Skilled lower extremity motor development in children with spastic cerebral palsy

Eileen Fowler PhD, PT

Peter William Shapiro Chair
Director Research & Education, Center for CP at UCLA/OIC
Tarjan Center
University of California, Los Angeles

Center for Cerebral Palsy at UCLA

Selective Voluntary Motor Control

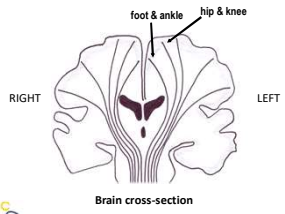
Ability to perform **isolated** joint movements upon request, without using mass flexor/extensor patterns and without undesired movement at other joints, such as mirroring

Overview

1. Selective motor control = skilled movement of the lower extremities (legs)
2. Clinical assessment
3. Mirroring
4. Biomechanical assessment of SMC
5. SMC as a prognostic factor for interventions
6. Camp Leg Power intervention to improve SMC
   - Motor outcomes
   - Brain imaging outcomes

Corticospinal tracts

Control selective voluntary motor control

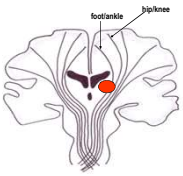


Spastic Cerebral Palsy (CP) – Multiple Impairments

- Spastic CP is an injury to the developing brain
- Associated with premature birth & low birth weight
- Developmental disability

Corticospinal tract damage in spastic CP

- Commonly injured in spastic CP
- White matter damage of prematurity
  - Periventricular leukomalacia (PVL)
- Responsible for voluntary movement
  - Force
  - Speed
  - Timing
  - Pattern
- Distal structures more vulnerable (foot / ankle)
- Mirroring - ipsilateral tract preservation



Clinical Assessment of SMC – Skilled Movement

Upper Extremity

"Fine motor"

Clinical Evaluations for CP? – MANY

1. ABILIHAN,
2. AHA,
3. Melbourne,
4. Quest
5. Box & Blocks
6. Jebsen Taylor,
7. 9-hole peg
8. Purdue Pegboard

Lower Extremity

Clinical evaluations for CP? NONE

- Selective Control Assessment of the Lower Extremity (**SCALE**)

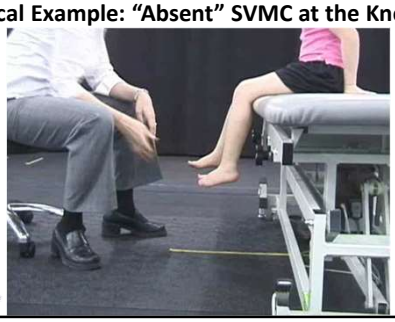
Clinical Example: "Impaired" SVMC at the Knee

Selective Control Assessment of the Lower Extremity SCALE

- 10-15 minutes to complete
- Ask patient to perform selective movement for each joint
- Each joint is graded separately: hip, knee, ankle, subtalar and toes
- 0=no movement or synergy, 1=impaired, 2=normal
- Max score for each lower limb =10 points
- Obligatory mirroring is a common reason for an impaired score

Fowler EG, Staudt LA, Greenberg MB, Oppenheim WL
Dev Med Child Neurol 51:607-614, 2009

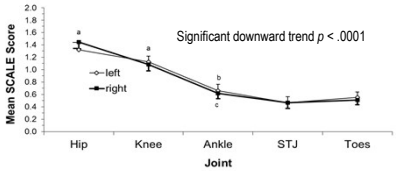
Clinical Example: "Absent" SVMC at the Knee



Clinical Example: "Normal" SVMC at the Knee

Greater Distal Impairment

SCALE Score Hip >Knee >Ankle >STJ >Toes



Findings are consistent with increased vulnerability of the CST medial tracts.

Fowler EG, Staudt LA, Greenberg MB
Dev Med Child Neurol 52:264-269, 2010

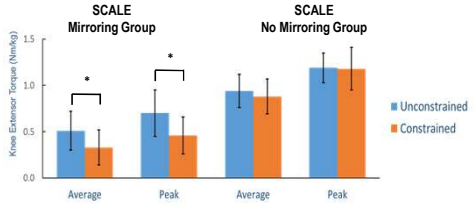
Mirroring – Maladaptive Plasticity

Studies have focused on upper extremity mirroring in spastic unilateral CP
- Preservation of ipsilateral corticospinal tracts (Friel research)

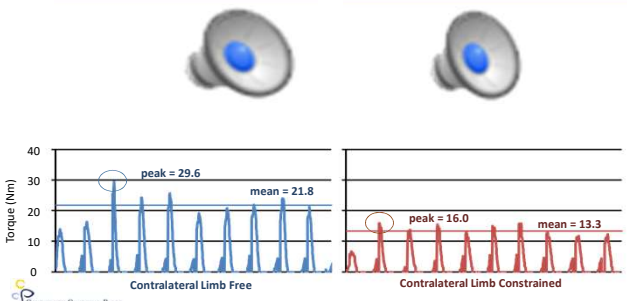
Less is known about lower extremity mirroring and in bilateral CP
- Critical for function as walking requires interlimb coordination

Cohort of 47 participants with bilateral spastic CP in our lab
- 25 (53%) exhibited mirroring at one or both knees
- 12 (26%) at the ankle

Mirroring and Knee Joint Torque Production



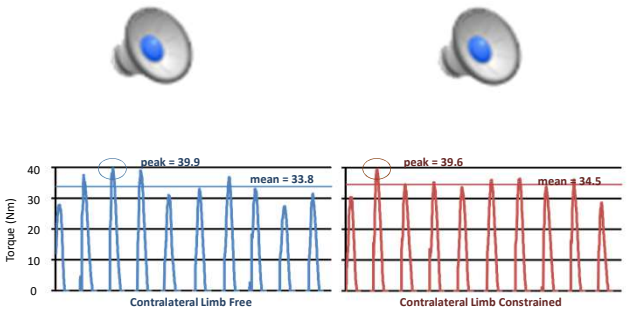
*p<.001, paired t test



Knee Extensor Torque: 90 deg/s

Clinical Evidence of CST impairment

- Greater distal impairment consistent with CST damage
- Mirroring experiment suggests that neural drive from one hemisphere is controlling bilateral muscle groups

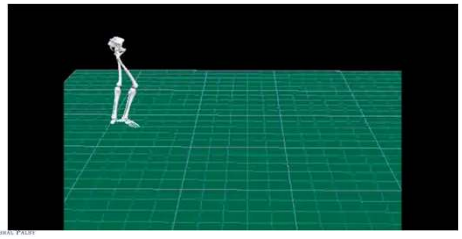


Knee Extensor Torque: 90 deg/s

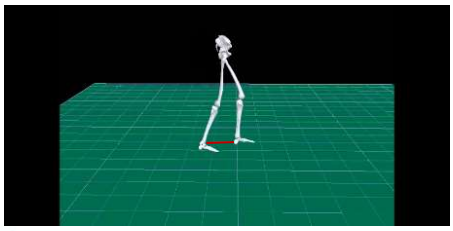
SMC required for skilled lower extremity movement

Walking and kicking – swing phase (non weight bearing)

Normal Selective Motor Control:
Independent Hip And Knee Coordination During Swing



Impaired Selective Motor Control:
Reduced Step Length



Normal Selective Motor Control:
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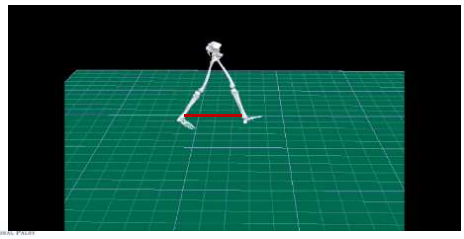
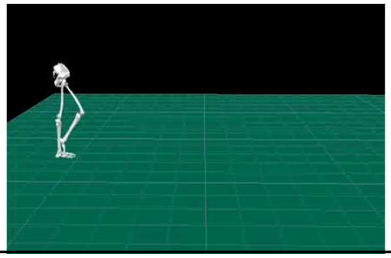


Absent Selective Motor Control:
Markedly Reduced Step Length



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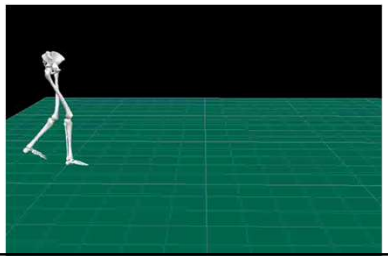

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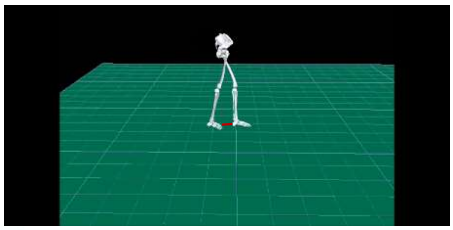
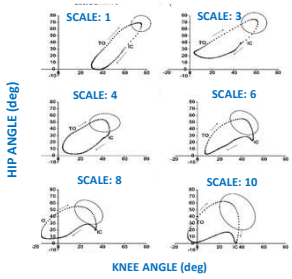
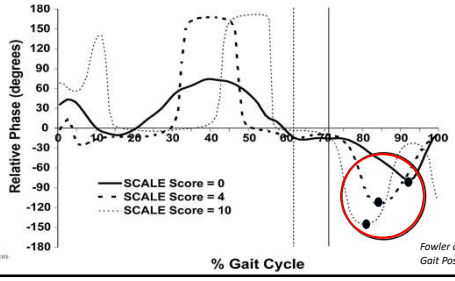


Hip and Knee Coordination
Angle-angle diagrams: exemplar limb data



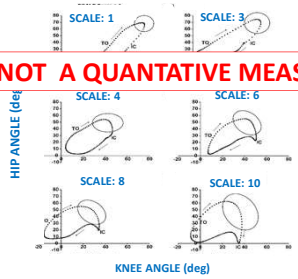
Fowler and Goldberg
Gait Posture 29:102-107, 2009

Minimum Relative Phase (MRP) Analysis
One number to represent hip and knee coordination



Fowler and Goldberg
Gait Posture 29:102-107, 2009

Measure Hip and Knee Coordination
Angle-angle diagrams: exemplar limb data

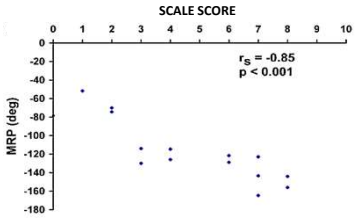


NOT A QUANTATIVE MEASURE

Fowler and Goldberg
Gait Posture 29:102-107, 2009

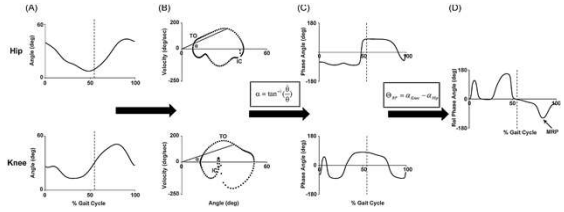
SCALE – MRP Correlation

Bilateral CP, GMFCS I-IV, n=15



Fowler and Goldberg
Gait Posture 29:102-107, 2009

Quantify Hip and Knee Coordination
Dynamic Systems Theory
Minimum Relative Phase (MRP) Analysis



Fowler and Goldberg
Gait Posture 29:102-107, 2009

Does our clinical measure of skilled movement predict who does better with treatment?

Hamstring Lengthening Surgery

- Patients have shown more improvement in knee extension during stance as opposed to swing

(Baumann et al, 1980, Carney et al., 2006, Thometz, 1989)

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Pre-Op Patient #1 Poor Selective Motor Control

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Case Examples: Similar Patient Characteristics

Patient	Gender	Pre-Op Age (yrs)	Time Between Analysis (yrs)	GMFCS (Mobility)	Hamstring Spasticity Score*
1	M	10.5	1.8	III	2
2	F	9.6	2.3	III	2

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*Ashworth Scale
Goldberg, Fowler, Oppenheim.
Clin Orthop Rel Res (2012) 470:1320-1326

Pre-Op Patient #2 Good Selective Motor Control

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Pre-Op Patient #1 Poor Selective Motor Control

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Pre-Op Patient #2 Good Selective Motor Control

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Pre-Post Hamstring Lengthening

Patient	SCALE Score		Normalized Stride Length	
	Left leg	Right leg	Pre	Post
1	2	3	0.62	0.57
2	6	5	0.72	0.79

- If the goal is to improve stride length, good SMC is required (≥5 SCALE)
- Knee extension during stance improved in both patients

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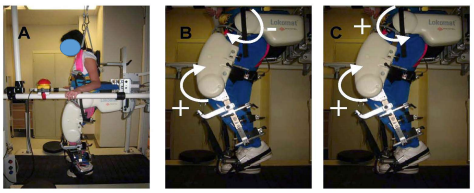
Goldberg, Fowler, Oppenheim. Clin Orthop Rel Res (2012) 470:1320-1326

Hip and Knee Moments during Robotic Walking
Forceful Knee Extension Task



Uncoupled moments
Good SVMC

Coupled moments
Poor SVMC

+ = extensor, - = flexor

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Gait Training: Improve Stride Length?

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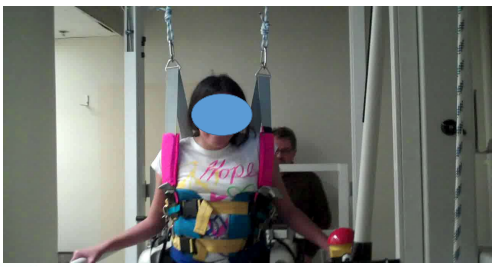
Post Robotic Hip and Knee Moments
Overground Walking following 1 Session

Participant	Limb	SCALE	Δ Step length/BH	Response category
A	L	7	+.02	Responder
	R	6	+.02	Responder
B	L	3	-.05	Non Responder
	R	2	-.02	Non Responder

In general, limb SCALE scores of >5 are responders

Robotic Gait Intervention



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CAMP LEG POWER!

Can we improve lower extremity motor function and CST outcomes?

- Short-term intensive therapy is appropriate for teaching skilled movement
- 15 sessions of intensive therapy over 1 month period, 3 hours/day
- Ambulatory children with spastic CP
- **Selective motor control** exercises: high dose and challenging
- Included sensory experiences without braces
- Outcomes: motor ability, parent perception, brain imaging of CSTs

Participants

3 Summer Camps

All children

- Ambulatory with spastic CP between 5 and 17 y.o.
- 23 children participated in the study
- Race: 16 White (6 Hispanic ethnicity), 4 Asian, 2 Black, 1 mixed

Brain imaging data (subset of children)

- Children with bilateral CP born premature with PVL on MRI (damage to CSTs)
- Able to lie still and meet criteria for MRI: no baclofen pumps, shunts, incompatible metal etc.
- 12 participants with CP- Prisma 3T scanner, age range 7-16 y.o.
- 12 typically developing children, age range 7-16 y.o.

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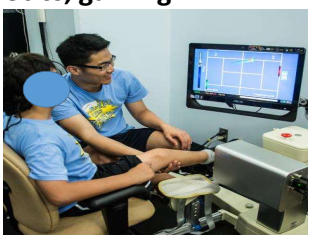
High dose, robotics, gaming

Biodex: high speed torque development



Robot – skilled isolated ankle movement

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Motor practice

Isolated knee extension

Step length

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Ankle robot dosage

	Left Ankle			Right Ankle		
	# of Sessions	Min/ Day	Reps/ Day	# of Sessions	Min/ Day	Reps/ Day
Mean	13.8	5.9	**332.6**	13.8	6.0	**342.4**
SD	1.2	0.7	122.6	1.1	1.0	140.4

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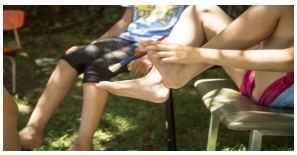
Motor practice & Sensory enrichment

Walking and exercising – dif. textures



Exercise and activities for all joints including toes

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Maintenance: Home Exercise Program

3 months:

- Selective motor control exercises with parents at least 3 times per week
- Isolated joint motion: hip, knee, ankle, subtalar and toe joints
- Illustrations and written instructions provided
- Adherence
  - Parental calendars = 2.6 times weekly

Example: Ankle joint isolated joint exercises

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Motor Outcomes

Assessments: Pre, Post and 4 month Follow-up

- Parental perception - Canadian Occupational Performance Measure
- Walking speed - 10 meter walk run
- Walking endurance - 6 minute walk distance
- Gross Motor Function Measure (GMFM-66)
- Knee strength and power: Biodex
  - Speed range = 0 - 300 deg/s
  - Grouped into low (0-4 pts) and high (5-9 pts) limb SCALE score groups

Statistical analysis

- Repeated Measures ANOVA with post hoc paired t-tests - normal distribution
- Bootstrapping re-sampling method for data not normally distributed
- significance level set at $P < 0.05$

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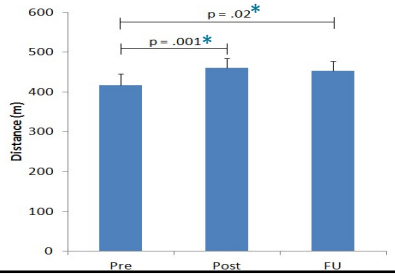
Walking Endurance: 6 Min Walk Test



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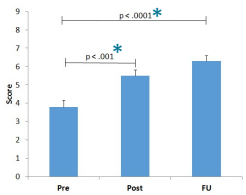
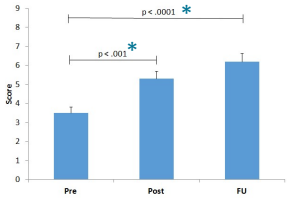
Parent Perspective (COPM)

Performance



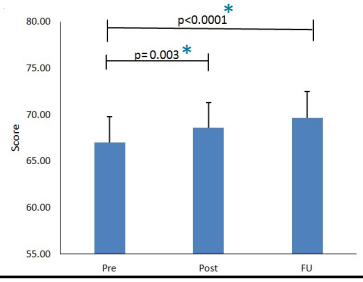
Satisfaction



Clinically important difference = 2 pts
Law et al. 2005

* Statistically significant improvement

Gross Motor Function Test



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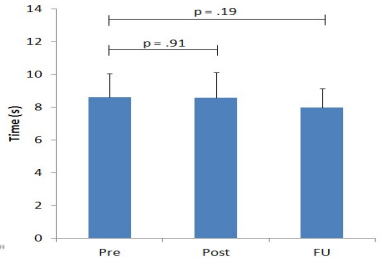
Walking Speed: 10m Walk Run Test



No Change

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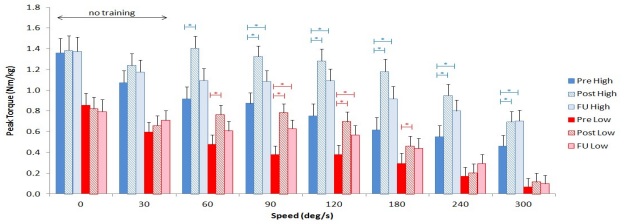
Knee Joint Extensor Torque – Left

Preliminary Results Years 1 & 2



High SCALE score group = 5 – 9 pts, n=7

Low SCALE score group = 0 – 4 pts, n=9

Mean +/- SE

Summary: Motor Function Outcomes

Significant pre-post and pre to follow improvements ($p < .05$):

1. Parental perception of motor ability and satisfaction
2. Walking endurance
3. Gross motor function
4. Knee joint strength and power
   - better selective motor control led to improvement at more speeds and greater maintenance at follow-up

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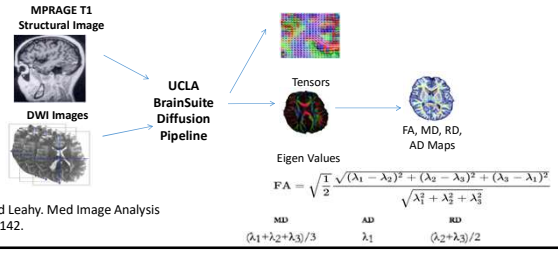
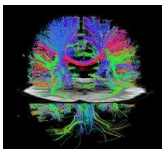
Methods – Diffusion Weighted Imaging

- BrainSuite – Shattuck et al. UCLA Brain Mapping Center



Shattuck and Leahy. Med Image Analysis 2002;6:129-142.

Brain Imaging Outcomes



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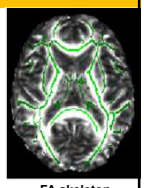
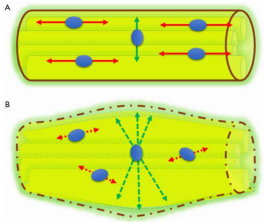
Tract Based Spatial Statistics (TBSS)



FA skeleton

- Voxelwise statistical analysis of the FA, MD, RD, AD data
- Statistics: Pre post changes and correlations performed
- Voxels with significant increases ($p<.05$) in FA, MD, RD, AD values were projected onto the mean FA skeleton.

Diffusion Tensor Imaging – movement of water molecules



A. Normal tract

FA = fractional anisotropy "**structural integrity**"
red arrows – diffusion in 1 clear direction & organized fibers

RD = radial (perpendicular) diffusion "**myelination**"
green arrows – barrier to radial diffusion

AD = axial (parallel) diffusion

MD = mean diffusion, average of RD and AD)

B. Damaged tract

FA = " loss of structural integrity"
red arrows – diffusion many directions
loss of fiber organization = **decrease**

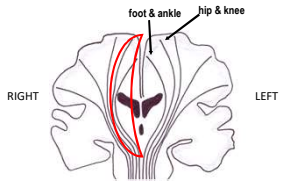
RD = "myelination"
green arrows – **increase** due to loss of myelin

(AD = diffusion is less parallel – typically decreases)
(MD = average of RD and MD)

In: J Quantitative Imaging in Medicine & Surgery 7 (4):398-421, 2017

Corticospinal tracts

Control selective voluntary motor control



Brain cross-section

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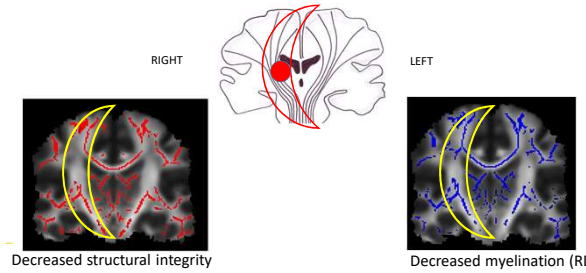
Can we measure the damage to the CSTs caused by CP?



Decreased structural integrity
(**red** = Control group FA > CP group, p< .05)

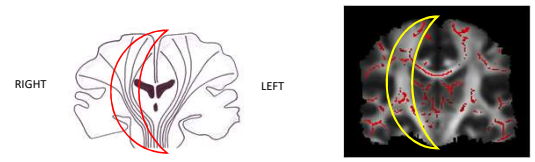
Decreased myelination (RD)
(**blue** = Control group RD < CP group, p<.05)

Brain Imaging Summary

- Significant reduction in structural integrity and myelination of the CSTs in the CP as compared to the control group.
- Children with greater SVMC exhibited greater structural integrity of the CSTs.
- Evidence of neural plasticity post Camp Leg Power. Changes in CSTs were consistent with increased myelination.
- Currently recruiting a "no camp" control group to rule out changes that could be due to maturation.

Center for Cerebral Palsy at UCLA

Does the structure of the CSTs correlate with SCALE?



Correlates with structural integrity (FA)
Red = areas where FA increases with SCALE score, p<.05

Future research

- Early intervention
- Premature babies with CST damage can improve SMC (photo courtesy of Barbara Sargent PhD PT, USC)
- Is it possible to prevent development of mirroring?

- Ankle – foot orthotics
- Common intervention
- Immobilizes the foot & ankle joints
- Should have time without braces for sensorimotor activities

Are there changes in the CSTs post the intervention?

Significant increases in myelination (RD, MD) found
Unpublished data – not shown

Center for Cerebral Palsy at UCLA

UCLA Research Team

- Evan Goldberg, PhD
- Marcia Greenberg MS, PT
- Kent Heberer, PhD
- Shantanu Joshi, PhD
- Carolyn Kelley, DPT
- Joyce Matsumoto, MD
- William Oppenheim, MD
- Christy Skura, DPT
- Loretta Staudt, MS, PT
- Andy Vuong, MS

Camp Counselors

- Jena Bailey
- Priyanka Bhakta
- Faraz Behrooz
- Yuhang Cai
- Jay Chan
- Kate Christoferson
- Isabel Chu
- Samantha David
- Theo Dunsky
- Samantha Fong
- Caitlin Fromknecht
- Lindsay Hoffman
- Rachel Hunsucker
- Julianna Lamm
- Olivia Lee
- Connie Lu
- Vivan Nguyen
- Steven Odom
- Tahoora Sadoughi
- Saskia van Ommeren-Egberts
- Erika Seto
- Kylen Soriano
- Kevin Sullivan
- Kevin Tea
- Stacey Yu

Evaluation PTs

- Bitte Healy MS PT
- Jennifer Pate DPT
- Bianca Mendonca DPT

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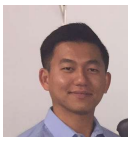
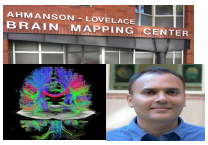
- Waters Foundation

Imaging Research Team



Andy Vuong PhD student



Shantanu Joshi, PhD

Joyce Matsumoto MD
UCLA Pediatric Neurology

Loretta Staudt MS PT

Thanks to the children and families who participated in this study

Thanks for your attention!