

Transcutaneous Spinal Neuromodulation Combined with Task-Specific Training Restores Sensorimotor and Autonomic Function After 12 Years of Clinically Complete SCI

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CHALLENGING THE PERMANENCE OF COMPLETE SCI: NEURAL PLASTICITY AND FUNCTIONAL RECOVERY

- For decades, clinically complete spinal cord injury (SCI) has been defined as a permanent loss of descending control. However, emerging evidence demonstrates that **the adult human spinal cord retains a robust, underutilized capacity for functional reorganization**. In severe SCI, disruption of supraspinal-spinal connectivity impairs sensorimotor integration, making restoration of sensory input—particularly **load-dependent proprioceptive feedback**—a **critical prerequisite for re-enabling coordinated movement**.
- While prior studies have shown partial motor recovery in chronic SCI using intensive activity-based training and invasive epidural stimulation, far less is known about restoring **motor and autonomic function concurrently using non-invasive neuromodulation**.
- We **hypothesize** that latent neural plasticity can be re-engaged even >12 years post-injury through a targeted combination of **transcutaneous spinal cord stimulation (tSCS)** at C5/C6, T11/T12, and L1/L2 paired with **high-repetition, sensory-motor training**.
- To maximize volitional drive and sensorimotor engagement, we integrate **adaptive exoskeletons** (Ekso Bionics NR and Wandercraft Atalante) with systematically decreasing robotic assistance (100% → 55%).
- This longitudinal single-subject study evaluates whether a comprehensive, repetitive protocol combining tSCS with adaptive robotic-assisted training can **re-establish functional supraspinal-spinal connectivity and simultaneously restore coordinated motor and autonomic functions** in an individual with chronic AIS-A SCI. These findings challenge existing definitions of injury completeness and broaden the therapeutic window for meaningful recovery.

METHODS

Subject

- Single male with chronic complete SCI (T4–T5), **>12 years post-injury (AIS-A)**.
- Additional **right C5–C7 brachial plexus root avulsion** causing complete right upper-limb deafferentation.

Study Design

- Longitudinal single-case study** (2020–present).
- 3 training sessions/week**, combining neuromodulation and task-specific, high-repetition activity-based training.

Interventions

1. Transcutaneous Spinal Cord Stimulation (tSCS)

- Electrode targets: **C5/C6, T11/T12, L1/L2**.
- Training parameters: **0–80 mA, 30 Hz, 10 kHz** carrier, consistent with published protocols.

2. Activity-Based Neurorehabilitation: Constraint-induced, high-repetition training including:

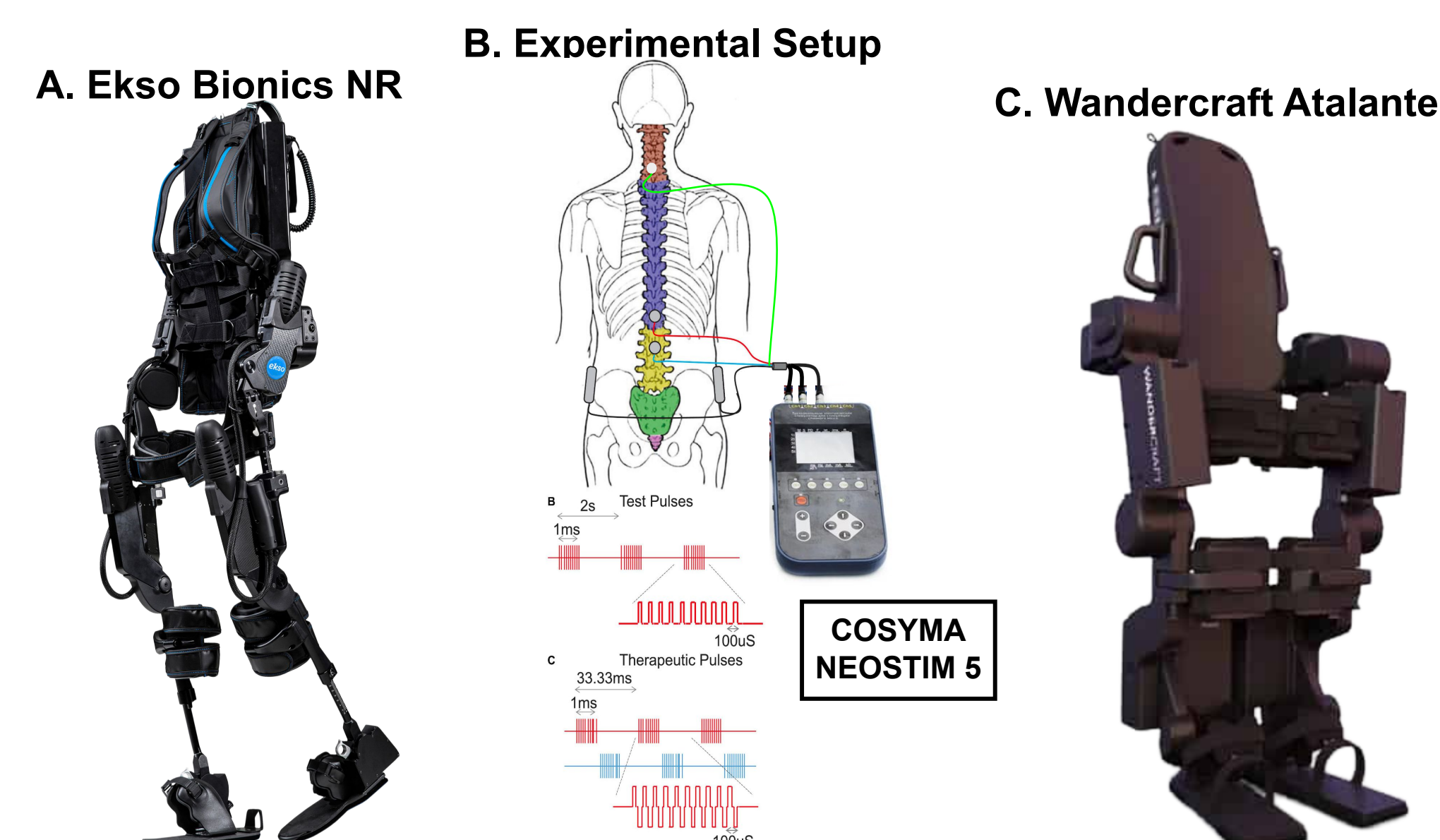
- Exoskeleton-assisted treadmill walking** (274+ sessions).
- Therapist-facilitated overground stepping.
- Sit-to-stand transitions.
- Recumbent elliptical (NuStep).
- Additional load-dependent sensory-motor tasks.

Robotic Systems

- Ekso Bionics NR** and **Wandercraft Atalante** exoskeletons.
- Adaptive assistance reduced in 5–10% **increments** (100% → ~55–45%) to increase volitional drive during initiation and swing phases.

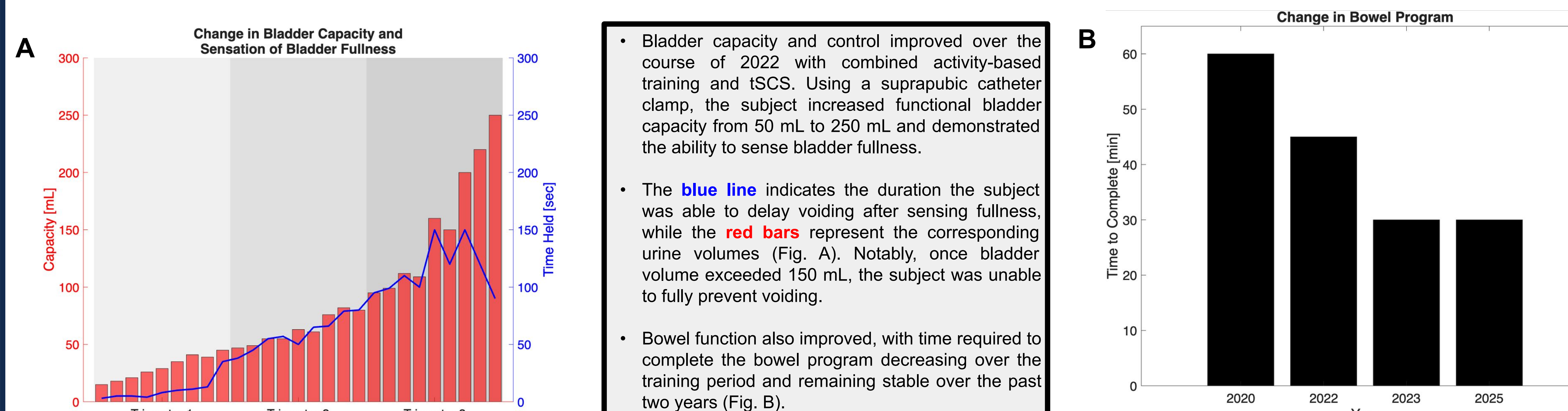
Monitoring & Data Collection

- EMG** for muscle activation.
- Kinematic/kinetic gait analysis** for stepping performance and movement quality.

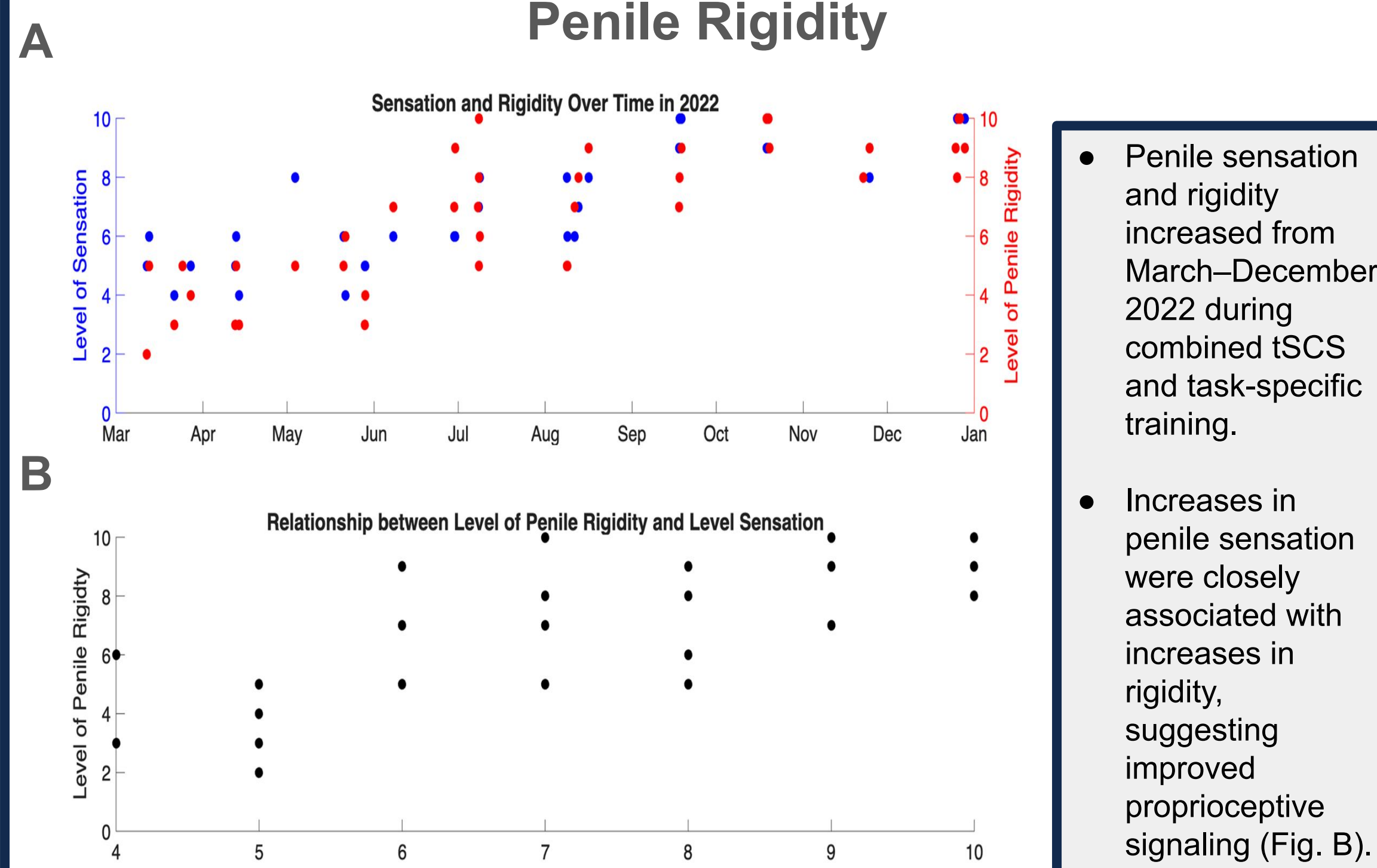


RESULTS

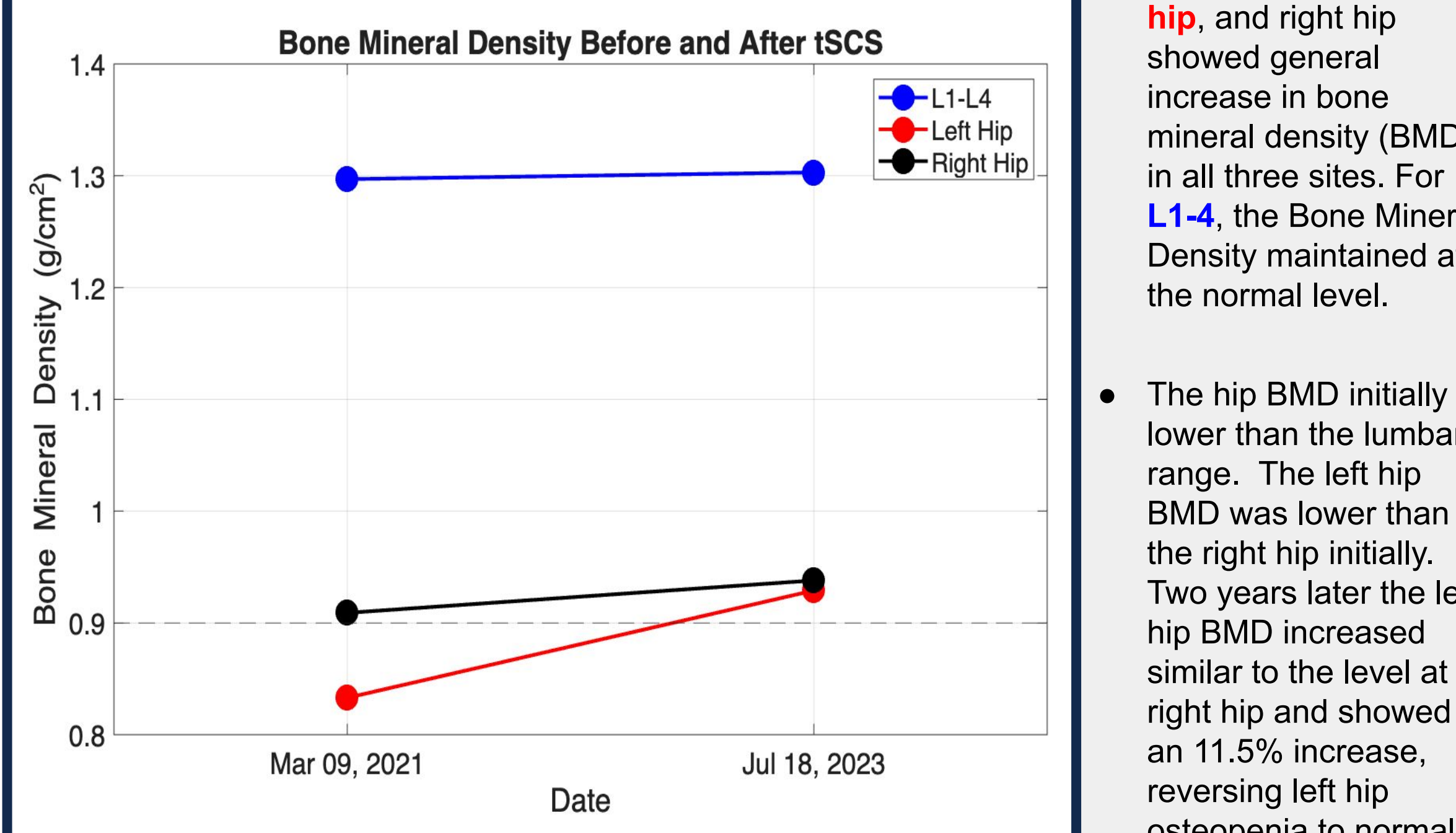
Improvement in Bladder Sensation and Reduction in Bowel Program



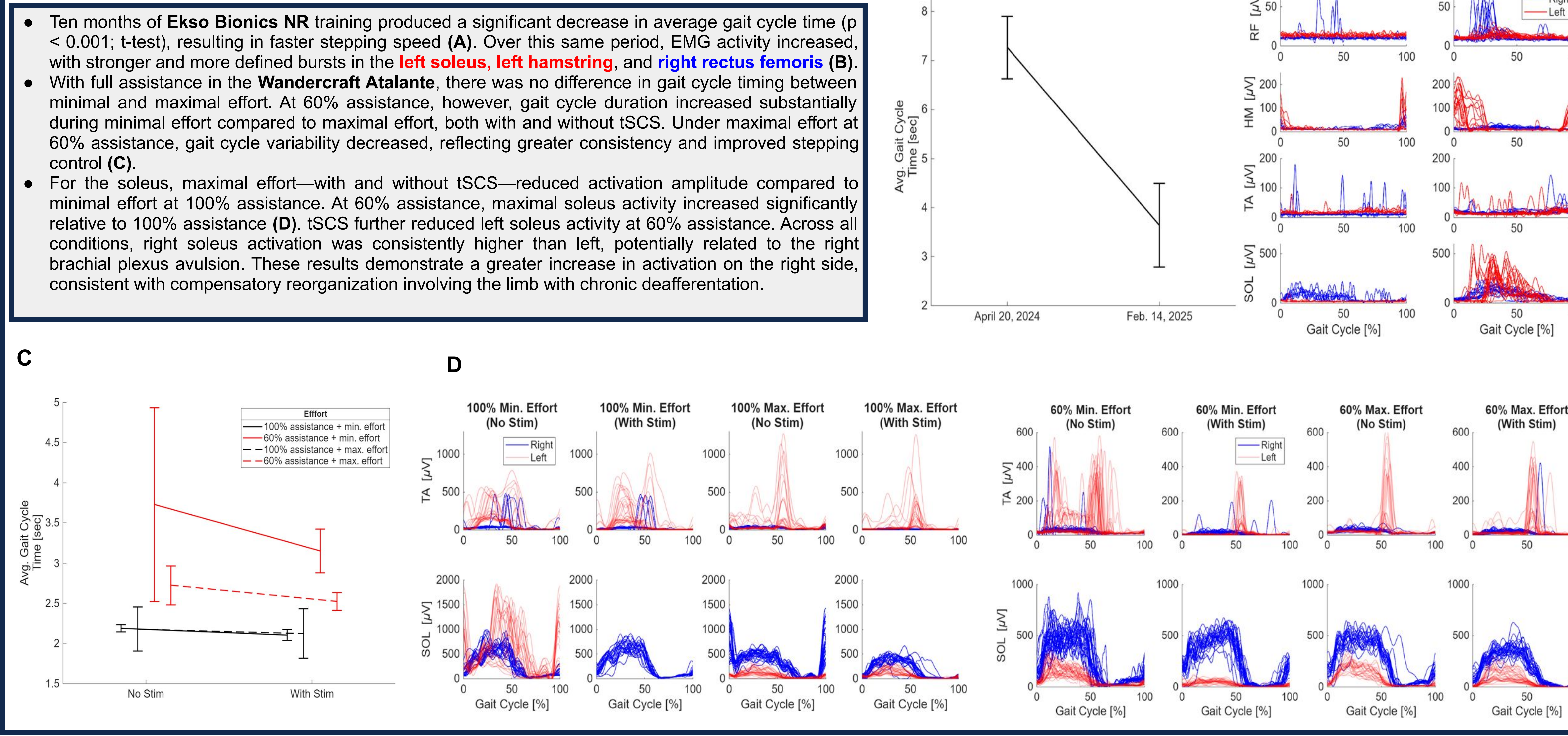
Increased Penile Sensation relates to Increased Penile Rigidity



Increases in Bone Density After 2 years of tSCS+ABNT



Muscle Activity Responds to Exoskeleton Reduced Assistance and Cortical Input



ADDITIONAL QUALITY OF LIFE IMPROVEMENTS

Sensorimotor & Functional Recovery

- Improved trunk control and postural stability during seated and standing activities
- Increased endurance, cardiovascular health, and reduced spasticity and clonus
- Greater confidence and safety during exoskeleton and gait training
- Improved circulation and skin integrity

Autonomic Function

- Improved cardiovascular regulation (reduced orthostatic hypotension and more stable blood pressure)
- Enhanced thermoregulation and sweating response
- Decreased frequency of urinary tract infections and autonomic dysreflexia episodes, resulting in fewer medical visits

Health & Wellness

- Reduced musculoskeletal and neuropathic pain
- Improved sleep quality and energy levels
- Enhanced bowel and bladder function
- No pressure injuries or related complications

Psychosocial & Emotional Wellbeing

- Enhanced mood, motivation, and confidence
- Greater optimism about recovery potential and long-term independence

CONCLUSION

- Effective Learning and Control:** The adaptive exoskeleton for rehabilitation facilitates a learning process that improves subjects' control over stepping. This progress can be quantified, with subject achieving stepping in exoskeleton at 55% robot-assistance.
- Learning Phenomenon:** A learning phenomenon was observed, characterized by consistent improvements in step cycle parameters and muscle activity as robot assistance levels decreased.
- Enhanced Sensations and Walking Patterns:** Subjects reported increased proprioceptive sensations, leading to more effective walking patterns and a faster step cycle.
- Consistent Adaptation:** Through repetitive training, subject consistently adapted to reduced assistance levels.
- Neural Plasticity and Functional Recovery:** These results are consistent with a greater level of functional supraspinal-spinal connectivity.
- Effective Strategy:** Reducing robot assistance effectively helped re-establish functional connectivity between the brain and spinal circuitry, improving stepping.

ACKNOWLEDGMENTS

I sincerely thank all of my team members for their dedication and support, including the staff at NextStep LA Paralysis Recovery Center and Reneu Health, as well as Pat and Nancy McKee, Ross Mason, and Jason and Debbie Brown (HINRI.org). I am also grateful to the MAS Family Foundation, Veterans United Foundation, Paralyzed Veterans of America, Swim with Mike Foundation, and the Dana & Albert R. Broccoli Charitable Foundation for their generous support. Finally, I extend my deepest gratitude to the Burroughs Wellcome Fund for honoring me as a distinguished SIn 2025 TPDA recipient, an acknowledgment that makes this work possible.