Early learning and exploration: Infant-robotic interaction

Thubi H.A. Kolobe, PT, PhD, FAPTA
Department of Rehabilitation Sciences
University of Oklahoma Health Sciences Center
E-mail: hkolobe@ouhsc.edu

NEON Summit
February 10, 2021

Objectives

- Discuss the role that robotic and sensor technology can play in preventive and early intervention.
- Describe how infant-robotic interaction can be optimized to promote movement learning in infants with or at risk for cerebral palsy (CP).
- Evaluate the merits of the Self-Initiated Prone Progression Crawler and other technologies in promoting early learning and exploration in very young infants with or at risk for CP.

Outline

- Early developmental screening and surveillance
- Importance of early mobility
- Movement learning and skill acquisition
  - Reinforcement and Error-based movement learning
- Technological interventions
- Limitation of mobility technology for young children

Collaborators, Students, and Research Assistants

Thubi H.A Kolobe, PT, PhD, FAPTA (PI) - OUHSC

Virginia Commonwealth University: Peter Pidcoe, PhD, DPT

OU College of Engineering: Andrew Fagg, PhD; David Miller, PhD; Lei Ding, PhD; Mustafa Ghazi, PhD

OUHSC College of Medicine: MD; Patricia Williams, MD; Julie Park, MD; Farida Abid, MD; Yu-tze Ng MD

OUHSC College of Public Health: Julie Stoner, PhD

Clinicians: Amy Laizure, PT, Sonja Johns, OTR/L, Laura Rauh, MPT, Amanda Porter, MPT, Elise Hughs, DPT

Students:

Graduate: Barbara Rule, PT, MS, Tricia Catalino, PT, DSc, PCS, Paula Cox, PT, MS, PCS; Michelle Bulanda, PT, MS, PCS, Joshua Southerland: OU

Entry-level: Chelsea Trusdell, Megan Warner, Dakota Brown, Tyler Schmidelburg: Kristen Schumpert, Kimberly Andrews, Emiily North

Under-graduates: Jay Kumar, Evan Fry, Andi Atkin, Niki Bray, Zach Mason

High School: OSSM: Rasheedat Raji, Grace Kim, Molly Haddox

Acknowledgements

National Institutes of Health

National Science Foundation

Presbyterian Health Foundation

National Institute of Neurological Disorders and Stroke

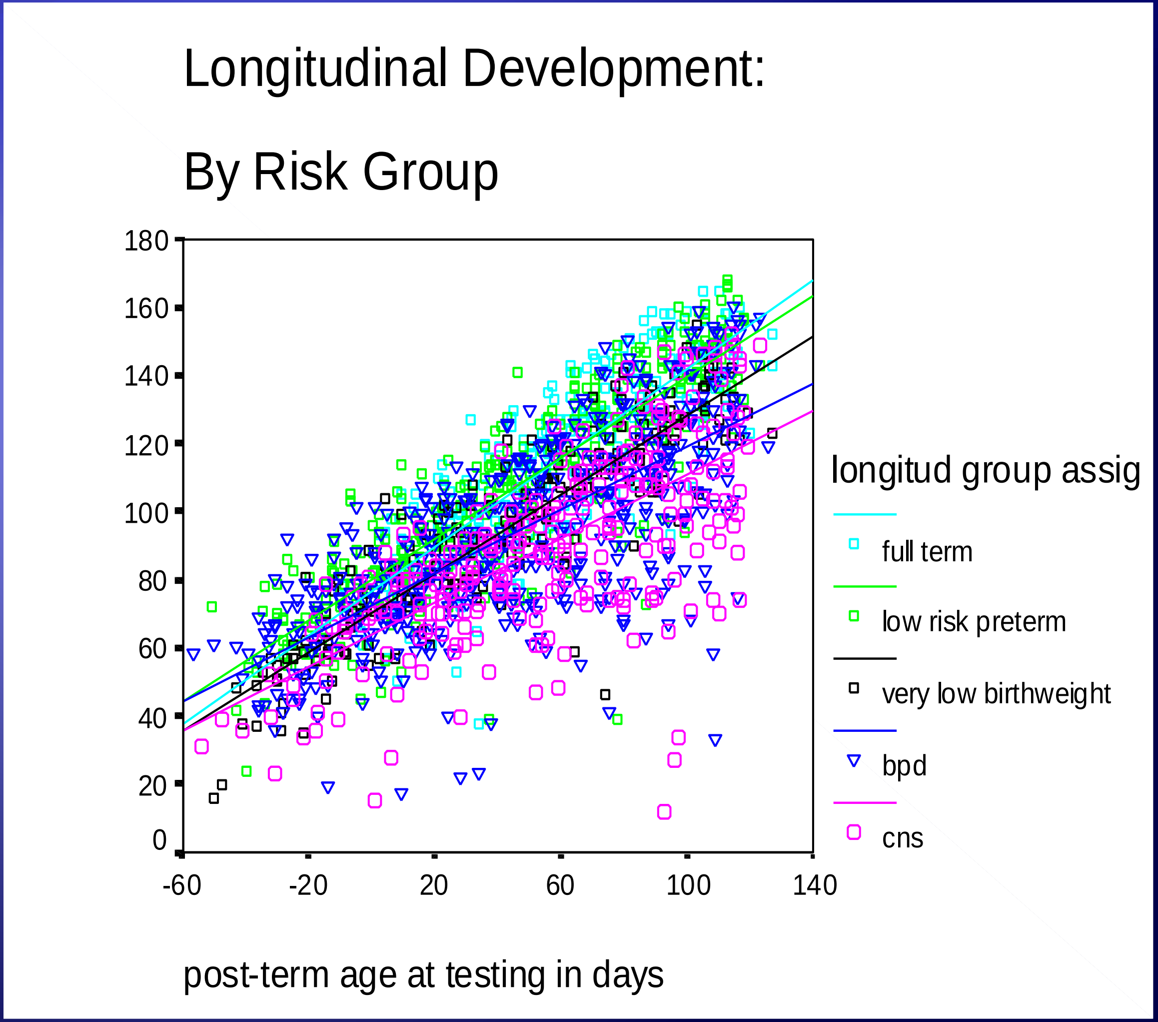
Research Supported by the Section on Pediatrics
American Physical Therapy Association

Foundation for Physical Therapy
PARTNER IN RESEARCH 2012

OU Health Sciences Center
Discovering. Teaching. Healing.

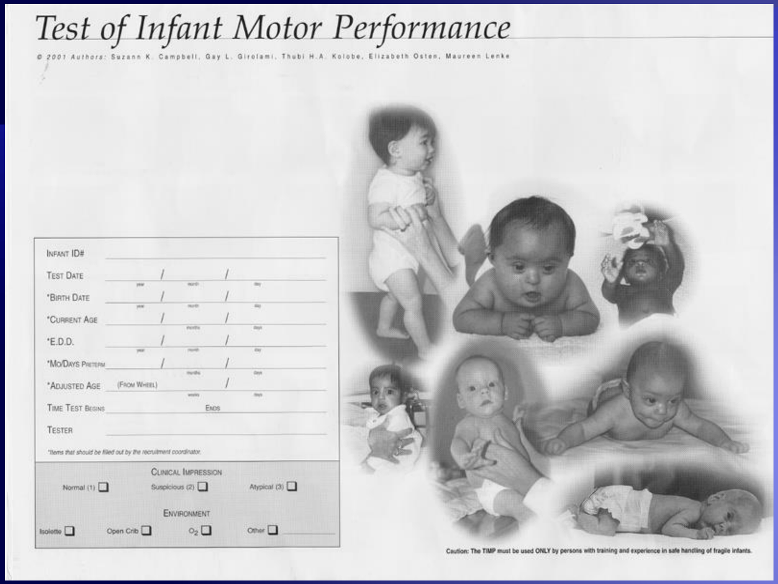
http://preemieprintsinfopage.blogspot.com/2014/01/preemie-prints-nicu-positioner.html#.YCM9V3lMEcA

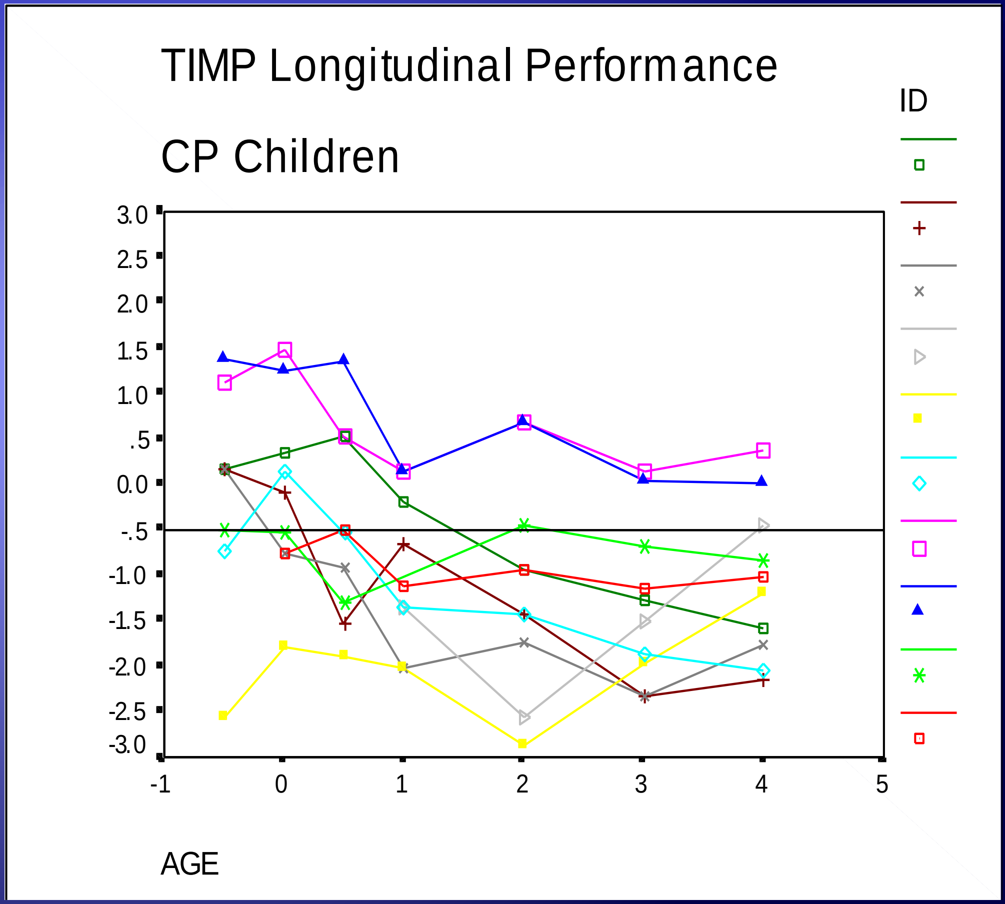
What do we know about early development of NICU graduates?



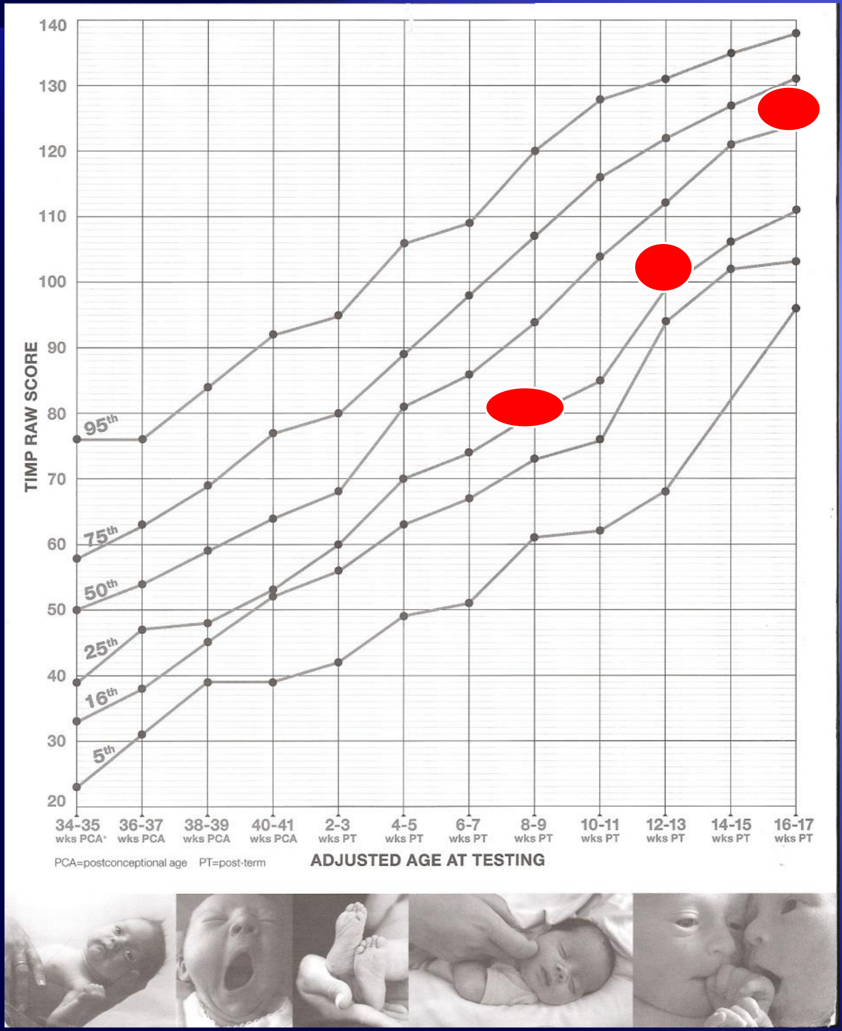
Campbell et al 2001

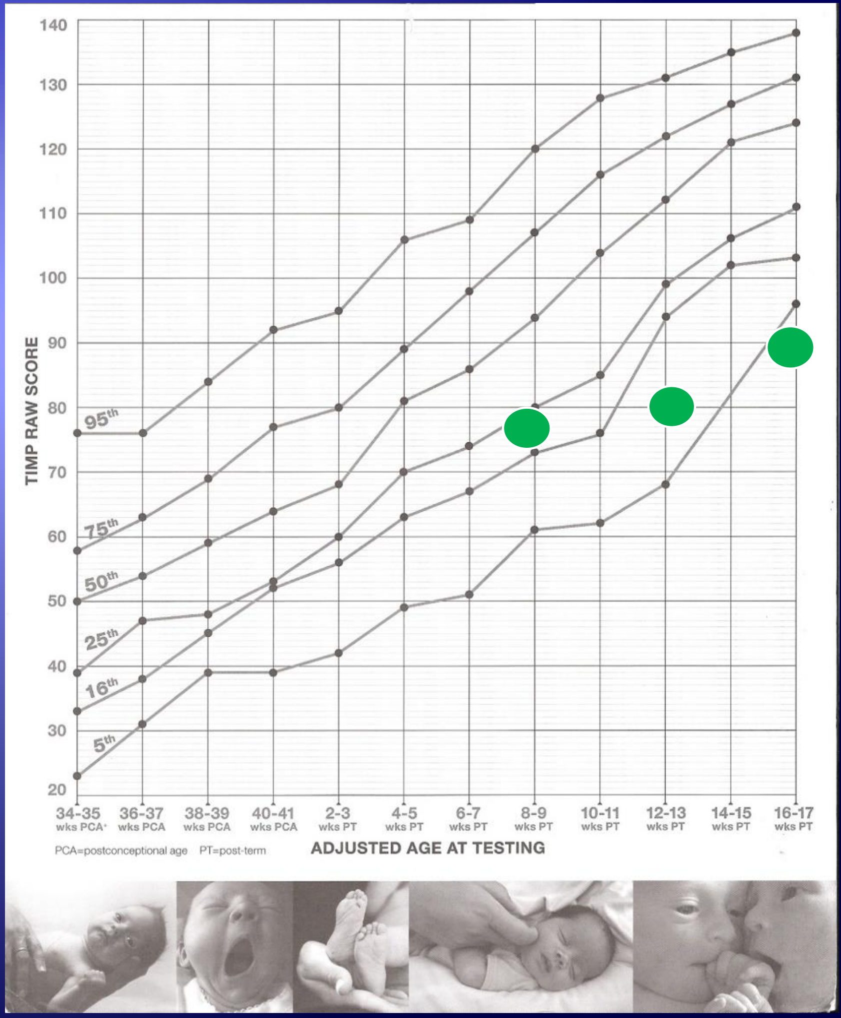
Barbosa et al, 2005



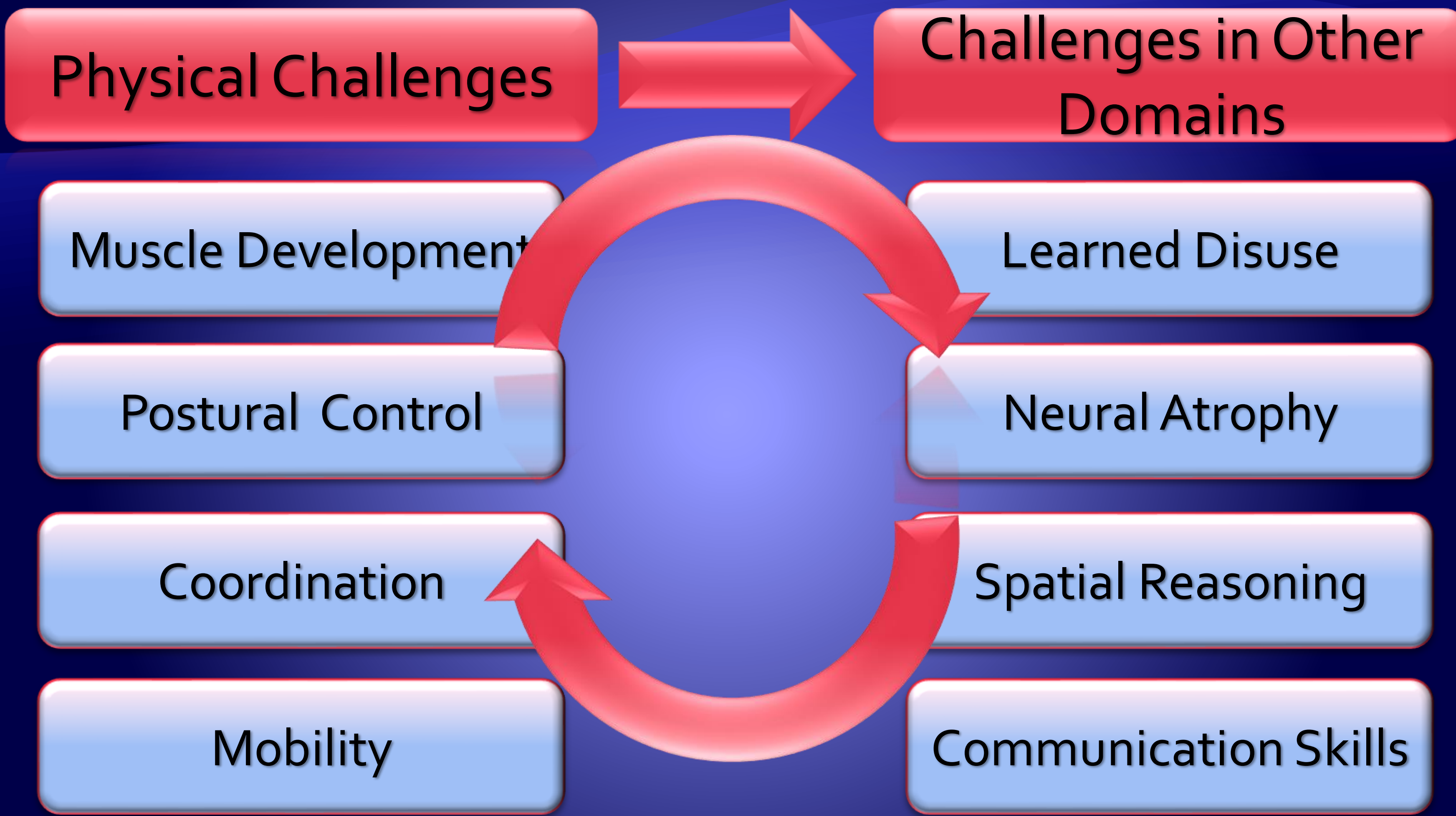


Surveillance using Percentile Ranking Scores





What do we know about early development and children with Cerebral Palsy?



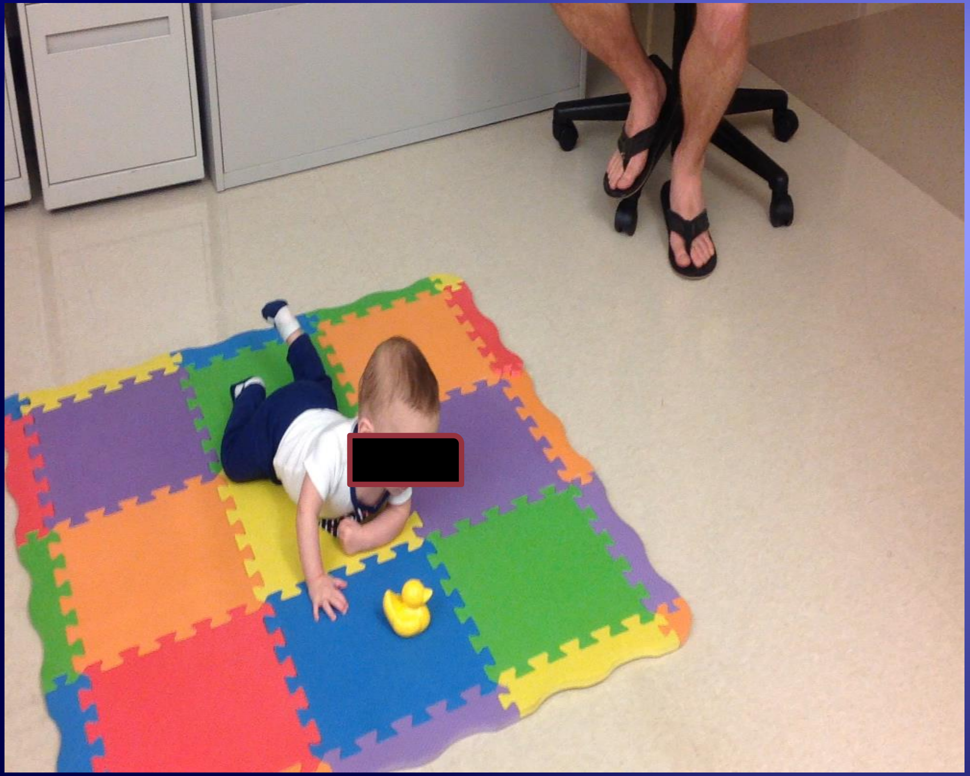
(Haddars-Algra, 2001)

What do we know about mobility in children with CP?

- Most potential achieved in the first 2 years (Morgan et al, 2016; Spittle et al, 2012) (Critical Period)
- Sustainable functional changes associated with neuroplastic changes (brain-behavior connection)
- Reach 90% of their gross motor potential by age 5 (Rosenbaum et al, 2002)

Early Mobility and Exploration Challenges

Movement is the gateway to learning -- it is essential to every aspect of health



What do we know about skill acquisition + neuroplasticity

- Task-Specific training
- Novel (i.e. the child cannot do it by themselves)
- Cognitively oriented
- Incorporate feedback, reward- and error-based learning.
- Maximize the limit of performance
- High repetition

Morgan et al, 2016; Kleim & Jones,2012

How can we incorporate the factors in interventions with young infants?

Technology

- Task-Specific training
- Novel (i.e. the child cannot do it by themselves)
- Cognitively oriented
- Incorporate feedback, reward- and error-based learning.
- Maximize the limit of performance
- High repetition

Morgan et al, 2016; Kleim & Jones,2012

Robotic and Sensor Technology: Requirements

- Machine learning paradigm: designed to optimize behavior by assisting execution of action and achieve outcome based on reward feedback.
- Requirements for use in movement learning are domain-specific policy representation for motor skill and reinforcement learning algorithms that work with the skill (Kober, 2013).

Robotic Reinforcement Movement Learning and Skill Acquisition

- Gained prominence in the movement science literature.

- Potential to accelerate movement learning in adults.

- Posits that motor (action) exploration is essential for reinforcement learning
  - (Wagner * Smith, 2008)

Reinforcement and Error-based Learning

- Reinforcement learning (RML) – a process by which a person or an artificial system (e.g., a robot) can learn a behavior that optimizes the reception of rewards (or penalties).
  - Is based on the selection of actions that are predicted to result in better accumulated outcomes.
    - Sutton & Barto, 1998

- Error-based learning (EBL) uses errors to improve performance by giving the subject information about the direction and magnitude of error resulting from their own actions.
  - Bastian et al, 2016; Diedrichson et al, 2010;

Reinforcement and Error-based Learning: Assumptions

- The individual understands the end-point of the task or skill
- Intact feedback mechanism.
- Increased and high quality sensory feedback.
- Self-initiated movement

Complementary: RML provides a mechanism to improve a performance learned from EBL

Reinforcement and Error-based Learning: Comparisons

RML

- Does not rely on a priori knowledge of a goal but makes use of exploration, which often results in slower learning and higher variability [11]
- Does not directly inform the person about how to improve performance [15]
- Shows better retention
- Basal ganglia believed to be specialized [16]

EBL

- Tends to help a person move closer to the target action, generally requires visual feedback, and promotes faster learning and sensory remapping[13]
- Easier to forget.[14]
- Cerebellum [16-18]

Complementary: RML provides a mechanism to improve a performance learned from EBL

Questions

- Can infants as young as 4 months old use technology to learn a new motor skill? (means-to-an-end)

  Can infants with brain insult use technology to learn a motor new skill? (means-to-an-end)

  If so, how? (mechanism)

  How effective?
  What are the neural connections to learning?

Prone Locomotion

- The earliest type of functional mobility available to infants -- severely compromised in children with CP.

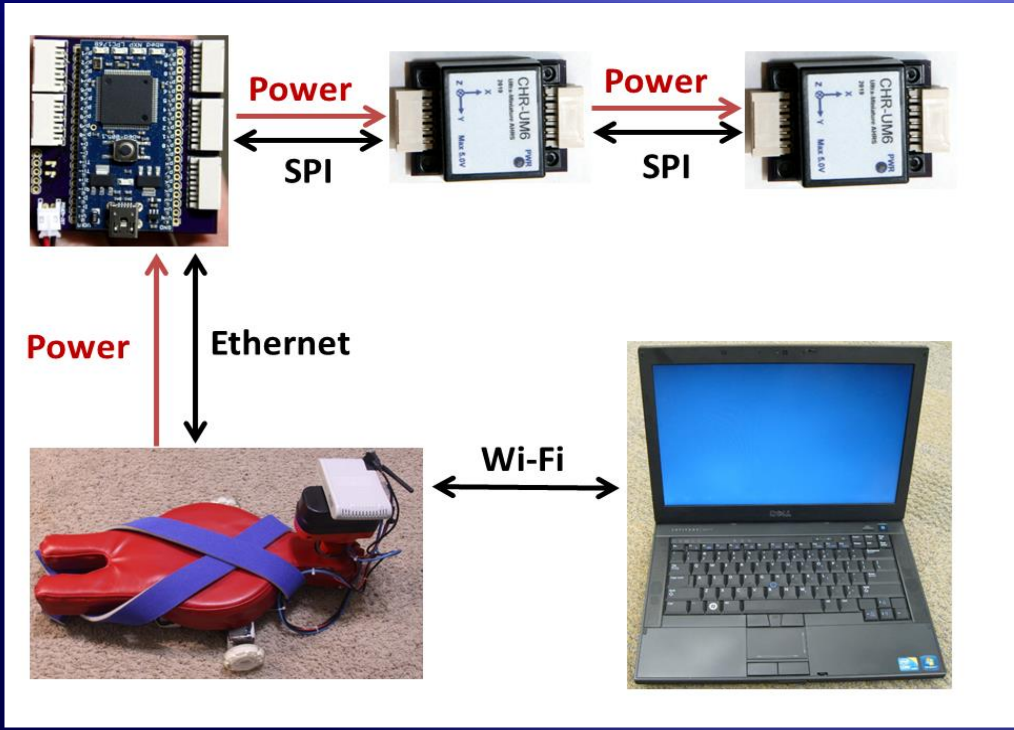
- Develops during a period of highly active synaptic formation in the brain.

- Development during infancy linked to other systems, such as vision, arousal, vestibular function, and perceptual-cognition

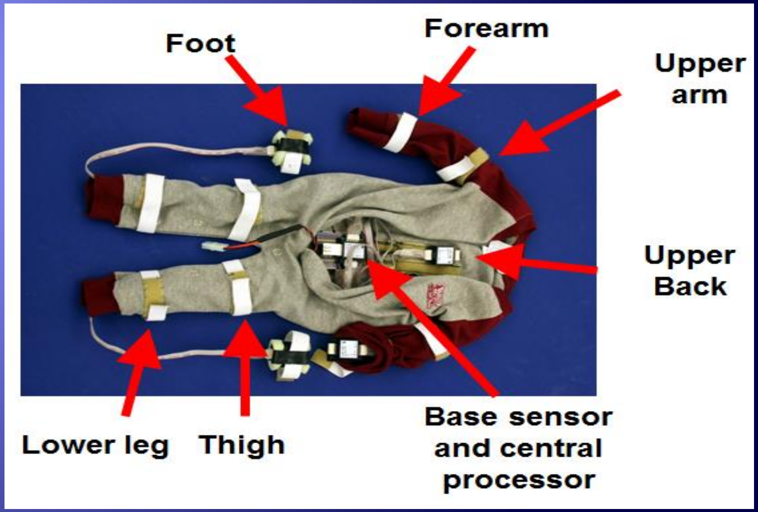
- Anderson et al, 2013; Campos et al, 2012; Herbert, Gross, & Hayne, 2007;

The Self-Initiated Prone Progression Crawler (SIPPC)

Kolobe, Pidcoe, et al, 2007; **Kolobe & Pidcoe, 2015 (US patent); Kolobe & Fagg, 2019**



Motion Capture Sensor Suit



Kolobe & Fagg, 2013

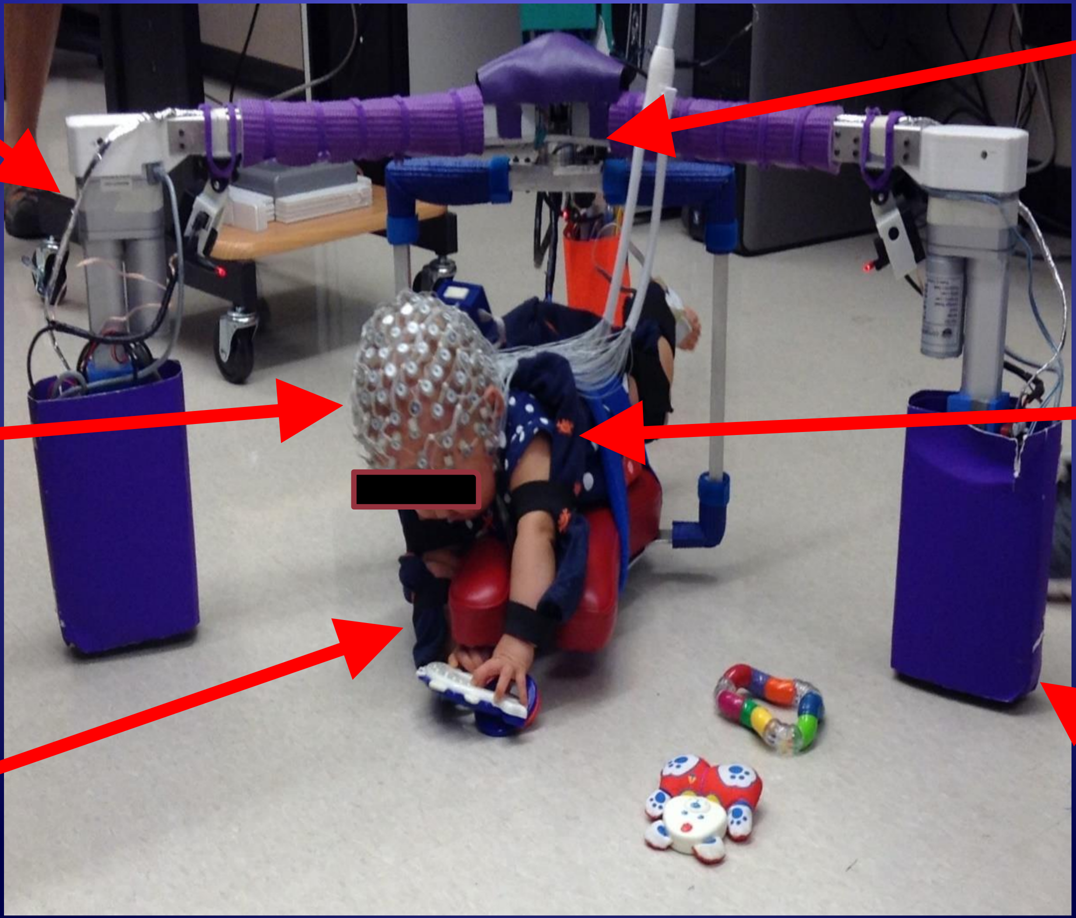
Funded by NICHD & Foundation for Physical Therapy

The Self-Initiated Prone Progression Crawler (SIPPC-3)

Kolobe & Pidcoe, 2015; Gazi, Fagg, Kolobe, Ding, Miller, 2015

Vertical Lift

6-Axis Load Cell



EEG Head Net

Kinematic Capture Suit

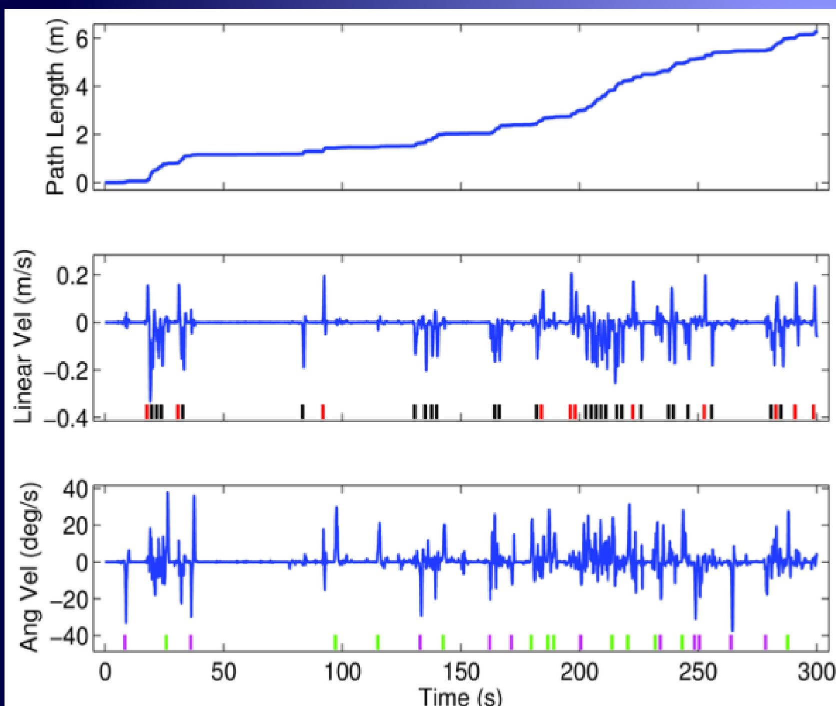
Infant Support

Omni-Wheels

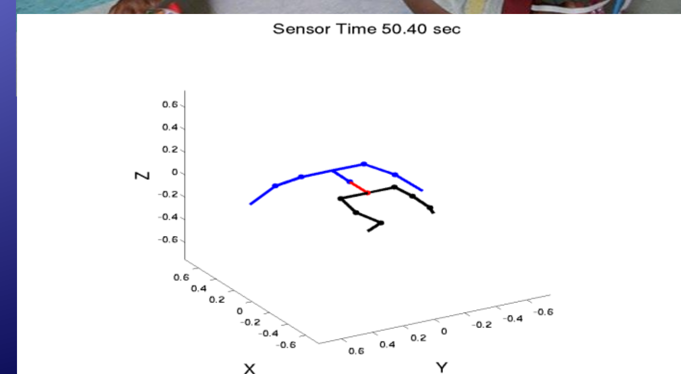
Funded by NSF

Type of information gathered

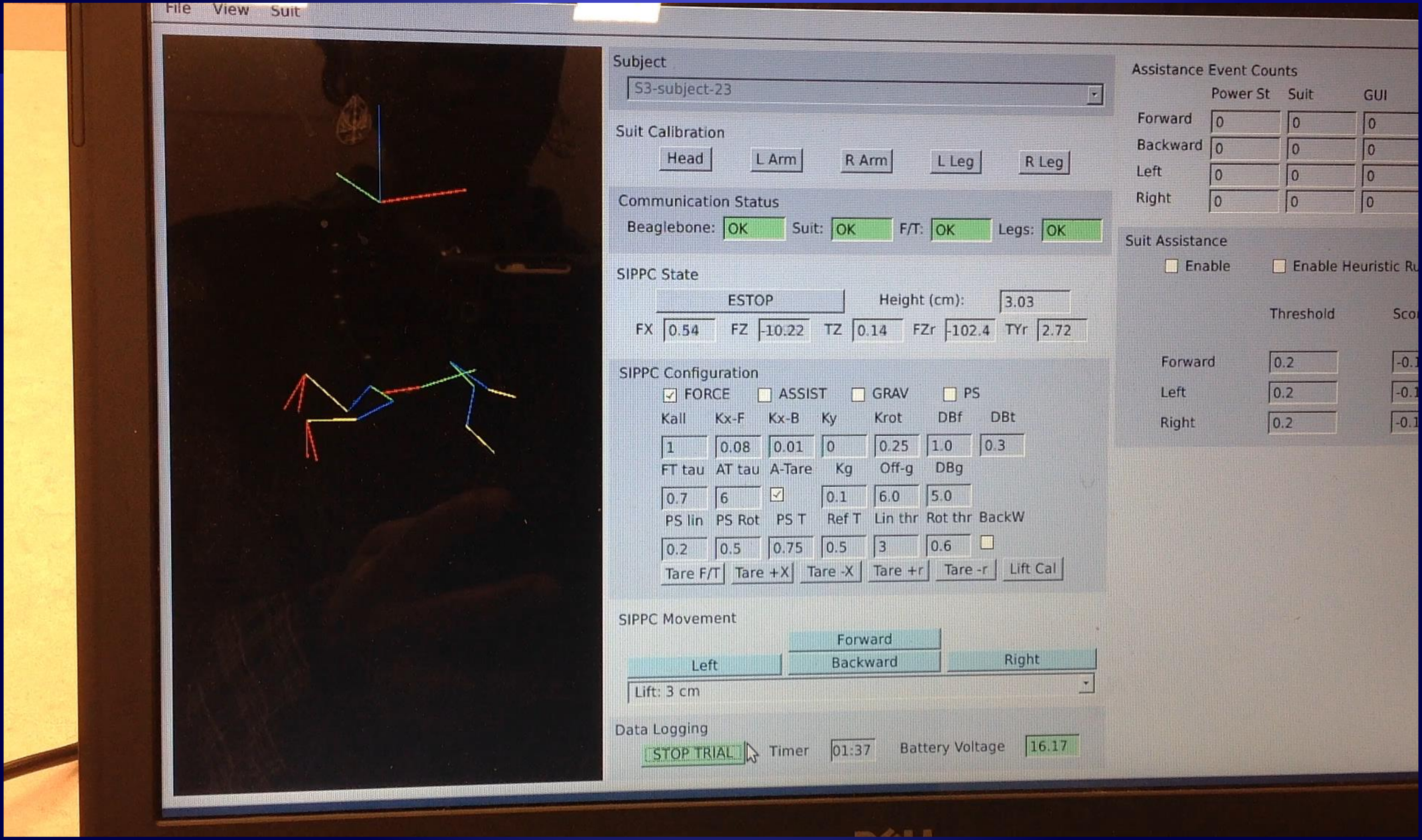
- **SIPPC:** Distance, direction travelled, type and timing of assist, weight shift.



- **Sensor suit:** Kinematics (type, timing, and frequency of arm and leg movements used) position and duration on head control



What the trainer sees and manipulates to assist infant– the interface

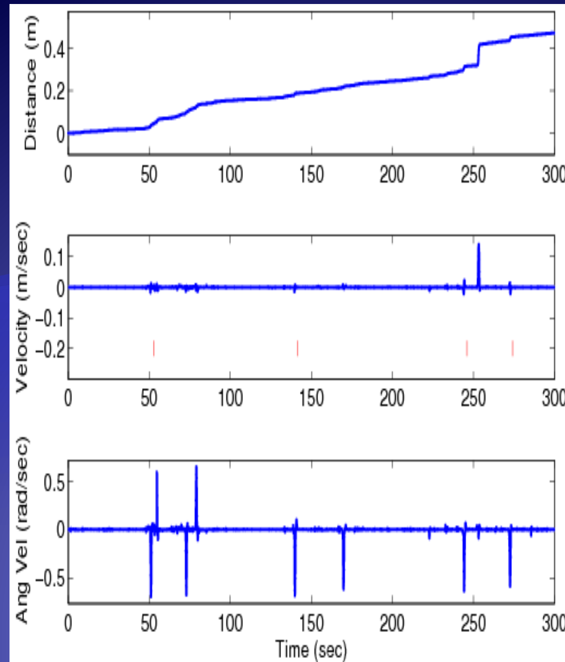


Example of information from the SIPPC across time:

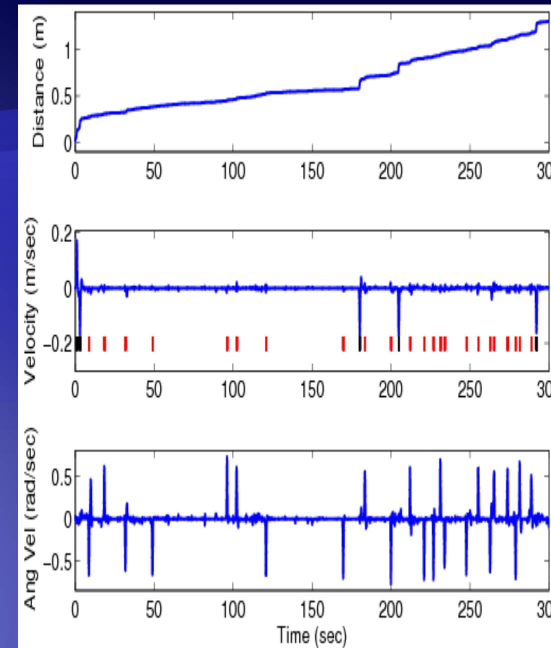
- total distance
- average velocity
- area explored
- weight distribution
- Assist function

Kolobe & Fagg, 2014

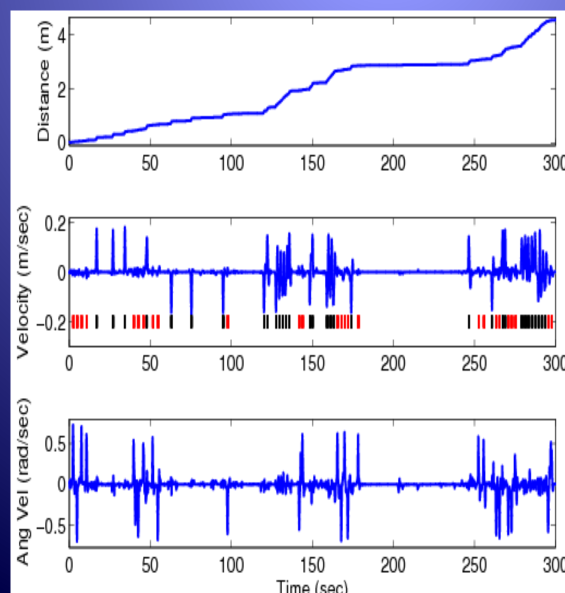
Week 1



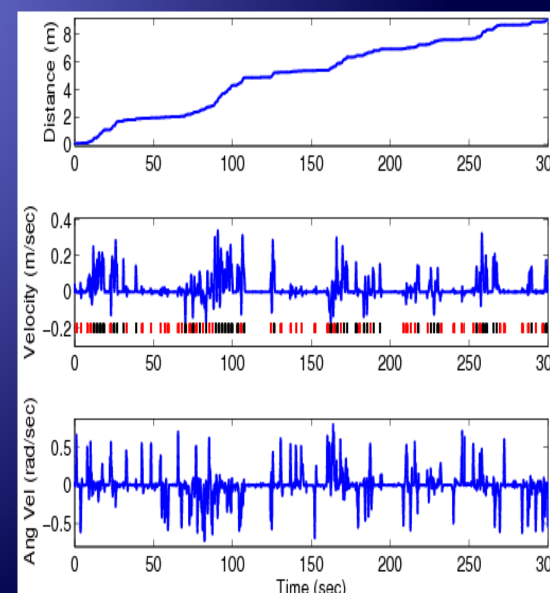
Week 4



Week 8

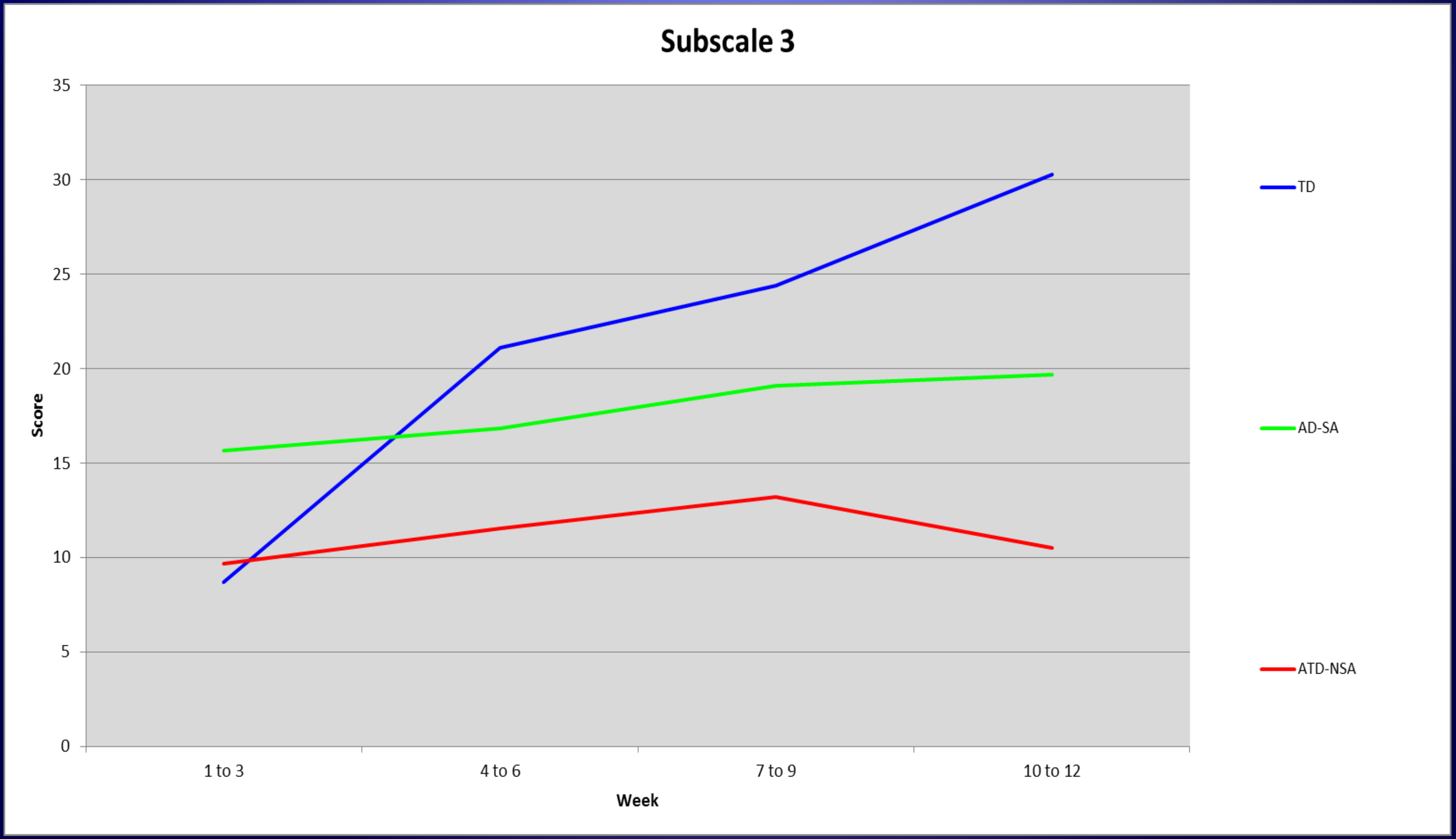


Week 12



Mastery and Proficiency in goal-directed locomotion using the SIPPC

Kolobe & Fagg, 2019

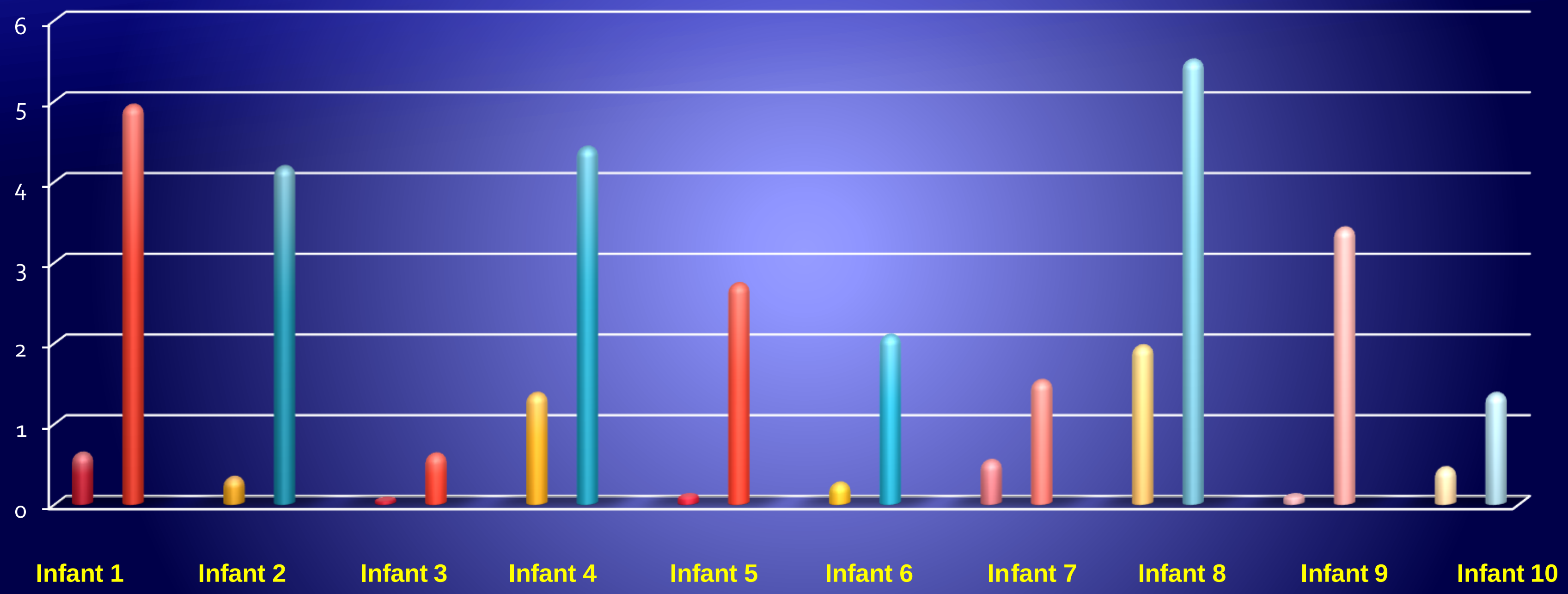


RML with Infants with Down Syndrome

Cox, Kolobe, Fagg, Schmiedeberg, 2015

Change in Mean Linear Distances Traveled

Cox, Kolobe, Fagg, Schmiedeberg, 2015



ANOVA: Difference between initial and greatest distance travelled statistically significant, $F = 4.90$; $p = 0.020$

What about Social Emotional Development?

- Goal Directed Behaviors (GDB): SE measure (Zachry & Mitchell, 2012): measure SE
- Motivation to Move scale – adapted (MTM-a): SE measure (Atun-Einy, Berger, & Scher, 2013)
  - Persistence to move relative to difficulty of task and/or lack of motor control
  - Proportion of the session spent in motion
  - Strength of external stimulus needed to elicit movement
- Movement Observation Coding System (MOCS) Mastery of Propulsion: SGPL measure (Rule, 2010)

Smart, DeGrace, Kolobe, 2016

What have we learned?

Infants are capable of engaging in robotic reinforcement learning. Importance of active participation

Increase in duration of head control (>3/5 min) preceded emergence of coordinated arm and leg movements.

Combination of error and reward based learning = better performance.

High correlation between an increase in frequency of SE behaviors and SGPL in infants at with or at risk for CP.

Emergence of simultaneous bilateral arm (and leg movement) associated with mastery of prone locomotion.

High correlation between frequency of spontaneous arm and leg movements and emergence of mastery (goal-directed strategies) critical threshold.

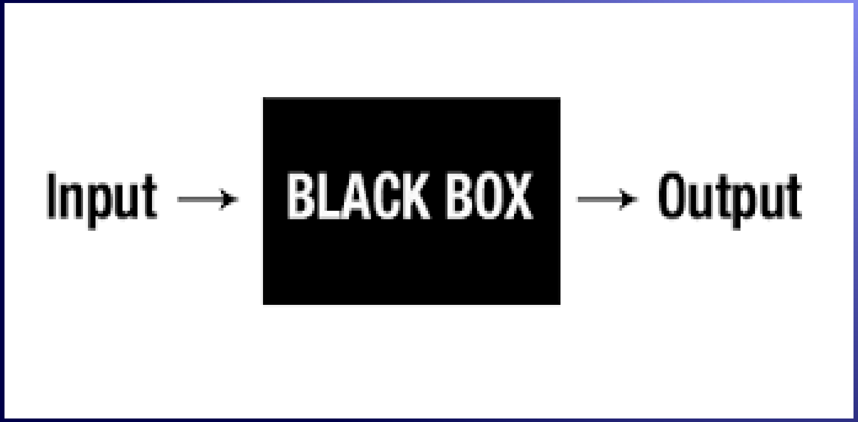
Slow learning curve in infants with low cognition

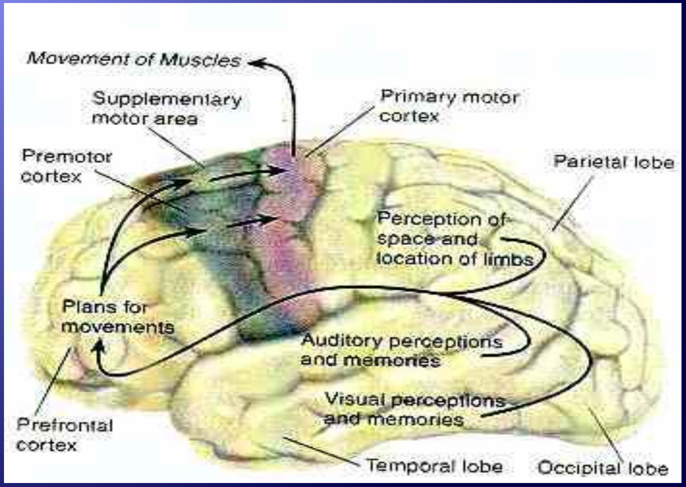
No Reaching… No prone locomotion

Kolobe & Fagg, 2019; Kolobe et al, 2015; 2017

What about neuroplastic changes?

How can we use technology to capture changes in the brain?





Carlson, Neil *Physiology of Behavior*, 6th ed. Needham Heights, MA: Allyn and Bacon, 1998

Brain Structure-Function Connection: Neuroplastic Responses

- Relieving spasticity is not sufficient therapy to cause long term change (Hoare et al, 2010).
- Repetition not sufficient to attain meaningful changes in motor behavior if participants are not actively engaged in an intervention (Kleim and Jones, 2010).
- Pathophysiological evidence for decreased cortical inhibition and results of increasing inhibition (Benninger *et al.*, 2011)
- Evidence that you gain what you train (Sakzewski et al, 2011)
- Newly learned movements are represented over large cortical areas (Kleim et al. 1998, Plautz et al. 2000)

Principles of Experience-Dependent Neural Plasticity and Their Translation to the Damaged Brain

Use it or loose it

Use it and improve it

Repetition matters

Intensity matters

specificity

Timing matters

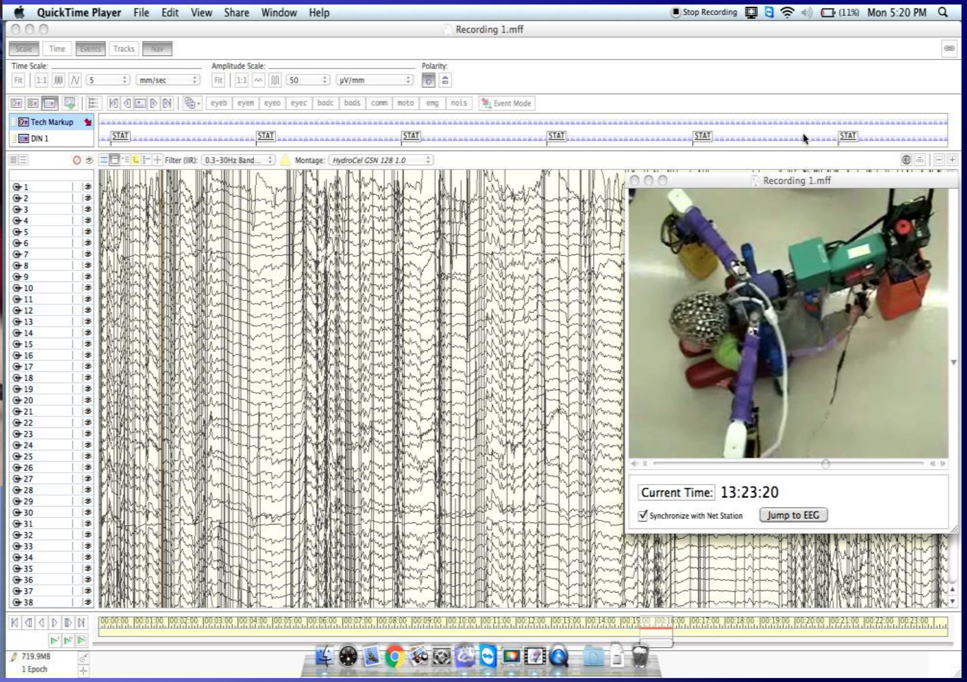
Salience matters

Age matters

Transference

Kleim & Jones: Principles of Plasticity, 2012

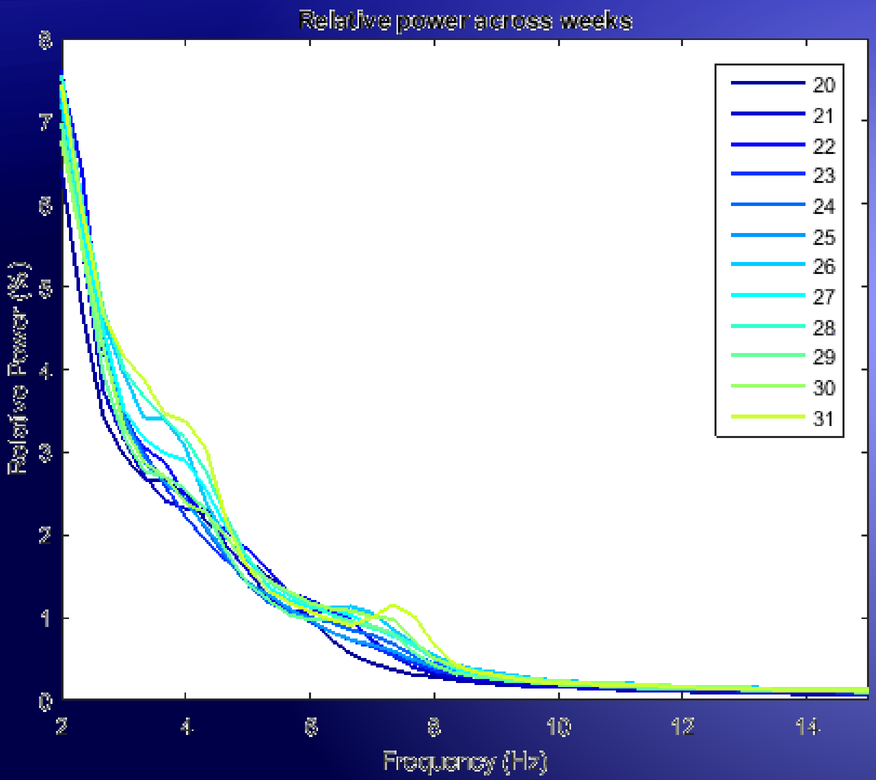
EEG

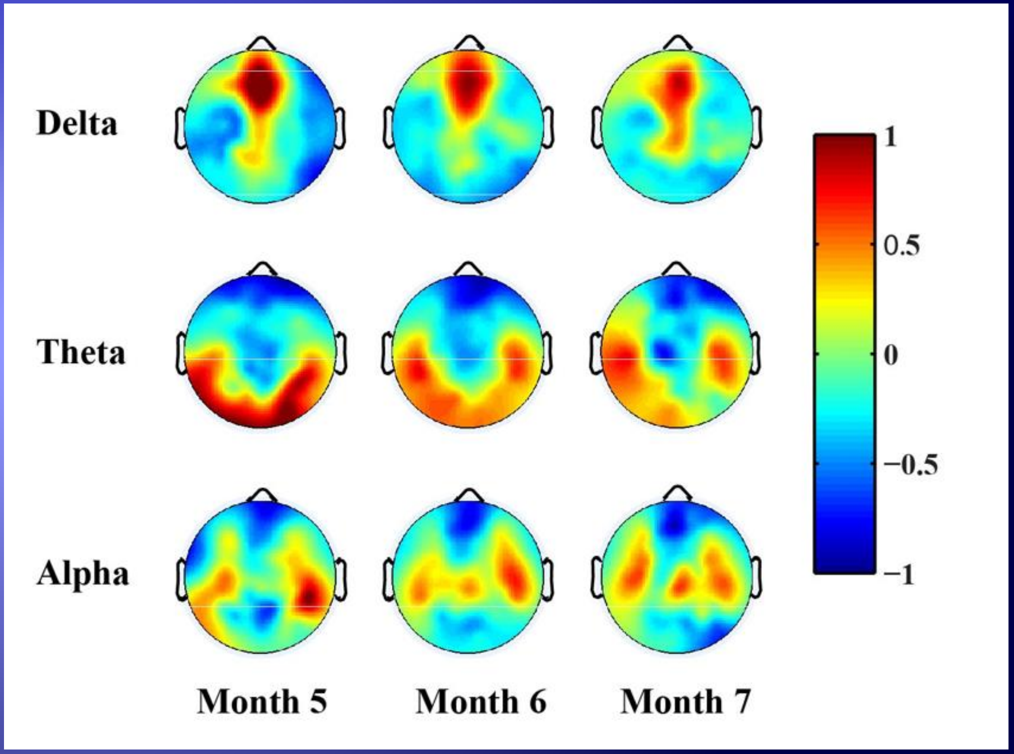


Xiao, Patino; Fagg, Kolobe, Miller, & Ding (2016)

EEG data - TD

Xiao, Patino; Fagg, Kolobe, Miller, & Ding (2016)





- *Relative power calculated from 1 to 30 Hz*
- *Each plot color represents different weekly age PSD*

- ***Frequency bands at each month defined by clustering results***
- ***Color bar represents normalized relative power***
- ***Top of each topographic map denotes the front of scalp***

Mobile technology

https://sites.usc.edu/dimpl/

ZeroG technology – upright functions and walking

https://www.aretechllc.com/products/zerog-gait-and-balance/

Technology Limitations

Access

Cost

Specificity

Portability

Summary

- Infants with or at high risk for CP can learn complex skills such as prone locomotion
- Importance of active participation in in skill acquisition
- Bypassing rate limiting factors can enhance skill acquisition or adaptive learning
- Significance of other domains must be considered –cognition
- Ability to reach is a major impediment to prone locomotion
- Task-specific training vital
- More work needed on understanding neuroplastic changes
- Technology development must be tailored to infant development

Challenge:
Institute of Medicine, 2009

"By 2020 -- 90% of clinical decisions will be supported by accurate, timely, and up to date clinical information, and will reflect the best available evidence on what works for whom, under what circumstances"

More work needed!

Questions?

TIMP References

- Barbosa VM. Campbell SK. Berbaum M. Discriminating infants from different developmental outcome groups using the Test of Infant Motor Performance (TIMP) item responses. Pediatric Physical Therapy. 2007; 19(1):28-39.
- Barbosa VM, Campbell SK, Sheftel D, Singh J, Beligere N. Longitudinal performance of infants with cerebral palsy on the Test of Infant Motor Performance and on the Alberta Infant Motor Scale. Phys Ther Occ Ped, 2003; 23:7-29.
- Campbell SK, Swanlund A, Smith E, Liao P-j, Zawacki L. Validity of the TIMPSI for estimating concurrent performance on the Test of Infant Motor Performance. Pediatr Phys Ther 2008;20:3-10.
- Campbell SK. Levy P. Zawacki L. Liao PJ. Population-based age standards for interpreting results on the test of motor infant performance. *Pediatric Physical Therapy. 2006; 18(2):119-25.*
- Campbell SK, Hedeker D. Validity of the Test of Infant Motor Performance for discriminating among infants with varying risk for poor motor outcome. *J of Pediatr*. 2001;139:546-51.

SIPPC References

- Campbell SK, Kolobe THA, Wright BD, Linacre JM. Validity of the Test of Infant Motor Performance for prediction of 6-, 9-, and 12-month scores on the Alberta Infant Motor Scale. Developmental Medicine and Child Neurology. 2002; 44:263-272.
- Campbell SK, Kolobe THA, Osten ET, Lenke M, Girolami GL. Evidence for the Construct Validity of the Test of Infant Motor Performance, Physical Therapy.1995; 75(7):585-596.
- *Ghazi, M., Nash, M., Fagg, A. H., Ding, L., Kolobe, T. H.A. and Miller, D. Novel Assistive Device for Teaching Crawling Skills to Infants. Springer Tracts in Advanced Robotics, 2016.113, DOI 10.1007/978-3-319- 27702-8_39.
- Kolobe T, Fagg, A. Robotic Reinforcement and Error-based Movement Learning during Skill Acquisition in Infants with and without risk for Cerebral Palsy. Dev Med Child Neurol, 2017; 59: 76. doi:10.1111/dmcn.116_13511
- Kolobe T. H.-A., Fagg, A. H., Pidcoe, P., Williams, P. (2015) Effectiveness of Reward- and Error-Based Movement Learning in Enhancing Self-Initiated Prone Locomotion in Infants with or at Risk for Cerebral Palsy. Proceedings of the the World Confederation of Physical Therapy Congress. Abstract A-613- 0000-03707. Singapore. May. ***(Selected as a State of the Art Presentation and awarded the Outstanding Platform Presentation Award.)***
- Kolobe, T.H., Pidcoe, P., Warner, M. Use of Robotics to Promote Prone Locomotion in Infants with and without Cerebral Palsy. Pediatric Physical Therapy, 2013, 25(1) 85-86.
- Kolobe, T.H.A, Fagg, A. The effect of sensor robotic technology on the development of prone mobility in infants with or at risk for cerebral palsy. *Developmental Medicine and Child Neurology. 2014,56 (s5), 60.*
- Kolobe, T.H., Pidcoe, P., Warner, M. Use of Robotics to Promote Prone Locomotion in Infants with and without Cerebral Palsy. Pediatric Physical Therapy, 2013; 25(1) 85-86.
- Kolobe THA, Bulanda M, Susman L. Predictive validity of the Test of Infant Motor Performance at Pre-school Age. Physical Therapy. 2004; 84: 1144-1156.
- Miller, D. P., Fagg, A. H., Ding, L., Kolobe, T. H., and Ghazi, M. A. Robotic crawling assistance for infants with cerebral palsy. In Proceedings of the AAAI’15 Workshop on assistive technologies emerging from artificial intelligence applied to smart environments. AAAI Press. 2015.
- *** Xiao, R., Xiao Q., Patino, A., Fagg, A.H., Kolobe, H.A., David P. Miller, D.P., Ding, L. Characterization of infant mu rhythm immediately before crawling: A high-resolution EEG study. NeuroImage, 2016;146, 47-57.**

EI References

- [1]Spittle A, Orton J, Anderson PJ, Boyd R, Doyle LW. Early developmental intervention programmes provided post hospital discharge to prevent motor and cognitive impairment in preterm infants. Cochrane Database of Systematic Reviews 2015, *Issue* 11. *Art. No.: CD005495. DOI: 10.1002/14651858.CD005495.pub4.*
- [2] Braadbaart, L, Williams, JHG, Waiter, GD. Do mirror neuron areas mediate mu rhythm suppression during imitation and action observation? International Journal of Psychophysiology, 89 (1), 99–105, 2013.
- Gonzalez SL, Reeb-Sutherland BC and Nelson EL. Quantifying Motor Experience in the Infant Brain: EEG Power, Coherence, and Mu Desynchronization.Front. Psychol. 7:216, 2016 doi: 10.3389/fpsyg.2016.00216
- Braadbaart, L., Williams, J.H.G., Waiter, G.D. (2013). Do mirror neuron areas mediate mu rhythm suppression during imitation and action observation? International Journal of Psychophysiology, 89 (1), 99–105.
- Marshall, P.J., Bar-Haim, Y., and Fox, N.A. (2002): Development of the EEG from 5 months to 4 years of age. Clin Neurophysiol. 113(8): 1199-1208

EI References

- Fletcher RW, Fletcher SW. Clinical Epidemiology. The essentials. 4th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2005; 35-58.
- Kolobe THA. Bulanda M, Susman L: Predictive validity of the Test of Infant Motor Performance at Pre-school Age. Phys Ther, 2004,84: 1144-11564.
- Molfese VJ, Thomson B. Optimality versus complications: Assessing predictive values of perinatal scales. Child Dev 1985;56:810-823.
- Spittle AJ, Doyle LW, Boyd RN. A systematic review of the clinimetric properties of neuromotor assessments for preterm infants during the first year of life. Dev Med Child Neurol 2008;50:254-266.
- Spittle AJ, Boyd RN, Inder TE, Dole TE. Predicting motor development in very preterm infants at 12 months' corrected age: the role of qualitative magnetic resonance imaging and general movements assessments. Pediatrics. 2009;123(2):512-517.