Robotics to Retrain Human Gait and Posture

Sunil K. Agrawal, Ph.D.
Professor of Mechanical Engineering and Rehabilitation Medicine
Director of ROAR Laboratories
Columbia University, New York, NY 10027
Email: Sunil.Agrawal@columbia.edu

Web: https://roar.me.columbia.edu

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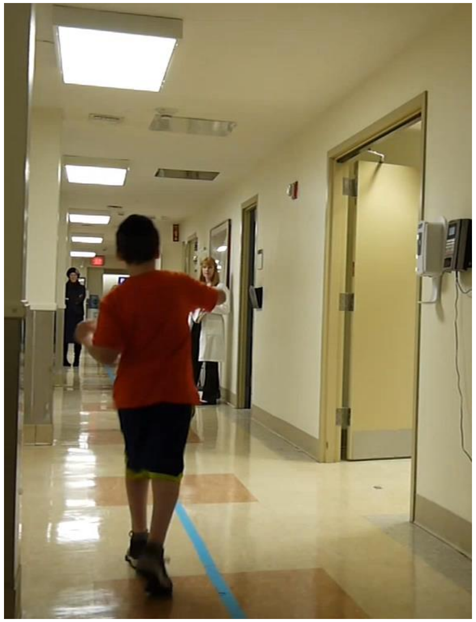
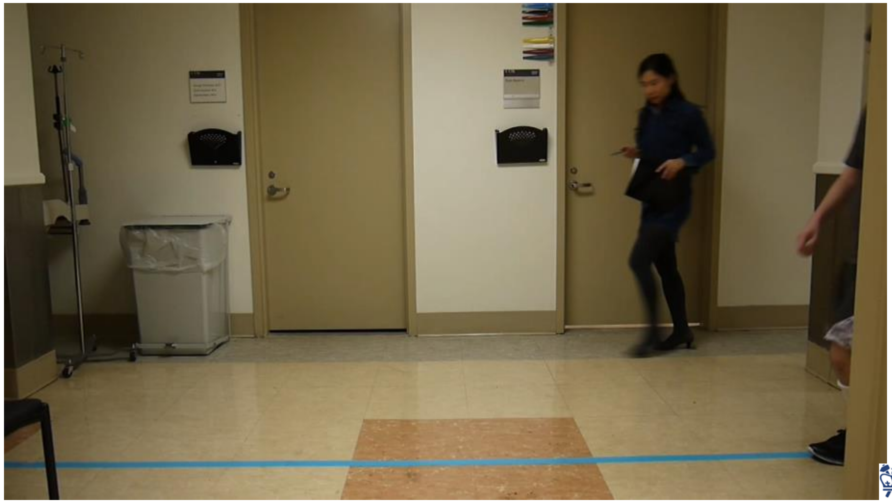
Gait abnormalities are not uncommon …



- How to improve gait and balance?
- Could robotics be of help?



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Gait Rehabilitation after Stroke

- Stroke – leading cause of functional disability, ~ 4 M survivors
- Survivors have one-sided weakness, asymmetry in gait
- Foot drop, toes drag, pelvic elevation, lack of balance and falls

- Labor intensive
- Back injuries
- Expensive

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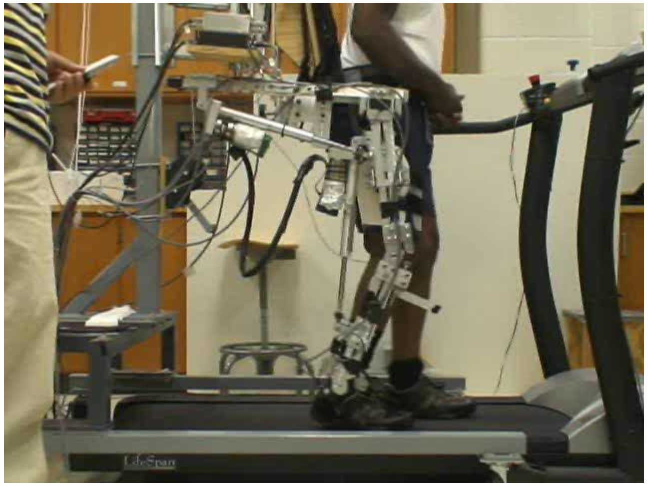
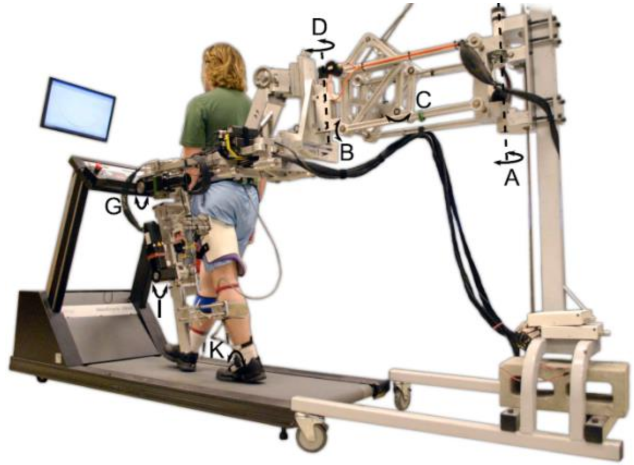
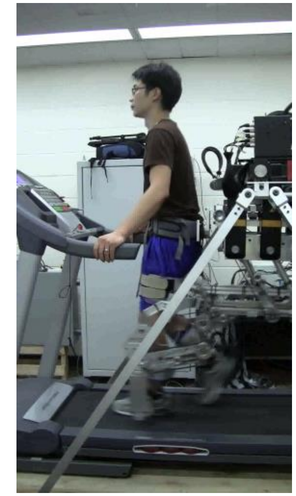
Why Robotics?

- Robotics can help retrain movements by modulating forces according to motor learning principles.
- Robots have to be carefully designed to provide variable practice, intensity, and promote problem solving.
- Robots can quantify “progress” and can also be used to ask basic science questions, e.g., “What if?”

From ALEX to ALEX III …



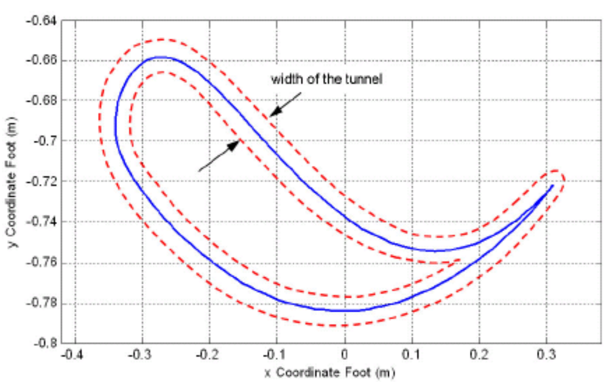


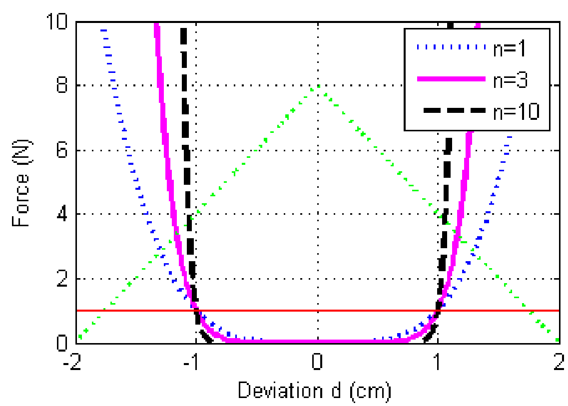


- Actuated hip/knee joints
- Other passive DOFs
- Visual feedback
- Force-tunnels

- ALEX II - All features of ALEX + Lunge DOF
- Used in either leg

- ALEX III – 12 active DOF, Bilateral design
- 4 active DOF at pelvis
- 4 active DOF each leg
- hip abduction & flexion
- Knee and Ankle control





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Pilot Studies with ALEX – 36 Healthy Subjects

- Visual Guidance (VG), Kinetic Guidance (FFC), Visual + Kinetic (VG+FFC)
- How do these forms of feedback assist in learning/retention of new gait ?

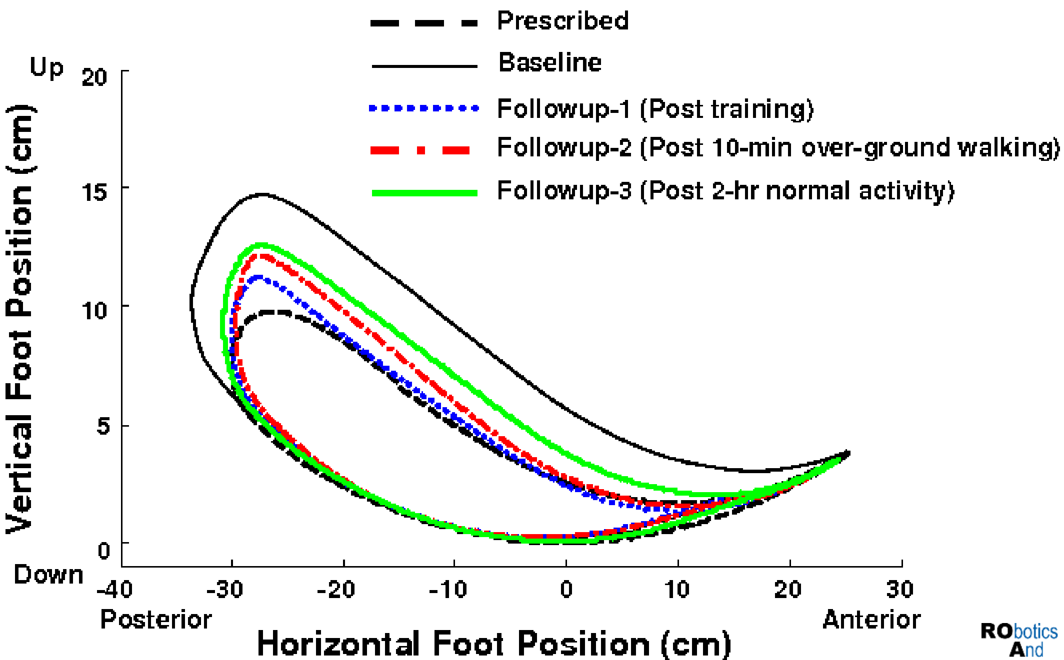
Table 1 Robot-assisted gait training procedure

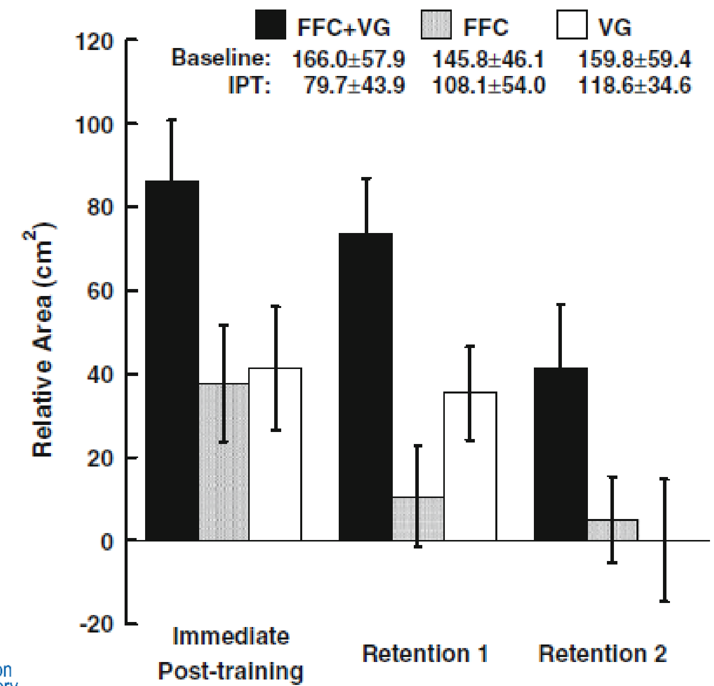
Training/testing epoch	Time (min)	Visual guidance			Force-field constraint[a]		
		FFC + VG[b]	FFC	VG	FFC + VG	FFC	VG
Determination of preferred speed	5	Off	Off	Off	Off	Off	Off
Baseline test	3	Off	Off	Off	Off	Off	Off
Training 1	10	On	Off	On	NW-HS	NW-HS	Off
Training 2	10	On	Off	On	NW-LS	NW-LS	Off
Training 3	10	On	Off	On	MW-HS	MW-HS	Off
Training 4	10	On	Off	On	MW-LS	MW-LS	Off
Training 5	10	On	Off	On	WW-HS	WW-HS	Off
Training 6	10	On	Off	On	WW-LS	WW-LS	Off
Immediate post-training test	3	Off	Off	Off	Off	Off	Off
Retention test 1	3	Off	Off	Off	Off	Off	Off
Retention test 2	3	Off	Off	Off	Off	Off	Off

[a] Three levels of wall width: narrow (1 cm; NW), medium (2 cm; MW), and wide walls (4 cm; WW); Two levels of stiffness coefficients (KFn): high (0.760 N; HS) and low stiffness (0.125 N; LS)

[b] Three experimental groups: visual guidance plus force-field constraint (FFC + VG), force-field constraint (FFC), and visual guidance only groups (VG)

Study: Role of Feedback in Gait Training





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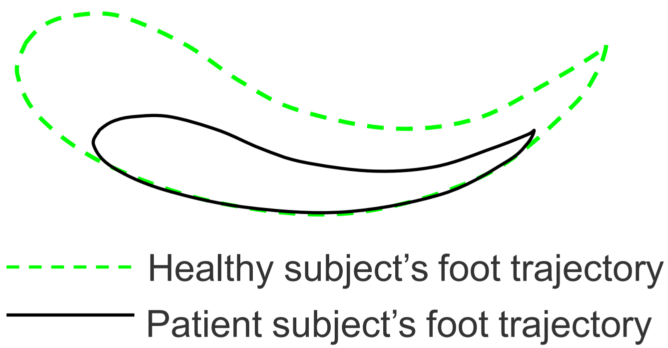
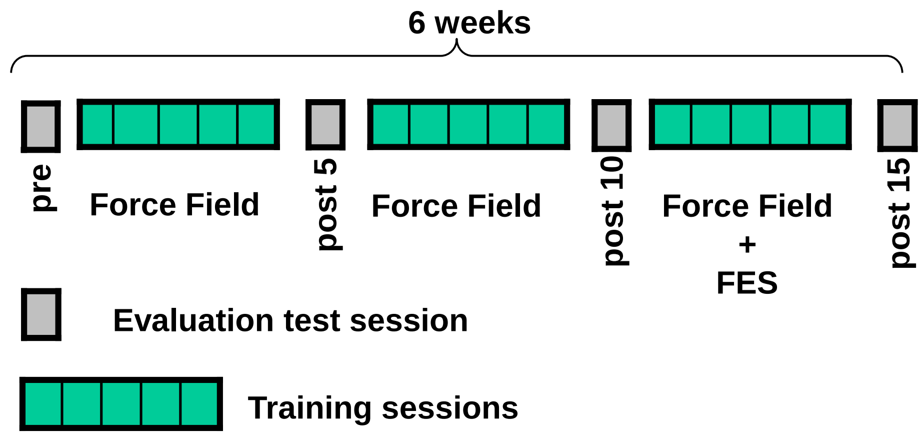
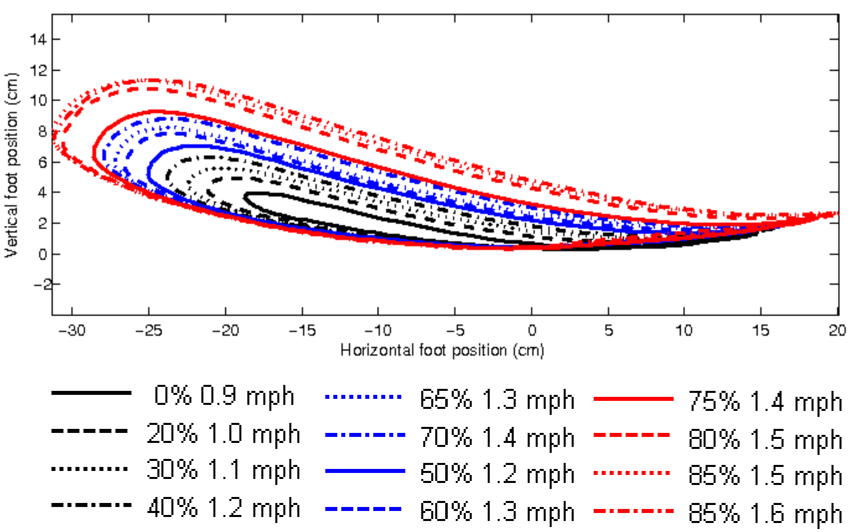
- Healthy subjects modified their foot path to a scaled-down trajectory after training
- Participants with compliant force field + visual guidance retained the modification longer than force field or visual guidance alone.
- Results provide a basis for retraining gait following stroke or other disorders.

Kim, S. H., Banala, S.K., Brackbill, E. A., Agrawal, S. K., Krishnamoorthy, V. and Scholz, J.P, “Robot-assisted Modification of Gait in Healthy Individuals”, *Experimental Brain Research,* 2010, Vol. 202, 809-824.

Chronic stroke patients: Can they learn to walk more normally after ALEX robotic training ?

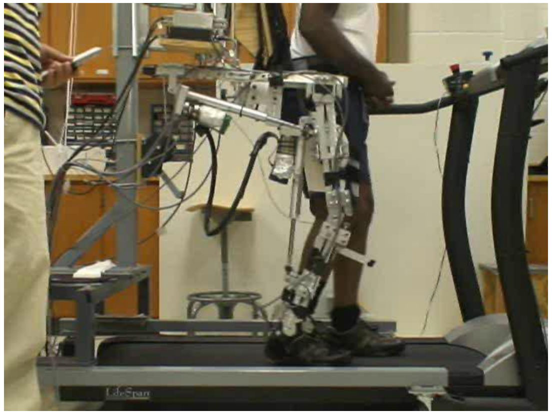




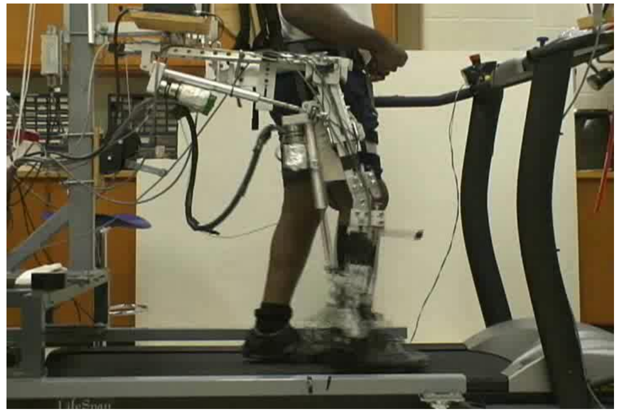


Sessions	Time (min)	Visual feedback	Force Field	Tunnel width (mm)	Stiffness (N)
Baseline	3	OFF	no	-	-
Pre-test	2	on	no	-	-
Training – 1	5	on	YES	10	0.76
Training – 2	5	on	YES	10	0.76
Training – 3	5	on	YES	10	0.125
Training – 4	5	on	YES	10	0.125
Mid-test	2	on	no	-	-
Training – 5	5	on	YES	20	0.76
Training – 6	5	on	YES	20	0.76
Training – 7	5	on	YES	20	0.125
Training – 8	5	on	YES	20	0.125
Post-test	2	on	no	-	-
Follow up 1	2	OFF	no	-	-
Follow up 2	2	OFF	no	-	-

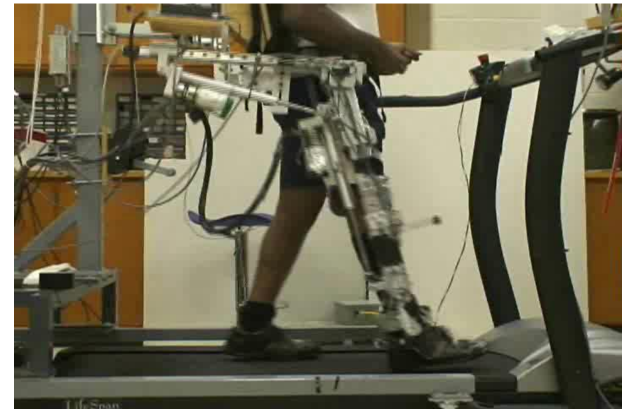
ALEX pre and post-training Videos of Stroke Patients



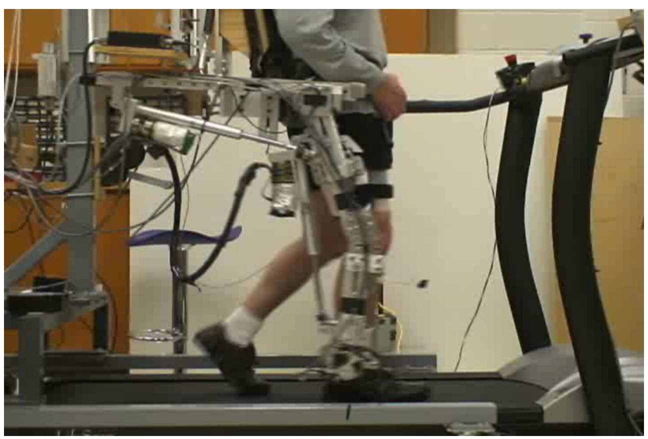
Session 2: 0.9 mph



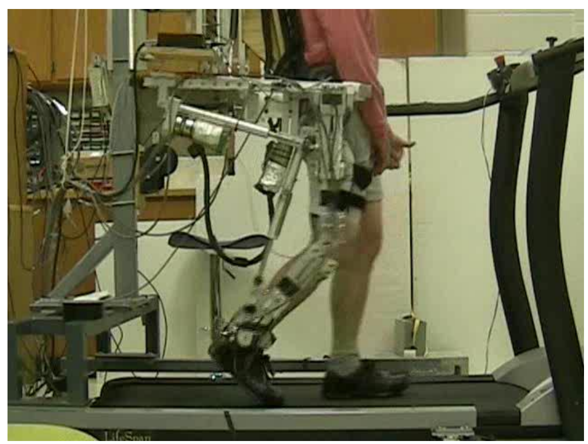
Post 15 Session training: 0.9 mph



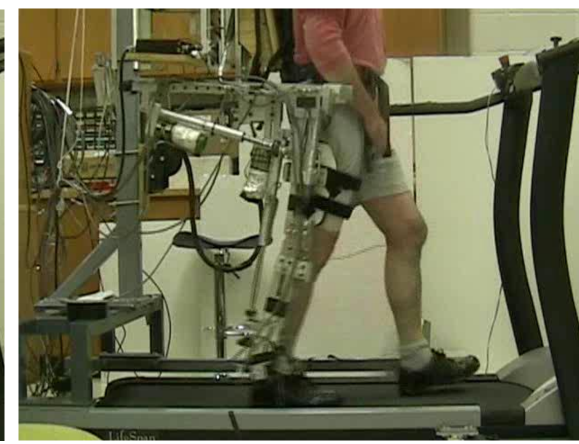
Post 15 Session training: 1.6 mph



Baseline: 1.3 mph

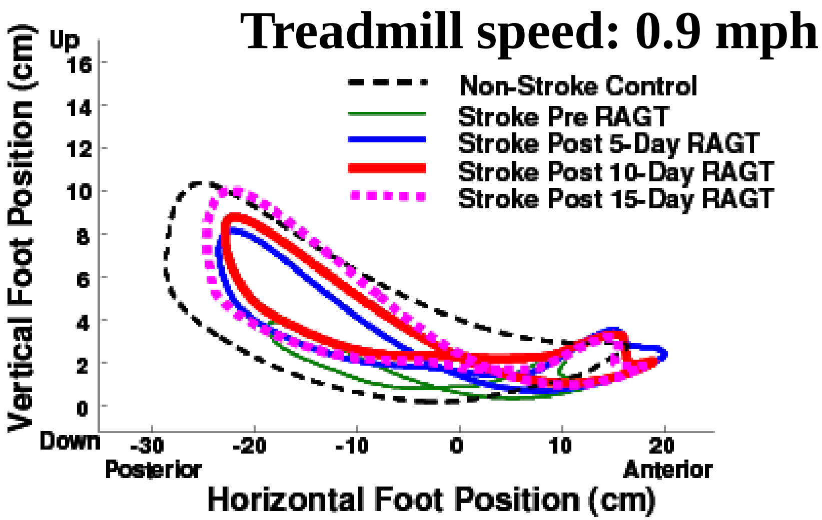


10 Session Training: 1.3 mph

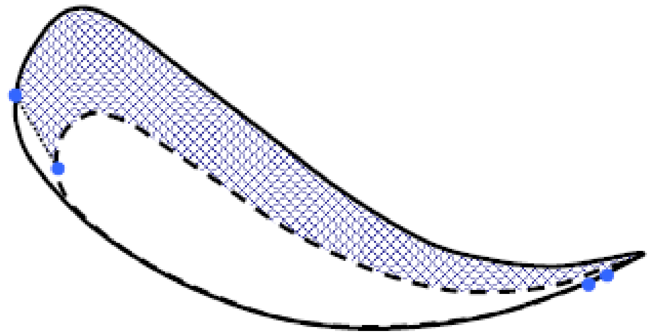


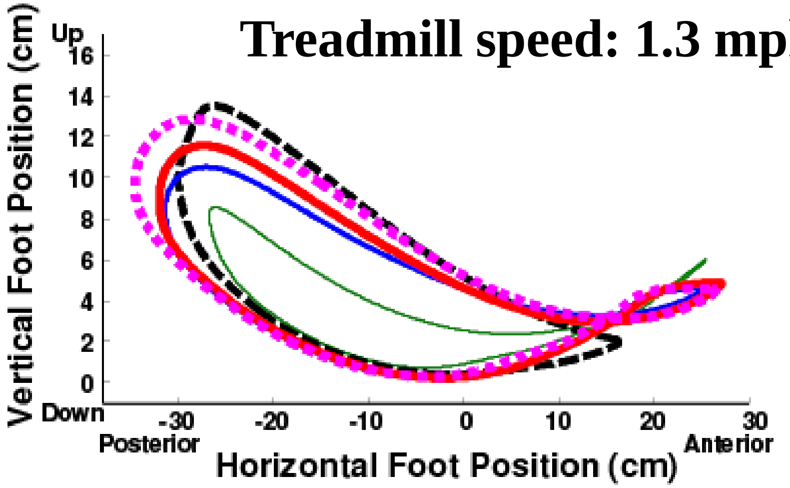
10 Session Training: 1.8 mph

Pre, mid, & post-Training Data with ALEX

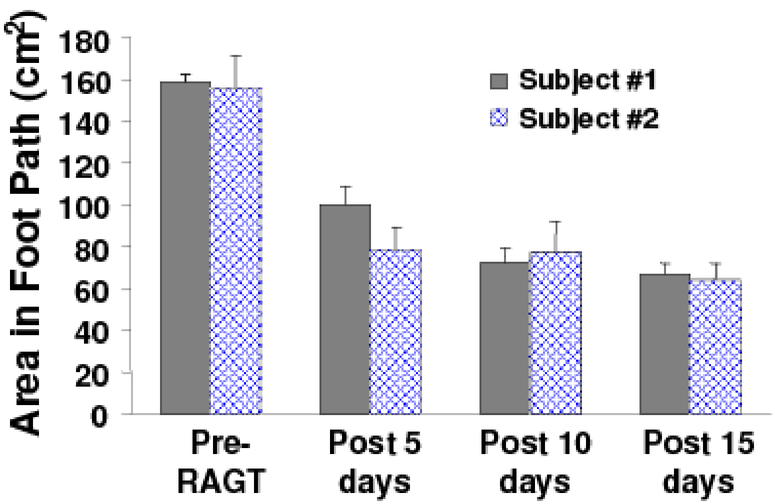


(a) Subject #1



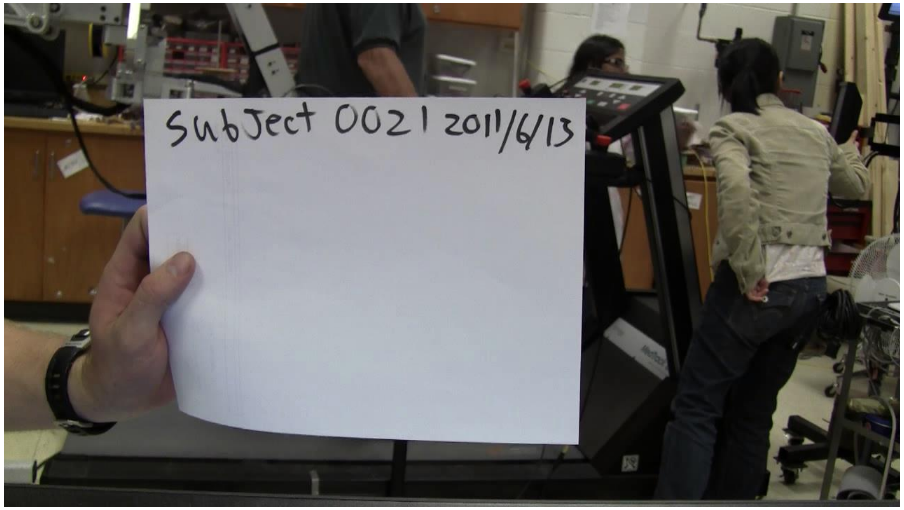


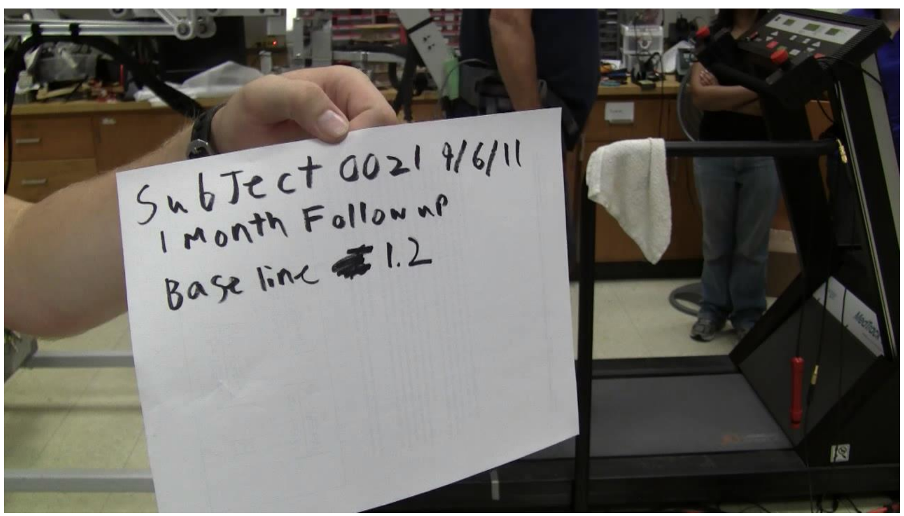
(b) Subject #2

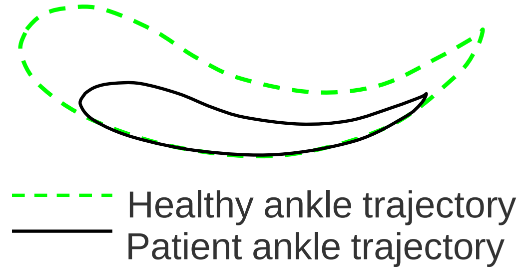


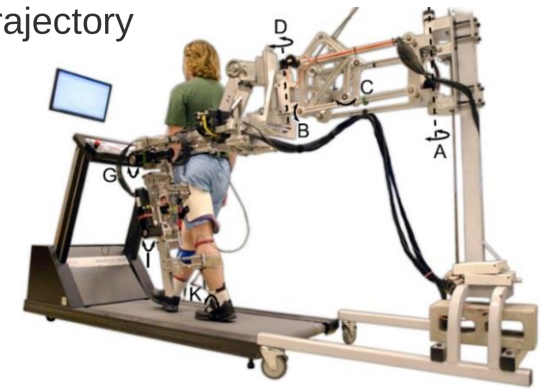
S. K. Banala, S. H. Kim, **S. K. Agrawal**, S. Banala, and J. P. Scholz, "Robot Assited Gait Training with Active Leg Exoskeleton (ALEX)", *IEEE Trans. on Neural Systems and Rehabilitation Engineering*, Vol. 17, No. 1, 2009 , 2-8.

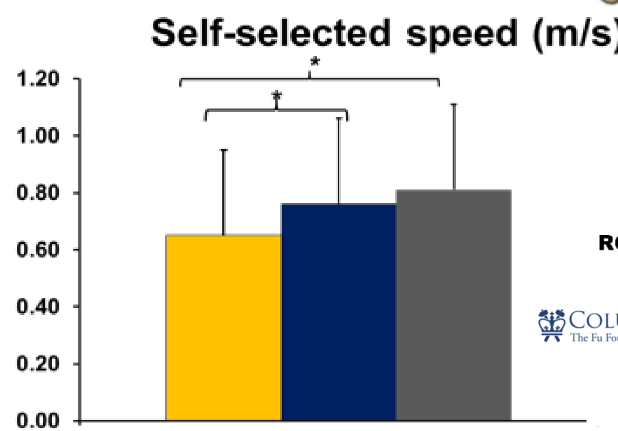
ALEX II: Gait Training of Stroke Patients
N=9, Six month follow up











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Srivastava, S., Kao, P.C., Kim, S.H., Stegall, P., Zanotto, D., Higginson, J, Agrawal, S. K., and Scholz, J. P., “Assist-as-needed Robot-aided Gait Training Improves Walking Function in Individuals Following Stroke”, *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2015, Vol. 23, No. 6, 956-963.

Exoskeletons are cool! What are the limitations?

- Not transparent to users
- Usually heavy, alters inertia
- Constrains degrees-of-freedom
- Joint alignment is an issue

Lokomat, Hocoma AG

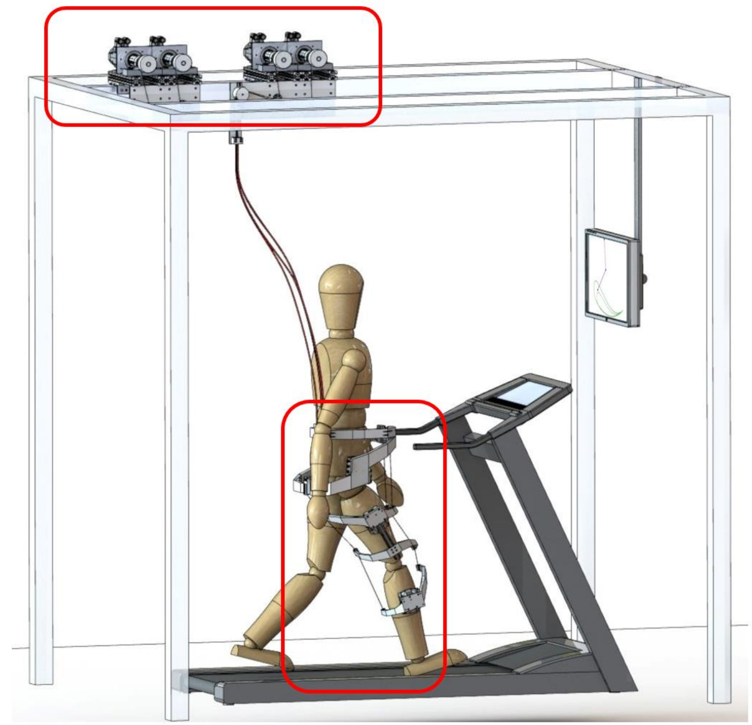
Alex II, Columbia U

Lopes, U of Twente

Design of C-ALEX …

- No mechanical "skeleton"
  - 3 cuffs on pelvis / thigh / shank
- No restriction on natural joint motion
- Lightweight
  - 3D printed cuffs with sparse interior
  - Pelvis / Thigh / Shank: 2.7kg / 1.0kg / 0.6kg

	Degrees of Freedom			**Moving Mass**
	Pelvis	Hip	Knee	
Human	6	3	1	15% B.W.
C-Alex	**6p**	**1a2p**	**1a**	**+1.6kg**
Lokomat	1p(+2p)	1a	1a	+21kg
Alex II	5p	1a2p	1a	+30kg
Lopes	2a1p	2a	1a	+6kg



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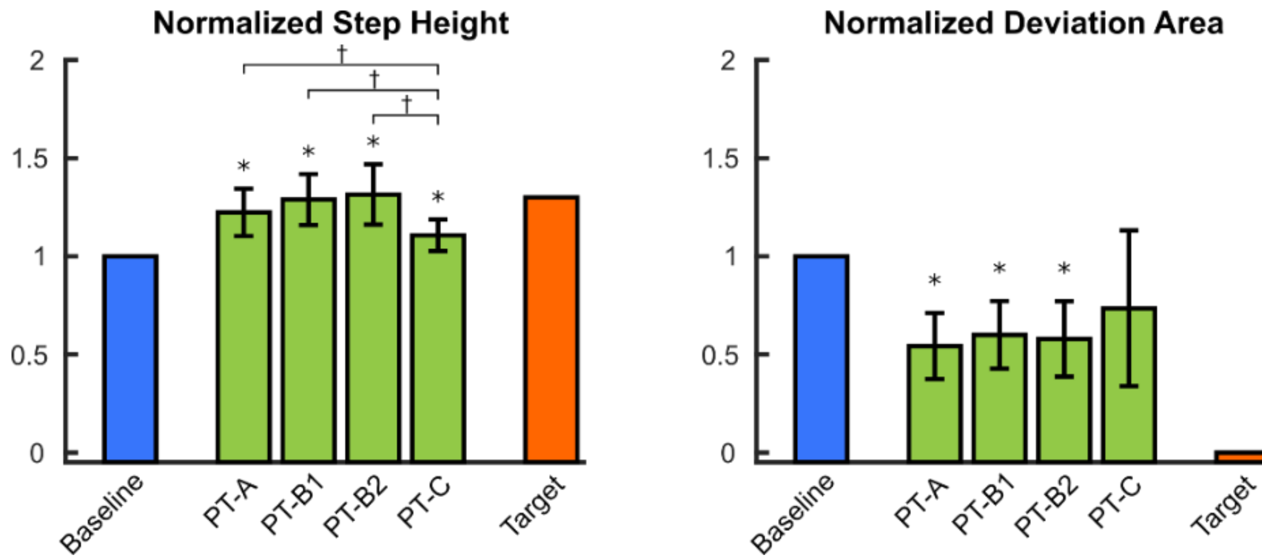
Jin, X., Cai, Y., Prado, A., and Agrawal, S. K., "Effects of Exoskeleton Weight and Inertia on Human Walking", *IEEE Conference in Robotics and Automation*, 2017.

C-ALEX: Cable-driven Active Leg Exoskeleton

No rigid links, 1/10th weight of rigid exos, no joint alignment



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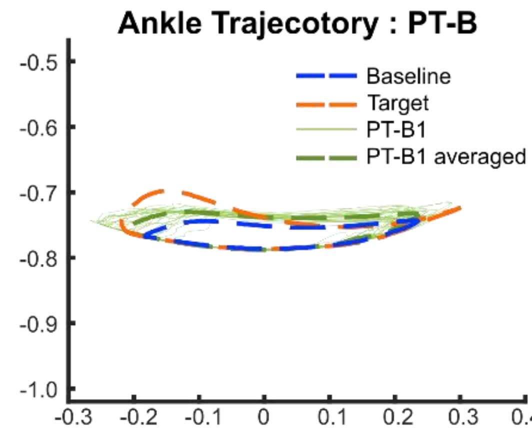
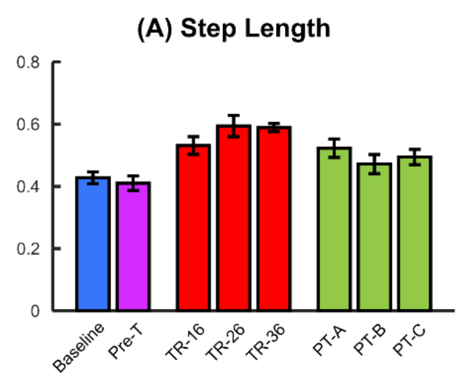
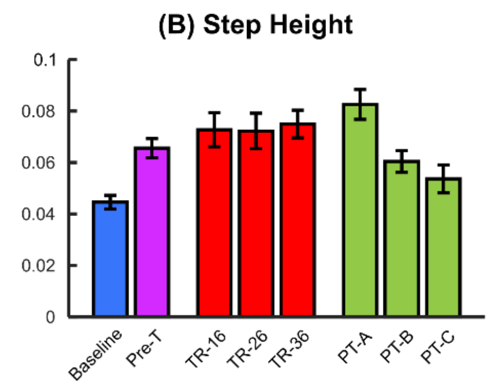
Jin, X., Cai, Y., Prado, A., and Agrawal, S. K., "Retraining of Human Gait - Are Lightweight Cable-driven Leg Exoskeleton Designs Effective?", *IEEE Transactions of Neural Systems and Rehabilitation Engineering*, Vol. 26, No. 4, 2018, pp. 847-856 .

C-ALEX: Cable-driven Active Leg Exoskeleton

Retraining Stroke Gait: Pilot study (n=10) single session







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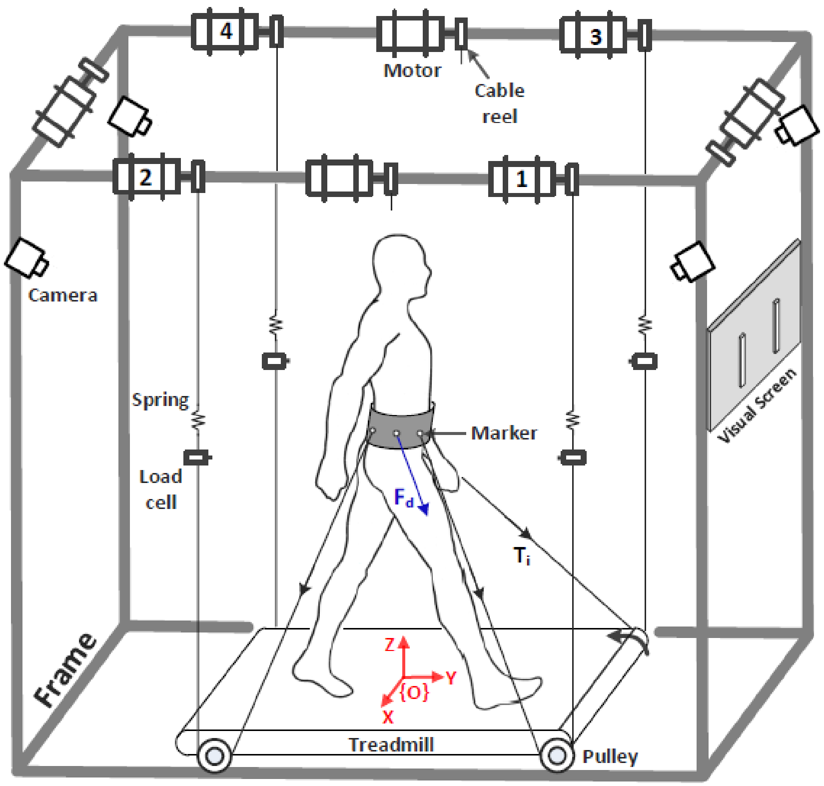
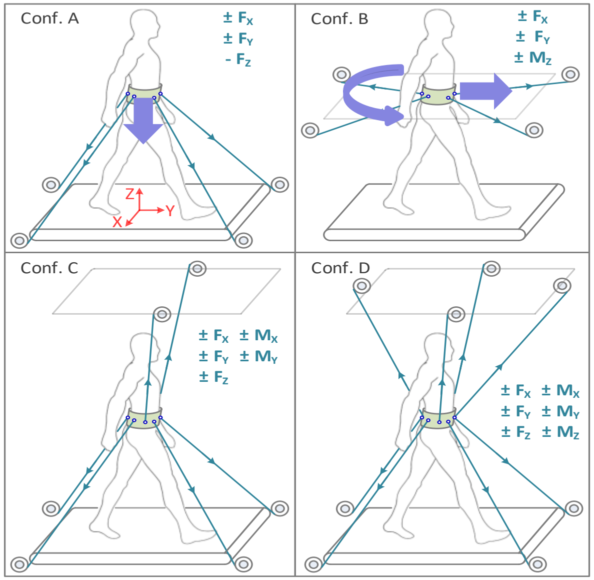
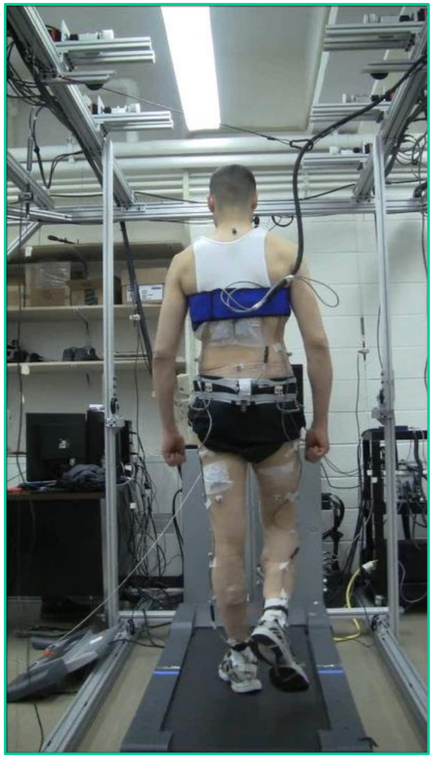
TPAD: Applies controlled forces on pelvis
Training during stance phase of gait







- Foot is in stance 62% of gait cycle
- Continuous or intermittent forces
- Synchronize with gait events
- Constraint-induced training with forces during walking

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Force asymmetry Experiment and Outcomes

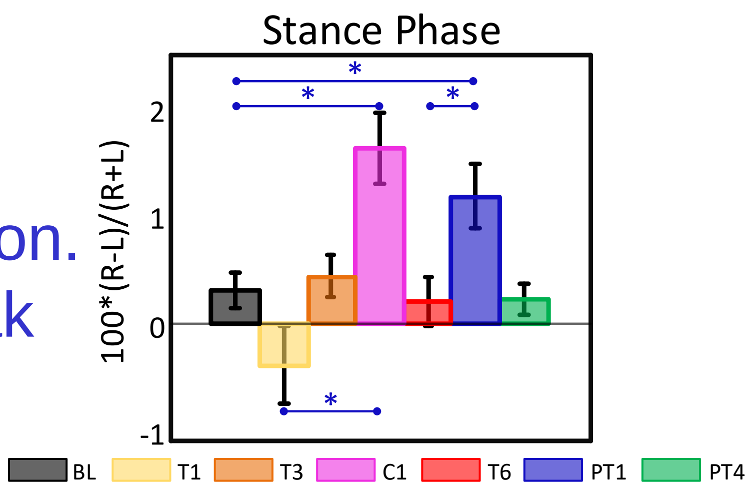
Experiment: A 10% BW force was directed along the right leg.

Details:

- 9 healthy sub. (20-35 yrs)
- Average weight: 71.5 kg
- Constant speed: 3.8 km/h

Results:

- Asymmetric pelvic motion.
- Longer right leg stance time.
- Higher right leg muscle activation.
- Potentially use this to train weak legs of hemiparetic patients.



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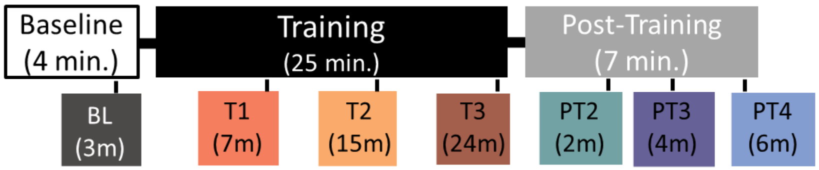
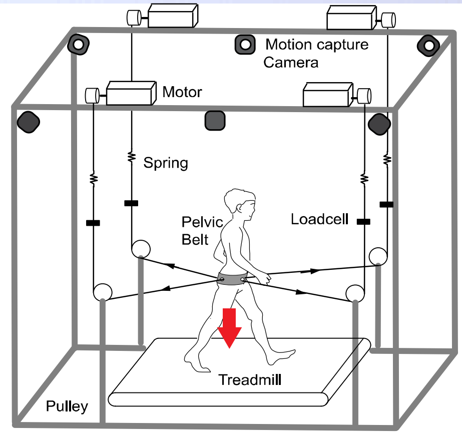
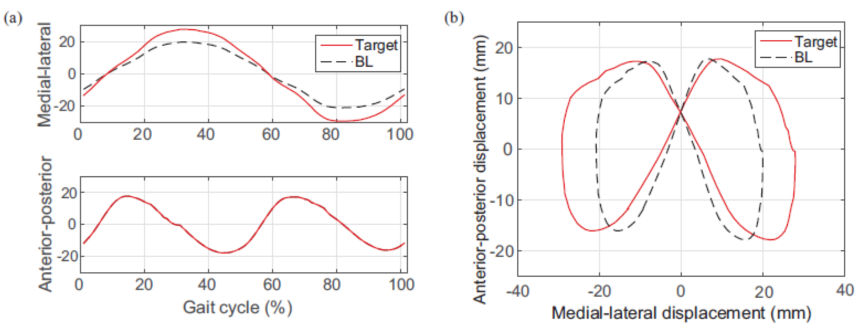
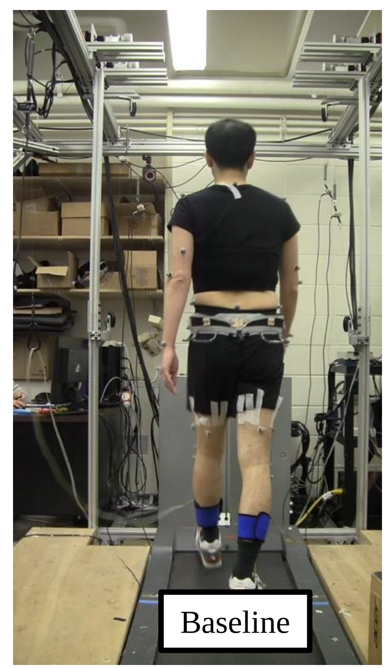
V. Vashista, D. Martelli and S. K. Agrawal, "Locomotor Adaptation to an Asymmetric Force on the Human Pelvis directed along the Right Leg," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 24, No. 8, 2016, 872-881.

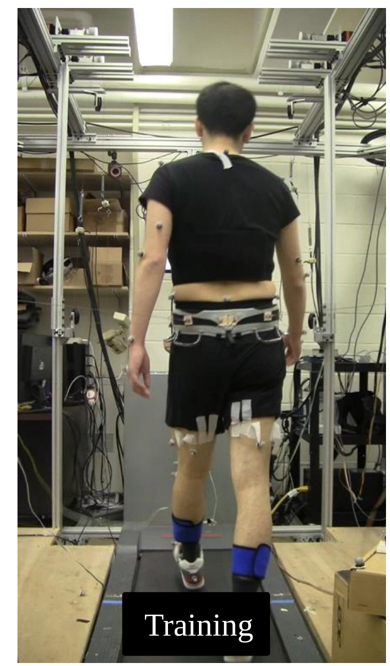
Closed-loop Force Control based on Pelvis Motion Enlarge ML Template by 40% – Single Session

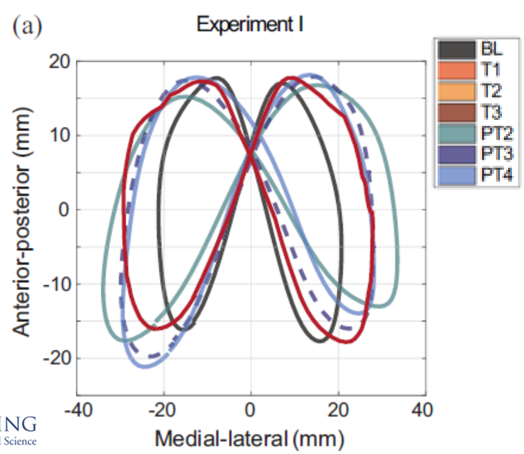












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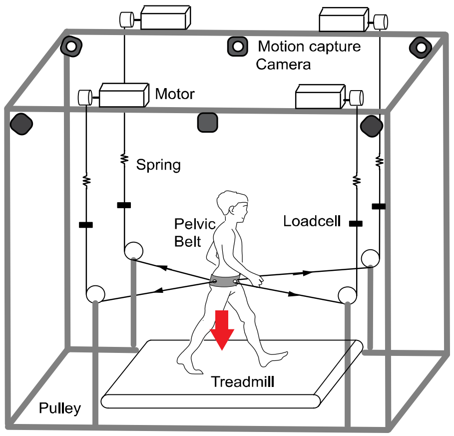
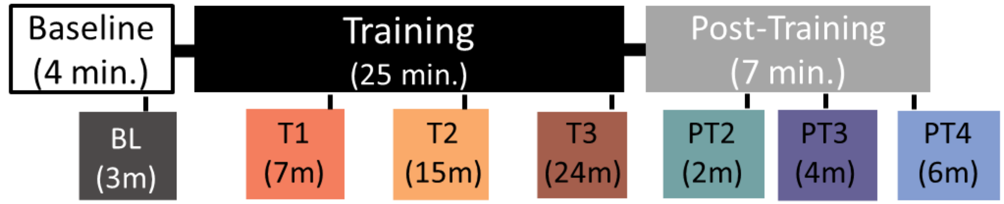
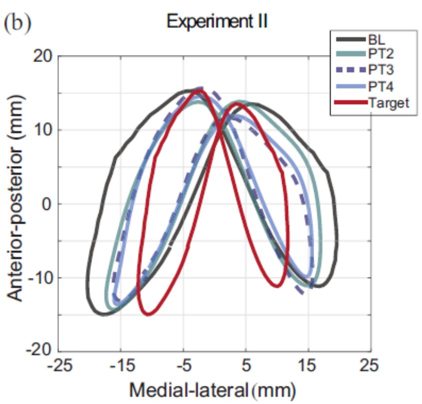
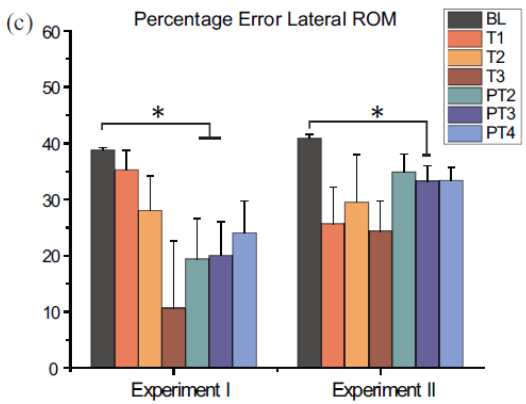
J. Kang, V. Vashista, S. K. Agrawal. "On the Adaptation of Pelvic Motion by Applying 3-dimensional Guidance Forces using TPAD", *IEEE Trans. Neural Rehab. Engineering* , 2017.

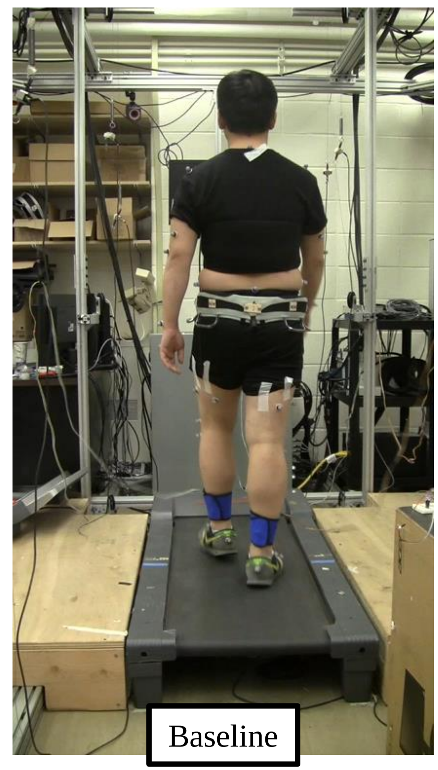
Closed-loop Force Control based on Pelvis Motion Reduce ML Template by 40% – Single Session

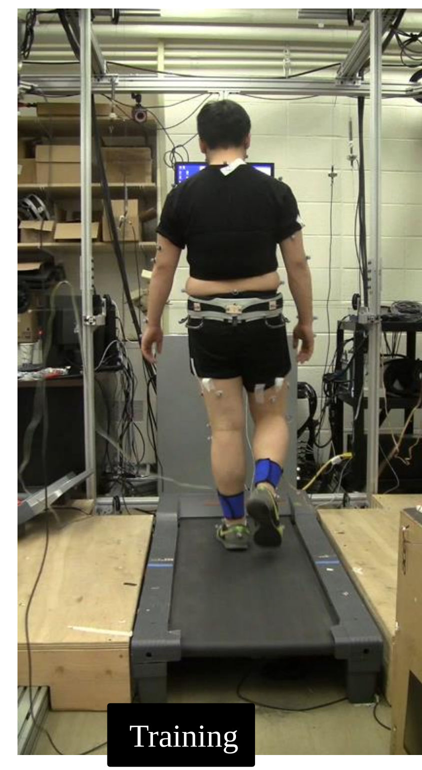












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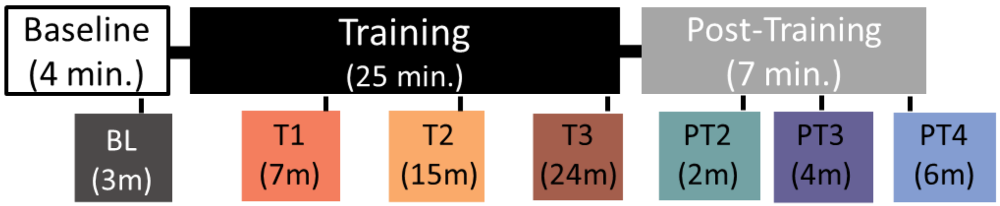
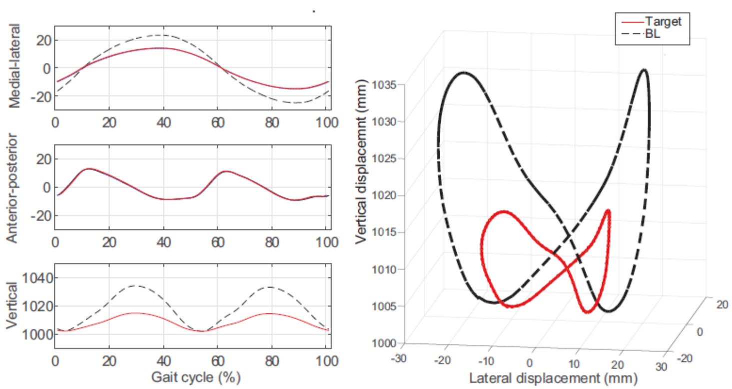
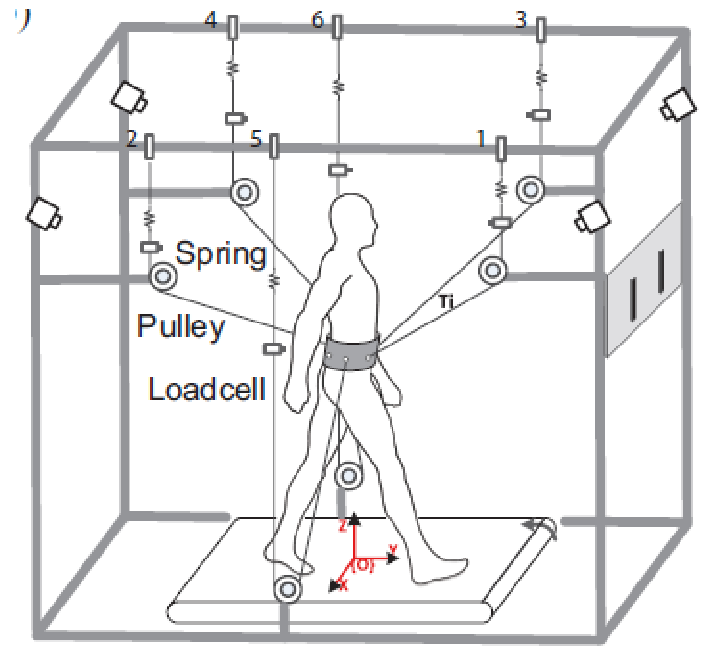
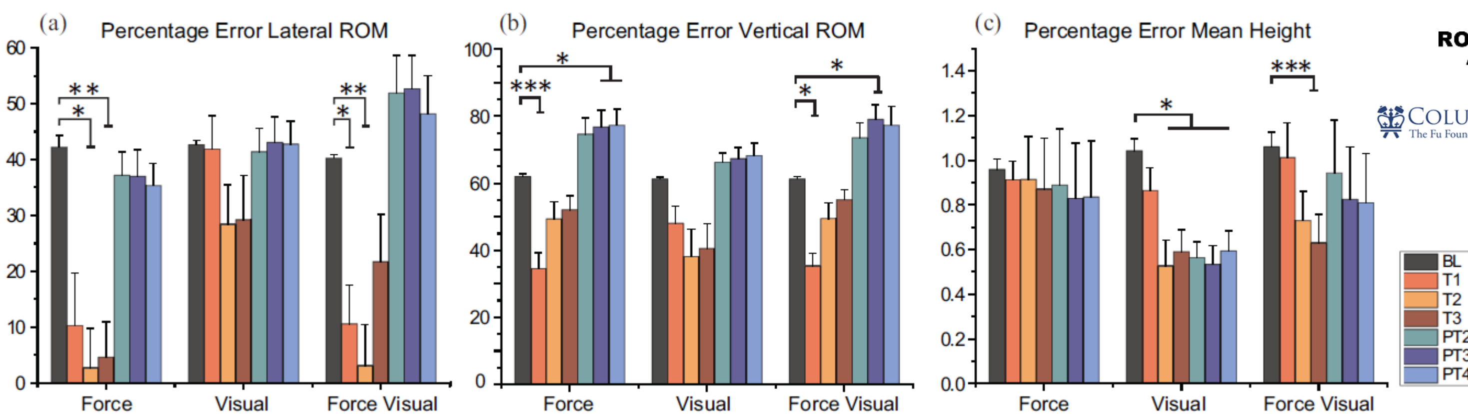
Closed-loop Force Control based on Pelvis Motion

Change both Lateral and Vertical Templates: Motivated by CP Gait









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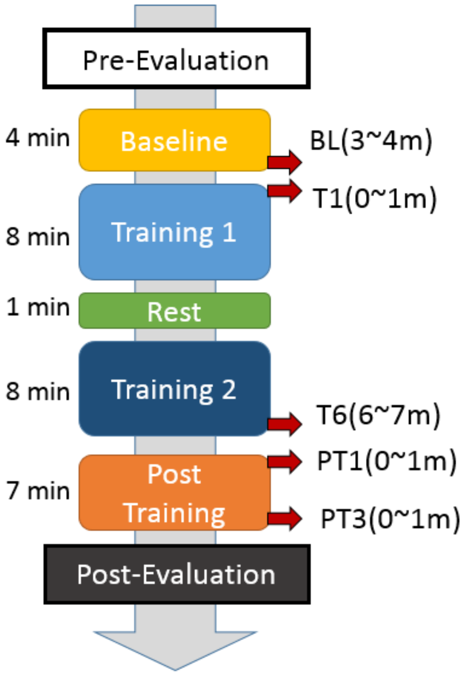
J. Kang, V. Vashista, S. K. Agrawal. "On the Adaptation of Pelvic Motion by Applying 3-dimensional Guidance Forces using TPAD", *IEEE Trans. Neural Rehab. Engineering*, 2017.

Crouch Gait of Children with CP

3 out of 1000 children are diagnosed with CP

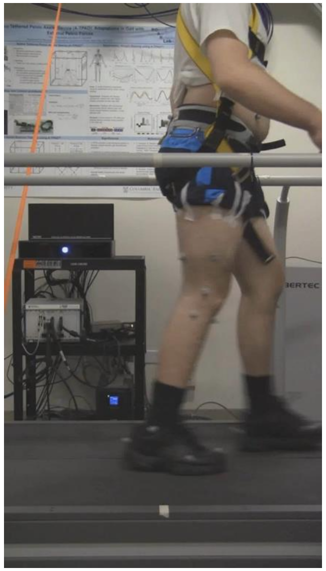
- Many children with CP have flexed hips, knees, and ankles
- Slow speed, Energy intensive, Joint deterioration
- 10% BW force was applied downwards symmetrically across both legs – 15 training sessions

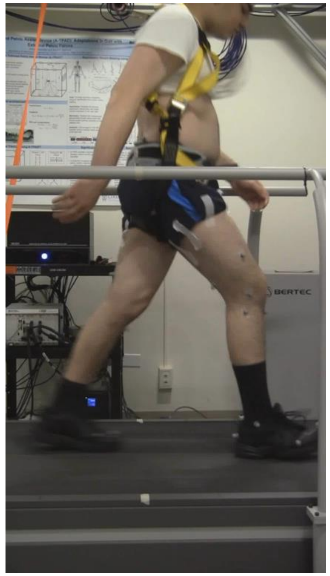
Protocol

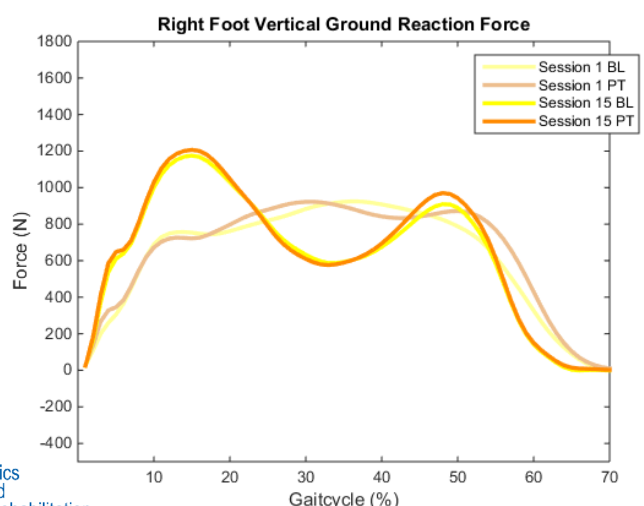


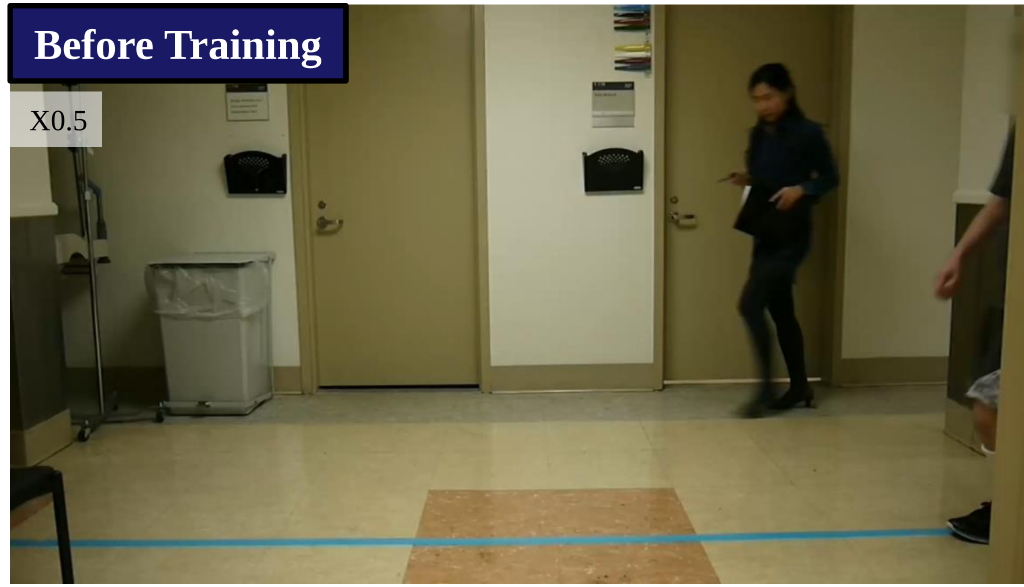
J. Kang, D. Martelli, V. Vashista, I. Martinez-Hernandez, H. Kim, S. K. Agrawal, "Robot-driven Downward Pelvic Pull to Improve Crouch Gait in Children with Cerebral Palsy," *Science Robotics*, Vol. 2, eaan2634, 2017.

Crouch Gait of Children with CP: Outcomes









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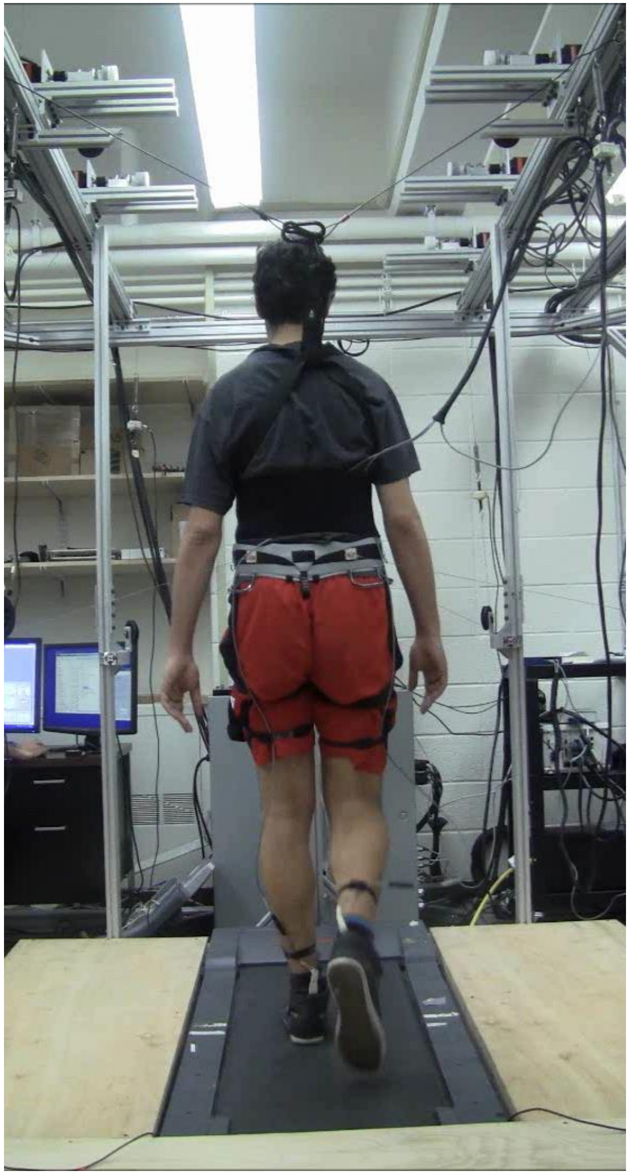
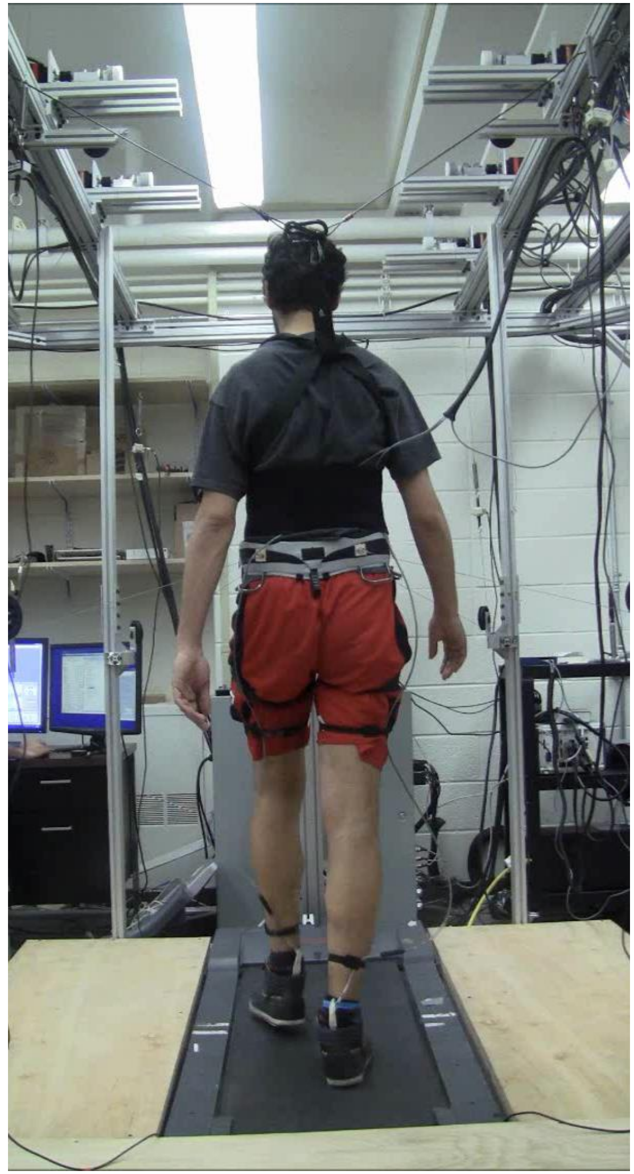
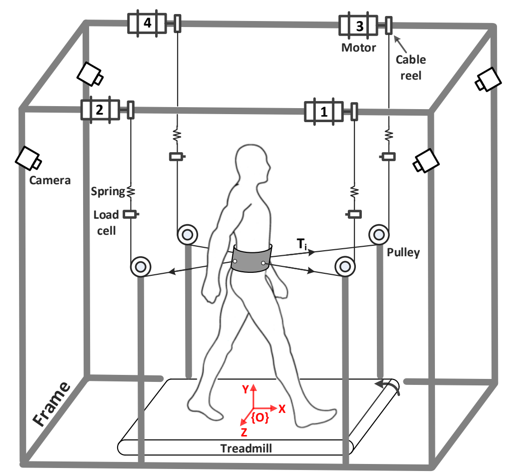
J. Kang, D. Martelli, V. Vashista, I. Martinez-Hernandez, H. Kim, S. K. Agrawal, "Robot-driven Downward Pelvic Pull to Improve Crouch Gait in Children with Cerebral Palsy," *Science Robotics*, Vol. 2, eaan 2634, 2017.

Training elders to improve balance & prevent Falls

Tai-Chi is great but can we do better?







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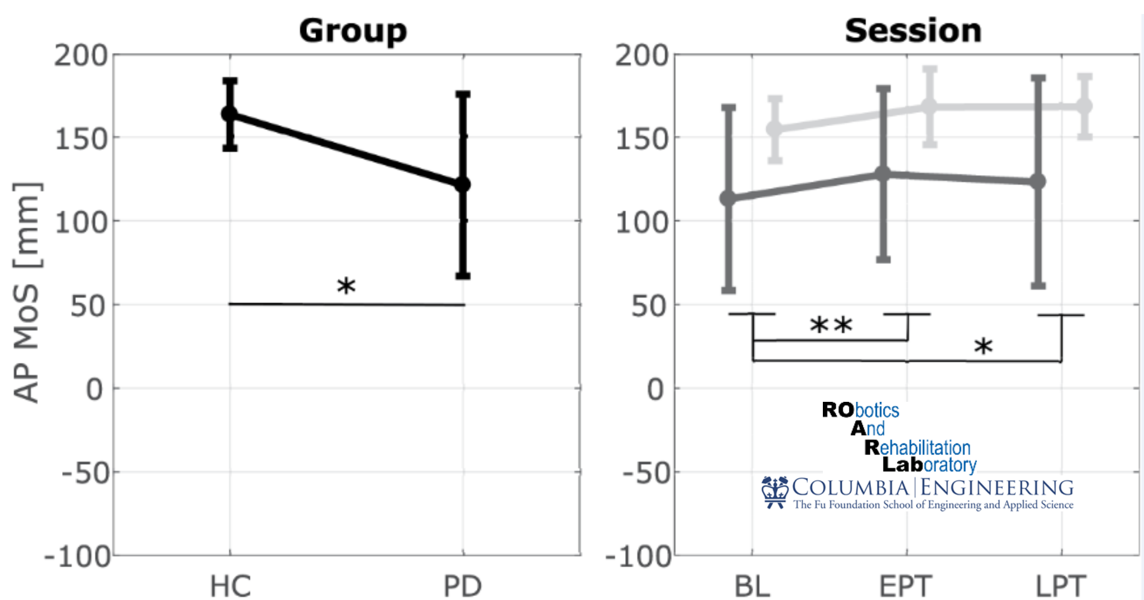
Perturbation Training of Parkinson Patients
Margin of Stability Trends are similar to controls …

Variable	PD Group	HC Group	p-value
Age [years]	64.3 ± 7.4	64.7 ± 7.3	.924
Gender [male/female]	7/2	6/3	1
Height [cm]	169.6 ± 6.1	172.9 ± 6.1	.261
Weight [kg]	75.5 ± 15.7	75.6 ± 8.9	.993
TUG [s]	9.46 ± 3.70	7.81 ± 1.44	.230
5MWT [m/s]	1.39 ± 0.11	1.42 ± 0.15	.606
Treadmill Speed [m/s]	0.89 ± 0.12	0.9 ± 0.17	.871

New York City CBS Local News clip on "Perturbation Training of Balance in Parkinson Patients".



D. Martelli, L. Luo, J. Kang, U. J. Kang, S. Fahn, and S. K. Agrawal, "Adaptation of Stability During Perturbed Walking in Parkinson's Disease", *Scientific Reports**, 2017. (*nature.com)

Wrap Up: Posture training with pelvis and trunk

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M. I. Khan, V. Santamaria, S. K. Agrawal, "Improving Trunk-Pelvis Stability Using Active Force Control at the Trunk and Passive Resistance at the Pelvis," *IEEE Robotics and Automation Letters*, Vol. 3, No. 3, 2018, pp. 2569-2576.

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Thank you

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