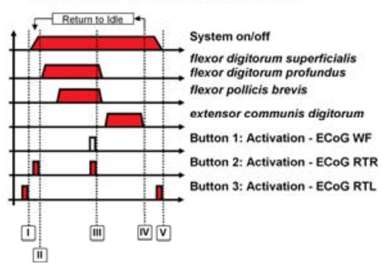
Subject 2 pressed one of three buttons to control the neuroprosthesis. Each button was associated with a dataset of ECoG signals recorded previously from subject 1. The system randomly extracted a single trial of the corresponding dataset which was classified by a nearest neighbour classifier. The classification 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.




**Stimulation Sequence for Palmar Grasp**

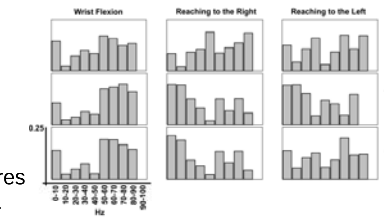



**Stimulation Sequence for Lateral Grasp**




### 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 [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


This work was supported by the Toronto Rehabilitation Institute and the Ontario Ministry of Health and Long Term Care.


## References


1.Chin C.M., et al., Identification of arm movements using correlation of electrocorticographic spectral components and kinematic recordings. J.Neur Eng 2007. 4(2):p.146-158.



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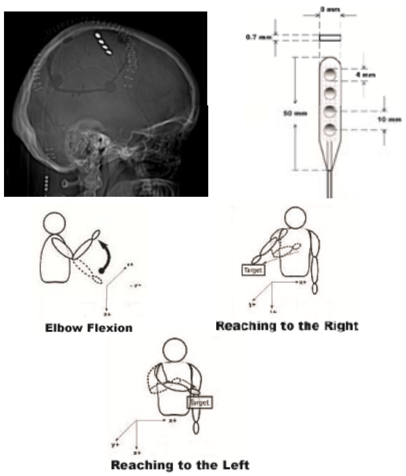
Partners:

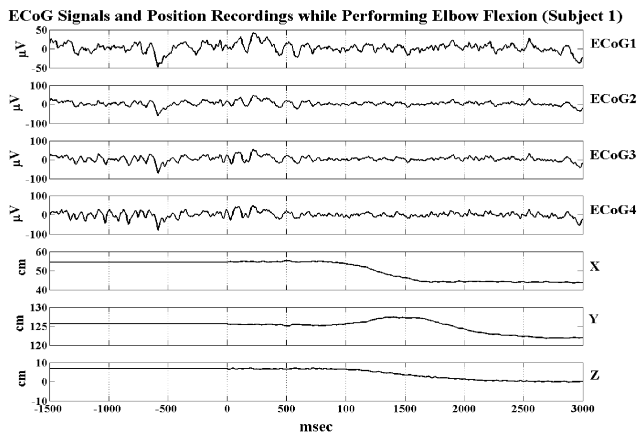
# Identifying Movements from Cortical Signals

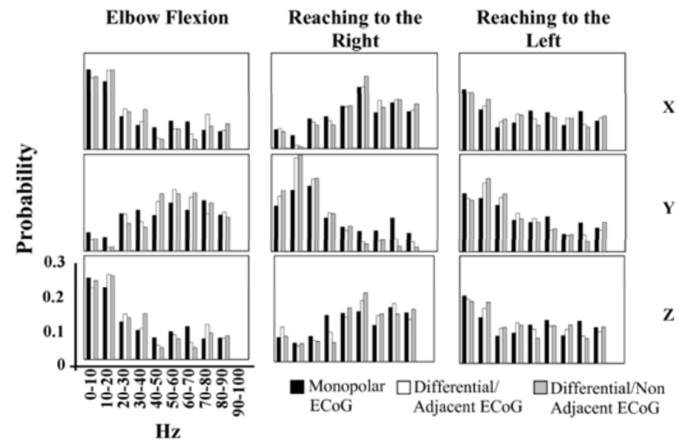
## Electrocorticographic Signals Reflect Specific Motor Tasks

**César Márquez Chin [1,2,3], Andres M Lozano[4], Robert Chen[4], Milos R Popovic[1,2]**

[1] Rehabilitation Engineering Laboratory, Toronto Rehab, [2]Institute of Biomaterials and Biomedical Engineering, University of Toronto, [3]iDAPT Technology Research and Development Team, Toronto Rehab, [4]Toronto Western Research Institute, Toronto Western Hospital




## Long-Term Goal

- To use the electrical activity of the brain to control assistive devices: a brain-machine interface (BMI)

## Purpose of the Study

- Explore the changes elicited by specific movements in the electrical activity of the motor cortex.
- Identify features in the electrical signals from the brain that show consistent behaviour in relationship to movement.

## Background

- The amplitudes of different frequency components in the electrical activity of the brain change during voluntary movement (real or imagined).
- These changes have been used to identify the occurrence of specific arm movements.
- Electrocorticographic (ECoG) signals are recorded intracranially with sensors placed on the surface of the brain.

## Materials and Methods

- Two individuals with subdural electrodes implanted for the treatment of essential tremor and Parkinson's disease participated on this study.
- Participant performed specific arm movements (see figure above)
- ECoG signals and arm kinematics were recorded simultaneously

### Analysis

- ECoG signals were analyzed in different configurations including monopolar and difference between adjacent and non adjacent electrodes
- Time-frequency distributions were generated for each ECoG signal (resolution of 1.5 Hz)
- Spectral components with the highest absolute correlation coefficients with the kinematic recordings were grouped using a histogram were the amplitude of each column represents the probability that a spectral component in a given frequency bandwidth will be correlated with movement

## Results

- The histograms generated with this process are unique and consistent for each one of the performed movements.
- This suggests that the histograms may be used as features to classify ECoG signals automatically

## Discussion

- This work represents a significant step towards the creation of technology that allows the use of brain activity to control assistive devices
- Potential applications include augmentative communication and restoration/facilitation of movement

## References

1.Chin CM et al., Identification of arm movements using correlation of electrocorticographic spectral components and kinematic recordings, J Neural Eng, 4(2), pp. 146-58, 2007.

**Partners:**

The views expressed in this poster do not necessarily reflect those of any of the granting agencies.

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# Detection of Movement Onset: Brain-Machine Interfaces


Steven McGie[1,2] and Milos R. Popovic[1,2]

1. Toronto Rehabilitation Institute
2. IBBME, University of Toronto


## Motivation

•Brain-machine interfaces are systems where a user's neural activity is used to control effectors (i.e.. assistive devices).
•They are potentially useful for individuals (such as those with severe paralysis or high-level spinal cord injury) who cannot use conventional controls strategies.

## Objective

•To develop an automated analysis program for assessing the accuracy of movement onset time predictions.
•To determine the ideal method of predicting movement onset time in pilot data.

## Methods

*Experiments*

•Recordings were obtained from primary motor cortex (M1)
  •2 subjects had EEG (surface) electrodes
  •2 subjects had ECoG (subdural) electrodes
  •4 electrodes per subject, in all cases
•Subjects performed various upper limb movements
•Relevant EMG signals were measured simultaneously

*Analysis Methods*

•Preprocessing
  •Monopolar
  •Bipolar
  •Principal component analysis
•Criterion functions (applied over a sliding time window):
  •Bandpower
  •Bandpower Integral
  •Phase
  •Variance
  •Sum of Differences
  •Fractal Dimension
  •Spectral Entropy
  •Change Point Analysis
•Thresholding (wide range of values tested)

*Accuracy Assessment*

•Comparison of predictions to thresholded EMG signals
  •ROC curves (tested all thresholds)

## Results

•Change point analysis and phase ineffective
•All other criteria of some use
•Ideal parameters unclear
•ECoG clearer than EEG

## Conclusions

•Most of the analysis techniques tested can accurately predict movement intention onset time, given proper parameters
•A wide range of parameters and analysis techniques should be used to obtain ideal predictions
•Automated analysis developed herein can easily be applied to new data from different sources

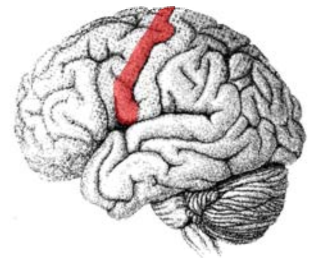

**Figure 1**. Diagram of a human brain, with the primary motor cortex (M1) highlighted. Neural signals in the current study were all recorded from M1.

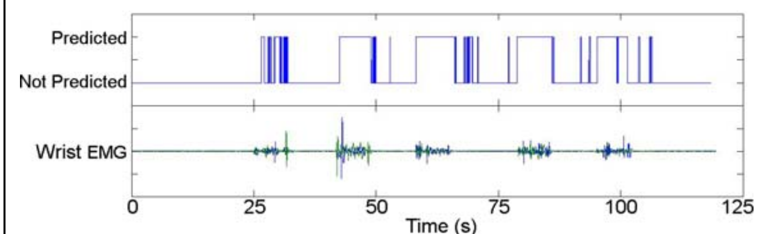


**Figure 2**. Sample of the most accurate predictions generated (ROC curve area = 0.863). These results are from an elbow flexion trial with Subject 2 (ECoG), and are based on increases in the sum of differences.

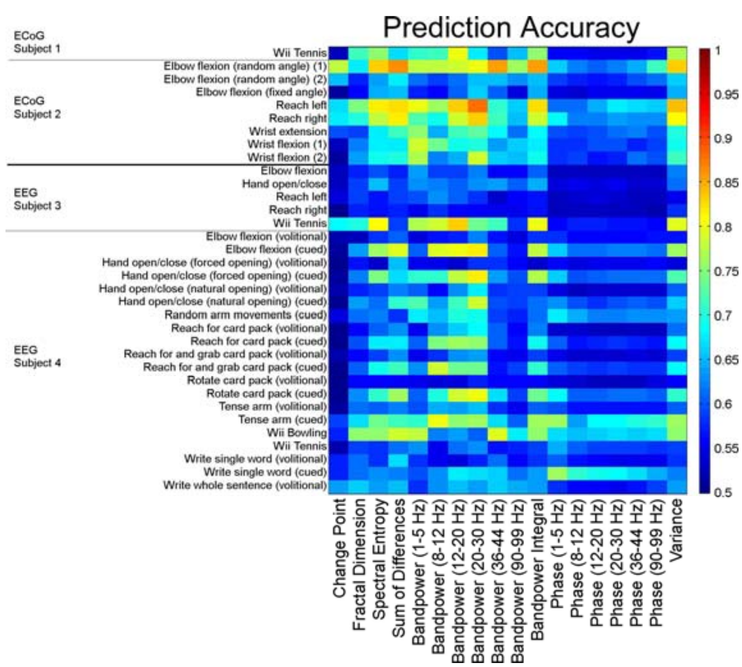


**Figure 3**. Best ROC curve areas for each analysis method, when applied to data from each movement type. Warmer colors (towards red) indicate higher prediction accuracy. A value of 1 would indicate perfect prediction, while a value of 0.5 indicates purely random predictions.

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The authors acknowledge the support of Toronto Rehabilitation Institute who 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.

**Partners:**

# A NEW INTRAMUSCULAR ELECTRODE FOR FUNCTIONAL ELECTRICAL STIMULATION IN THE RAT

Mary K Nagai, MD, PhD; Abdulkadir Bulsen, MSc Eng; Abdolazim Rashidi, BSc Eng; Milos R. Popovic, PhD,
REL, Toronto Rehabilitation Institute, Toronto, ON and University of Toronto, Toronto ON

## 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

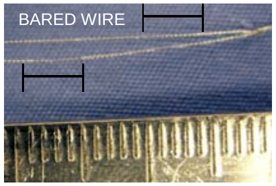
K.W. Dabney, M. Ehrenshteyn, C.A. Agresta, J.L. Twiss, G. Stern, L. Tice and S.K. Salzman (2004) A model of experimental spinal cord trauma based on computer-controlled intervertebral distraction: characterization of graded injury. Spine 29: 2357-2364

K.G. Pearson, A.H. Acharya, K. Fouad (2005) A new electrode configuration for recording electrmyoraphic activity in behaving mice. Journal of Neuroscience Methods. (Submitted)

## METHODS

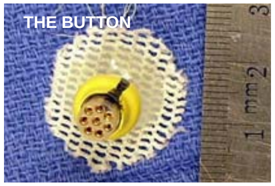
Key Features of the Internal Component:

- A slip knot is used to attach the electrode to a Keith needle for:
  - Easy passage from the scapula to the lower extremity
  - Easy implantation of the electrode into the muscle
  - Design allows for variable lengths of electrode
  - Can be used for FES and for EMG studies

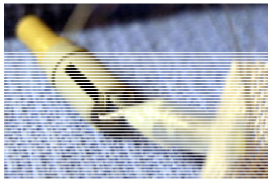



Key Features of the External Component:
(The BUTTON)

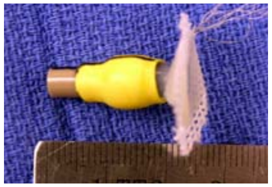
- The mesh allows for easy stabilization in the subcutaneous tissues
- Light weight
- A variable number of muscles can be studied at any given time (photo shows an 8 pin connector)
- Individual or groups of muscles can be stimulated using FES and EMG studies can be performed simultaneously




- The polypropylene tube attached to the mesh provides added protection for the fine electrode wires as they are passed up to the external connector (8 pin in these photos)



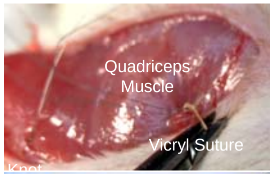
- The Button with the external connector protrudes 2 cm above the surface of the skin, allowing for easy connection to the FES and EMG equipment



## RESULTS

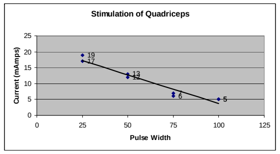
Implanted Electrode:

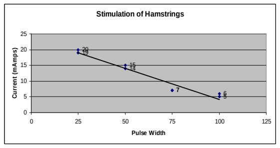
- Sterrad sterilized
- The electrode is implanted in the proximal quadriceps muscle
- The vicryl suture prevents the electrode from becoming displaced in the muscle
- A knot in the wire itself at the distal end of the electrode prevents it from being pulled through in the opposite direction




Post-op Day 1:

- The rat sustained an moderate incomplete spinal cord injury using the distraction spinal cord injury model (Dabney et al, 2004)
- The Button was implanted between the scapula and the wires brought down to the quadriceps muscle and the hamstring muscle and implanted in the respective muscle.
- The Button was easily connected to the Compex Motion FES system
- The quadriceps muscle and hamstring muscles were stimulated using the Compex Motion FES system.
- A linear response curve was obtained for both muscles
- With increasing pulse width the amount of current required to generate a contraction of the muscle in question decreases




## CONCLUSIONS AND FUTURE PLANS

- The new electrode was designed, easily fabricated and implanted with no complications into rats with an incomplete SCI.
- This electrode causes minimal tissue damage.
- Its presence in the quadriceps and hamstrings in the rat did not appear to alter the gait nor the daily behavioural activities of the rat.
- The electrode is durable, inexpensive and most importantly user friendly
- Future plans involve examining the pathophysiology of FES in rats with incomplete moderate spinal cord injuries

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

J. Zariffa[1,2,3], M.K. Nagai[1,3], Z.J. Daskalakis[4] and M.R. Popovic[1,2,3]

1. Institute of Biomaterials and Biomedical Engineering, University of Toronto
2. Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto
3. Toronto Rehabilitation Institute
4. Schizophrenia Program, Department of Psychiatry, Centre for Addiction and Mental Health

## 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).

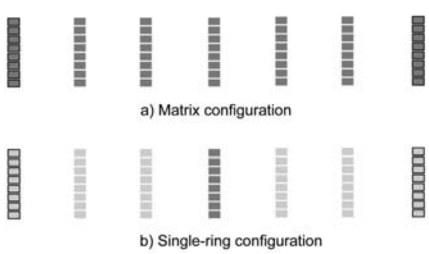



**Fig. 1**: The matrix and single-ring contact configurations. Dark contacts are the ones whose data is available in the classification process.

- 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.

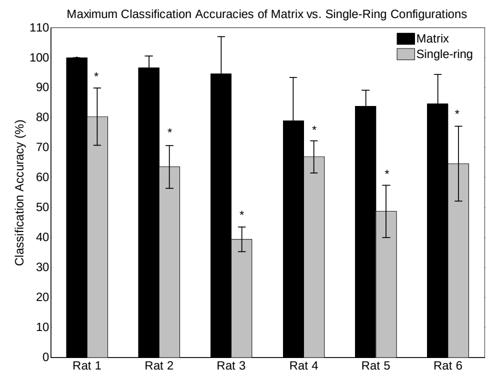



**Fig. 2**: Comparison of the maximum classification accuracies obtained with each contact configuration, for each rat.

- 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.

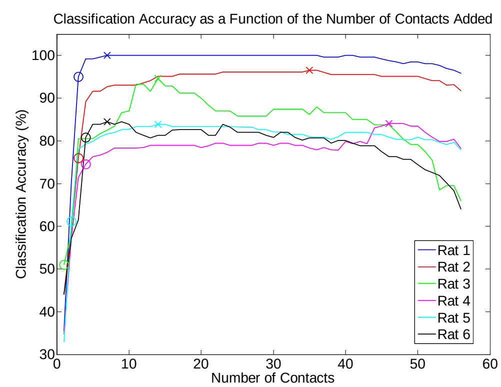



**Fig. 3**: Classification accuracy as a function of the number of contacts used in the matrix configuration. Markers denote the maximum accuracy achieved (x) and the point at which the performance surpasses the maximum accuracy of the single-ring configuration (o).

## 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.

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# Bioelectric Source Localization in the Rat Sciatic Nerve

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## Introduction

- Monitoring the activity of specific neural pathways is crucial for improving control of neuroprostheses.
- Using a multi-contact nerve cuff, the problem can be approached as a bioelectric source localization task, similar to EEG source localization.
- This approach requires a finite-element model of the nerve.
- We want to determine what performance can be achieved with an idealized nerve model.

## Methods

*Data Collection*

- Experiments were performed on five male Long-Evans rats.
- A 56-contact polyimide spiral nerve cuff (1 mm diameter) was placed on the sciatic nerve (Figure 1).
- 3 stimulating nerve cuffs were placed on the tibial, peroneal, and sural branches of the sciatic.
- Short pulses were used to stimulated the nerve branches individually and in every combination (100 trials per combination).

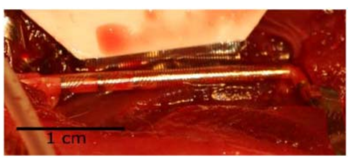


**Fig1** – 56-contact cuff on a rat sciatic nerve

*Source Localization*

- The goal of the source localization is to identify the combination of stimulated branches from the sciatic nerve recordings.
- A finite-element model with an idealized geometry was constructed, and included endoneurium, perineurium, epineurium, encapsulation tissue, cuff, and saline layers (Figure 2).
- The model was used to construct a leadfield.
- The source localization was solved using the sLORETA algorithm [1].

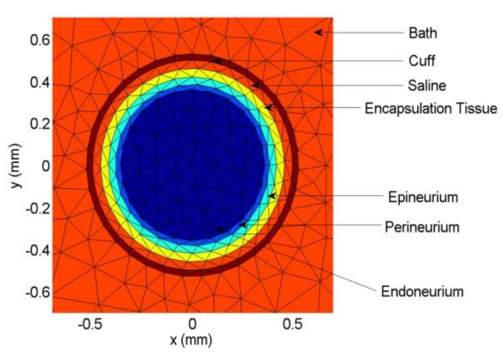


**Fig2** – Finite-element nerve model with idealized geometry

## Results

- The results are summarized using 2D projections (Figure 3).
- In order for the source localization approach to be considered successful, the single-branch cases (top three rows in the Figure) should show activity at distinct locations, and the multiple-branch cases (bottom four rows) should show activity at those same regions in the correct combinations.
- The results in the Figure do not correspond to these patterns, indicating that the source localization approach with an idealized nerve model was not successful.

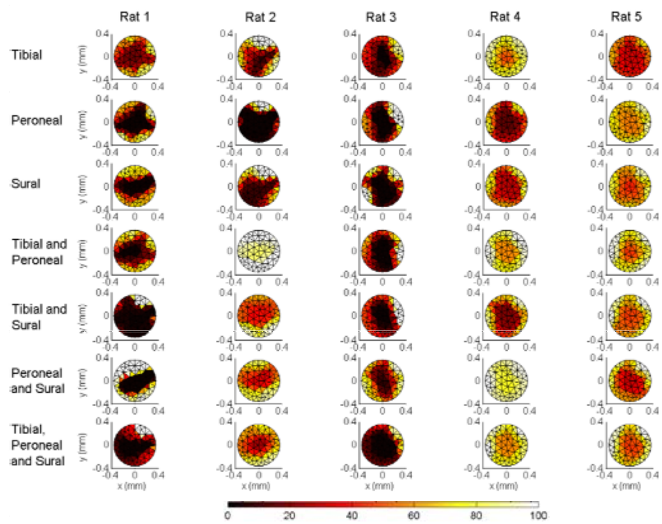


**Fig3** – Source localization estimates

## Conclusions

- In this particular situation (round spiral cuff on a small nerve), the bioelectric source localization approach did not yield the desired performance.
- In order to improve performance, more detailed and nerve-specific finite-element models or other means to obtain accurate leadfields would be necessary.
- Other methods for improving performance would include noise reduction strategies and constraining the inverse problem solution in physiologically meaningful ways.

## References

[1] Pascual-Marqui, *Meth. Find. Exp. Clin. Pharamaol.*, 2002

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The authors acknowledge the support of Toronto Rehabilitation Institute who 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.

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