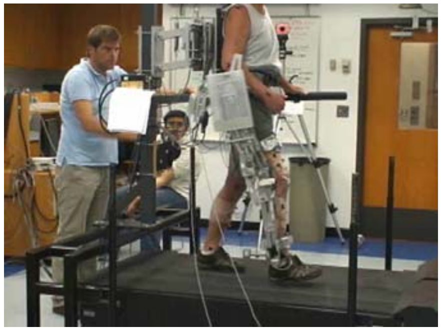
Exoskeletons for Gait Assistance and Training of the Motor Impaired



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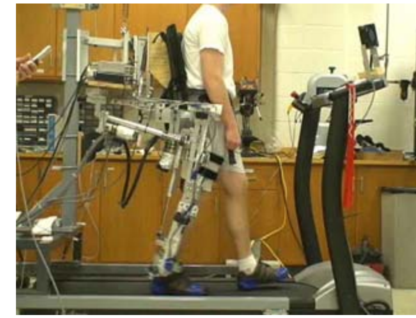


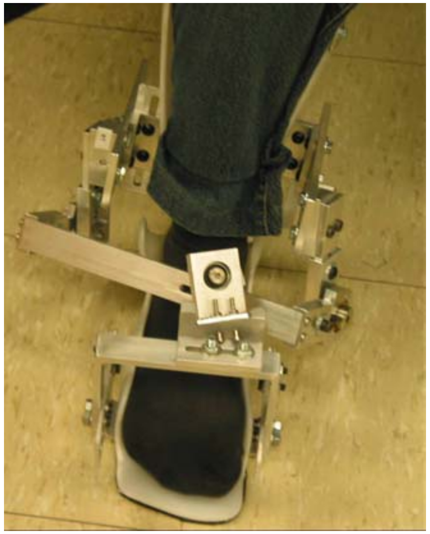
Website:
http://mechsys4.me.udel.edu/research/medical_robotics

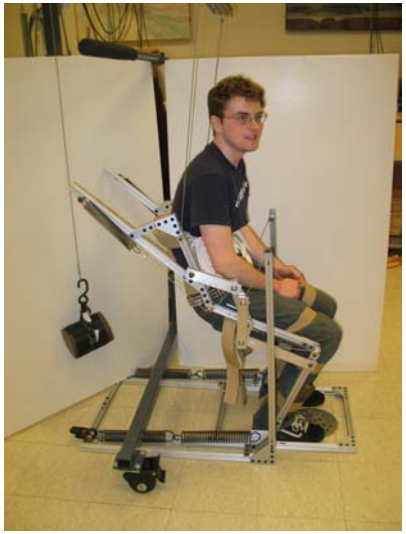
NIH Bioengineering Research Partnership: RO1 HD 38582 (2002-2007)
NIDRR SCI Model Systems Center Grant-RIC (2006-2011), NIH R24-RIC (2006-2008)

Mechanical Systems Laboratory

University of Delaware

Robotics – *Rehabilitation and Neuro-motor Training Special Need Infants*





J. C. Galloway, J.C. Ryu, S. K. Agrawal, "Babies driving robots: Self-generated mobility in very young infants", ***Intelligent Service Robotics***, 2008.

Gait Rehabilitation after Stroke

- US: 7.7 million people with stroke, 700K new cases
  250K people with spinal cord injury, 11K new cases
- Stroke - leading cause of functional disability
  - one-sided paralysis - hemiparesis
  - survivors have residual gait deficits
  - slower than normal speed of walking
  - asymmetric gait, less time on affected limb
  - lack of ankle dorsi-flexion: foot drop,
    toe drag, pelvic elevation, leg circumducts
  - limited ground reaction: issue of weight shift,
    increased risk of fall.

Edgerton Lab (SCI manual Rehab)

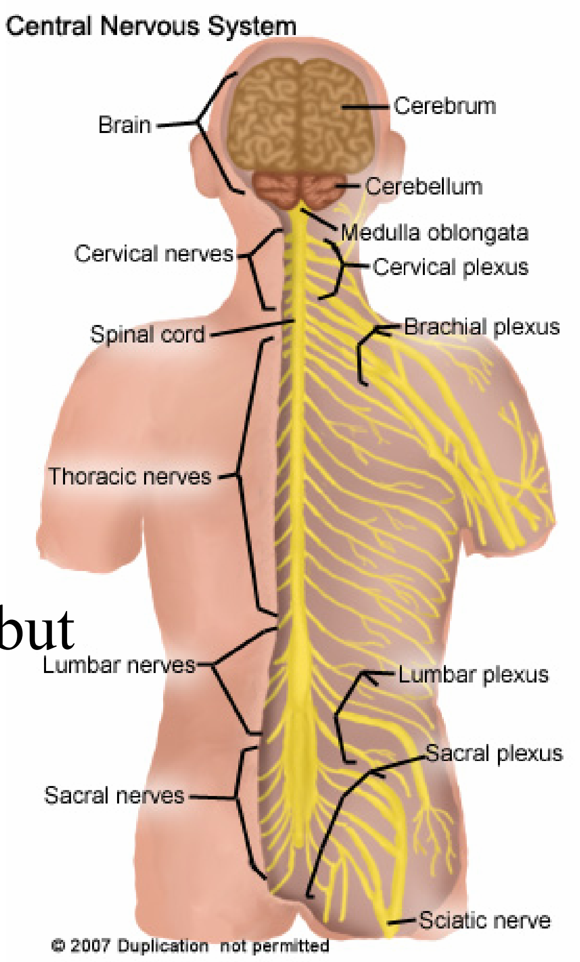
- Rehabilitation is important for recovery
  -Manual rehab: labor intensive, expensive
  -Machine rehab: Not optimized for learning

Motor Learning Questions ?

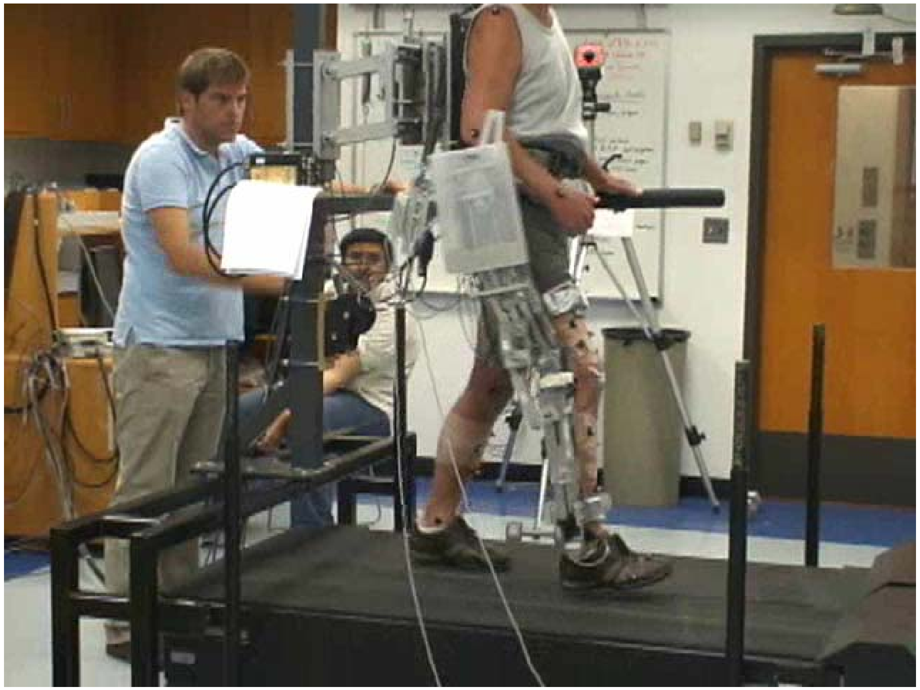
- Brain has ability to change: *Neuro-plasticity*
  - Injury-induced plasticity
    - maximize function in spite of damage
    - brain cells surrounding the damaged area change to take over function
  - Developmental plasticity: Infants

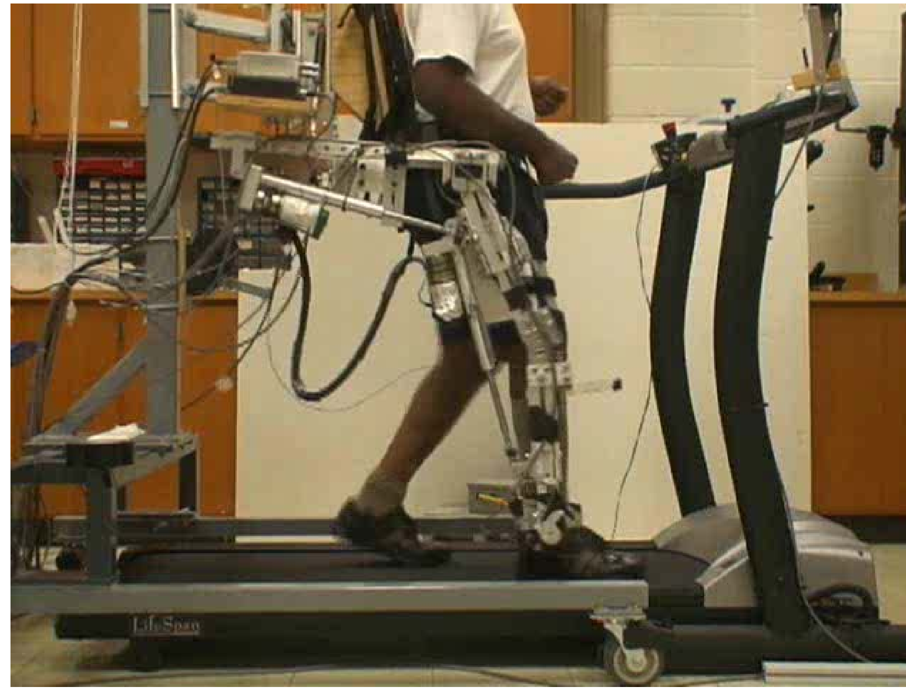
- Learning requires feedback during training
  - Frequent feedback improves performance but is bad for retention

- Can robots retrain gait of healthy subjects?
- What role does feedback play during training?
- Can a chronic stroke subject improve gait?
- What is a good retraining protocol?



Un-motorized and Powered Exoskeletons: Gait Rehab





- Gravity Balancing Orthosis (GBO)
- Less expensive and Safe
- Subjects trained with
  - Altered gravity at joints
  - Visual feedback, Patient control

- Active Leg EXoskeleton (ALEX)
- Training flexibility due to motors
- Subjects trained with
  - Forces on the foot to lie within tunnels
  - Visual feedback, Patient control

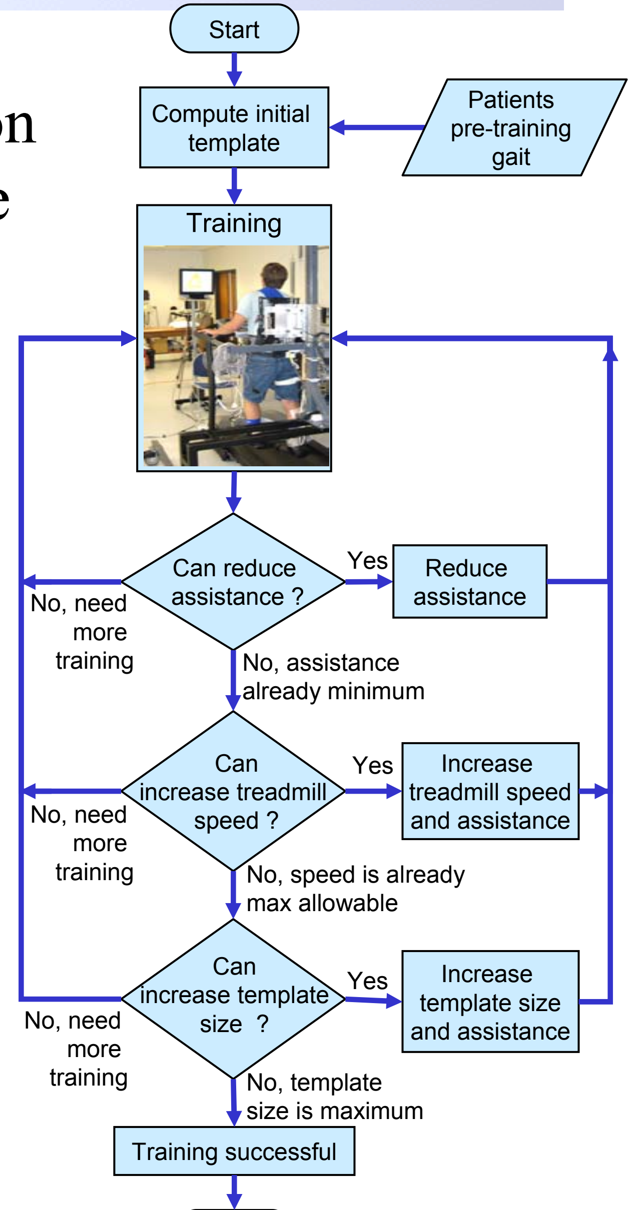
S. Banala, S. K. Agrawal, A. Fattah, J. P. Scholz, V. Krishnamoorthy, K. Rudolph, W. L. Hsu, "Gravity Balancing Leg Orthosis and its Performance Evaluation", ***IEEE Trans. in Robotics***, Vol. 22, No. 6, 2006, 1228-1239.

Gravity Balancing Orthosis (GBO)

- Gravity plays an important role in human motion
- At slow speeds, gravity is dominant joint torque

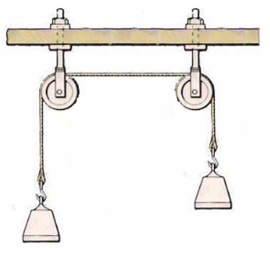
- How would leg respond if gravity is lowered during swing?
- How to exploit the results in gait retraining?

- How to design an exoskeleton to achieve this property?
- How to provide feedback to optimize learning?

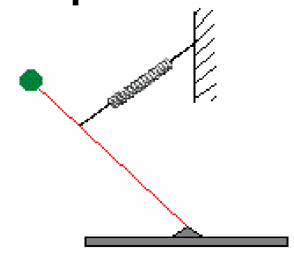


What is Gravity Balancing ?

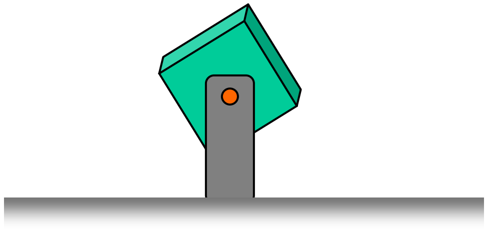
Gravity balancing is equivalent to PE being constant.



Counter weights

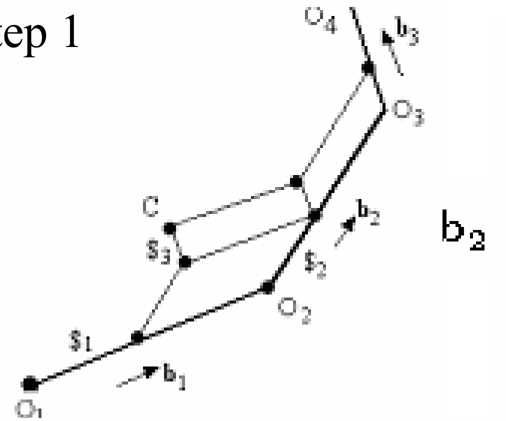


Springs



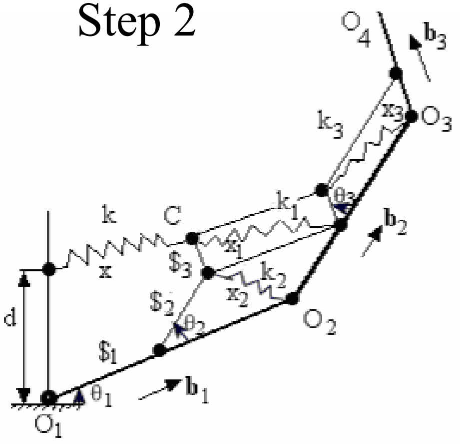
Fix center of mass

Step 1

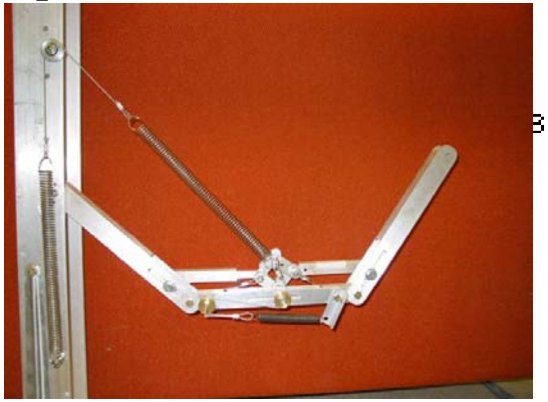


$$\mathbf{r}_{O_1C} = \$_1\mathbf{b}_1 + \$_2\mathbf{b}_2 + \$_3\mathbf{b}_3$$

Step 2

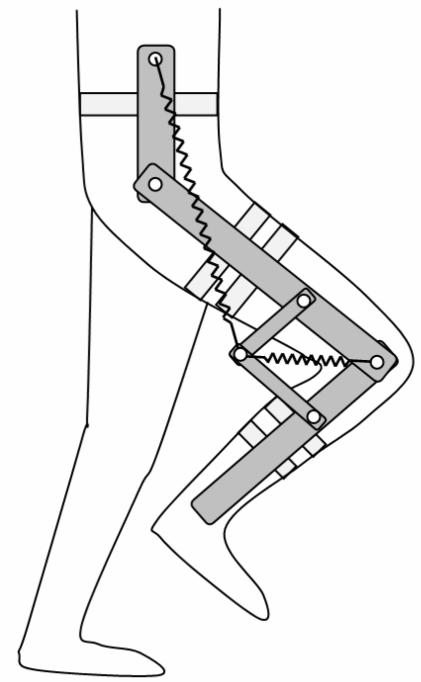


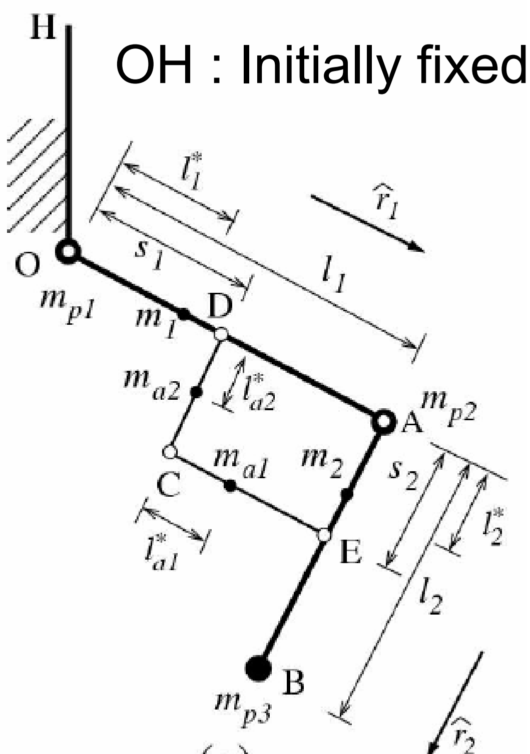
Step 3



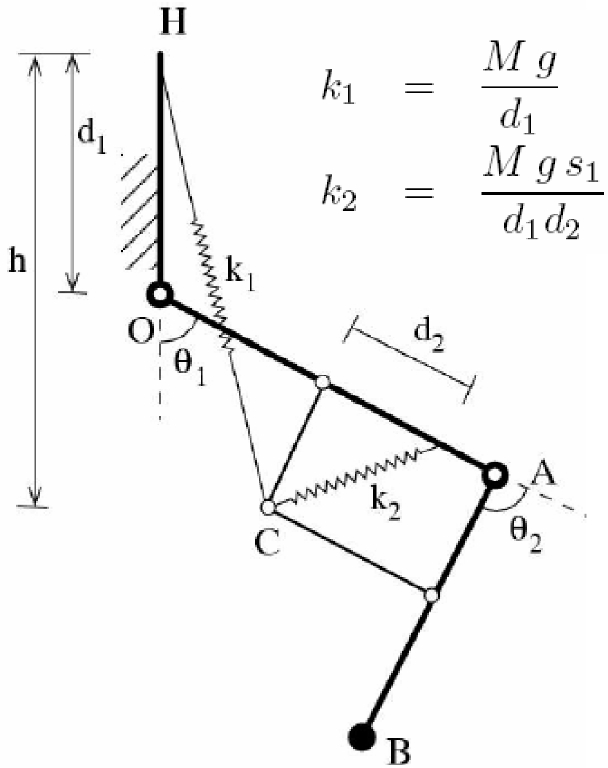
Sunil K. Agrawal, Glenn Gardner, Stephen Pledgie, “Design and Fabrication of a Gravity Balanced Planar Mechanism Using Auxiliary Parallelograms”, ***Journal of Mechanical Design, Trans of the ASME***, Vol. 123, No. 4, 2001, 525-528.

Gravity Balancing: Design Principle





(a)



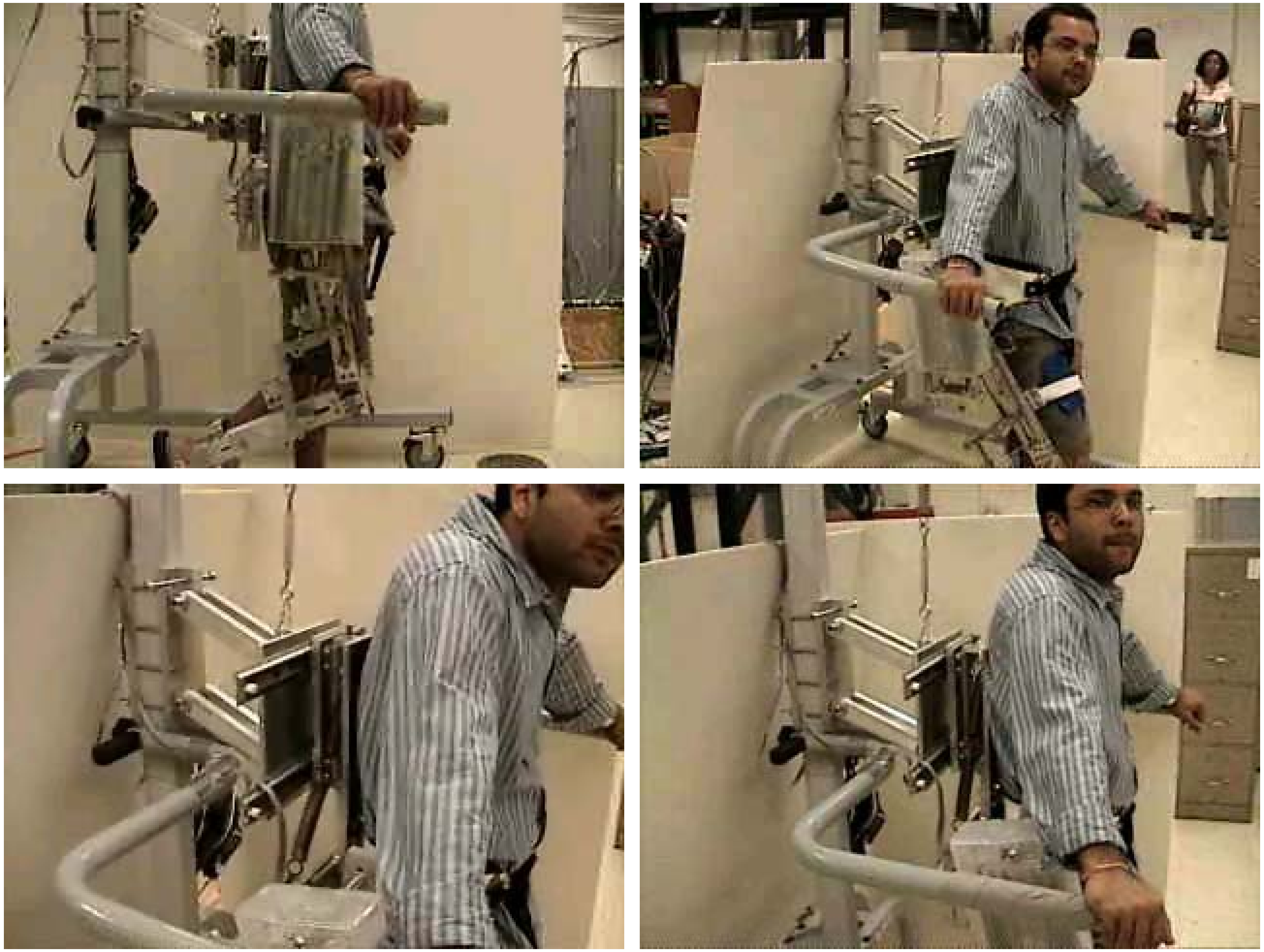
$$k_1 = \frac{M g}{d_1}$$

$$k_2 = \frac{M g s_1}{d_1 d_2}$$

- System remains gravity balanced if the leg abducts
- Account for weight of leg and Exoskeleton
- Parameters relate to fractional balancing

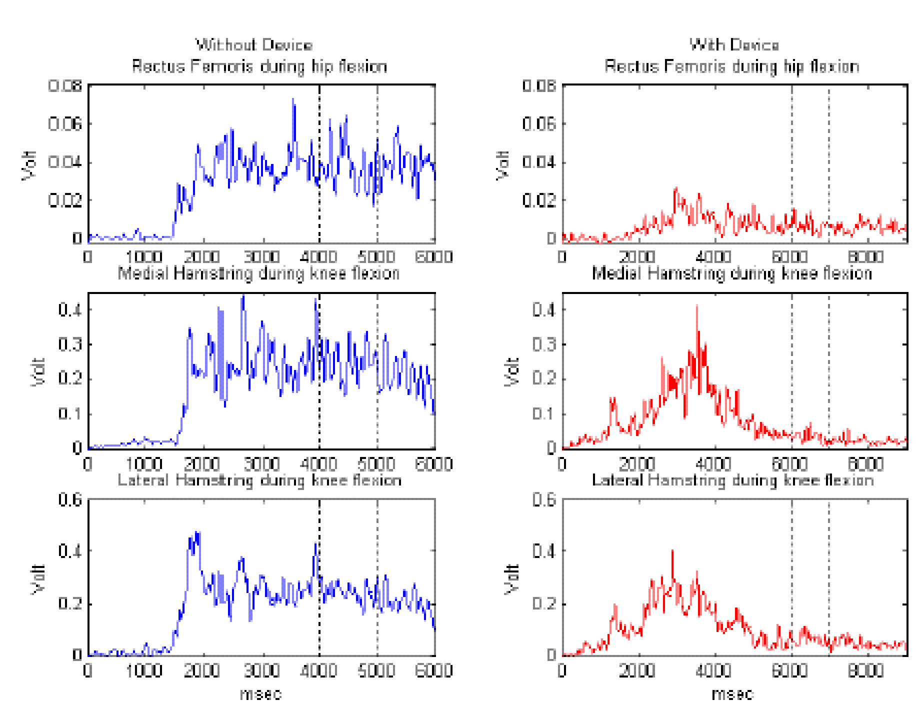
S. K. Agrawal and A. Fattah, “Theory and Design of an Orthotic Device for Full or Partial Gravity-Balancing of a Human Leg During Motion”, ***IEEE Trans on Neural systems and Rehabilitation Engineering***, 2004, Vol. 12, No. 2, 157-165.

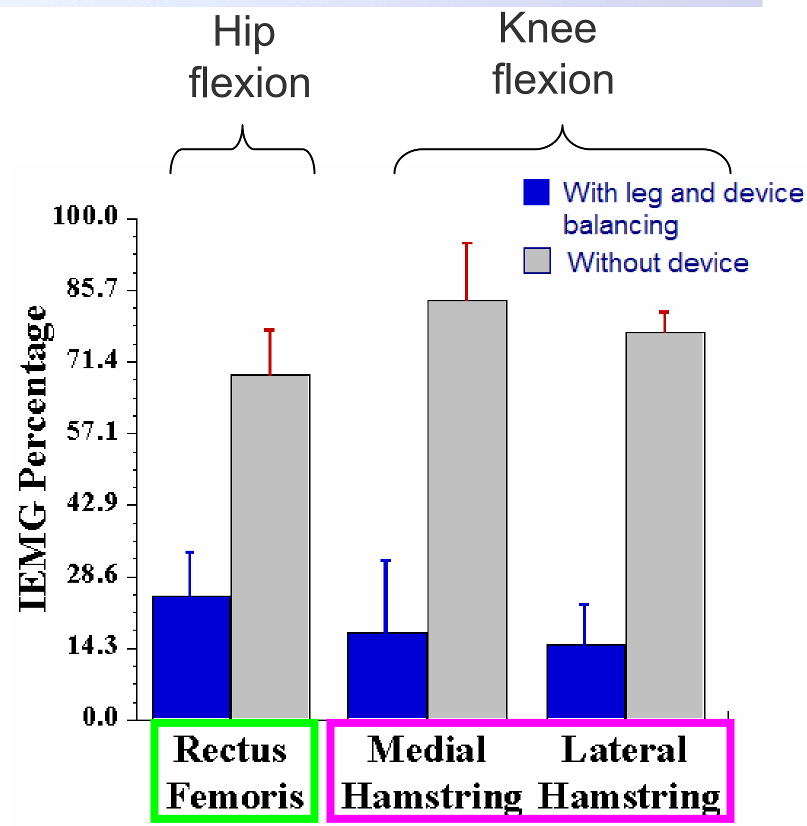
GBO: Exoskeleton Features

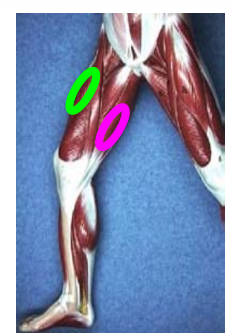


- Gait involves interaction between upper and lower body: 4 DOFs added wrt walker
- Encoders collect joint/trunk data, Two 6-axis force/torque sensors
- real-time visual display of their gait: angle-angle plot, Cartesian plots

Static Tests: Does GBO affect Muscle EMGs?



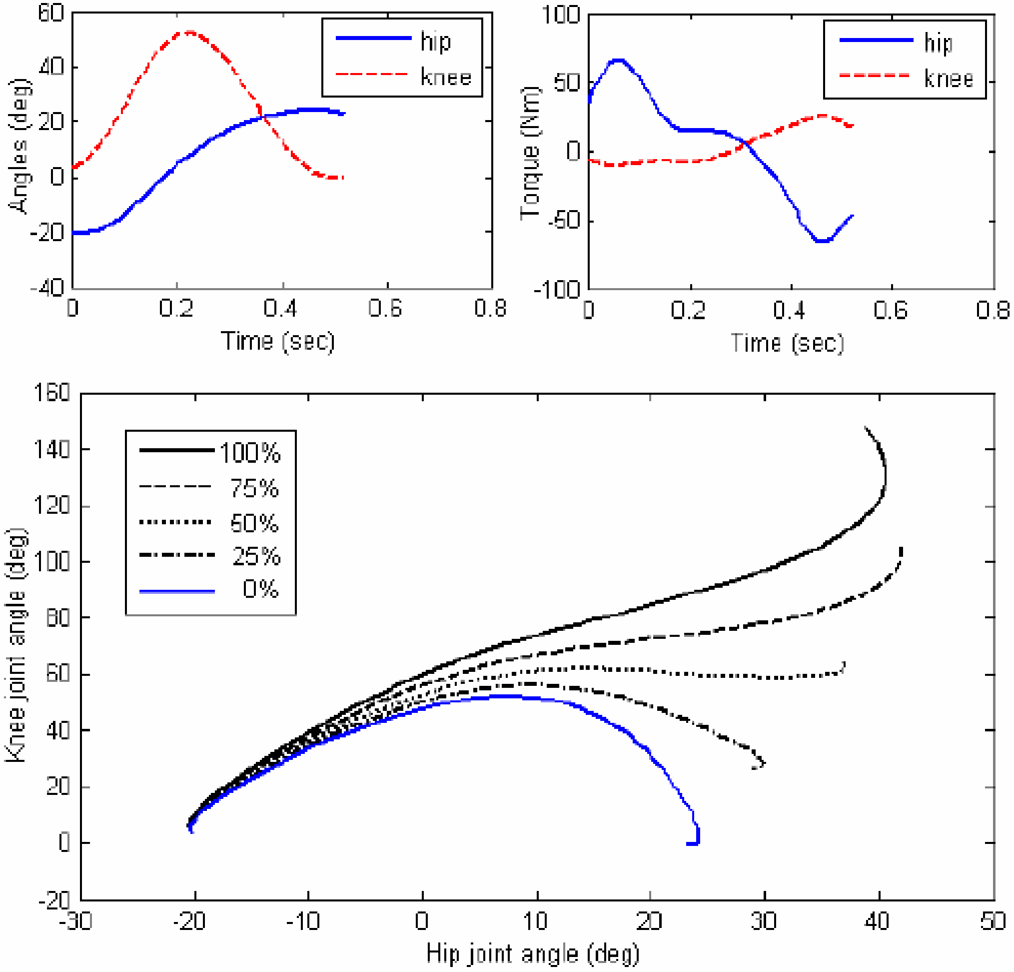




Comment: EMG is not zero

- Passive elasticity of muscles & tissue
- Complete relaxation needs training
- Joint alignment with soft tissue
- Some device friction

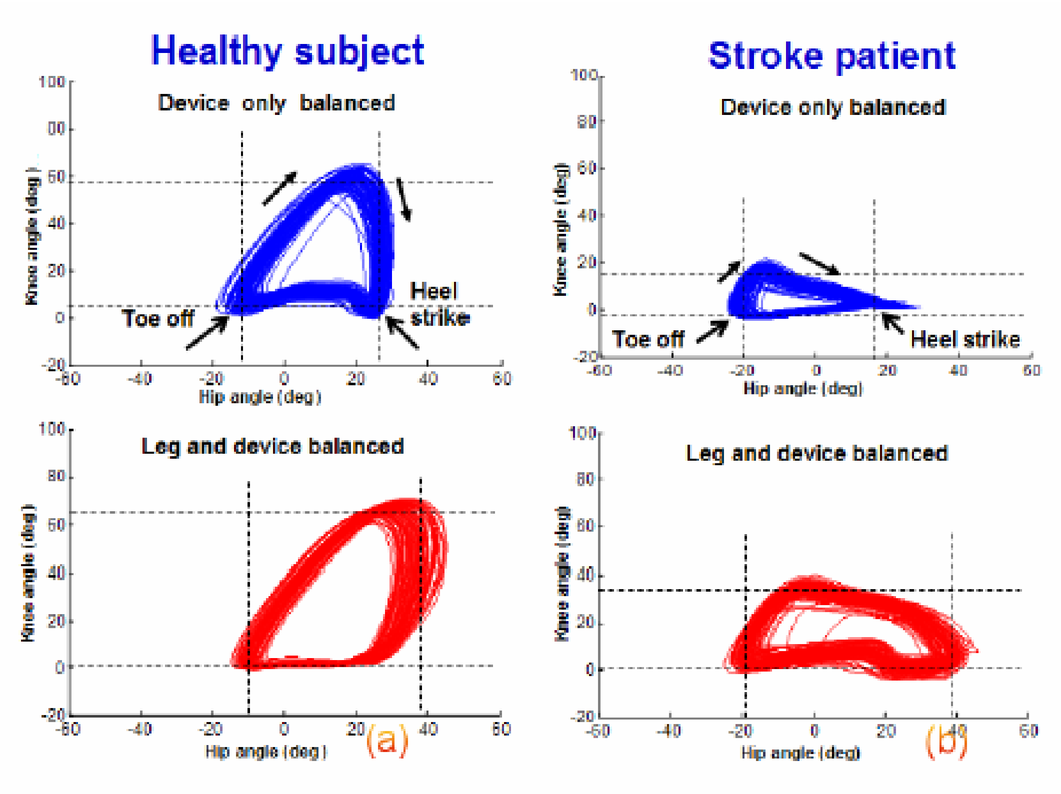
GBO: Can it alter the range of motion of the Leg?

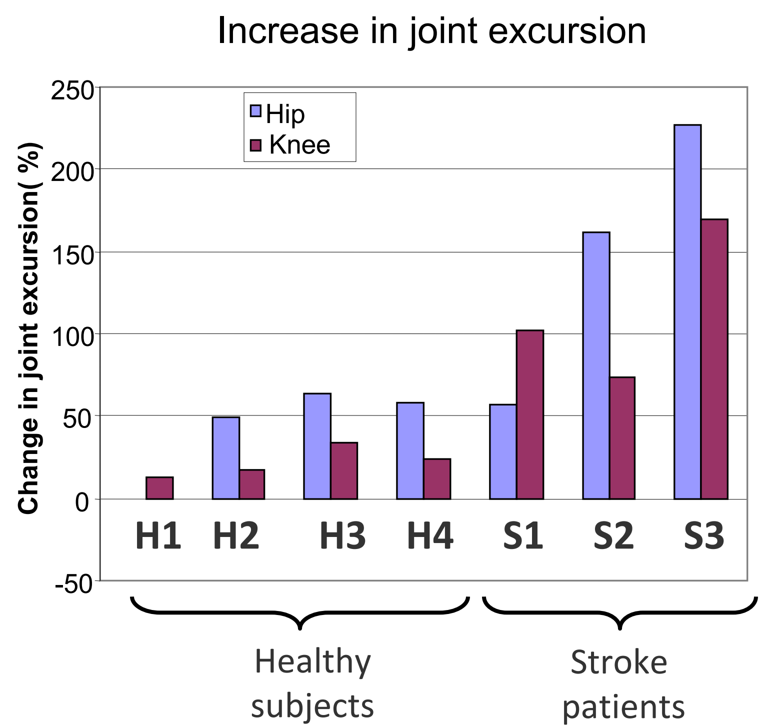


Increase in Range of Motion

S. K. Agrawal, S. Banala, A. Fattah, V. Sangwan, V. Krishnamoorthy, J. P. Scholz, and W. L. Hsu, "Assessment of Motion of a Swing Leg and gait Rehabilitation with a Gravity Balancing Exoskeleon", ***IEEE Trans. on Neural Systems and Rehab Engineering***, Vol. 15, No. 3, 2007, 410-420.

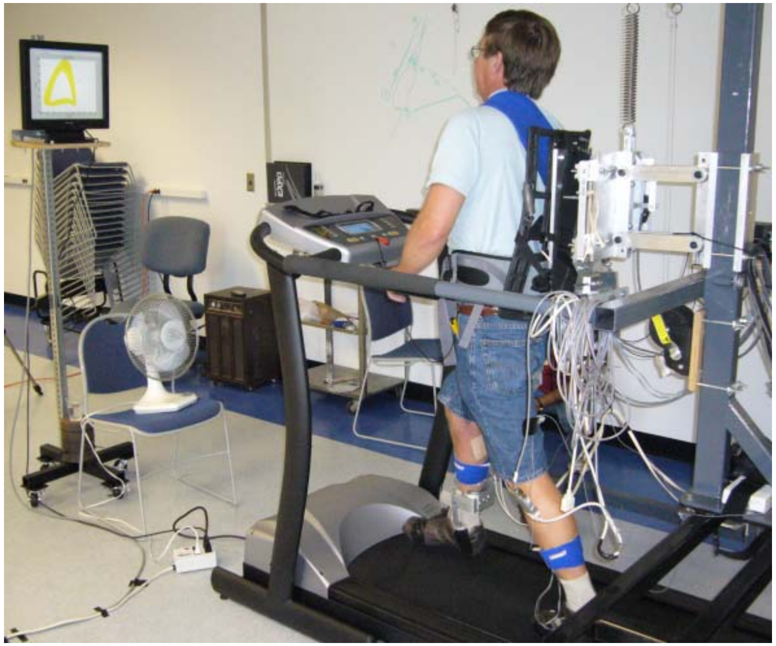
GBO: Range of Motion Healthy & Stroke Subjects

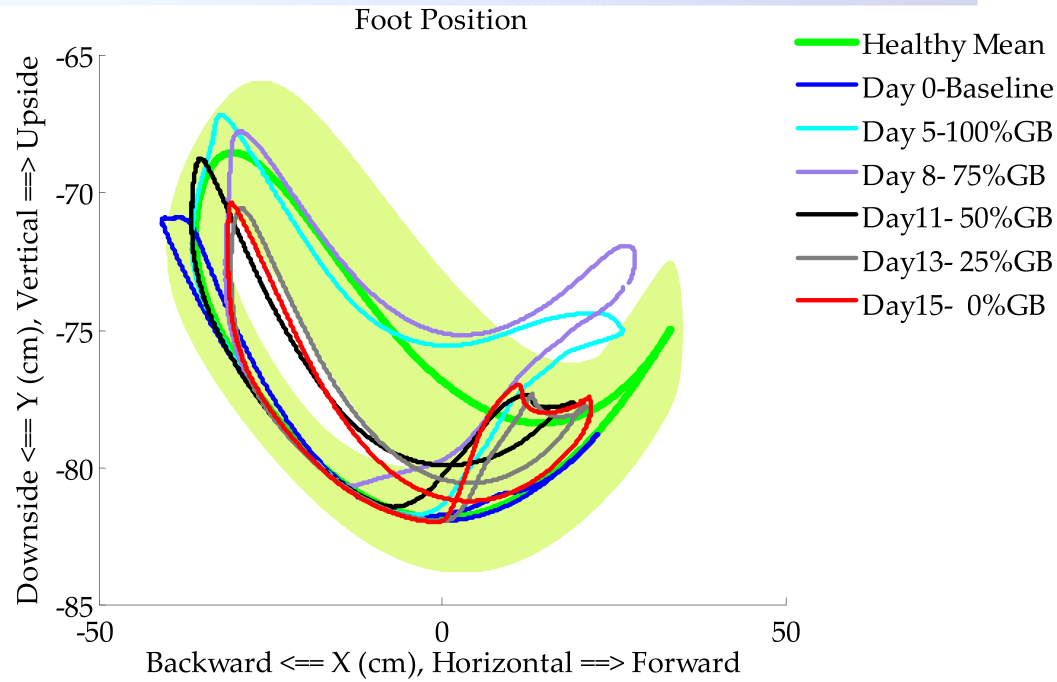


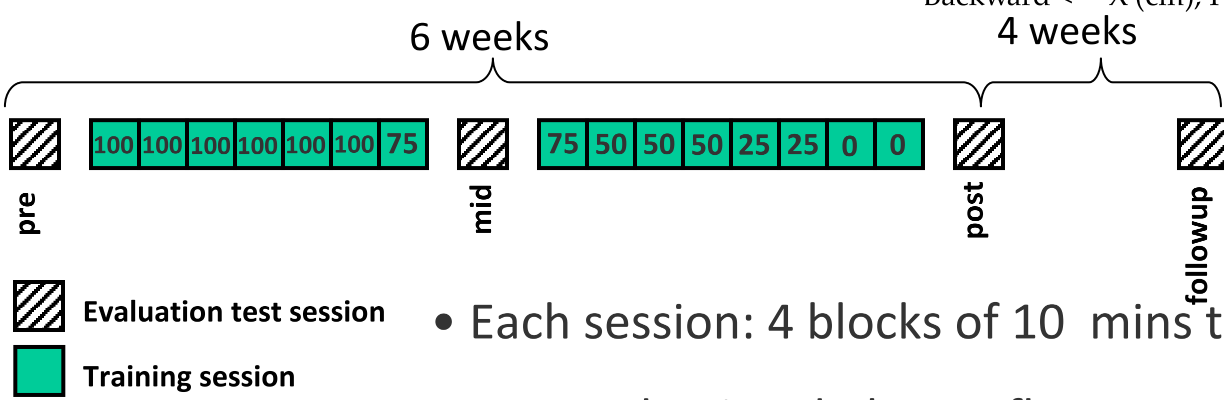


S. Banala, S. K. Agrawal, A. Fattah, J. P. Scholz, V. Krishnamoorthy, K. Rudolph, W. L. Hsu, "Gravity Balancing Leg Orthosis and its Performance Evaluation", ***IEEE Trans. in Robotics***, Vol. 22, No. 6, 2006, 1228-1239.

GBO: Gait Training of a Stroke Survivor





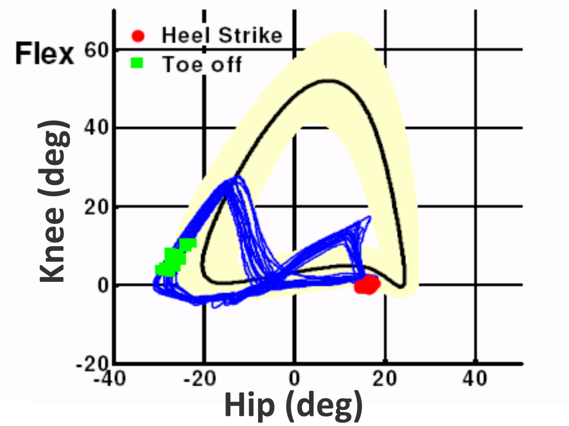


- Each session: 4 blocks of 10 mins training
- FES on dorsi and plantar flexors
- Visual guidance: continuous or intermittent

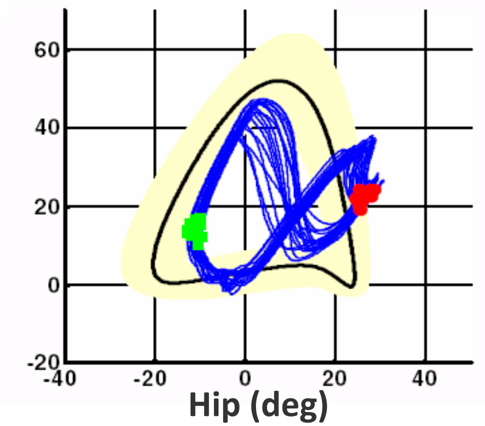
GBO: Training Results in the Device

Device only balanced (0% leg balancing)

Sess 1

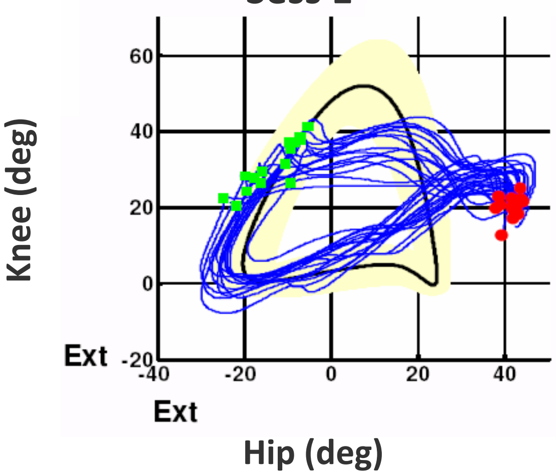


Sess 15

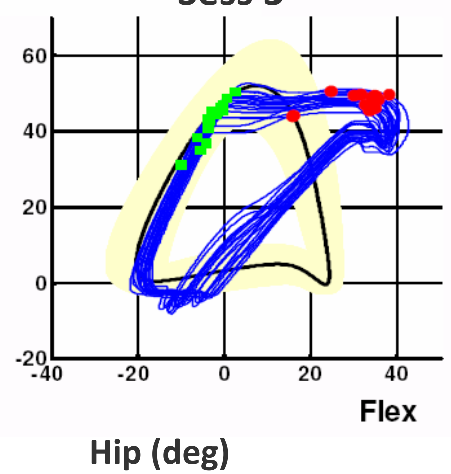


Device and Leg balanced (100% leg balancing)

Sess 1



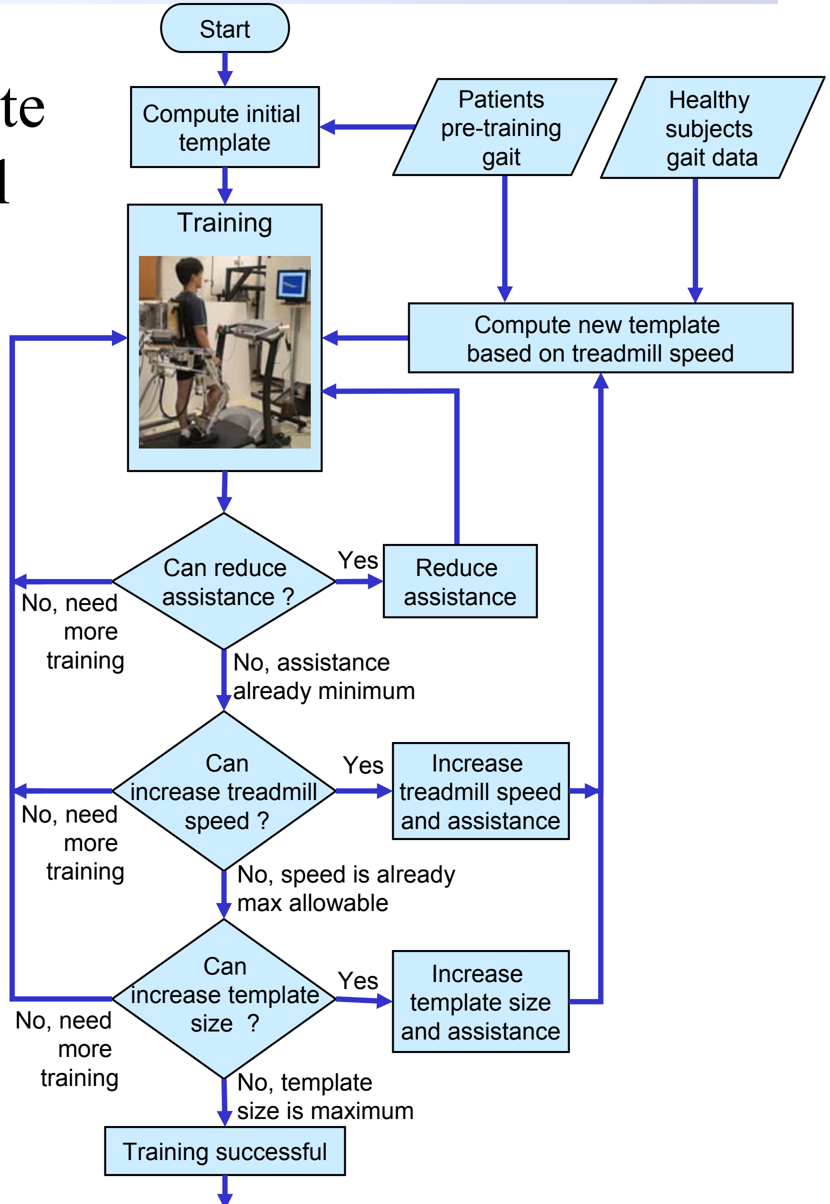
Sess 3



Active Leg Exoskeleton (ALEX)

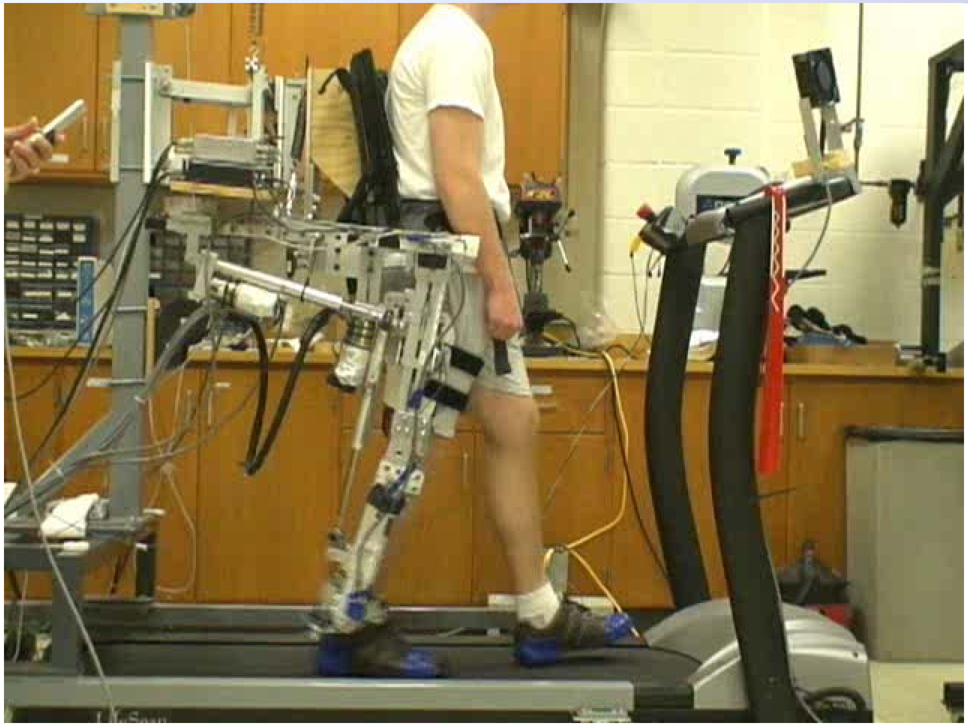
- Assistance to the foot outside a template tunnel during training, similar to manual therapy.

- Training parameters
  - Diameter of the tunnel
  - Force field characteristics within and outside the tunnel
  - Change in the foot template
  - Change in the treadmill speed
  - Visual display – angle plots, foot position



Active Leg Exoskeleon (ALEX): Design

- Similar support structure as the GBO, does not use springs
- Hip and knee joints are actively driven by servomotors
- Real-time control Using dSpace, encoder and load cell data
- Visual feedback of foot trajectory



Tech Challenges !!!

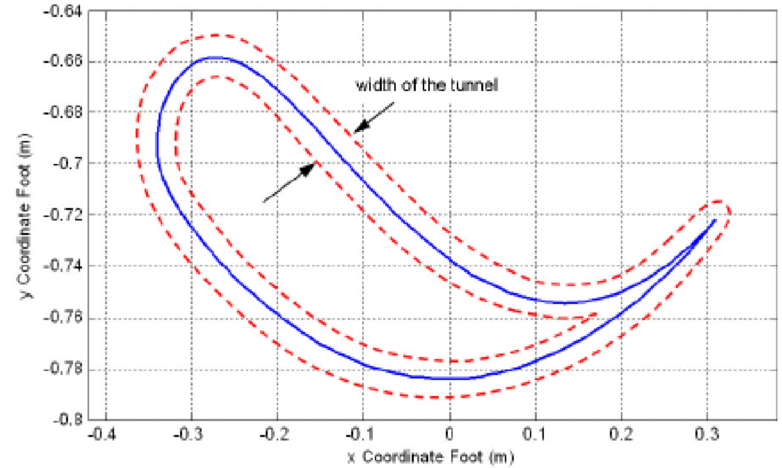
- How to back-drive the motors in the presence of friction?
- Model-based control requires parameters of machine and human

Clinical Challenges !!!

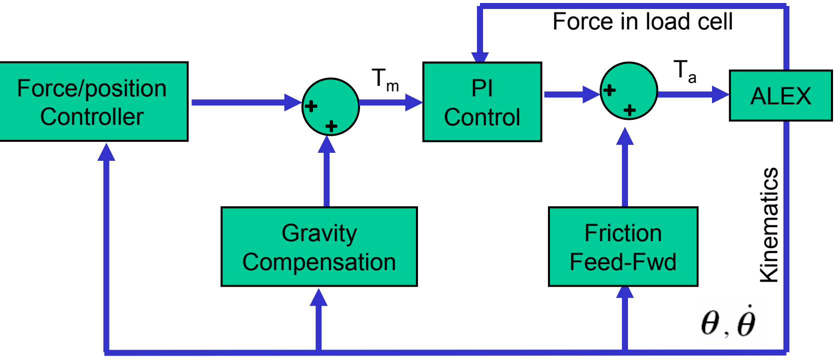
- Learned helplessness – avoid habituation to specific inputs
- Resist undesirable motions
- User participation – key to learning

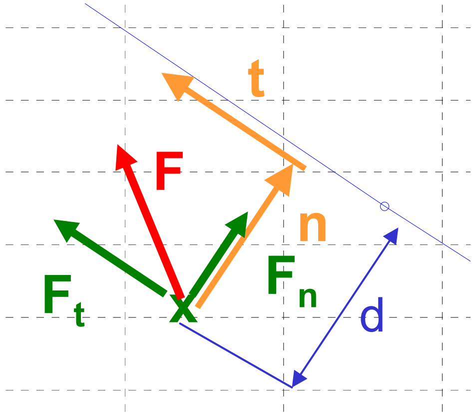
ALEX: Force-field Controller

- Virtual tunnel around foot – Tests since 2006.
- within walls: user-controlled motion
- walls guide foot along desired trajectory

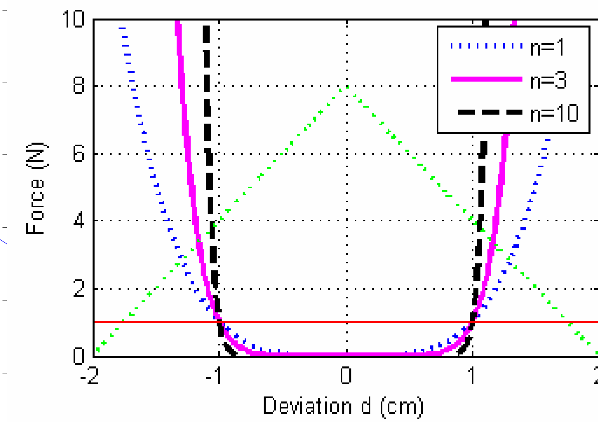


- Control Law $\boldsymbol{\tau}_m = \mathbf{J}^T \boldsymbol{F} + \mathbf{G}(\boldsymbol{\theta}) + \boldsymbol{f}$





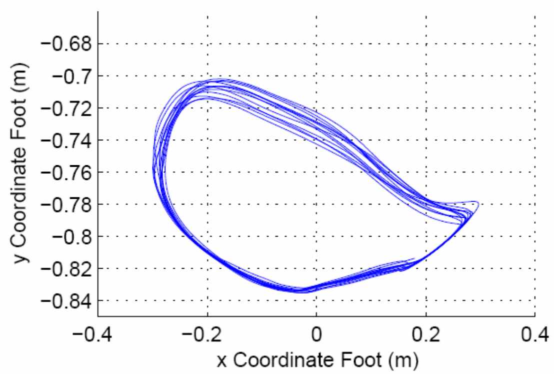
wall steepness



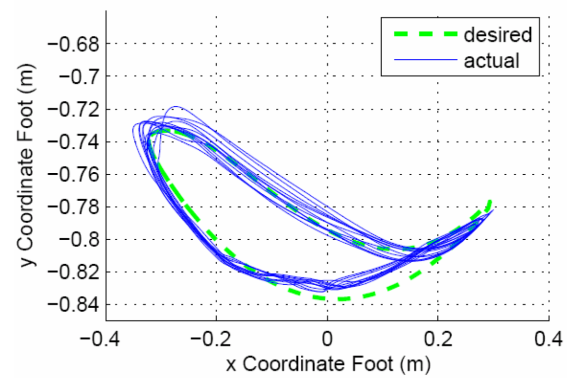
S. K. Banalaa, A. Kulpe, and S. K. Agrawal, "A Powered Leg Orthosis for Gait Rehabilitation of Motor Impaired Patients", **IEEE International Conference on Robotics and Automation**, 2007. (Also ICORR 2007)

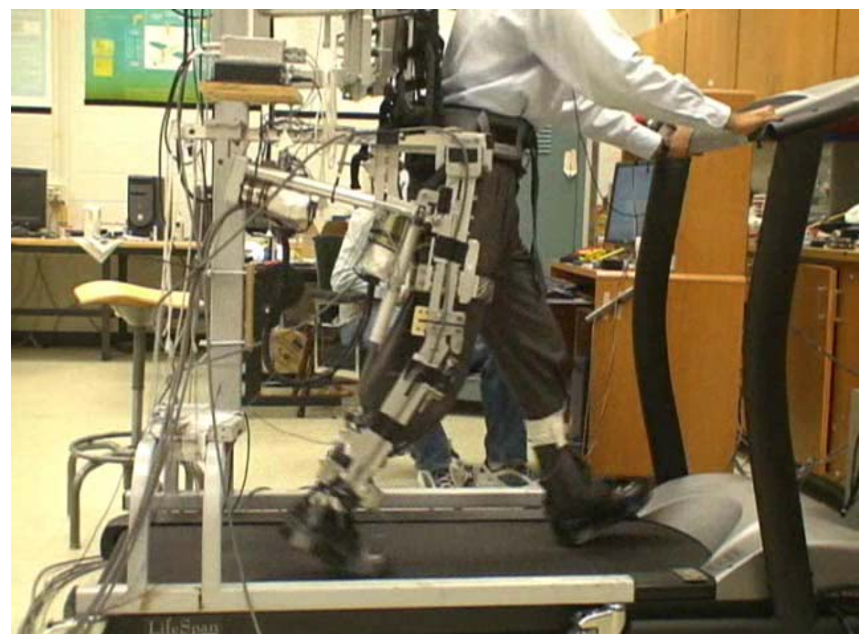
ALEX: Pre/Post Training Videos of a Healthy Subject

before training

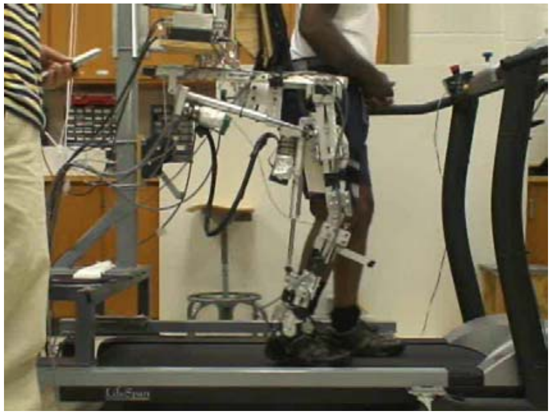


no assistance / feedback – post training

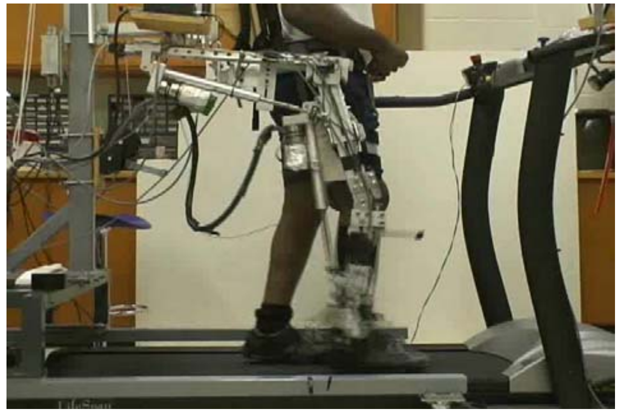




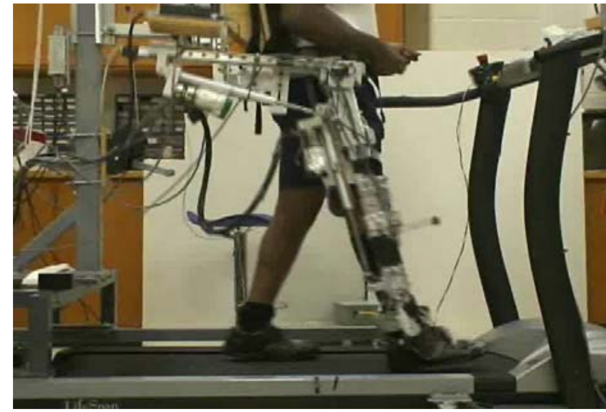
ALEX: Training Study with Stroke Subjects



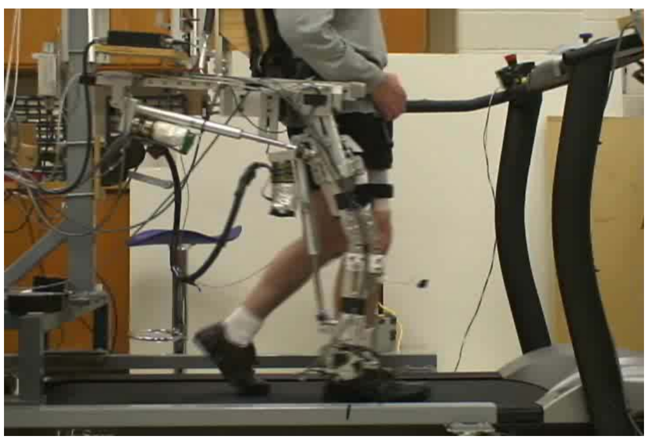
Session 2: 0.9 mph



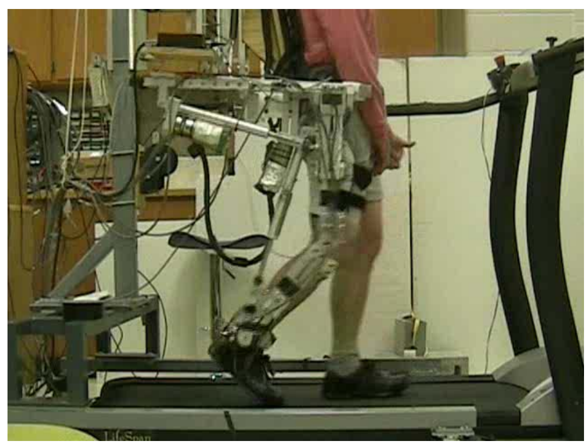
Post 15 Session training: 0.9 mph



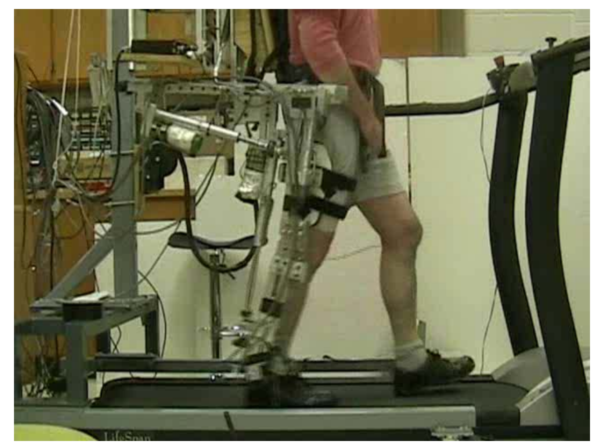
Post 15 Session training: 1.6 mph



Baseline: 1.3 mph



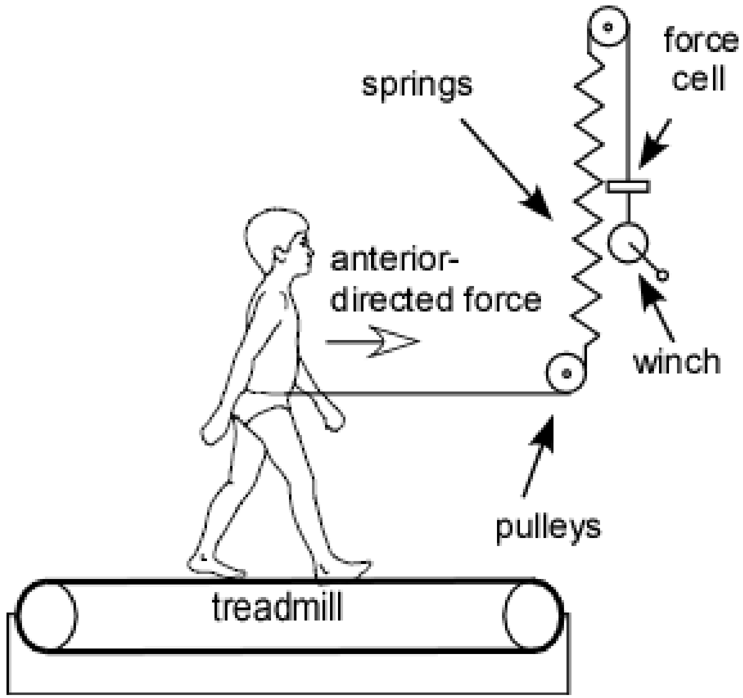
10 Session Training: 1.3 mph

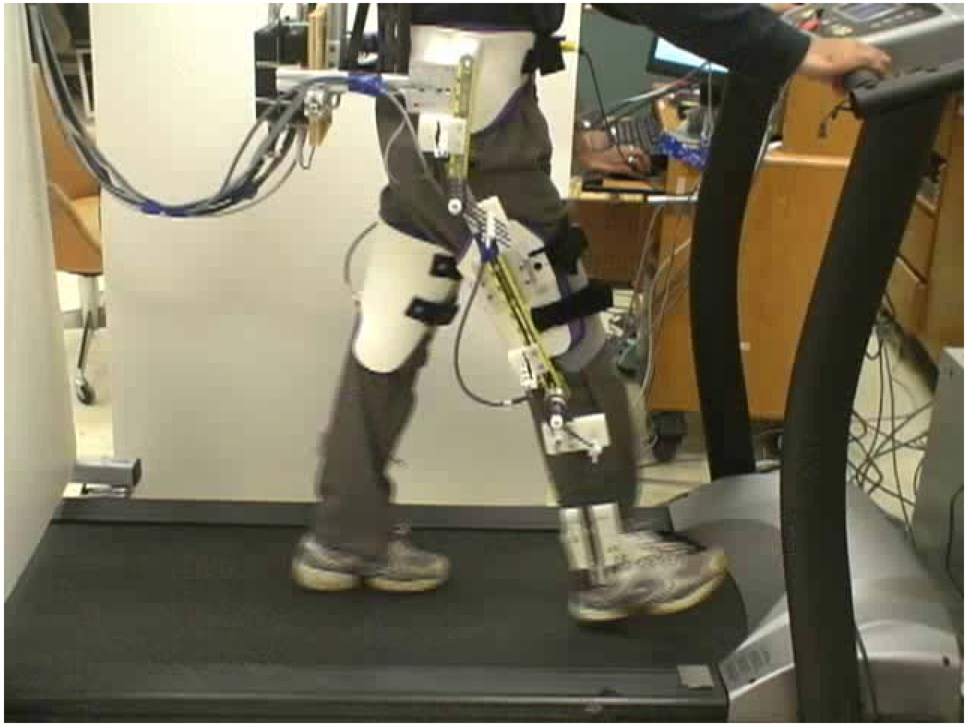


10 Session Training: 1.8 mph

S. K. Banala, S. H. Kim, S. K. Agrawal, and J. P. Scholz, “Robot Asssited Gait Training with Active Leg Exoskeleton”, under revision **IEEE Trans. on neural Systems and Rehab Engineering**, 2008.

Swing-Assist Un-motorized Exoskeletons (SUE)

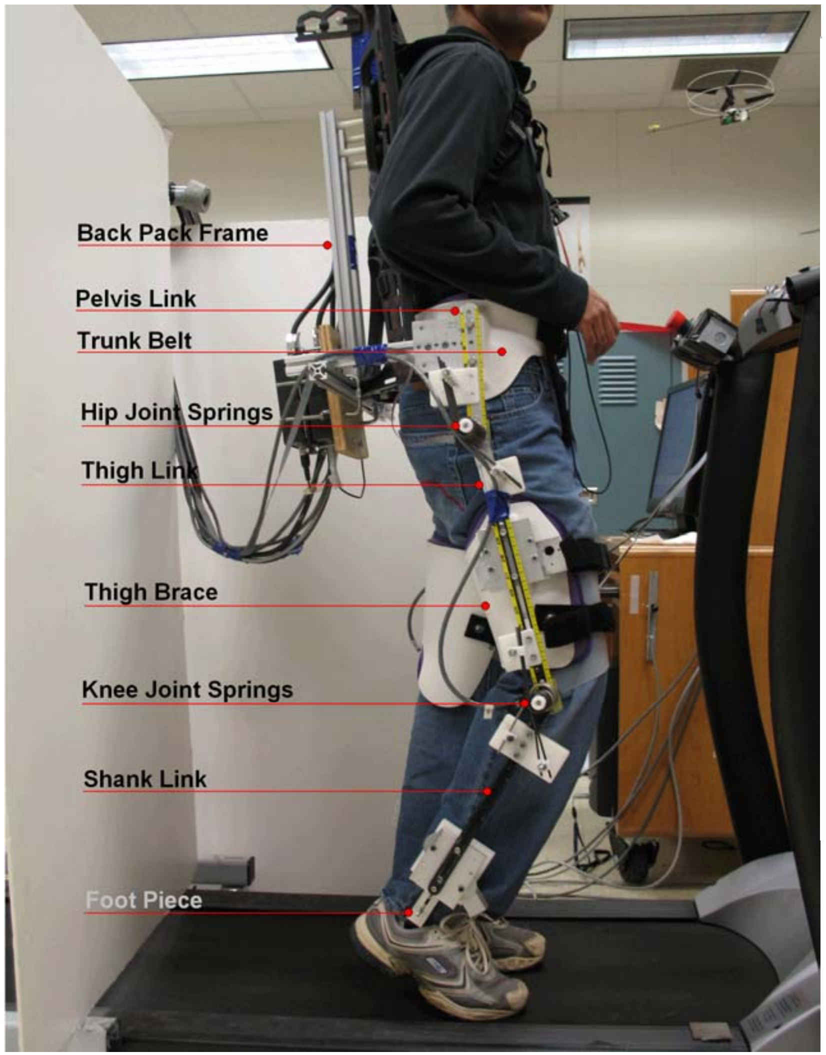


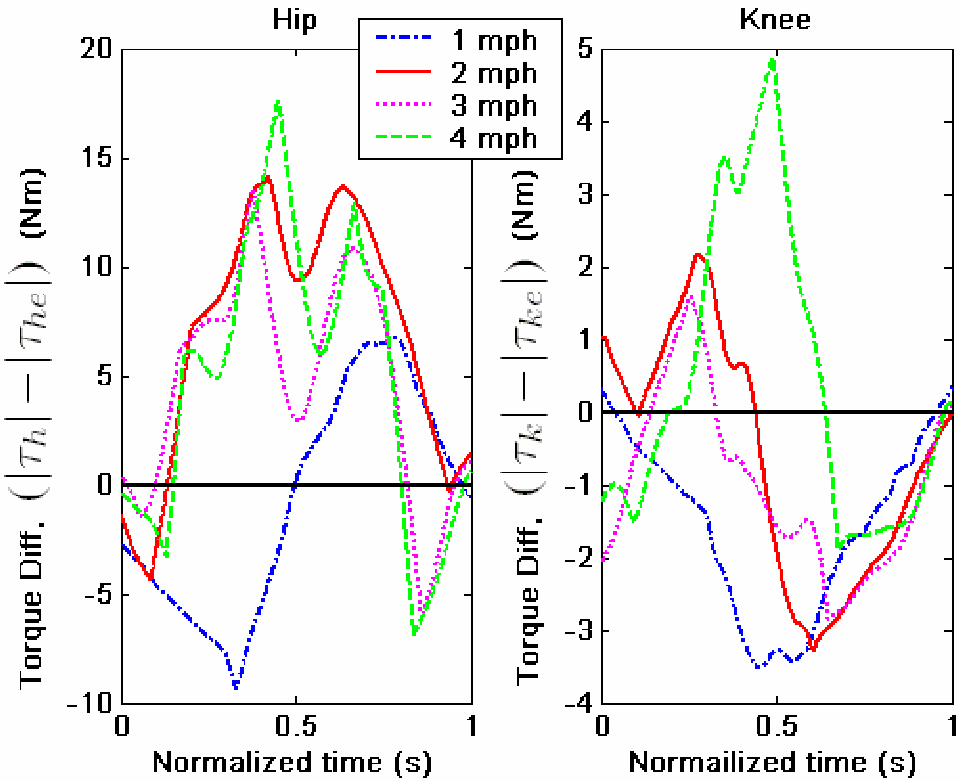


- **Torsion springs** at hip and knee joints.
- **Energy from treadmill** charges springs during stance and releases during swing
- **Design Parameters -** Torsion constants and equilibrium position of the springs
- **Walking model** used to optimize the design

K. K. Mankala, S. K. Banalaa, and S. K. Agrawal, "Passive Swing Assistive Exoskeleton for Motor Incomplete Spinal Cord Injury Patients", **IEEE International Conference on Robotics and Automation**, 2007.

SUE: Preliminary Results





Conclusions & Future Work

• Robotics can assist in gait retraining of stroke survivors through appropriate exoskeletons integrating motor learning principles

• Studies with stroke survivors suggest that un-motorized gravity modulating orthoses with intermittent visual feedback can improve gait. Huge potential for (smaller) clinics due to lower costs.

• Results with ALEX suggest that force constraints on the foot with feedback can improve gait of stroke survivors and enhance movements of healthy subjects - huge potential in sports training

• *BRP R01 renewal* (Scored < 10%, 5-year, $3.8M, Expecting May) – Bilateral GBO and ALEX integrated with 2 DOF AFO, Clinical testing with 30 subjects to compare training with GBO, ALEX , BWSTT.

Acknowledgments

Mechanical Systems Group

Sai K. Banala, PhD Student*
Vivek Sangwan, PhD Student
Ji-Chul Ryu, PhD Student
Zaeem Khan, PhD Student
Liz Brackbill, PhD Student
Susanne Kirchel, M.S. Student (TU Stuttgart)

K. Pathak, PhD
Abhishek Agrawal, M.S.
Sean McIntosh, M.S.
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Physical Therapy Group

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