

## Spinal Cord Injury: a vision for future rehabilitation efforts

Andrew C. Smith, PT, DPT, PhD

 @DrAndrewCSmith



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## Objectives

At the end of the session, participants will be able to:

- Theorize ways of how MRI could inform clinical management of individuals with SCI.
- Formulate ideas of how recent innovations could enhance clinical outcomes in our patients.
- Identify ways in which pre-clinical research could be translated into patient management.

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"SCI: a vision for future rehabilitation efforts"

### Outline:

- Status Quo
- Improved Prognosis?
- Can Stimulation Help?
- Adaptive Technologies

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## What typically happens after SCI...



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## Prognosis for Ambulation: using motor scores



**ASIA** INTERNATIONAL STANDARDS FOR NEUROLOGICAL CLASSIFICATION OF SPINAL CORD INJURY (ISNCSCI) **ISCOS**

Hip flexors	L2	
Knee extensors	L3	
Ankle dorsiflexors	L4	
Long toe extensors	L5	
Ankle plantar flexors	S1	

Crozier 1992, Waters 1994, Dobkin 2006

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## Prognosis for Ambulation: Clinical Prediction Rules

A clinical prediction rule for ambulation outcomes after traumatic spinal cord injury: a longitudinal cohort study

Joost J van Meulen, Albert J F Himmer, A Roger T Donders, Martin H Pons, John J Utman, J. Kevin Cui, Alexander C H Gans, Hendrik Van de Meent, for the SCI Study Group

Age >65 years	12. Mobility Indoors
Motor score L3	0. Requires total assistance
Motor score S1	1. Needs electric wheelchair or partial assistance to operate manual wheelchair
Light touch score L3	2. Moves independently in manual wheelchair
Light touch score S1	3. Requires supervision while walking (with or without devices)
Total	4. Walks with a walking frame or crutches (swing)
Only the best score of each motor score or light touch score should be applied for the prediction rule (see Met)	
<b>Table 2. Clinical prediction rule variables</b>	
	5. Walks with crutches or two canes (reciprocal walking)
	6. Walks with one cane
	7. Needs leg orthosis only
	8. Walks without walking aids

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### Prognosis for Ambulation Using Motor Scores: Limitations

- Sedation? Lower extremity fracture? Spinal Shock?
- Lack of Specificity in Outcome
- Determining Plan of Care

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### What if?

- we had imaging, or other biomarkers, that could tell us more about what damage had been done to the spinal cord?
- adding this new information to clinical information (e.g., motor and sensory testing results) could allow more accurate and specific prognosis?

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### What if?

More accurate and specific prognosis and identification of specific injury to the spinal cord allowed clear clinical pathways for SCI Rehab?

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"SCI: a vision for future rehabilitation efforts"

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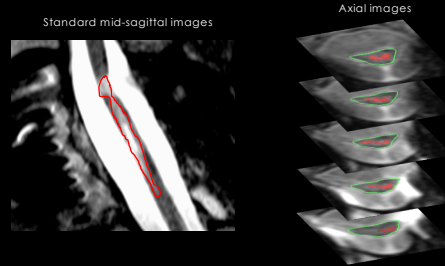
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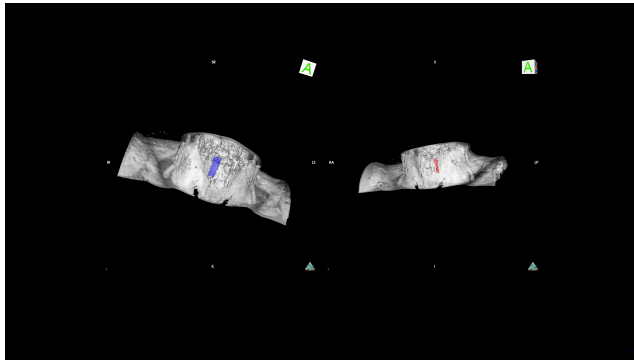
### Advanced MRI for Spinal Cord Injury

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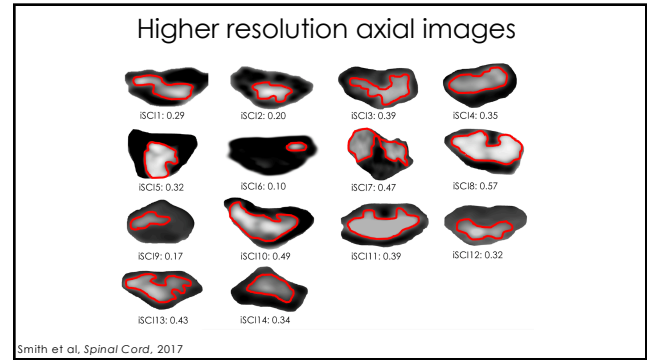
### T<sub>2</sub>-weighted spinal cord images



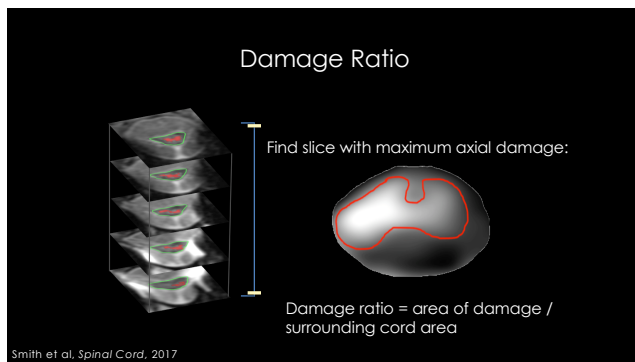
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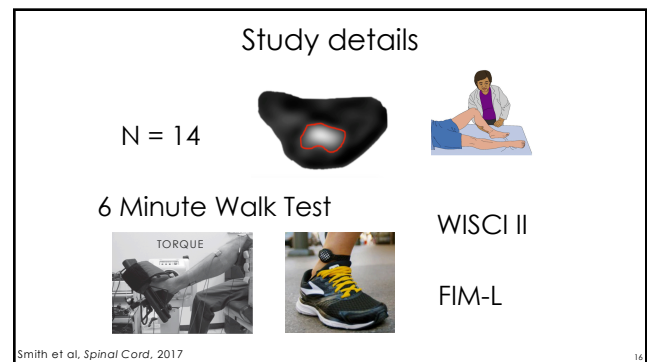
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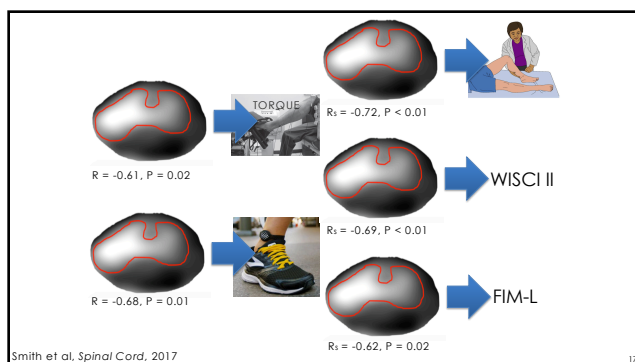
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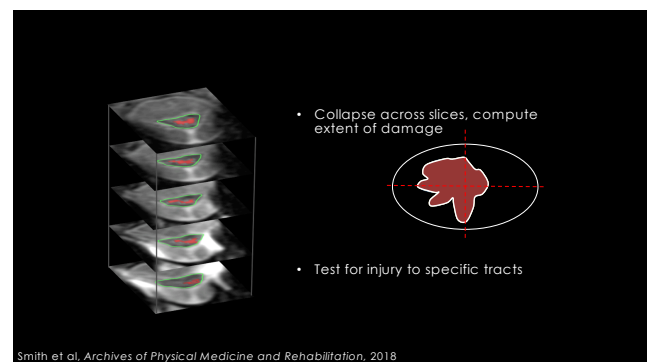
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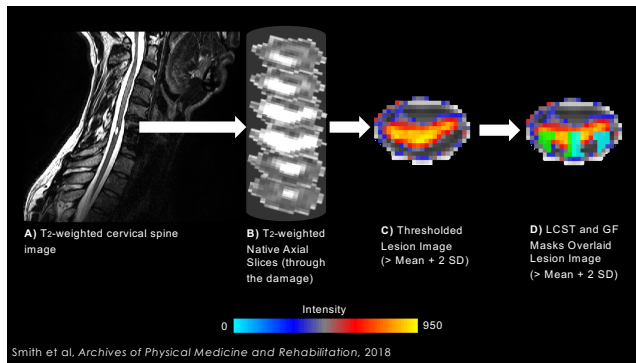
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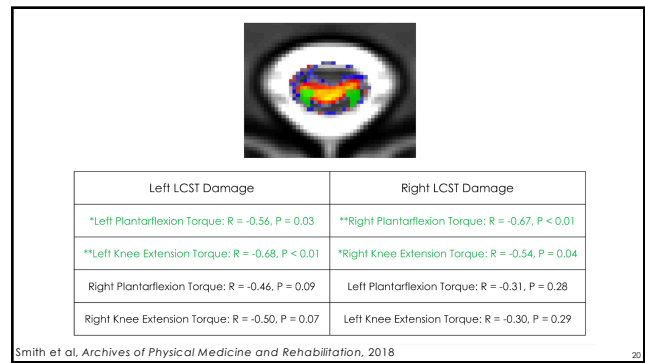
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Ann Neurol. 2019 May 18. doi: 10.1002/ana.25505. [Epub ahead of print]

**Residual Descending Motor Pathways Influence Spasticity after Spinal Cord Injury.**

Sangari S<sup>1</sup>, Lundell H<sup>2</sup>, Kirshblum S<sup>3</sup>, Perez MA<sup>1</sup>.

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- Kessler Institute for Rehabilitation, Department of Physical Medicine and Rehabilitation, Rutgers New Jersey Medical School, Newark, NJ, USA.

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**NIH**

**Eunice Kennedy Shriver**  
National Institute of Child Health and Human Development

National Center for Medical Rehabilitation Research (NCMRR)  
R03HD094577

**CRAIG** + **Spinal Cord Injury Model System**

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**My NCMRR R03 team**

Dr. Denise O'Dell Dr. Stephanie Albin Dr. Jeff Berliner

Mitch Sevigny Dr. David Dungan Dr. Ken Weber Prof. Jim Elliott

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**Machine learning, convolutional neural networks (CNN)**

**nature**

Letter | Published: 25 January 2017

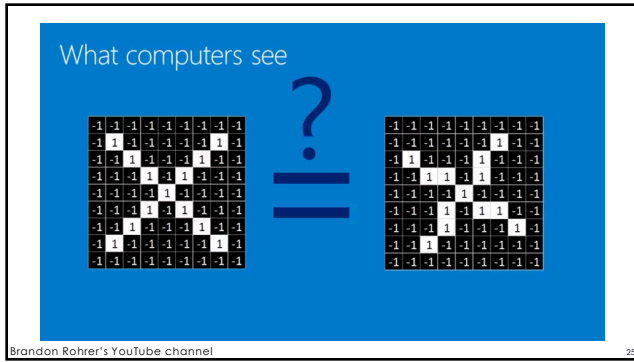
**Dermatologist-level classification of skin cancer with deep neural networks**

Andre Esteva, Brett Kuprel, Roberto A. Novoa, Justin Ko, Susan M. Swetter, Helen M. Blau & Sebastian Thrun

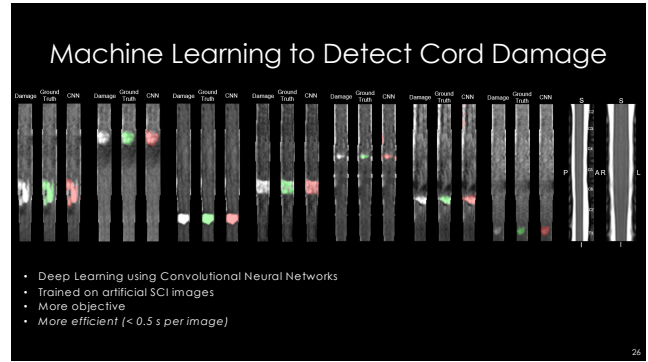
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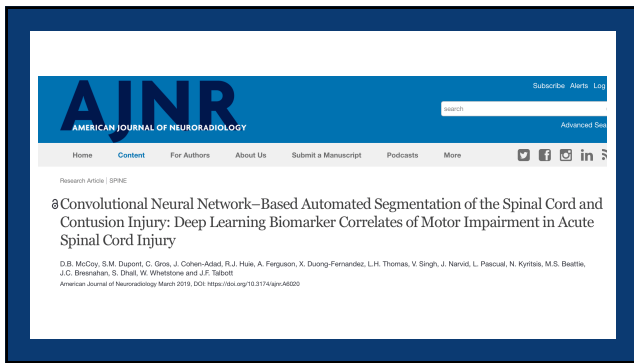




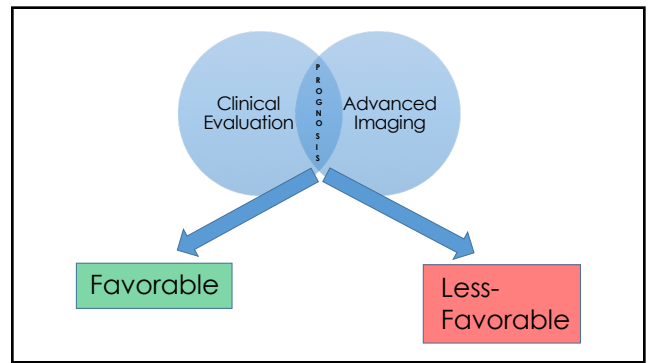
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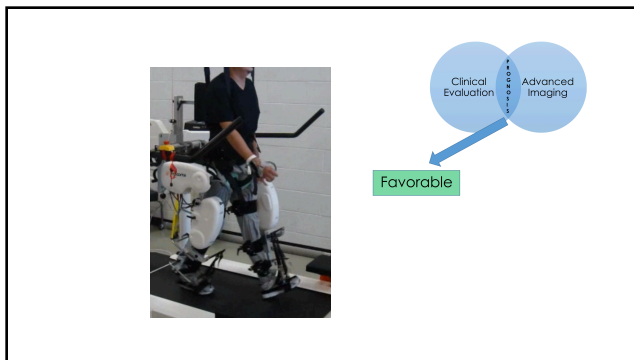
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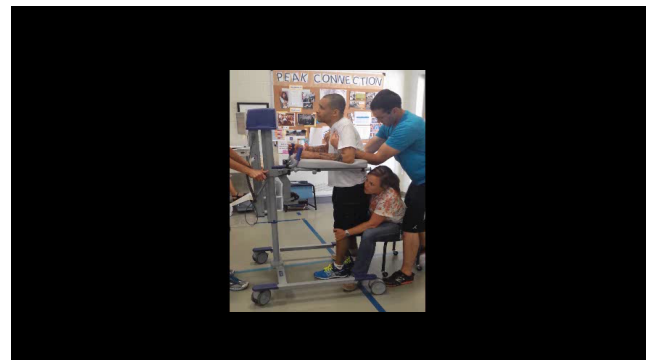
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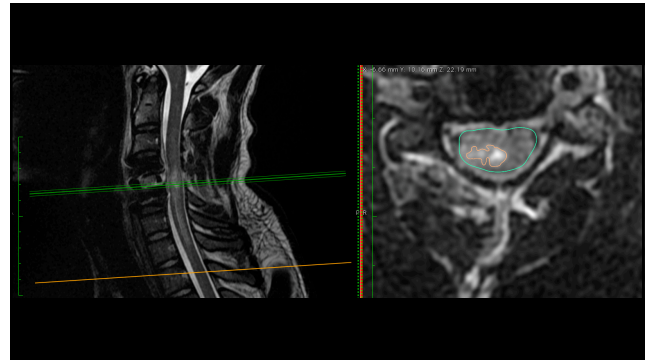
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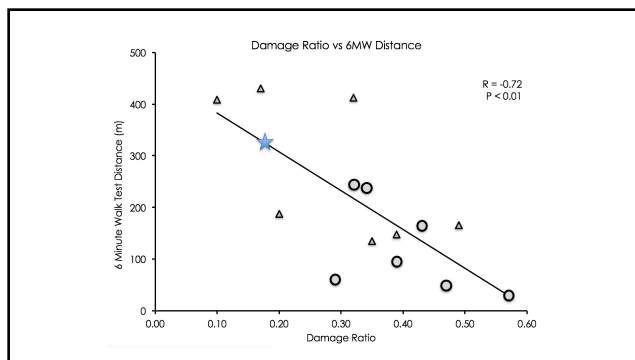
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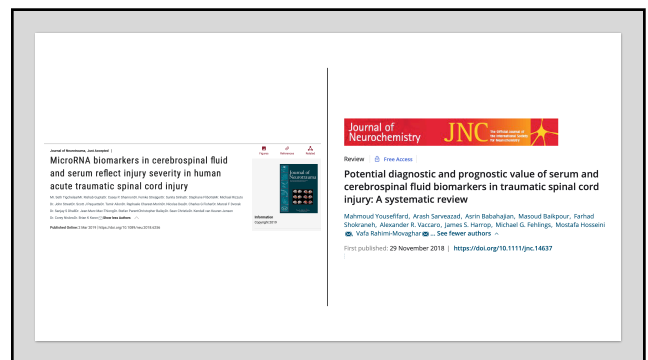
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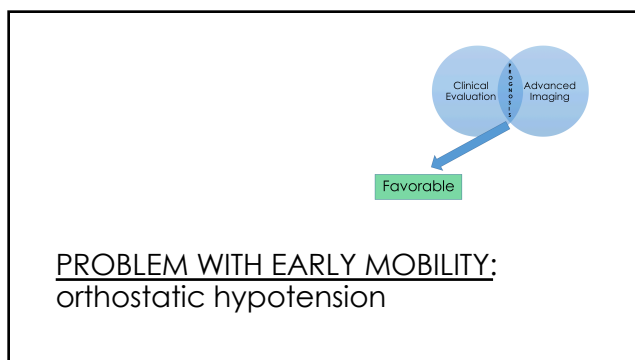
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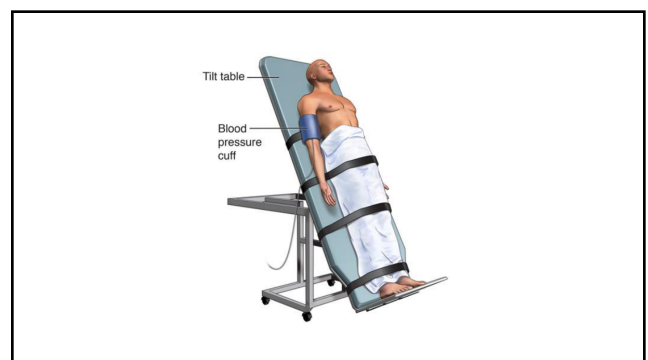
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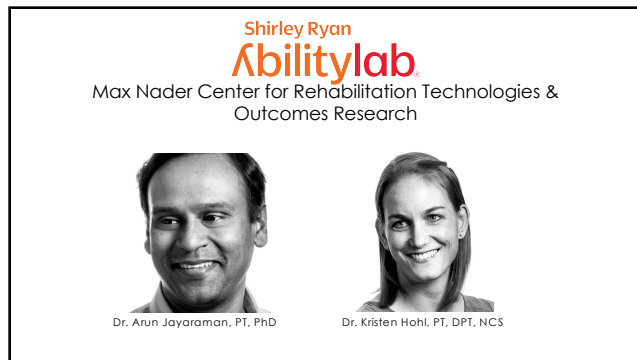
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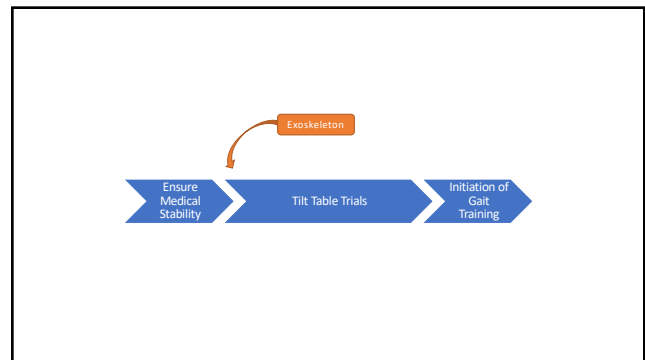
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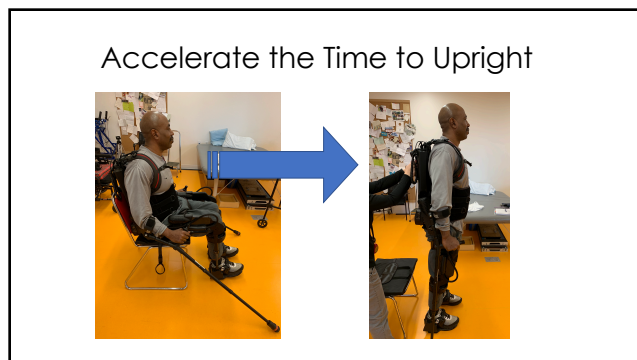
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HOW EARLY CAN I?

- N=7
- Primary purpose of study was assessing for neurological recovery when intervening early or late with EKSO + FES in inpatient rehabilitation
- Did not wait for tilt table tolerance to initiate exoskeleton training

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HOW EARLY CAN I?

- 85 total training sessions
- 2 hypotensive events
- 2% occurrence

```

graph LR
    A[Ensure Medical Stability] --> B[Tilt Table Trials]
    B --> C[Initiation of Gait Training]
    D[Exoskeleton] --> B
  
```

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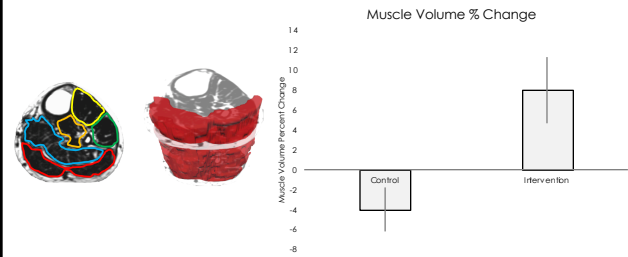


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Exoskeleton training may be best for early mobility and avoiding orthostatic hypotension

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...also may help with muscle atrophy

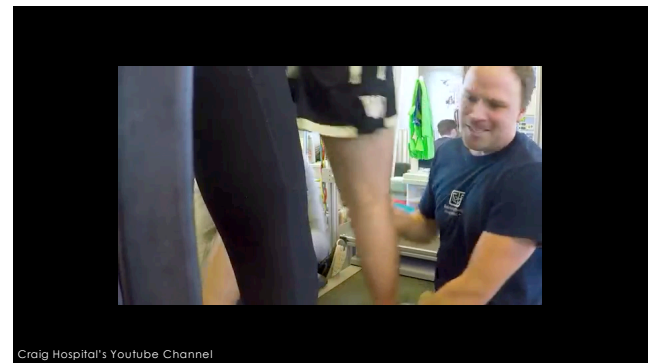


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Less-Favorable

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"SCI: a vision for future rehabilitation efforts"

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## Epidural stimulation

### THE LANCET

Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: a case study

Prof Susan Harkema, PhD, Yuri Gerasimenko, PhD, Jonathan Hodes, MD, Prof Joel Burdick, PhD, Claudia Angeli, PhD, Yangsheng Chen, PhD, Christie Ferreira, BSc, Andrea Willhite, BA, Enrico Rejc, MSc, Prof Robert G Grossman, MD, Prof V Reggie Edgerton, PhD

Published: 20 May 2011

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**EDITOR'S CHOICE**  
**Altering spinal cord excitability enables voluntary movements after chronic complete paralysis in humans**  
 Claudia A. Angeli, V. Reggie Edgerton, Yuri P. Gerasimenko, Susan J. Harkema  
 Brain, Volume 137, Issue 5, 1 May 2014, Pages 1394-1409, <https://doi.org/10.1093/brain/awu038>  
 Published: 07 April 2014 [Article history](#)

**RESEARCH ARTICLE**  
**Effects of Lumbosacral Spinal Cord Epidural Stimulation for Standing after Chronic Complete Paralysis in Humans**  
 Enrico Rejc, Claudia Angeli, Susan Harkema  
 Published: July 24, 2015 • <https://doi.org/10.1371/journal.pone.0133988>

**Enabling Task-Specific Volitional Motor Functions via Spinal Cord Neuromodulation in a Human With Paraplegia**  
 Peter J. Grabin, PhD, Igor A. Lantov, MD, PhD, Dmitry G. Saperko, PhD, Massimo G. Van Straten, PT, Megan L. Gil, DPT, Jeffrey A. Strimren, MD, Jonathan G. Colner, BS, Qing T. Chabian, DPT, Lisa A. Bado, MS, Morgan B. Larkin, BS, Andrew P. Thompson, MS, Cesar Lujano, MS, Kaito A. Sugimoto, MD, Peng H. Gao, PhD, Yuri P. Gerasimenko, PhD, V. Reggie Edgerton, PhD, Kristen G. Zhao, PhD, Kandel H. Lee, MD, PhD

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**RESEARCH ARTICLE**  
**Common neural structures activated by epidural and transcutaneous lumbar spinal cord stimulation: Elicitation of posterior root-muscle reflexes**  
 Ursula S. Holsteeller<sup>1,2</sup>, Brigitta Freund<sup>3</sup>, Heinrich Binder<sup>4</sup>, Karen Missias<sup>1,2</sup>  
 DOI: 10.1371/journal.pone.0140713 <http://dx.doi.org/10.1371/journal.pone.0140713>

**Epidural stimulation with locomotor training improves body composition in individuals with cervical or upper thoracic motor complete spinal cord injury: A series of case studies**  
 Daniela G.L. Terson de Paiva, Susan J. Harkema & Claudia A. Angeli

**Article** Published: 31 October 2016  
**Targeted neurotechnology restores walking in humans with spinal cord injury**  
 Fabian B. Wagner, Jean-Baptiste Magnard, Camille G. Le Gall-Magnard, Robin Dennerbrun, Salf Kiani, Marco Capogrossi, Andreas Rowald, Immanuel Saffari, Wenzel Caban, Eliza Prosser, Wolfgang Nix, Laura A. McCadden, Roman Hengstenberg, Isabelle Padoa, Anna Martin, Perine Baglini, Eduardo Pardo, Kristian Van Den Heuvel, Grigore David, Brigitte Schürch, Steffen Prutting, Fabio Basso, John Prior, Nicholas Bawa, W. R. Buchman, Tara Neuhoff, Nels Hunter, Stefano Carli, Joachim van Zanten, Vincent Gagnon, Tim Denner, Wendie Lambert, Karen Missias, Jocelyne Bloch & Grigore Courtine  
 Nature 543, 65–71 (2016) | [Download Citation](#)

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The Big Idea: Epidural Stimulation Research for SCI. Christopher & Dana Reeve Foundation

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## Improvements even when the stimulator is OFF...

"We show the progressive recovery of voluntary leg movement and standing without scES in an individual with chronic, motor complete SCI throughout 3.7 years of activity based interventions utilizing scES configurations" ~Rejc et al, 2017, *Scientific Reports*

"P1 and P2 could transit from sitting to standing and walking independently with crutches. P1 could even walk without an assistive device for several steps. Consequently, P1 and P2 increased their WISCI scores from 13 to 16 and 6 to 13, respectively. They displayed substantial improvements in clinical evaluations such as ten-metre and six-minute walking tests without EES." ~Wagner et al, 2019, *Nature*

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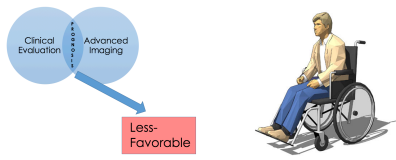
**Spinal cord epidural stimulation for voluntary movement after spinal cord injury: current state of the research.**

August 1<sup>st</sup>, 2019

Andrew C. Smith, PT, DPT, PhD; Candace Tefertiller, PT, DPT, NCS;  
 Meghan Joyce, PT, DPT, NCS; Rachel S. Tappan, PT, DPT, NCS; Alex Lubahn, PT, DPT;  
 Celisa Hahn, PT, DPT; Enrico Rejc, PhD


[Neurolpt.org](http://Neurolpt.org) → [Special Interest Groups](#) → [SCI](#) → [New and Noteworthy](#)

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Epidural Stim too invasive? Patient cannot afford the cost?



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**Transcutaneous Stimulation**


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Dr. Candy Tefertiller, PT, DPT, PhD, NCS

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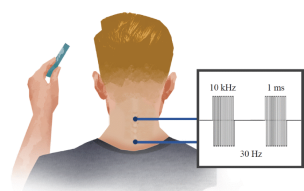
What about upper extremity function?

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IEEE Trans Neural Syst Rehabil Eng. 2018 Jun;26(6):1272-1278. doi: 10.1109/TNSRE.2018.2834339.

**Transcutaneous Electrical Spinal Stimulation Promotes Long-Term Recovery of Upper Extremity Function in Chronic Tetraplegia.**

Inancil F, Samelima S, Gad P, Edgerton VR, Hofstetter CP, Moritz CT.

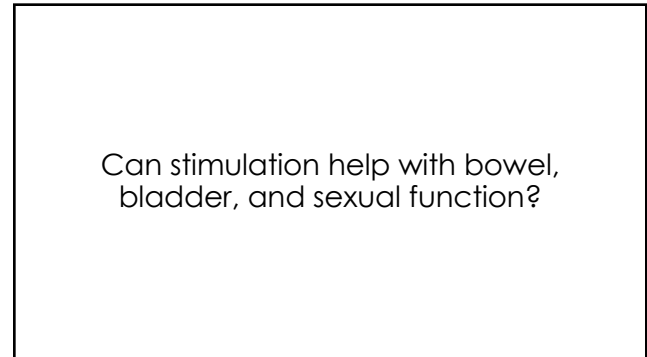


"functional gains were maintained in the absence of stimulation and persisted for over three months of follow-up with no further treatment."

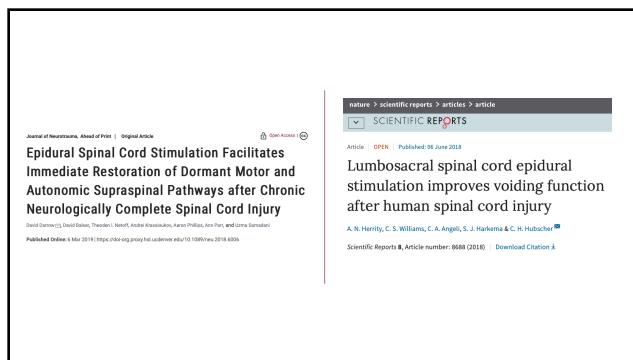
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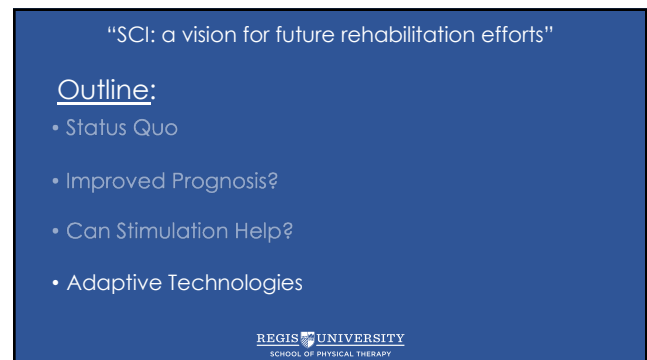
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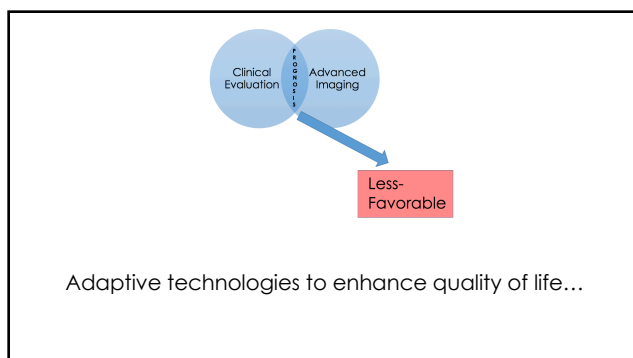
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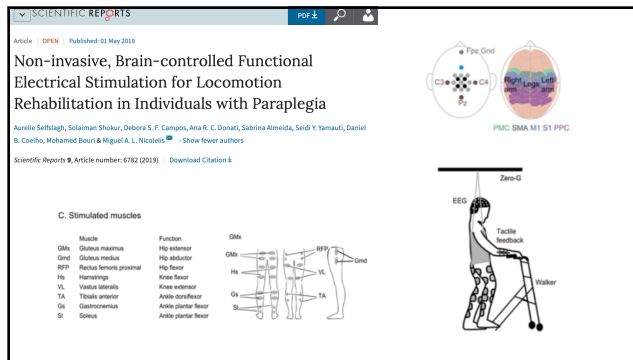
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**Vox**

## Disabled people don't need so many fancy new gadgets. We just need more ramps.

Technology isn't always the answer.

By s.e. smith | Apr 30, 2019, 7:30am EDT

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"SCI: a vision for future rehabilitation efforts"

In Summary:

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- Adaptive Technologies

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## Acknowledgements

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- Craig Hospital
- Shirley Ryan Ability Lab
- Collaborators: Jim Elliott, Ken Weber, Denise O'Dell, Stephanie Albin, David Dungan, Jeff Berliner, Arun Jayaraman, Kristen Hohl, Candy Tefertiller, Enrico Rejc, Rachel Tappan, Meghan Joyce
- Former research participants

@DrAndrewCSmith

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## References

1. Crozier KS, Cheng LL, Graziani V, Zorn G, Herbison G, Dittunno JF. Spinal cord injury: prognosis for ambulation based on quadriceps recovery. *Spinal Cord*. 1992;30:742-747.
2. Waters RL, Adkins RH, Yakura JS, Sie I. Motor and sensory recovery following incomplete tetraplegia. *Arch Phys Med Rehabil*. 1994;75:67-72.
3. Dobbin B, Apple D, Barbeau H, et al. Weight-supported treadmill vs over-ground training for walking after acute incomplete SCI. *Neurology*. 2006;66:484-493.
4. Van Middendorp JJ, Hosman AJ, Donders AR, et al. A clinical prediction rule for ambulation outcomes after traumatic spinal cord injury: a longitudinal cohort study. *Lancet*. 2011;377:1004-1010.
5. Hicks KE, Zhao Y, Follath N, et al. A simplified clinical prediction rule for prognosticating independent walking after spinal cord injury: a prospective study from a Canadian multicenter spinal cord injury registry. *Spine J*. 2017;17:1383-1392.
6. Wilson JR, Grossman RG, Frankowski RT, et al. A clinical prediction model for long-term functional outcome after traumatic spinal cord injury based on acute clinical and imaging factors. *J Neurotrauma*. 2012;29:2263-2271.
7. Smith AC, Weber KA, Parish TB, et al. Ambulatory function in motor incomplete spinal cord injury: a magnetic resonance imaging study of spinal cord edema and lower extremity muscle morphometry. *Spinal Cord*. 2017;55:672-678.
8. Smith AC, Weber KA, Parish TB, et al. Lateral corticospinal tract damage correlates with motor output in incomplete spinal cord injury. *Arch Phys Med Rehabil*. 2018;99:1588-1595.
9. Estévez A, Kupel B, Novoa RA, et al. Dermatologist-level classification of skin cancer with deep neural networks. *Nature*. 2017;542:115-118.
10. McCoy DB, Dupont SM, Cohen-Addad J, et al. Convolutional neural network-based automated segmentation of the spinal cord and 52gulation injury: deep learning biomarker correlates of motor impairment in acute spinal cord injury. *AJNR Am J Neuroradiol*. 2019;40:737-744.
11. Tachibana S, Gupta R, Shannon CP, et al. MicroRNA biomarkers in cerebrospinal fluid and serum reflect injury severity in human acute ischemic spinal cord injury. *J Neurotrauma*. 2019; doi:10.1089/neu.2018.6256. [Epub ahead of print].
12. Tachibana S, Shannon CP, Tachibana A, et al. MicroRNA biomarkers in cerebrospinal fluid and serum reflect injury severity in human acute ischemic spinal cord injury. *J Neurotrauma*. 2019; doi:10.1089/neu.2018.6256. [Epub ahead of print].
13. Harkema S, Gerasimenko Y, Hodges J. Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: a case study. *Lancet*. 2011;377:1925-1934.
14. Appel CA, Edgerton VR, Gerasimenko YB, Harkema SJ. Altering spinal cord excitability enables voluntary movements after chronic complete paralysis in humans. *Brain*. 2014;137:1394-1407.

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### References (continued)

1. Rejc E, Angel CA, Harkema S. Effect of lumbosacral spinal cord epidural stimulation for standing after chronic complete paralysis in humans. *PLoS One*. 2015; 10(7):e0133998. doi: 10.1371/journal.pone.0133998.
2. Grahn PJ, Lavrov IA, Sayenko DG, et al. Enabling task-specific volitional motor functions via spinal cord neuromodulation in a human with paraplegia. *Mayo Clin Proc*. 2017;92(4):544-554.
3. Hubscher US, Freund S, Binder H, Minassian K. Common neural structures activated by epidural and transcutaneous lumbar spinal cord stimulation: Elicitation of posterior root-muscle reflexes. *PLoS One*. 2018;13(1):e0192013. doi: 10.1371/journal.pone.0192013.
4. Tesson de Paleville DGL, Harkema SJ, Angel CA. Epidural stimulation with locomotor training improves body composition in individuals with cervical or upper thoracic motor complete spinal cord injury: A series of case studies. *J Spinal Cord Med*. 2019;42(1):30-38.
5. Wagner FB, Mignardot JB, Le Goff-Mignardot CG, et al. Targeted neurotechnology restores walking in humans with spinal cord injury. *Nature*. 2018;563(7729):65-71.
6. Rejc E, Angel CA, Atkinson D, Harkema SJ. Motor recovery after activity-based training with spinal cord epidural stimulation in a chronic motor complete paraplegic. *Sci Rep*. 2017;7(1):13476.
7. Sayenko DG, Rath M, Ferguson AR, et al. Self-assisted standing enabled by non-invasive spinal stimulation after spinal cord injury. *J Neurotrauma*. 2019;36(9):1435-1450.
8. Rath M, Yaffe AJ, Ranganathan S, et al. Trunk stability enabled by noninvasive spinal electrical stimulation after spinal cord injury. *J Neurotrauma*. 2018;35(21):2540-2553.
9. Francis E, Samadani S, Gerasimov VR, Hubscher CH. Transcutaneous electrical spinal stimulation promotes long-term recovery of upper extremity function in chronic paraplegia. *IEEE Trans Neural Rehabil Eng*. 2018;26(6):1272-1278.
10. Unger J, Rodriguez S, Perez MA. A novel cortical target to enhance hand motor output in humans with spinal cord injury. *Brain*. 2019;142(1):1-12.
11. Dargatzis D, Butler D, Naloff TL, Krassioukov A, Phillips A, Parr A, Samadani U. Epidural spinal cord stimulation facilitates immediate restoration of dominant motor and autonomic supraspinal pathways after chronic neurologically complete spinal cord injury. *J Neurotrauma*. 2019. doi: 10.1089/neu.2018.6006. [Epub ahead of print].
12. Henry AN, Williams CS, Angel CA, Harkema SJ, Hubscher CH. Lumbosacral spinal cord epidural stimulation improves voiding function after human spinal cord injury. *Sci Rep*. 2018;8(1):8468.
13. Sefiagh A, Shakur S, Campos DSF, et al. Non-invasive, brain-controlled functional electrical stimulation for locomotion rehabilitation in individuals with paraplegia. *Sci Rep*. 2019;9(1):6782.