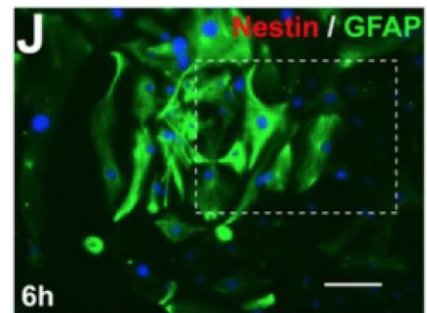
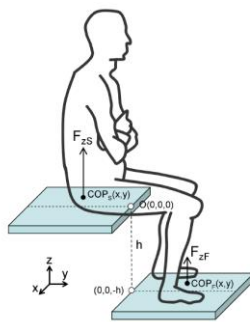


# Rehabilitation Engineering Laboratory



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## About the Rehabilitation Engineering Laboratory

### History

The Rehabilitation Engineering Laboratory was established in 2001 at the Lyndhurst Centre of Toronto Rehab, University Health Network. 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, sitting, 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 make muscles contract. FES can be used to generate movement in paralyzed muscles or to re-train weak muscles and the central nervous system. This technology is also called *neuroprosthesis*.

### Accomplishments 2014-2016

- MyndTec Inc. commercialized our FES Therapy for reaching and grasping. The product is called MyndMove® (approved by Health Canada)
- Developed EEG-based brain machine interface that can distinguish 5 different grasping postures
- Completed a randomized control trial with FES Therapy for walking in chronic incomplete SCI patients
- Developed electrical stimulation tool to direct and accelerate movement of the neural precursor cells
- Published more than 44 peer-reviewed journal papers and filed 6 patents
- Trained 6 postdoctoral fellows, 9 PhD students and 4 MSc/MASc students

### 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.6302, or [www.toronto-fes.ca](http://www.toronto-fes.ca)

## Research at the Rehabilitation Engineering Laboratory

### Neuroprosthesis for Reaching and Grasping

Our reaching and grasping neuroprosthesis is designed for individuals who cannot reach and/or grasp voluntarily. These individuals can 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 a person's stability while sitting, by stimulating paralyzed trunk muscles using FES. This sitting neuroprosthesis will improve the ability to perform such tasks as reaching and wheeling. We are currently studying the mechanisms of balance in the trunk and how they are affected by muscle paralysis. This analysis will form the basis for developing the FES system for balance during sitting.

### Neuroprosthesis for Standing

The neuroprosthesis for standing and balancing is a device that will allow some neurologic patients to stand up, perform stable "hands-free" standing, and sit down again. At least two applications of this technology are envisioned: (1) this device will be used as an independent system to allow complete SCI patients to stand; and (2) the neuroprosthesis will be used 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.

## Novel Neuroprosthesis

People with spinal cord injury have impaired movements of their arms and/or legs, due to paralyzed muscles. Rehabilitation using electrical muscle stimulation is very advantageous for this population. However, one aspect that often limits the use of electrical stimulation is the rapid onset of muscle fatigue. A muscle in this condition will contract less efficiently in response to the stimulation. Muscle fatigue can be explained by the fact that electrical stimulation can only make a portion of the total fibers within a muscle contract and they are all contracted at the same time. In the current project, we are developing a new stimulation method that would activate most of the muscle fibers at different times in a sequence regulated by a cyclic pattern.

## Equipment

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

- Compex II stimulators
- MyndSearch & MyndMove 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
- ARMEO and ReJouce systems for upper limb rehabilitation
- Ultrasound system
- Transcranial Magnetic Stimulation System Medtronic Mag Pro R30
- 6-camera Raptor Motion Analysis system
- Various EMG and EEG measurement systems

## Our People

### Principal Investigators

**Dr. Milos R. Popovic** (biomedical engineering), Head of the Laboratory, Toronto Rehab Chair in Spinal Cord Injury Research, Senior Scientist, Associate Director Research and Tenured Professor

**Dr. Julio Furlan** (neurology), Affiliate Clinician Scientist and staff neurologist,

**Dr. Cesar Marquez-Chin** (biomedical engineering), Research Scientist

**Dr. Kei Masani** (exercise physiology), Research Scientist

**Dr. Jose Zariffa** (biomedical engineering), Research Scientist

### Postdoctoral Fellows

**Dr. Robert Babona-Pilipos** (biomedical engineering)

**Dr. Austin J. Bergquist** (exercise physiology)

**Dr. Aravind Kumar Namasivayam** (speech/language)

**Dr. Bastien Moineau** (physiotherapy)

**Dr. Hossein Rouhani** (biomedical engineering)

### Graduate Students

**Sharon Gabison**, PhD student

**Martha Gabriela Garcia-Garcia**, PhD student

**Bojan Gavrilovic**, MHSc student

**Stephanie Iwasa**, PhD student

**Lazar Jovanovic**, PhD student

**Eric Ma**, MASc student

**Sara Mahallati**, PhD student

**Andresa R. Marinho**, PhD student

**Luka Milosevic**, PhD student

**Matija Milosevic**, PhD student

**Kramay Patel**, PhD student

**Takashi Yoshida**, PhD student

**Umalkhair Ahmed**, MHSc student

**Ying X. Zhi (Derek)**, MHSc student

## Support Staff

**Zina Bezruk**, Administrative Assistant  
**Betty Chan**, Grants & Accounts Coordinator  
**Naaz Desai**, REL Manager, Research Coordinator and Physiotherapist  
**Esther Oostdyk**, Secretary  
**Abdulazim Rashidi**, Research Engineer  
**Dr. Vera Zivanovic**, Research Coordinator

## Awards and Distinctions

### 2016

- **Dr. Bastien Moineau** was awarded the **AGE-WELL Graduate Student and Postdoctoral Award in Technology and Aging**
- **Dr. Bastien Moineau** was awarded the **Spinal Cord Injury Ontario Postdoctoral Fellowship**
- **Lazar Jovanovic** was awarded the **Institute of Biomaterials and Biomedical Engineering International Scholars Program Award**
- **Kramay Patel** was awarded the **Vanier Canada Graduate Scholarship (Vanier CGS), Natural Sciences and Engineering Research Council of Canada**
- **Saima Ali** was awarded **2<sup>nd</sup> Place** in **Bioelectrical Engineering Poster Presentations, Undergraduate Engineering Research Day**
- **Saima Ali** was awarded the **Natural Sciences and Engineering Research Council of Canada, Undergraduate Student Research Award**

### 2015

- **Andresa Marinho-Buzelli** was awarded the **Neural Engineering and Therapeutics Team Excellence Award**, Toronto Rehab Institute.
- **Bojan Gavrilovic** was awarded the **Sleep Science Team Excellence Award**, Toronto Rehab Institute.
- **Kramay Patel** was awarded the **Institute of Biomaterials and Biomedical Engineering Undergraduate Summer Research Program Best Poster Award**
- **Dr. R. Babona-Pilipos** was awarded the **Faculty of Medicine, Health Commercialization Award - 1st Place**
- **Sharon Gabison** was awarded the **Faculty of Medicine, Health Commercialization Award – 2nd Place**
- **Kramay Patel** was awarded the **2015 Undergraduate Summer Research Program Elevator Talks – 2nd Place**
- **Dr. Milos Popovic** was awarded **2014 University Health Network’s Inventor of the Year Award**

- **Sara Mahallati** was awarded the **Top Six Poster Presentations Award** at the 4th joint International Spinal Cord Society (ISCoS) and American Spinal Injury Association (ASIA) Meeting, Montreal, Canada
- **Dr. Austin Bergquist** was awarded the **Canadian Institute of Health Research Postdoctoral Fellowship**
- **Kramay Patel** was awarded **The Sunnybrook Research Prize Competition – 1st Place**
- **Sara Mahallati** was awarded the **Best Abstract and Poster Award, 3<sup>rd</sup> place** at the 4th joint International Spinal Cord Society (ISCoS) and American Spinal Injury Association (ASIA) Meeting, Montreal, Canada
- **Martha Garcia** was awarded the **Natural Sciences and Engineering Research Council of Canada, CREATE – CARE Travel Award**
- **Stephanie Iwasa** was awarded the **Wildcat Graduate Scholarship, Institute of Biomaterials and Biomedical Engineering, University of Toronto**
- **Matija Milosevic** was awarded the **Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellowship Program for Foreign Researchers, Tokyo, Japan, (declined)**
- **Matija Milosevic** was awarded the **Natural Sciences and Engineering Research Council of Canada, Postdoctoral Fellowship**
- **Eric Ma** was awarded the **2015 Gordon Cressy Student Leadership Awards, Faculty of Applied Sciences and Engineering, University of Toronto**
- **Kramay Patel** was awarded the **Natural Sciences and Engineering Research Council of Canada, Undergraduate Student Research Award**
- **Saima Ali** was awarded the **Natural Sciences and Engineering Research Council of Canada, Undergraduate Student Research Award**

## Recent Posters

### Grasping

1. Detecting Recurrent Hand Postures of SCI Individuals in Wearable Camera Video
2. Does the Intensity of the Occupational Therapy Impact the Upper Limb Functional Outcome in Sub-acute SCI
3. Improving Voluntary Upper Limb Function in Individuals with Chronic Incomplete Spinal Cord Injury

### Sitting

4. Development of a Neuroprosthesis for Improved Trunk Stability after SCI
5. A Method to Estimate and Reduce the Sensitivity of Multi-segment Kinematic Assessment of Human Trunk to Soft Tissue Artifact

## Standing

6. A garment-based neuro-orthosis to help individuals with paralysis stand independently
7. Improving Standing Stability using Closed-Loop Control of Functional
8. Modeling Muscle Activity Patterns Underlying Postural Responses to Multi-directional Perturbations in Standing
9. Modeling of multi-directional muscle activity patterns during standing
10. Real Time Motion Tracking with Inertial Sensors to Help People with a Disability to Stand Independently

## Novel Neuroprostheses

11. A novel method to reduce muscle fatigue during functional electrical stimulation for people with spinal cord injury
12. Closed-loop Controlled Neuroprosthesis Design with Optimized FES Parameters to Minimize Muscle Fatigue

## Walking

13. FES Therapy for Walking in Incomplete SCI Patients Walking Competency

## Brain Function

14. Single-unit Recordings From Human Neocortical Slices Maintained In-vitro

## Sleep Apnea

15. Factors Predisposing to Worsening of Sleep Apnea in Response to Fluid
16. Investigate the Effect of Upper Airway Narrowing on Inspiratory Airflow
17. Design and Validation of a Portable and Affordable Device to Measure Body Composition

# Detecting Recurrent Hand Postures of Spinal Cord Injured Individuals in Wearable Camera Video

Elizabeth Sumitro<sup>1,2</sup>, José Zariffa<sup>1,2</sup>

<sup>1</sup>Institute of Biomaterials and Biomedical Engineering, University of Toronto, <sup>2</sup>Toronto Rehabilitation Institute, University Health Network

## Introduction

- Hand function recovery is crucial for tetraplegic spinal cord injured (SCI) individuals. [1]
- Existing hand function assessments are limited to a clinical setting, are not more frequent than every few weeks, and are not representative of hand use in an everyday context [2].
- Wearable cameras can provide monitoring of progress at home and in the community, permitting more frequent assessments that is more representative of the true impact of rehabilitation strategies.
- While manual analysis of the resulting lengthy videos is infeasible, automatic summarization would facilitate interpretation by a clinician.
- **Objective:** To develop a clustering algorithm that can automatically identify recurring hand postures in wearable camera video and create a report summarizing its findings. The report is intended for use by a clinician to efficiently review grip posture quality in a patient's daily life, and thus evaluate the hand function recovery of an individual with a spinal cord injury.

## Methods

- 1) Data Collection**  
Wearable cameras (Looxie, GoPro Hero4) used to collect first person video of SCI participants performing activities of daily living in a simulated home environment (HomeLab).
- 2) Hand Segmentation**  
Hand pixels identified using Li & Kitani segmentation technique [3]
- 3) Hand Region Identification**  
350x160 pixel bounding box placed around hand(s) based on segmentation results
- 4) Feature Extraction**  
Masked Histogram of Oriented Gradients (HOG) features extracted from each region

## 5) Hand Posture Clustering

Clustering algorithm developed based on the Determinantal Point Process approach proposed by Huang et. al in [4]

## 6) Summary Report

Report summarizing clustering results shared with clinicians to validate its usefulness for the evaluation of hand function recovery.

## Results: Summary

Clustering was performed for 375 frames from each of 4 spinal cord injured participants. Average results across the 4 participants are reported in the table below:

Results	Average (n=4)
% successful clusters	99.0% ± 1.8%
Purity of successful clusters	81.3% ± 8.8%
% redundant clusters	54.5% ± 5.1%
% postures found	46.1% ± 9.5%

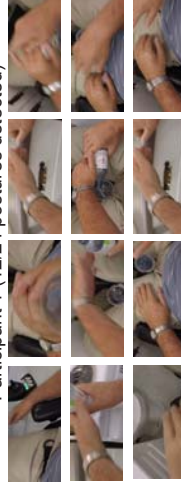
Evaluation Metrics:

- % successful clusters: percentage of clusters that correspond to an identifiable posture (i.e. cluster successful if at least 50% of hand regions are the same posture)
- Purity of the successful clusters\*: # of correctly classified hand regions / total # of hand regions in cluster
- % redundant clusters: percentage of clusters representing the same posture as another cluster
- % postures found: percentage of hand postures detected by algorithm compared to total number of postures as determined by manual labelling

\* Correct classifications determined via manual labelling

## Results: Unique Hand Postures Detected by Algorithm

Participant 1 (12/24 postures detected)



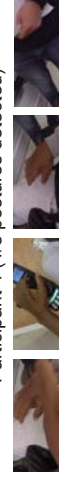
Participant 2 (12/22 postures detected)



Participant 3 (3/10 postures detected)

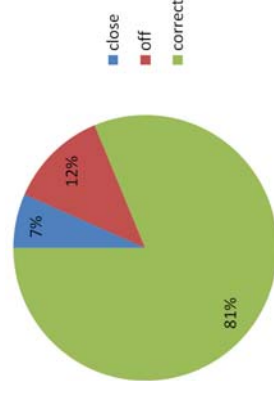


Participant 4 (4/8 postures detected)



## Results: Cluster Quality

On average, what percentage of hand regions are correctly classified (correct), classified as a similar posture (close), and classified as a posture that is not at all similar (off)?



Example:



## Conclusion

- The current clustering algorithm is capable of separating hands by posture with moderate success. It achieves an average purity of 81.3% for data from SCI participants.
- However, 54.5% of clusters were redundant and only 46.1% of postures were detected.
- Optimizing the algorithm to reduce redundancy and missed postures will enable automatic summarization of lengthy wearable camera video.
- This will facilitate the evaluation of hand function interventions, thus helping to restore independence to SCI individuals and lowering associated healthcare costs.

## Acknowledgments



## References

- [1] K. D. Anderson, *J Neurotrauma*. 2004, 21, 1371-83.
- [2] S. Kalsi-Ryan et al. *World neurosurgery*. 2014, 82, 3, 509-518.
- [3] C. Li and K. M. Kitani. *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*. 2013, 3570- 3577.
- [4] D.-A. Huang et al. *CVPR 2015*.

# Does the Intensity of the Occupational Therapy Impact the Upper Limb Functional Outcome in Sub-acute SCI

## Introduction

In North America, Spinal Cord Injury (SCI) survivors total 345,000, with 16,500 new cases added every year.

Roughly 45% of SCI survivors are tetraplegic, who are often unable to use their arms and hands following the injury, and consider improving arm and hand function their #1 priority.

## Objectives

To test whether therapy intensity is more relevant than the therapy modality in improving voluntary hand function in incomplete, sub-acute C3-C7 SCI individuals, we elected to compare:

- LOW Intensity Conventional Occupational Therapy (COT) - 45 min per day (COT1)
- HIGH Intensity COT - 2 h per day (COT2)
- LOW Intensity functional electrical stimulation (FES) therapy - 45 min per day
- HIGH Intensity FES therapy - 1 h of FES + 1 h of COT per day (FES+COT)

## Methods

Retrospective analysis of data pooled from Phase I and II randomized control trials, conducted between 2003 and 2011

### Interventions

COT - routinely used strengthening and stretching exercises and practice of activities of daily living (ADLs) (1,2).  
FES - performed ADLs while being assisted with FES

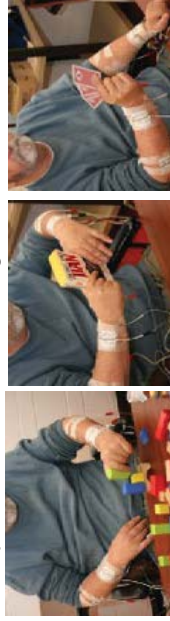


Figure 1: FES Therapy

## Results

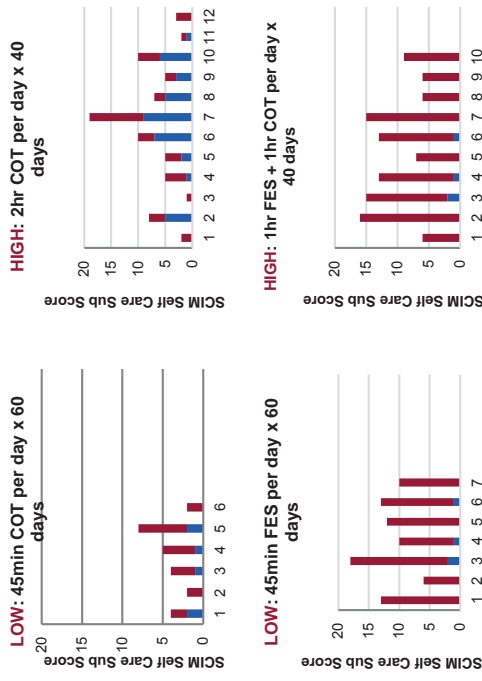
Table 1: Summary of Baseline Patient Characteristic

Patient Characteristics	COT1 (n=6)	COT2 (n=12)	FES+COT (n=10)	FES (n=7)
Age (years) mean (± SD) range	53.2 (± 10.8) (34 - 63)	44.8 (± 16.3) (20 - 65)	43.7 (± 17.7) (18 - 66)	37.7 (± 19.0) (19 - 64)
Sex (number (%))	6 (100%) 0 (0%)	9 (75%) 3 (25%)	8 (80%) 2 (20%)	7 (100%) 0 (0%)
Level of SCI (n)	3 2 1 0 0	0 7 4 1 0	1 3 1 5 0	0 1 2 3 1
Days since SCI mean (± SD) range	39.2 (± 23.1) (15 - 76)	56.3 (± 22.7) (22 - 102)	69.9 (± 38.1) (33 - 134)	62.3 (± 43.0) (15 - 142)

Table 2: Functional Outcome Measures

Low Intensity	Before	After	Gain	High Intensity	Before	After	Gain
Average SCIM Self Care Sub Score							
COT1 (n=6)	1.0 (±0.9)	4.2 (±2.2)	3.2 (±1.6)	COT2 (n=12)	3.3 (±3.1)	6.4 (±5.0)	3.2 (±2.4)
FES (n=7)	0.6 (±0.8)	11.7 (±3.7)	11.1 (±3.2)	FES + COT (n=10)	1.9 (±1.7)	12.1 (±5.2)	10.2 (±3.9)
Average FIM Self Care Sub Score							
COT1 (n=6)	7.3 (±2.1)	21.7 (±9.5)	14.3 (±7.8)	COT2 (n=12)	7.8 (±3.2)	17.8 (±10.8)	10.0 (±9.1)
FES (n=7)	6.1 (±0.4)	30.0 (±8.4)	23.9 (±8.5)	FES + COT (n=10)	8.1 (±2.4)	28.2 (±11.3)	20.1 (±10.1)

Figure 2: SCIM Self Care Sub Score comparison of Intensity and Modality for individual patients before (■) treatment and gain (■) realized after treatment. (max SCIM Self Care Sub Score = 20 points)



## Conclusions

- Increased therapy intensity alone may not always be beneficial.
- Intervention type plays a significant role in determining functional changes.
- Regardless of intensity doses, COT alone resulted in similar outcomes, as did FES therapy with or without COT.
- Both HIGH and LOW Intensity FES groups yielded much better outcomes compared to HIGH and LOW Intensity COT interventions alone.

## References

- [1] Thrasher et al. Neurorehabilitation and Neural Repair. 2008. 22(6): 706-714.
- [2] Popovic et al. Neuromodulation. 2005. 8(1): 60-74.



# Improving Voluntary Upper Limb Function in Individuals with Chronic Incomplete Spinal Cord Injury



**Milos R. Popovic<sup>1,2</sup>, Naaz Kapadia<sup>1</sup>, and Vera Zivanovic<sup>1</sup>**

<sup>1</sup> Lyndhurst Centre, Toronto Rehabilitation Institute  
<sup>2</sup> Institute of Biomaterials and Biomedical Engineering, 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

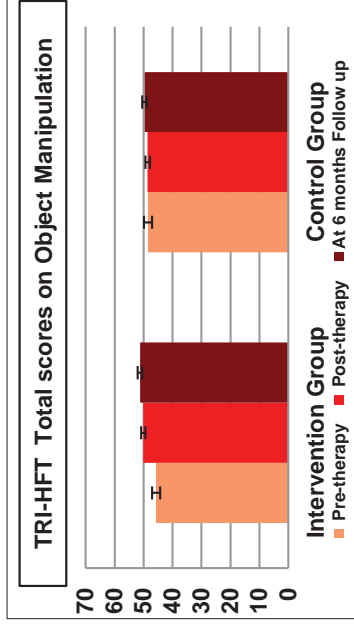
- Pilot randomized control trial in chronic (>24 months) incomplete C4-C7 SCI
- Control: n=3 and FES therapy: n=5
- Both groups received 39 sessions of therapy
- Control group received 1h of conventional occupational therapy (COT) and intervention group received 1h of FES therapy.
- Primary outcome measure was TRI-HFT and secondary outcome measures were FIM Self Care Sub score and SCIM Self Care Sub score.

## Subject Demographics

Feature	Control Group	Intervention Group	P value
Age (years)	49 ± 16.35	47.2 ± 2.23	
Mean age ± SEM	62	54	0.922
Median age	15-70	25 to 73	
Age range			
Sex (n)			
Males	3	5	1.0
Females	0	0	
Cause of SCI (n)			
MVA	1	2	0.250
Fall	0	1	
Other causes	2	2	
Level of SCI (n)			
C3	0	0	
C4	2	0	0.393
C5	1	5	
C6	0	0	
Time since SCI (years)			
Mean time ± SEM	4.83±1.04	10.6±4.43	
Median time	6	5	0.436
Time range	2.5 to 6	2 to 26	

## Results

- FIM self care sub-score** improvements at discharge and at 6 months: **FES therapy: 4.6\*** and **8.3\*** points, & **COT: 0** and **1.4** points, respectively.
- SCIM self care sub-score** improvements at discharge and at 6 months: **FES therapy: 2.2\*** and **3.6\*** points & **COT: 0.7** and **1.7** points, respectively.
- TRI-HFT 10 objects** improvements at discharge and at 6 months: **FES therapy: 4.3** and **5.5** points, & **COT: 0** and **1.1** points, respectively.



TEST	Control Group (Mean scores)		Intervention Group (Mean scores)	
	Before	After 6 Month	Before	After 6 month
FIM Self Care Sub-scores	16.6	18	19	23.6*
SCIM Self Care Sub-score	5.6	6.3	7.3	10.5*
TRI-HFT Components				
10 Objects	48.5	48.6	49.7	45.7
Rectangular Blocks	30	31.2	26	40.8
Instrumented Cylinder Torque Values (Nm)	3.1	3.1	6.16	1.7
Credit Card Force Values (N)	13.3	16.5	15	8.6
Wooden Bar Thumb Direction Length Values (cm)	10	10	10	0.9
Wooden Bar Little Finger Direction Length Values (cm)	10	10	10	6
				18*
				11.3

## FES Therapy Participant



## Conclusions

- Restoration of voluntary hand function in chronic (>24 months) incomplete SCI is possible using FES therapy.
- Improvements in hand function and thereby increase in level of independence are significant with FES therapy.

## Recommendations

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

## References

- Popovic, Kapadia, Zivanovic, Furlan, Craven, and McGillivray, *Neurorehabilitation and Neural Repair*, vol. 25, No. 5, pp: 433-442, 2011.
- Popovic, Thrasher, Adams, Takes, Zivanovic, and Tonack, *Spinal Cord*, vol. 44, No. 3, pp. 143-151, 2006.
- Kapadia, Zivanovic, Furlan, Craven, McGillivray, and Popovic, *Artificial Organs*, vol. 35, No. 3, pp: 212-216, 2011.

## Partners:



Rehabilitation Engineering Laboratory

Toronto Rehabilitation Institute

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# Development of a Neuroprosthes for Improved Trunk Stability after SCI


Kramay Patel<sup>1,2</sup>, Matija Milosevic<sup>2,3</sup>, Kei Masani<sup>2,3</sup>, Milos R. Popovic<sup>2,3</sup>



<sup>1</sup>Department of Engineering Science, University of Toronto; <sup>2</sup>Rehabilitation Engineering Laboratory, Toronto Rehabilitation Institute - UHN; <sup>3</sup>Institute of Biomaterials and Biomedical Engineering, University of Toronto



## Introduction

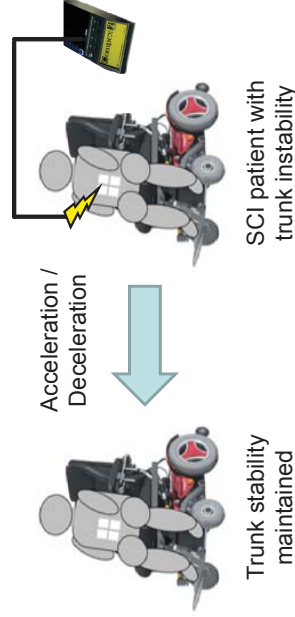
- Trunk stability is a major problem for individuals with thoracic and cervical spinal cord injury (SCI)
- 

Acceleration / Deceleration

Falls can cause secondary injuries or worsen primary ones
- Functional electrical stimulation (FES) is a technology that uses small current impulses to contract muscles
- FES has been used on the trunk to improve posture, forward reaching, and manual wheelchair propulsion
- Applicability of FES on improving dynamic trunk stability in response to external perturbations has not been tested

## Hypothesis

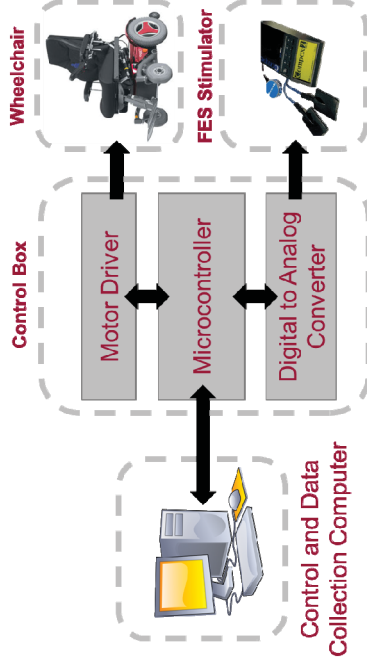
- FES can be used on the trunk muscles, in a feed-forward and directionally-dependent manner, to contract trunk muscles in response to dynamic external perturbations during sitting



## Methods

### Wheelchair Perturbation System

- A powered wheelchair and a FES stimulator were interfaced with custom made LabVIEW™ software and controller

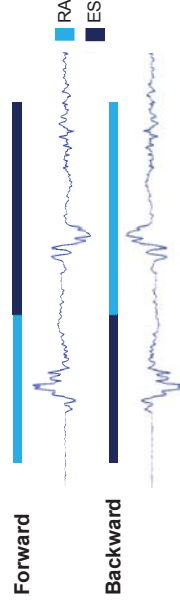


### Data Collection

- One sensor (3DOF accelerometer) was mounted on the wheelchair and another (3DOF accelerometer, magnetometer and gyroscope) was mounted on the spine of the subjects (Shimmer Inc.)

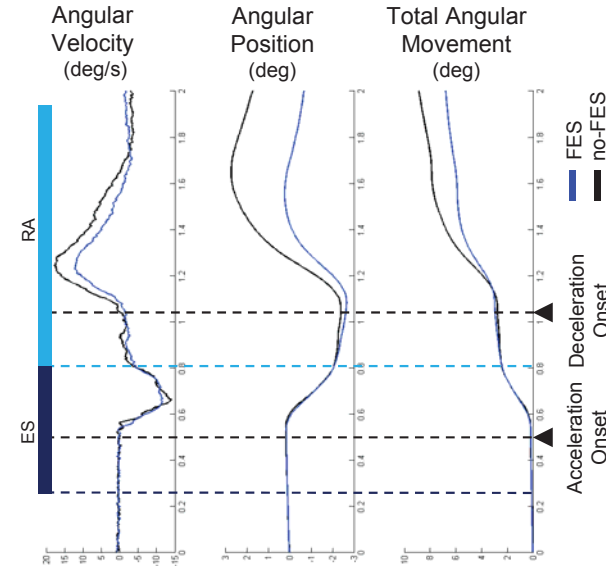
### Experimental Protocol

- Subjects were seated on the wheelchair and stimulation electrodes were attached bilaterally to their rectus abdominus (RA) and erector spinae (ES) muscles
- Subjects were perturbed in the forward / backward direction with / without electrical stimulation (as shown below)



## Results

- A case study was performed on an able-bodied individual
- Total angular sway after perturbation was considerably reduced in trials where FES was applied to stiffen muscles.



## Conclusions

- We developed the first neuroprosthesis for improving sitting stability in a powered wheelchair
- FES can be used directionally to improve trunk stability in dynamic perturbations
- Larger study is required to statistically validate results

## Acknowledgments

John David Chibuk from Kiwi Wearables, Abdolazim Rashidi and Carlos Buzelli

### Partners:



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

Rehabilitation Engineering Laboratory  
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# A garment-based neuro-orthosis to help individuals with paralysis stand independently

B Moineau<sup>1</sup>, M Alizadeh-Meghbrazi<sup>2</sup>, G Stefan<sup>2</sup>, K Masani<sup>1,3</sup>, MR Popovic<sup>1,3</sup>



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2) Myant inc., Toronto. 3) Institute of Biomaterials and Engineering, University of Toronto.



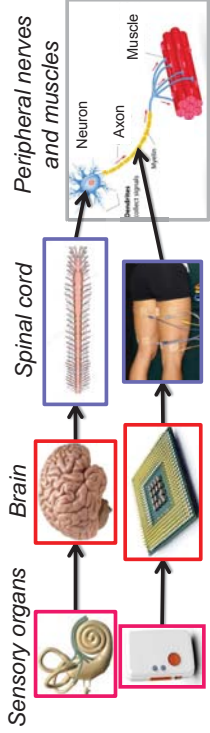
## Introduction

- Individuals with **spinal cord** or **stroke** injury who experience **paralysis** in their legs and trunks can have difficulty **standing** and even sitting.
- **Electrical stimulations** of paralyzed muscles can be used to regain movements.
- Stimulations can be controlled based on real-time monitoring of the **body position**.

### Objectives:

Design a practical method to **stimulate muscles** and accurately **track movements** during common sitting and standing activities.

## Design



### Device requirements

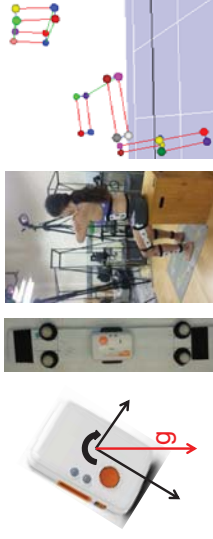
- Easy to wear and remove
- Apply comfortable stimulations
- Usable at home in daily life

### → Solutions

- Dry fabric electrodes embedded in a compression garment
- Inertial motion sensors tracking the position of limbs and trunk

## Methods

- **Creation and refinement of fabric electrodes**  
Iterative testing (comfort, contraction) for different shape, materials and assembly techniques.
- **Evaluation of inertial motion sensors**
  - Use of accelerometers and gyroscopes to measure in real time pitch and roll of body limbs and trunk.
  - Comparison with 3D motion analysis during sitting posture, sit-to-stand and standing posture.



Inertial measurement unit containing 3 accelerometers and 3 gyroscopes, and 3D motion analysis set-up for legs, thighs and trunk

## Findings on Fabric Electrodes

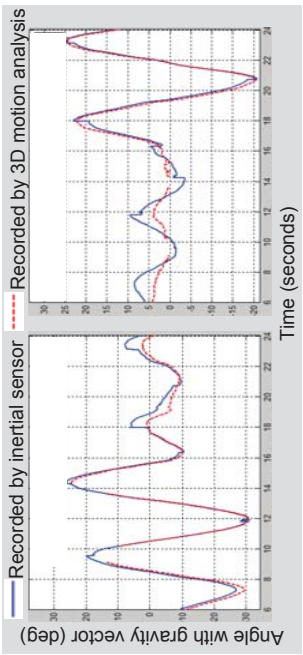
- **Garment in silver-coated yarn**
  - Breathable and slides on the skin
  - Various knitting techniques available
  - Can be knitted as one piece into a sleeve
  - Stimulations uncomfortable on hairy skin
- **Garment with conductive polymer cover**
  - Comfortable contraction, even on hairy skin
  - Not breathable and sticks to the skin (impractical)



## Results of Inertial Motion Sensor

RMS error	All	Sitting	Sit-to-stand	Standing
Pitch	2.8 ±2.1	2.0 ±0.9	2.1 ±0.6	4.2 ±3.1
Roll	2.8 ±1.6	2.1 ±0.7	3.4 ±2.0	2.8 ±1.6

- ✓ Pitch: Forward flexion from vertical position
- ✓ Roll: Lateral bending from vertical position
- ✓ RMS error: Root mean square of differences between the inertial sensors and the 3D analyses (mean ±std dev of 6 sensors, in degrees).
- Integration error was reset when the sensor was still (position updated with gravity), but **drift** can still happen.
- Some **roll tracking error** happened during sit-to-stand.
- Need to improve orientation estimation by combining properties of accelerometers and gyroscopes.



Example of trunk pitch and roll measurements during standing (RMS = 2.1 deg)  
The participant was asked to sway back and forth, then left and right.

## Prospects

- Find the optimal combination of electrode materials for comfort, contraction and usability.
- Improve motion sensors' algorithm for complex tasks (hectic or combined motions).
- Conduct clinical trials with a first prototype and individuals with acute or chronic neurological injury.



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Dean Connor and Maris Uffelmann Donation

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Made in Canada

# Improving Standing Stability using Closed-Loop Control of Functional Electrical Stimulation



Michael Same, Hossein Rouhani, Kei Masani, Milos Popovic  
 Institute of Biomaterials and Biomedical Engineering, University of Toronto  
 Rehabilitation Engineering Laboratory, Toronto Rehabilitation Institute, University Health Network



## Introduction

- **Functional Electrical Stimulation (FES)** - patterned electrical stimulation of paralyzed muscles to induce contractions
- We propose that application of FES to lower limb muscles in closed-loop could facilitate hands-free stance in SCI patients →
  1. Enable performance of activities of daily living while standing
  2. Exercise paralyzed muscles and decrease secondary complications
- **Hypothesis:** That a PID control strategy (Fig. 1) applying FES to ankle plantarflexor and dorsiflexor muscles can actuate the ankle joints effectively by mimicking control strategies employed in able-bodied stance.

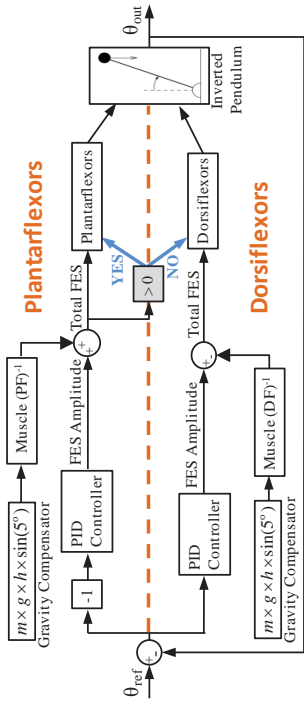


Figure 1: Block diagram of PID control strategy

## Methods

- Inverted pendulum standing apparatus (IPSA - Figure 2)
  - Subject attached via foot straps to an inverted pendulum which rotates in sagittal plane in response to torque from ankles
  - Simulates quiet stance while minimizing voluntary control
  - Knees and hips locked in extension → isolates ankle joint
  - Weight added to IPSA to simulate subject's body weight

- Procedure in 2 able-bodied individuals:
  - Electrodes applied to plantarflexors and dorsiflexors
  - Individualized PID gains determined based on simulations and modelling of muscle dynamics
  - Controller modulated FES intensity based on fluctuations in the inverted pendulum angle
  - Various test paradigms - quiet stance, perturbations, step response
- Trial conditions:
  - FES (with control strategy implemented)
  - Voluntary (no FES applied, subject balanced IPSA using voluntary control)

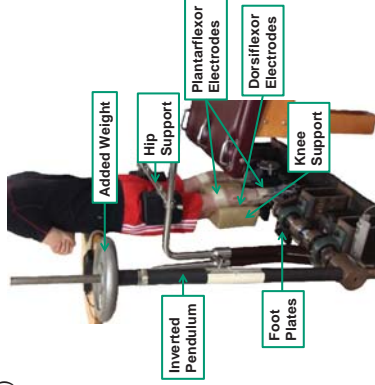


Figure 2: The inverted pendulum standing apparatus (IPSA)

## Results

- Inverted pendulum reliably maintained about 5° and 9° reference angles
- Improved performance over voluntary control in all paradigms (Fig. 3):
  - Quiet Stance - Root mean square error (RMSE) = 0.14° vs. 1.1°
  - External Perturbations - RMSE = 0.68° vs. 1.5°
  - Step Response + Body Weight Matching - RMSE = 1.0° vs. 1.5°
- Simulations successful in selecting appropriate controller gains



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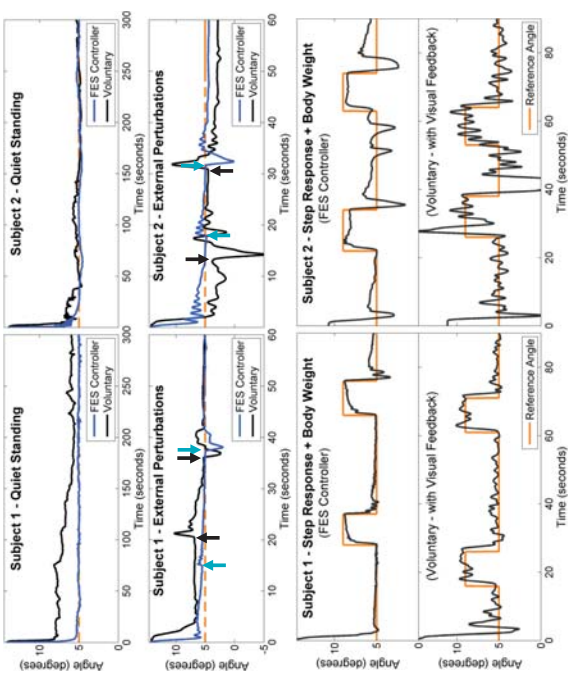


Figure 3: inverted pendulum angles during 5-min quiet standing trials (top); 60-sec trials with anterior and posterior perturbations (arrows) (middle); and step response trials with body weight matching (bottom). Reference angles are displayed in orange.

## Conclusions

- Results indicate the potential of the control strategy to overcome deficits in voluntary control.
- Strategies employed mimic those observed in able-bodied stance.
- Ability of the IPSA to minimize voluntary control has been verified.
- Technique could ultimately be employed for facilitating stance in complete paraplegia, or for retraining incomplete paraplegic stance.

## Partners:



Medical Research and Innovation Program of the Research Council of Canada  
 Canadian Institutes of Health Research  
 Institute for Innovation in Health Care

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

## Purpose

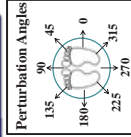
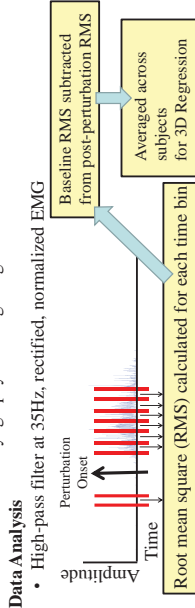
To characterize muscle activation patterns underlying postural balance responses to multi-directional perturbations in standing

## Background

- Functional electrical stimulation (FES) activates muscles by directly applying electric current through electrodes
- FES therapies facilitate recovery of muscular function in neurologically disordered patients
- Interests lie in the development of FES controllers that would assist patients with maintaining postural standing balance
- Modeling muscle activity as a function of direction and time is essential for developing future FES controllers

## Method

- Subjects**
- Young healthy adults, n = 9 (male, 16 – 23 yrs)
- Tasks**
- Multidirectional perturbations during quiet standing
  - 8 cm displacement, 35 cm/s peak velocity
- Measurements**
- Surface electromyography of 16 right leg and trunk muscles
- Data Analysis**
- High-pass filter at 35Hz, rectified, normalized EMG

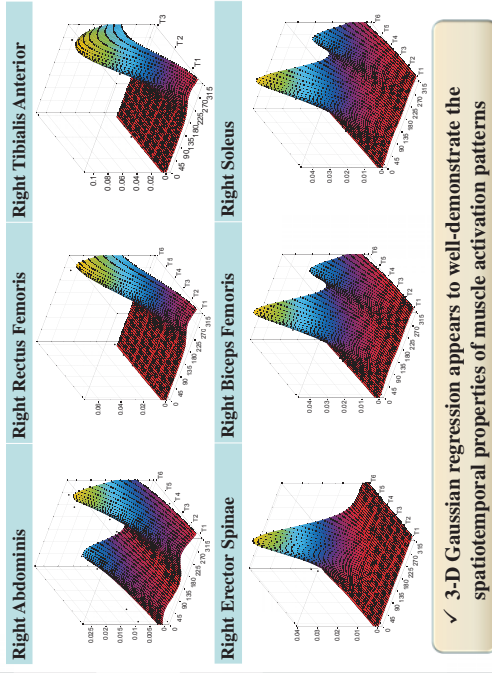
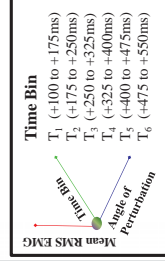


## Results & Discussions

### Gaussian Regression of Mean RMS EMG Across Subjects vs. Direction, Time Bin

$$z = [a_1 e^{-\frac{(x-h)^2}{c_1}} + a_2 e^{-\frac{(x-h)^2}{c_2}}] \times [a_3 e^{-\frac{(y-b)^2}{c_3}}]$$

where  $z$  = mean RMS EMG,  $x$  = angle of perturbation,  $y$  = time bin,  $a_n$  = arbitrary constant,  $b_n$  = direction/time bin at which maximum response is expected, and  $c_n$  = width at half-maximum amplitudes



✓ 3-D Gaussian regression appears to well-demonstrate the spatiotemporal properties of muscle activation patterns

### Quantification of Goodness of Fit

#### R<sup>2</sup> Reported for Each Muscle

Muscle	R <sup>2</sup>	Muscle	R <sup>2</sup>
SOL	0.9464	STN	0.9257
PER	0.9581	BCF	0.9343
MGA	0.9601	RCF	0.9811
TBA	0.9678	TFL	0.9798
LGA	0.9418	GLU	0.8412
VME	0.9920	SPI	0.9005
VLA	0.9914	OBL	0.8410
SMN	0.9362	ABS	0.3792

Mean R<sup>2</sup> ± SD Across Muscles

Mean R<sup>2</sup> ± SD 0.9048 ± 0.1475

✓ Statistical analysis strongly indicates the accuracy of Gaussian regression to be generally high

## Conclusion

- 3-dimensional Gaussian regression model serves to be a powerful tool in profiling spatiotemporal properties of muscle activity patterns underlying postural responses to perturbations during standing
- Future FES controllers aimed at supporting standing balance can exploit this Gaussian regression model of muscle activity patterns to mimic healthy muscle activity in neurologically disordered patients

References:  
Masami, K., Shin, V. W., Veitch, A. H., Thirubhar, T.A., Kawashima, N., Morris, A., et al. (2008). Postural reactions of the trunk muscles to multi-directional perturbations in sitting. *Euro J. Clinical Biomechanics*, 21, 176-182. Retrieved August 11, 2014. From <http://www.science-direct.com/science/article/pii/S1885389608001294>



# Modeling of multi-directional muscle activity patterns during standing



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Toronto Rehabilitation Institute

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## Purpose

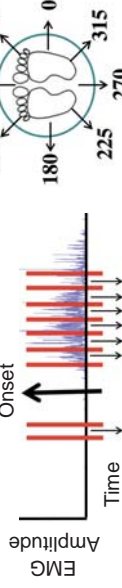
To model muscle activity patterns evoked by multi-directional perturbations during standing with respect to direction and time, for the development of an FES standing neuroprosthesis

## Background

- Functional electrical stimulation (FES) is a promising technology to restore standing balance in persons with motor disabilities
- FES uses electrical current to innervate muscle contractions
- To develop an FES standing neuroprosthesis, it is essential to identify the postural response to perturbations during standing

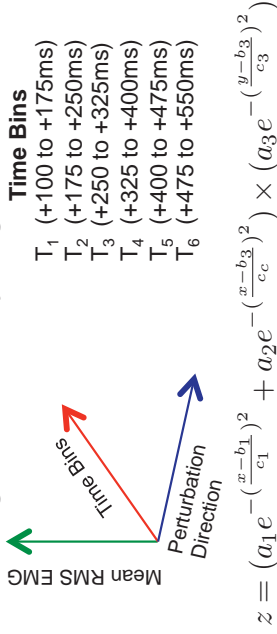
## Methods

- Subjects:**
- Young healthy adults (n = 9, male, 16–23 yrs)
- Tasks:**
- Trunk-level mechanical impulse perturbations during standing (8 cm displacement, 35 cm/s peak velocity)
  - Each of 8 directions has 10 trials, randomized
- Measurements:**
- EMG of 16 leg and trunk muscles
- Data Analysis:**
- EMG high-pass filtered (35 Hz), rectified, normalized
  - EMG RMS calculated for 6 time bins in each direction
  - Subtracted from baseline and averaged across all subjects



## Methods (Cont'd)

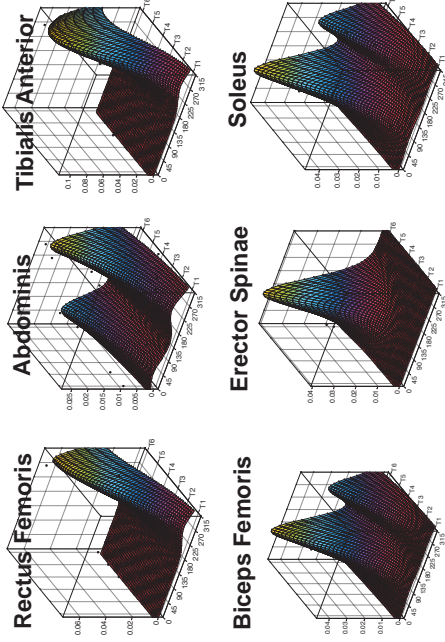
Modeling of muscle activity using Gaussian fit



where  $\mathbf{z}$  = mean RMS EMG,  $\mathbf{x}$  = angle of perturbation,  $\mathbf{y}$  = time bin,  $\mathbf{a}_n$  = arbitrary constant,  $\mathbf{b}_n$  = direction/time bin at which maximum response is expected, and  $\mathbf{c}_n$  = width at half-maximum amplitudes

## Results

1. Gaussian model agrees with the spatiotemporal characteristics of the muscle activation patterns



## Results (Cont'd)

2. Gaussian model has high goodness of fit

Muscle	R <sup>2</sup>	Muscle	R <sup>2</sup>
SOL	0.9464	STN	0.9257
PER	0.9581	BCF	0.9343
MGA	0.9601	RCF	0.9811
TBA	0.9678	TFL	0.9798
LGA	0.9418	GLU	0.8412
VME	0.9920	SPI	0.9005
VLA	0.9914	OBL	0.8410
SMN	0.9362	ABS	0.3792

Overall R<sup>2</sup> = 0.9048 ± 0.1475

## Conclusions

- 3D Gaussian model serves to be a powerful tool in profiling the spatiotemporal characteristics of muscle activity patterns underlying postural responses to perturbations during standing
- Future FES controllers aimed at supporting standing balance can utilize this Gaussian model of muscle activity patterns to mimic healthy muscle activity in patients with motor disabilities

## References:

Masani, Kei, Vivian W. Sin, Albert H. Vette, T. Adam Thrasher, Noritaka Kawashima, Alan Morris, Richard Preuss, and Milos R. Popovic. "Postural reactions of the trunk muscles to multi-directional perturbations in sitting." *Clinical Biomechanics* 24, no. 2 (2009): 176-182.



# Real Time Motion Tracking with Inertial Sensors to Help People with a Disability to Stand Independently

Andrew Passalacqua<sup>1,3</sup>, Bastien Moineau<sup>1,2</sup>, Milos R. Popovic<sup>1,2,3</sup>  
<sup>1</sup>Rehabilitation Engineering Laboratory, <sup>2</sup>Toronto Rehabilitation Institute, <sup>3</sup>University of Toronto

## Introduction

- Functional electrical stimulation is used to obtain muscle activity in diverse neurological diseases.
- We want to design a new generation of neuro-prosthesis allowing standing in people who can't.
- Such device needs to "know" body orientation at all points in time to maintain user's balance.
- Orientation can be tracked, real time, by computing pitch, roll and yaw angles of inertial sensors.
- Those are sets of 3 accelerometers and 3 gyroscopes, having some limits.

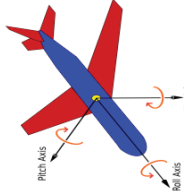


Fig 1. Visualization of roll, pitch and yaw axes.



Fig 2. Commercially available inertial sensor

- Accelerometer's accuracy reduces in the presence of high frequency noise (fast motions)
- Gyroscopes assess angular velocity and suffer from a low frequency drift through integrating constant error.
- High And low pass Finite Impulse Response (FIR) filters cause a linear drift in the time domain for the calculated results.

## Objectives

Design a recording method using inertial sensors and algorithm treatment for tracking body orientations in 3 dimensions which is:

- as accurate as a 3D infrared camera system;
- providing results with minimal delay (continuous near-real-time computation).

## Methods

- Accuracy of Shimmer™ sensors were tested by comparing the orientations calculated from its sensors and by the Cortex 3D system.
- Six rigid rectangular pieces were strapped tightly to lower limbs and trunk, on both sides of a volunteer.
- One inertial sensor and two infrared markers were placed aligned on each piece.
- Data were synchronously recorded while the volunteer performed sit-to-stand, leaning, rotating, squatting, sitting and standing.



Fig 3. Set-up before initiating a sit-to-stand test.

- Each trial had a duration of 1 minute where the Shimmer sampled at 51.2 Hz and Cortex at 200 Hz.
- Shimmer orientation was obtained by updating a direct cosine matrix angular velocity at each time-step.
- Initial positions were obtained using accelerometer data and gyroscopic drift was removed by the use of an extended Kalman filter.
- Thus, angular velocity was solely used to determine orientation of the sensors.
- 3D orientations was obtained "classically" with the cameras' software. Joint angles were obtained by subtraction of segments' orientation.

## Results

- The 8 data sets recorded during small movements showed an average difference between Shimmer and Cortex of  $2.6 \pm 7.4$  deg with an average standard deviation of  $0.7 \pm 0.3$  deg.
- The 5 data sets recorded during large movements showed an average difference of  $1.3 \pm 6.4$  deg with an average standard deviation of  $4.2 \pm 4.0$  deg.
- So far, the method used to synchronize the data caused an offset that create errors in the latter records, increasing errors, particularly for quick and large movements.

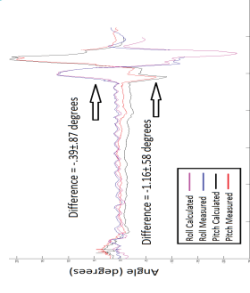


Fig 4. Roll and pitch of the trunk from inertial sensors and cameras during chest sway and rotations

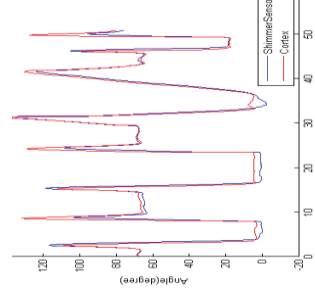


Fig 5. Flexion angle of the left hip during sit-to-stand movements at different speed (0 = hip extension)

- Offline, one cycle of the program took 0.65  $\pm 0.12$  ms to execute. The sample rate being 51.2Hz, there was a margin of 18.8 ms left for other computations before the next sensors recording.

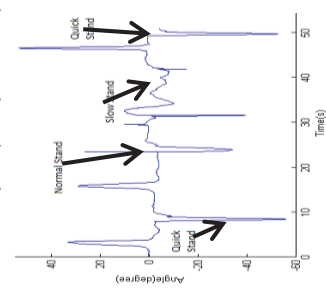


Fig 6. Sensors error compared to Cortex for hip flexion

## Conclusion

- All significant drops in accuracy were due to the error in the initial estimate by the accelerometer or by the offset caused from our synchronization technique.
- This preliminary experiment shows that it is possible to accurately track the orientation of 6 sensors together in a real-time way.
- The very short computation time will allow us to conduct other tests at higher frequency.
- By strictly using angular velocity for our calculations, which is accurate at high frequencies, none of the incoming data is filtered resulting in zero-time delay in the calculated orientation.
- Error in orientation calculation increased during faster movements. Solutions might be to optimize synchronization and to sample inertial sensors data at higher frequency.

## References

- Premierani, W. & Bizard, P. (May 17, 2009). Direction Cosine Matrix IMU: Theory.
- Lee, Hyung-Jik, and Seul Jung. "Gyro a Mobile Inverted Pendulum Robot System." 2009 IEEE International Conference on Industrial Technology (2009).

## Acknowledgements

Thank you to Dr. Moineau and Dr. Popovic for giving me the opportunity to work on this project.

# A novel method to reduce muscle fatigue during functional electrical stimulation for people with spinal cord injury



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- 2) Automatic Control Laboratory, ETH Zurich, Zurich, SWITZERLAND
- 3) Lyndhurst Centre, Toronto Rehabilitation Institute, Toronto, CANADA
- 4) Institute of Biomaterials and Biomedical Engineering, University of Toronto, Toronto, CANADA



## PURPOSE

To explore the fatigue-reducing ability of spatially distributed sequential stimulation (SDSS) for major lower limb muscle groups

## Experiment

**Subjects:**

- Able-bodied male subjects: n = 11
- SCI male subjects: n = 17

**Task:**

- Knee extension, knee flexion, plantar flexion, and dorsiflexion
- Isometric, repetitive contraction in a sitting posture for 2 min, 300 ms-on and 700 ms-off (see right column)
- Comparison between **SES** and **SDSS** (see right)
- 4 trials for each joint with each condition per subject in a day, 2 separated days for 2 conditions
- FES: Pulse frequency, 40 Hz; Pulse width, 250 us
- 180 sec fatiguing task

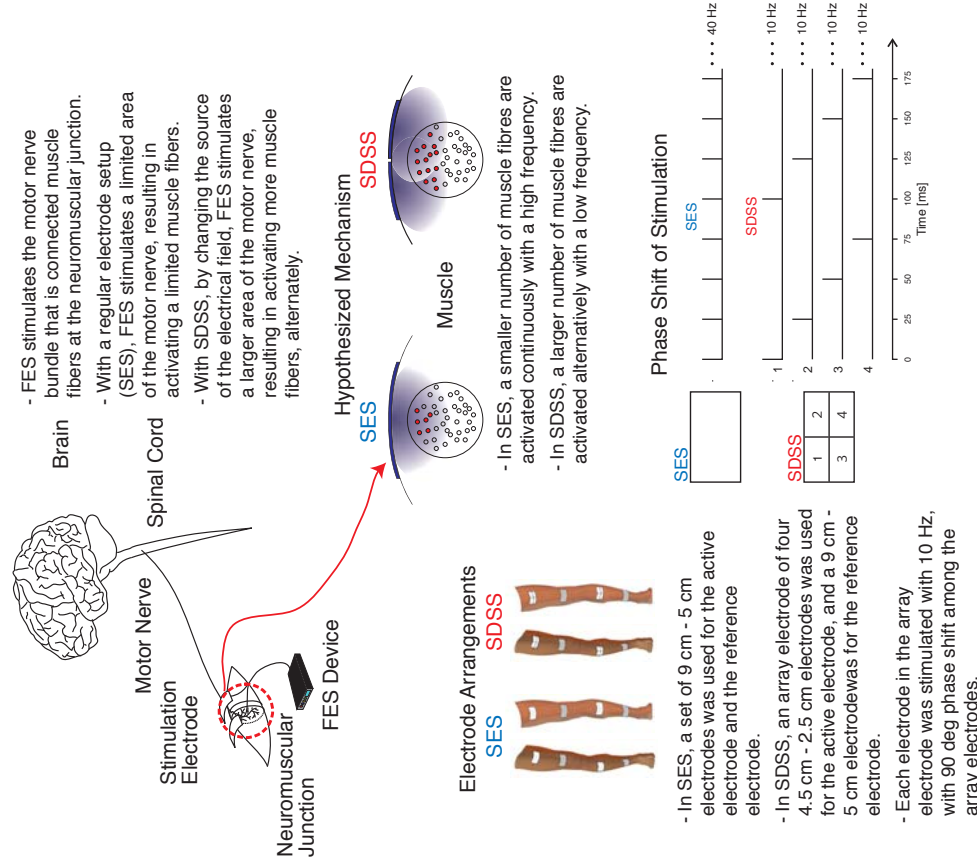
**Measurements:**

- Joint torque

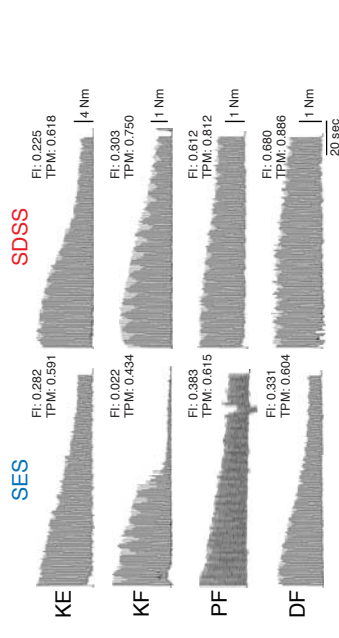
**Analysis:**

- Fatigue Index (FI): Torque at the end of the fatiguing task normalized to the maximum torque
- Torque Peak Mean (TPM): The mean of peak torques throughout the whole bout of fatiguing stimulation, normalized to the mean peak torque values of the initial five stimulus trials

## 1 Spatially Distributed Sequential Stimulation (SDSS) & Single Electrode Stimulation (SES)



## 2 Comparison between SDSS and SES



- While, in SES, the torque gradually decreased due to fatigue, the decrement of torque was not that prominent in SDSS.

- SDSS showed significantly less fatigue compared to SES in SCI individuals and in able-bodied subjects except for knee flexors.

## CONCLUSION

- The effectiveness of using SDSS to reduce muscle fatigue was shown in individuals with SCI and able-bodied individuals except for knee flexors.
- The results warrant the potential of SDSS to prolong training sessions of various FES therapy.





# Closed-loop Controlled Neuroprosthesis Design with Optimized FES Parameters to Minimize Muscle Fatigue

Hossein Rouhani, Karen E. Rodriguez, Kei Masani, Milos R. Popovic  
Rehabilitation Engineering Laboratory, Toronto Rehabilitation Institute, University Health Network & IBBME, University of Toronto



Toronto Rehabilitation Institute  
Institute of Biomaterials and Biomedical Engineering  
UNIVERSITY OF TORONTO

## Introduction

- Functional Electrical Stimulation (FES): as neuroprosthesis to substitute for the lost neural control for grasping, walking or standing in individuals with spinal cord injury, stroke, etc.
- Rapid onset of muscle fatigue in response to FES is a major challenge in design of neuroprostheses
- Torque generated at a joint using FES rectangular pulse depends on the pulse amplitude (PA) and width (PW)
- Influence of PA and PW on muscle fatigue was never investigated

## Objective

Introducing an algorithm to choose optimal pulse shape parameters (amplitude and width) for FES pulse that attain different levels of muscle force for longer time periods and result in minimal muscle fatigue

## Experimental Protocol

- 3 healthy subjects
- 9 trials of 3-min FES application on ankle plantarflexors of each leg
- 3 level of PA (30,40,50 mA) and 3 levels of PW(150,300,450 [sec])
- At least 3 days rest between every two trials
- Measurement of ankle torque, maximum torque (MT), fatigue time (FT), and normalized torque-time integral (TI)

## Data Analysis

- Interpolate FT, TI, and MT over 3x3 grid of (PA,PW)
- Obtain all (PA,PW) combinations that result in a certain level of MT
- Calculate FT & TI for all (PA,PW) combinations above
- Find (PA,PW)<sub>OPT</sub> that minimizes FT or TI
- Repeat step 2 & 3 for other levels of MT
- Pass a line through all (PA,PW)<sub>OPT</sub> for different MT levels
- Modulate (PA,PW) over or near the line in step 6 for minimum muscle fatigue in closed-loop controlled neuroprosthesis design

## Conclusions

- We experimentally sought the optimal muscle fatigue performance among pulse width and amplitude combinations generating the same level of maximum torque
- High bilateral symmetry in different days => optimal choice can be later used in other clinical protocols
- Optimal choice of the pulse parameters should be updated for other individuals or after muscle training
- This algorithm can be applied for any other muscle

## References

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- Nguyen R et al. *Artificial Organs* 35:1174-1180, 2011
- Graham GM et al. *IEEE TNSRE*. 14:38-45, 2006

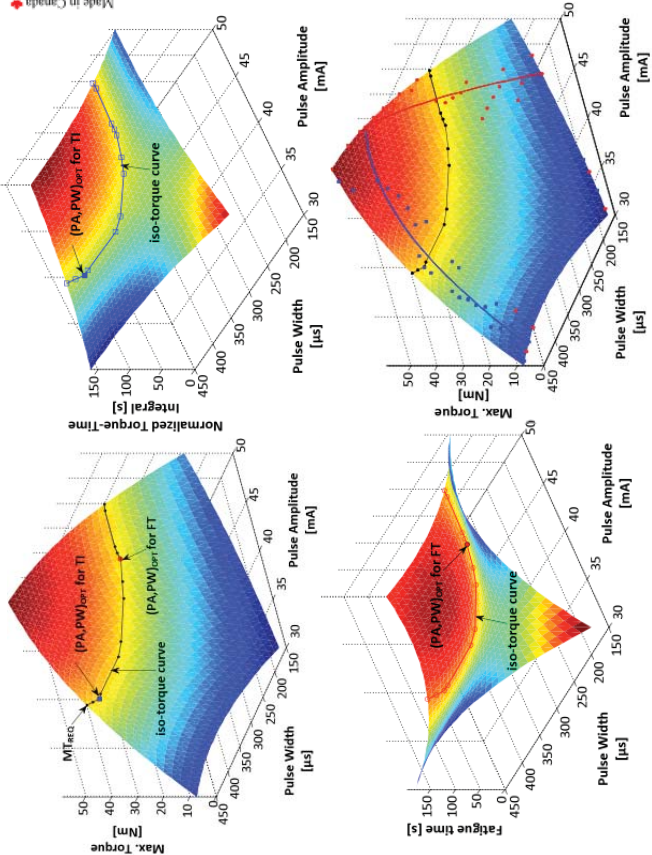


Fig1 – (a) An iso-torque curve ( $MT_{REQ}$ ) on a MT surface. (b,c)  $FT_{REQ}$  (red) and  $TI_{REQ}$  (blue) curves, resulted by the same (PA,PW)<sub>REQ</sub> combinations generating  $MT_{REQ}$ , on FT (b) and TI (c) surfaces. Minimum fatigue performance shown by red circle and blue square on FT and TI curves. (d) Red and blue curves show the “operating line” for PA and PW modulation that results in a sub-optimal muscle fatigue performance.

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**Acknowledgement:** This study was financially supported by Swiss National Science Foundation (SNSF), NSERC, and CIHR

## Partners:



# FES Therapy for Walking in Incomplete SCI Patients: Walking Competency

Milos R. Popovic<sup>1,2</sup>, Naaz Kapadia<sup>1</sup>, Kei Masani<sup>1,2</sup>, Lora Giangregorio<sup>4</sup>, Sander Hitzig<sup>3</sup> and Catherine Craven<sup>1,3</sup>



1. Toronto Rehabilitation Institute | University Health Network; 2. Institute of Biomaterials and Biomedical Engineering | University of Toronto; 3. Faculty of Medicine | University of Toronto; 4. Department of Kinesiology | University of Waterloo.



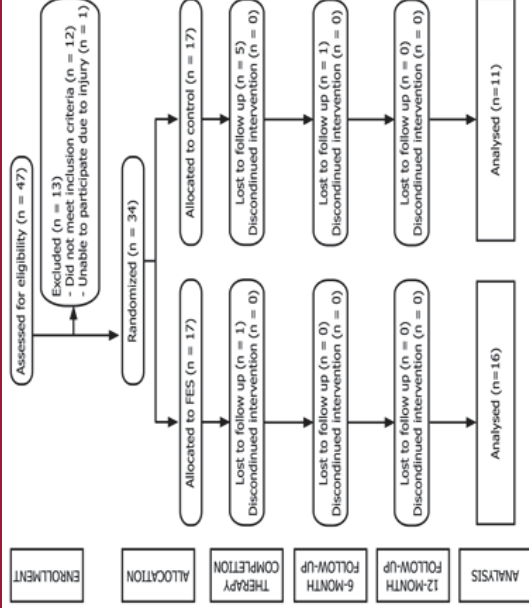
## Introduction

- In Canada, there are 86,000 individuals living with SCI, with approximately 3,400 new cases each year.
- Multichannel surface functional electrical stimulation (FES) therapy for walking has been used to improve voluntary balance and walking in SCI individuals.

## Objectives

- To investigate short- and long-term benefits of FES-assisted walking, while ambulating on a body weight support treadmill and harness system, vs. an exercise program, using RCT design.
- Improvements in gait and balance in individuals with chronic incomplete traumatic SCI were assessed before and after 16 weeks of thrice-weekly therapy.

## Methods

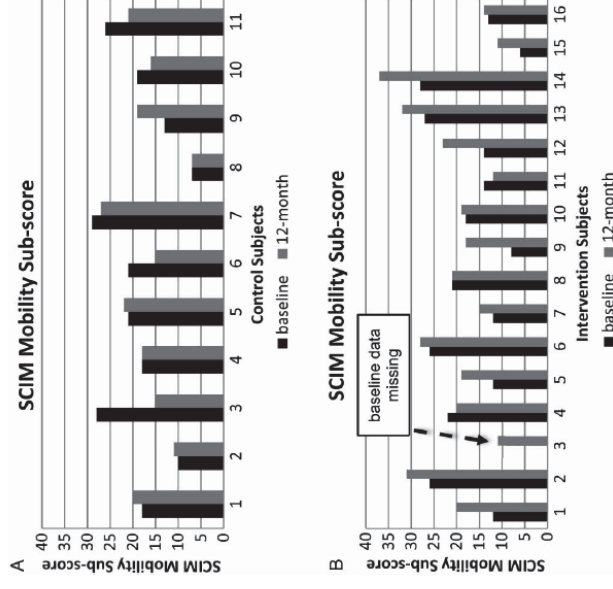


## Results

Table 1: Participant demographics Means and Standard deviations.

Variable	Treatment	Control	Total
Age (yrs)	56.59 (14.00)	54.06 (16.45)	55.32 (15.10)
Gender (M in %)	82.35 % (14)	70.59% (12)	76.5% (26)
Height (cm)	174.25 (7.89)	173.64 (9.20)	173.95 (8.44)
Weight (kg)	81.31 (13.05)	90.74 (38.99)	86.02 (26.03)
BMI	26.74 (3.88)	30.45 (14.35)	28.60 (10.52)
Duration Injury (y)	8.75 (9.74)	10.32 (11.13)	9.53 (10.33)
Para AIS C-D	17.65% (3)	29.41% (5)	23.5% (8)
Tetra AIS C-D	82.35% (14)	70.59% (12)	76.5% (26)
ASI Motor Score: UEMS	38.29 (7.44)	37.47 (13.83)	37.88 (10.95)
ASI Motor Score: LEMS	30.41 (8.19)	27.94 (9.76)	29.18 (8.96)
ASI Motor Score: TMS	68.71 (11.32)	65.47 (17.61)	67.09 (14.67)
Ambulatory Participants at Baseline	8 out of 11	13 out of 16	21 out of 27
Etiology of SCI: MVA	29.41% (5)	23.53% (4)	26.47% (9)
Etiology of SCI: Fall	47.06% (8)	41.18% (7)	44.12% (15)
Etiology of SCI: GSW	0% (0)	5.88% (1)	2.94% (1)
Etiology of SCI: Sports	5.88% (1)	23.53% (4)	14.71% (5)
Etiology of SCI: Other	17.65% (3)	5.88% (1)	11.76% (4)

Figure 1: Individual subject results on the SCIM Mobility Sub-score assessment: Control and Intervention group



## Conclusions

- The only statistically significant difference between the groups was observed with SCIM Mobility Sub-score.
- Intervention Group had better outcomes compared to the Control Group.
- On all other outcome measures there was no statistically significant difference between the groups.

## References

1. Kapadia et al. J Spinal Cord Medicine 2014;37(5):511-524.



Rehabilitation Engineering Laboratory  
 Institute of Biomaterials and Biomedical Engineering | University of Toronto  
 Toronto Rehabilitation Institute | University Health Network  
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The views expressed in this poster do not necessarily reflect those of any of the granting agencies.

# Single-unit Recordings From Human Neocortical Slices Maintained In-vitro

Sara Mahallati<sup>1,2</sup>, Milos R. Popovic<sup>1,2</sup>, Taufik A. Valiante<sup>1,3,4</sup>

1) Institute of Biomaterial and Biomedical Engineering | University of Toronto, 2) Rehabilitation Engineering Laboratory | Toronto Rehabilitation Institute | UHN, 3) Toronto Western Hospital Research Institute | Division of Fundamental Neurobiology | UHN, 4) Department of Surgery | Faculty of Medicine | University of Toronto

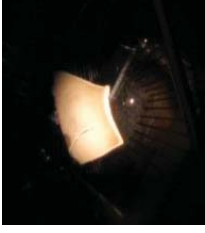
## Introduction

- Functional human brain networks have been investigated using EEG, iEEG, or fMRI, but the microcircuits underlying these networks are unexplored.
- Here we describe an approach to studying human microcircuits that utilizes human cortical tissue and simultaneous multisite electrophysiological recording.

## Methods

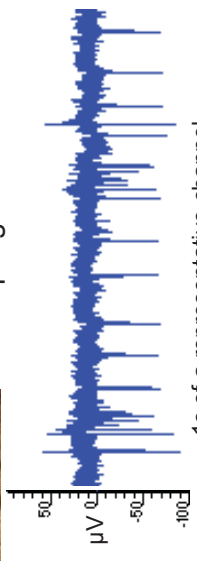
### Analyzed Tissue

- Human cortical slices (500  $\mu\text{m}$ ) excised at epilepsy surgery
- 60-channel In-vitro MEA recording
- ACSF perfusion: 15 mL/min



### Data Acquisition

- TiN array:
  - 200 $\mu\text{m}$  inter-electrode
  - 30 $\mu\text{m}$  contact diameter
- Sampling rate: 25 KHz



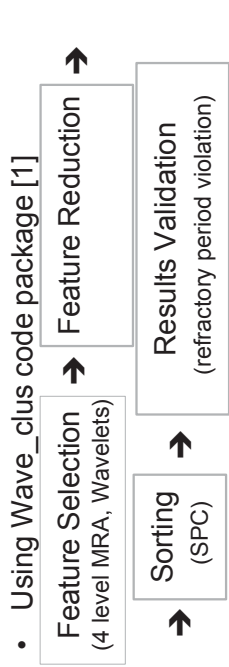
### Pre-Processing

- Multiunit activity: 0.3 - 3kHz

### Spike detection

- Negative threshold 4 times the average background noise level

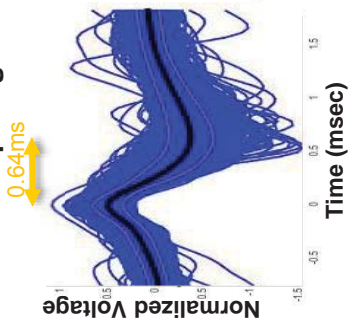
## Unit Classification



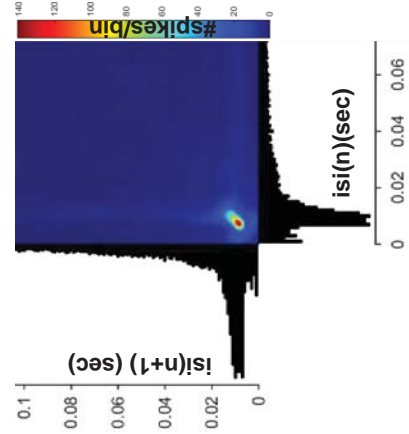
## Results and Discussion

Average spike waveform and Inter Spike Interval (ISI) return map of two representative neurons

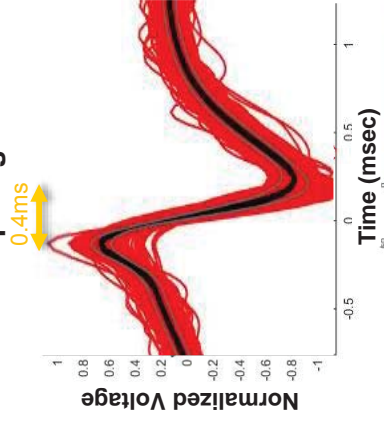
### Broad Spiking Unit



ISI return map of the broad spiking unit shows the fast spiking pattern



### Narrow spiking unit



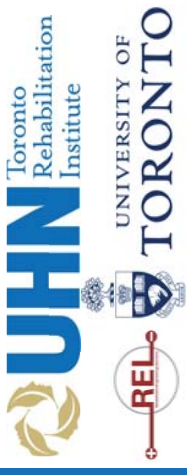
The narrow spiking unit exhibited regular spiking pattern with a firing rate that slowly varies during recording

- Units can be sorted ( $p < 0.0001$ ) into **narrow-spiking** ( $0.45 \pm 0.07\text{ms}$ ) and **broad spiking** units ( $0.74 \pm 0.13\text{ms}$ )
- These units display distinct patterns in their inter-spike intervals, i.e. **regular spiking** and **fast spiking**. Bursting pattern was also shown by some narrow spiking units.
- Further analyses will seek to create probabilistic map of spiking phenotypes and connectivity.

## References

- (1) Quiroga, Z. Nadasdy and Y. Ben-Shaul (2004) Neural Computation

# Factors Predisposing to Worsening of Sleep Apnea in Response to Fluid Overload in Men



B Gavrilovic<sup>1,2</sup>, T.D Bradley<sup>1,2</sup>, D Vena<sup>1,2</sup>, O Lyons<sup>1,2</sup>, J Gabriel<sup>1</sup>, M.R Popovic<sup>1,2</sup>, A Yadollahi<sup>1,2</sup>  
 1. Toronto Rehabilitation Institute – University Health Network and 2. Institute of Biomaterials and Biomedical Engineering, University of Toronto

## Introduction

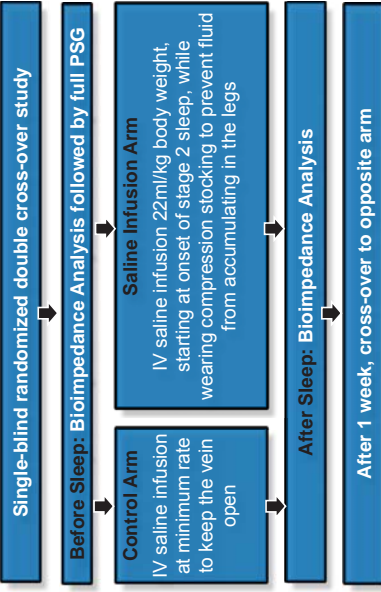
- Obstructive sleep apnea (OSA) is characterized by repetitive collapse of the pharynx during sleep
- OSA is highly prevalent in patients with fluid retaining conditions
- Bioimpedance is a simple and non-invasive measure to assess the amount of fluid in different body segments
- Using bioimpedance measurements, previous studies have shown that the greater the amount of fluid redistributing from the legs to the neck overnight, the greater the severity of OSA.

## Objective

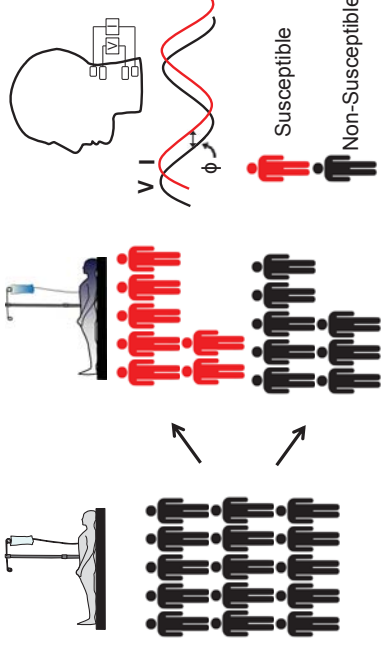
To investigate factors based on bioimpedance measurements of the neck, as well as other risk factors of OSA such as neck circumference, body mass index, and age that could put subjects at higher risk of developing OSA due to fluid overload.

## Study Design

**Inclusion Criteria:** Men with no history of sleep apnea, renal, cardiovascular, neurological, or respiratory diseases



## Methods



### Susceptible vs. Non-Susceptible Groups:

Susceptible participants were classified as those with at least a 100% increase in their apnea hypopnea index (AHI) from control to intervention, and having an AHI > 10 during the intervention arm

### Statistical Analysis:

**Within study arms:** paired t-test or Wilcoxon signed-rank test were used for normally and non-normally distributed data  
**Between participant groups:** Student t-test was used  
**To determine the effects of time, study arm, and group:** Repeated measures ANOVA was implemented

## Results

Variables	Non-Susceptible	Susceptible	P-Value
Age, years	39.6 ± 12.4	45 ± 6.4	0.324
Weight, kg	75.7 ± 11.9	78.7 ± 7.5	0.587
Height, cm	178.1 ± 5.6	175.4 ± 5.8	0.364
BMI, kg/m <sup>2</sup>	24.1 ± 3.2	25.8 ± 2.9	0.298
Neck Length, cm	12.5 ± 1.3	11.4 ± 1.4	0.160
Neck Fluid Volume, ml	280.8 ± 32.5	281.5 ± 71.8	0.984

## Results

Figure 2:

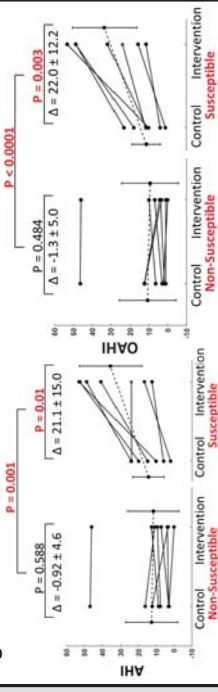
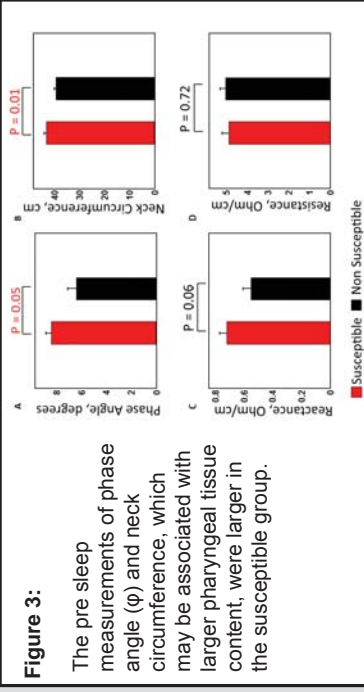


Figure 3:

The pre sleep measurements of phase angle (φ) and neck circumference, which may be associated with larger pharyngeal tissue content, were larger in the susceptible group.



## Conclusion

- In men, pre-sleep neck circumference and bioimpedance phase angle are associated with the development or worsening of OSA induced by saline infusion.
- Compared to control, saline infusion induced more fluid accumulation in the neck.
- These results may be used to improve the preoperative screening process to predict patients at high risk of developing sleep apnea due to fluid overloading.



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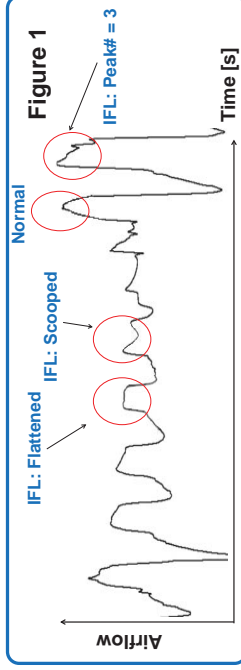
# Investigate the Effect of Upper Airway Narrowing on Inspiratory Airflow Contour

D. Zhi<sup>1,2</sup>, T.D. Bradley<sup>1,3</sup>, M.R. Popovic<sup>1,2</sup>, A. Yadollahi<sup>1,2</sup>

<sup>1</sup>University Health Network-Toronto Rehabilitation Institute; <sup>2</sup>Institute of Biomaterials and Biomedical Engineering, University of Toronto; <sup>3</sup>Department of Medicine, University of Toronto

## Introduction

- The existing technologies for evaluating upper airway (UA) narrowing are either invasive, expensive or difficult to conduct.
- UA narrowing contributes to inspiratory flow limitation (IFL), defined as sustained inspiratory airflow despite more respiratory effort.
- IFL changes normal airflow contour from rounded to distorted shape (Figure 1)<sup>1</sup>.
- Therefore the temporal patterns of airflow contour can be used as a surrogate to detect UA narrowing non-invasively.



## Objectives

- Investigate the relationship between the features extracted from airflow contour and UA narrowing.

## Methods

### Measurements in supine position<sup>2</sup>:

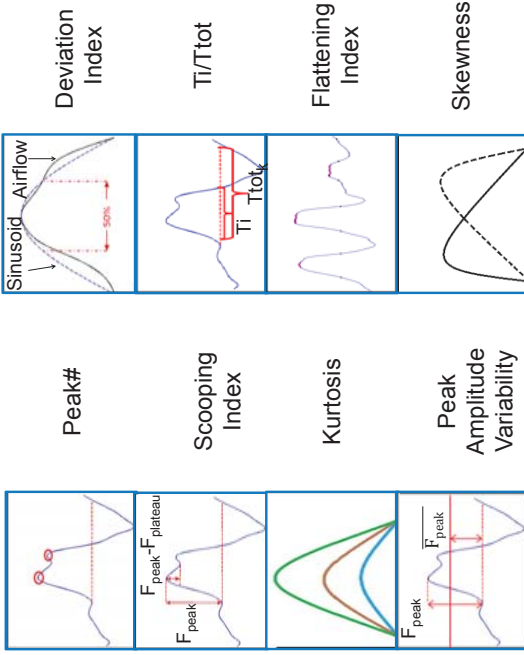
- Daytime full-polysomnography:
  - Nasal airflow
- Pre and post sleep UA anatomy:
  - Neck circumference (NC)
  - Cross-sectional area (UA-XSA)
  - Neck fluid volume (NFV)



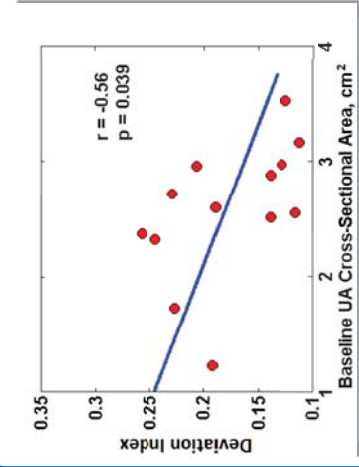
[BINAPS®, Salter Lab]

## Methods

### Extracted 8 features of airflow contour:



## Results



## Conclusions

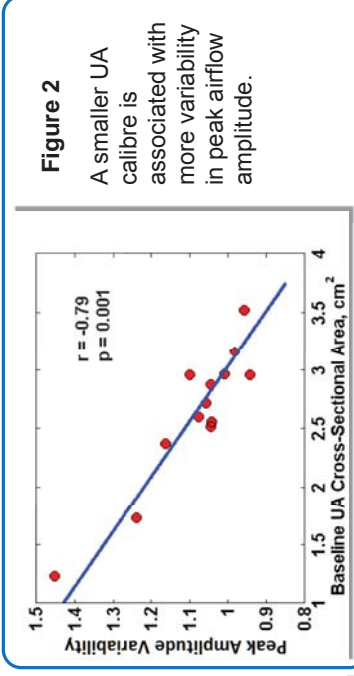
- Features extracted non-invasively from the temporal patterns of nasal airflow can be used to predict narrowing in the UA.
- Future work should investigate the use of un-supervised classifiers to classify different airflow contours based on the severity of UA narrowing.
- The proposed method could be used to investigate potential health consequences of milder degrees of UA narrowing in more susceptible population, such as children or pregnant women

## Acknowledgement



## Results

- 2447 inspiratory breaths from 16 men during sleep were investigated.



# Design and Validation of a Portable and Affordable Device to Measure Body Composition

B. Gavrilovic<sup>1,2</sup>, M.R. Popovic<sup>1,2</sup>, A. Yaddollahi<sup>1</sup>

<sup>1</sup> Toronto Rehabilitation Institute; <sup>2</sup> University of Toronto

## Introduction

Multi-frequency bioelectrical impedance analysis (BIA) is a non-invasive method to assess various body compositions such as

- Total body water
- Extra/Intracellular fluid
- Fat & muscle mass

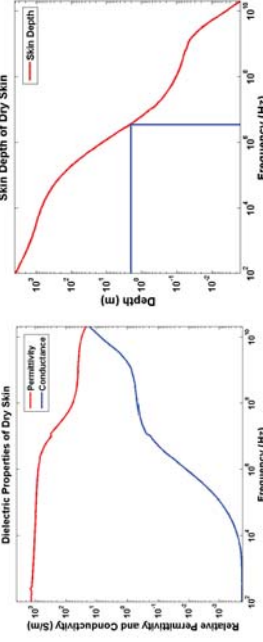
## Objectives

The available devices are either bulky, expensive, or cannot measure impedance continuously at multiple frequencies.

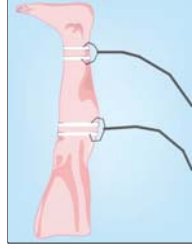
The objective of this study is to design and develop an affordable, accurate, and portable device that can measure electrical tissue properties.

## Background

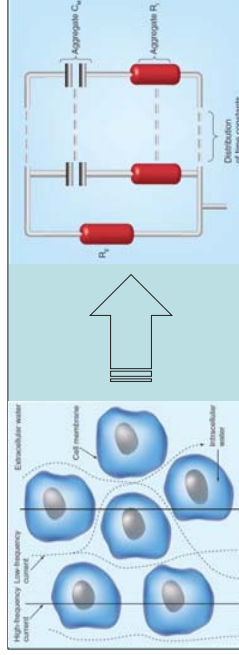
- Two forms of current move through the body
  - Diffusion of charged ions through the body
  - Time rate of change of electric fields (displacement current)
- Depth of current penetration is determined from Maxwell's equations, and varies based on tissue properties



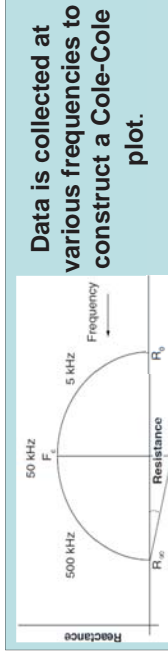
## Methods



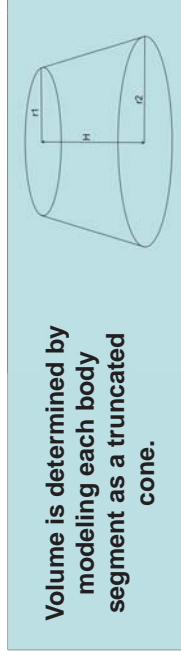
High frequency, low amplitude current is injected into body segments and the resulting voltage is measured.



At low frequencies current can only pass through the extracellular matrix due to the capacitance of the cells. As we increase the frequency more and more current will flow through the intracellular matrix.



Data is collected at various frequencies to construct a Cole-Cole plot.



Volume is determined by modeling each body segment as a truncated cone.

## Current Devices



### BioPac MP150

- Continuous data collection
- Multi channel device
- Single operating frequency



### ImpediMed SFB7

- Continuous data collection
- Single channel device
- Multiple operating frequencies

## Proposed System Specifications

- Frequency Range: 1kHz – 2MHz
- Current Amplitude: 400µA
- Continuous Data Collection: 2kHz
- Wireless Transmission
- Battery Life: 8 Hours
- Electrodes: Gold cup electrodes

## Future Work

- Design and build an affordable and portable BIS device with the specifications listed above.
- Simultaneous measurements at multiple body segments, including leg and neck.
- Test the accuracy and efficiency of the device compared with existing models.
- Potential Barriers
  - Generation of frequencies > 100kHz
  - Incorporating a large range of frequencies
  - Maintaining size and battery life