Title: Wearable Pediatric Sensory Transfer Devices for Improved Neuromotor Control of Impaired Limbs after Spinal Cord Injuries

Motivation: Sensory feedback is crucial to the development of neuromotor skills in children. The loss of haptic sensation or proprioception in the extremities due to neurological diseases or physical trauma can significantly diminish a child's ability to achieve fine, dexterous motor control in their affected limbs, or to control any prostheses or orthoses prescribed for rehabilitation. These sensory challenges often result in the disuse of the affected limbs or the rejection of assistive devices, which can subsequently lead to the overuse of contralateral limbs and other physical or psychological problems that may persist or, in some cases, worsen as a child develops. There exist surgical means of restoring sensory capabilities that involve relocating healthy nerves to sensory-impaired areas (nerve transposition), but these methods are expensive and invasive. Alternative approaches that are less invasive and more amenable to pediatric use are desperately needed.

Our Solution: We propose the development of a ***wearable pediatric sensory transfer device*** that acquires haptic and proprioceptive sensory information from (1) a powered prosthesis or orthosis or (2) regions of child's body desensitized by disease or trauma, and noninvasively displays that information to areas of the body still having intact sensory capability. The sensory transfer display will apply cutaneous vibrotactile and mechanotactile stimuli to the skin to convey encoded information about the state of sensory-impaired regions of the child's body (e.g. hands or feet), or the activity of an assistive device being used, with the intent of improving neuromotor learning and limb control. These sensory transfer displays will have the advantages of (1) being noninvasive and inexpensive in comparison to conventional nerve transposition surgeries and (2) being easily reconfigurable so that the method of sensory information encoding and the physical dimensions of the device can be modified to accommodate the growth of pediatric patients, changes in their conditions, or the type of assistive device being used.

Our **central hypothesis** is that the provision of transferred sensory information will facilitate the establishment of new feedback pathways that enable (1) greater recovery of natural limb motor skills lost due to pediatric sensory impairments and/or (2) dexterous control of pediatric powered prostheses or orthoses. The restored sensory capabilities availed by the proposed device will impact children with a variety of diseases and impairments including the following:

- **Peripheral neuropathy and Guillain-Barré syndrome**: restoration of tactile sensation on the hands and feet, as well as proprioception of ankles and fingers during walking or manipulation
- **Cerebral palsy**: improving grasp control and object perception/discrimination
- **Upper or lower extremity amputation or congenital limb differences**: enabling fine motor control of powered prostheses or orthoses by providing tactile sensation and proprioception

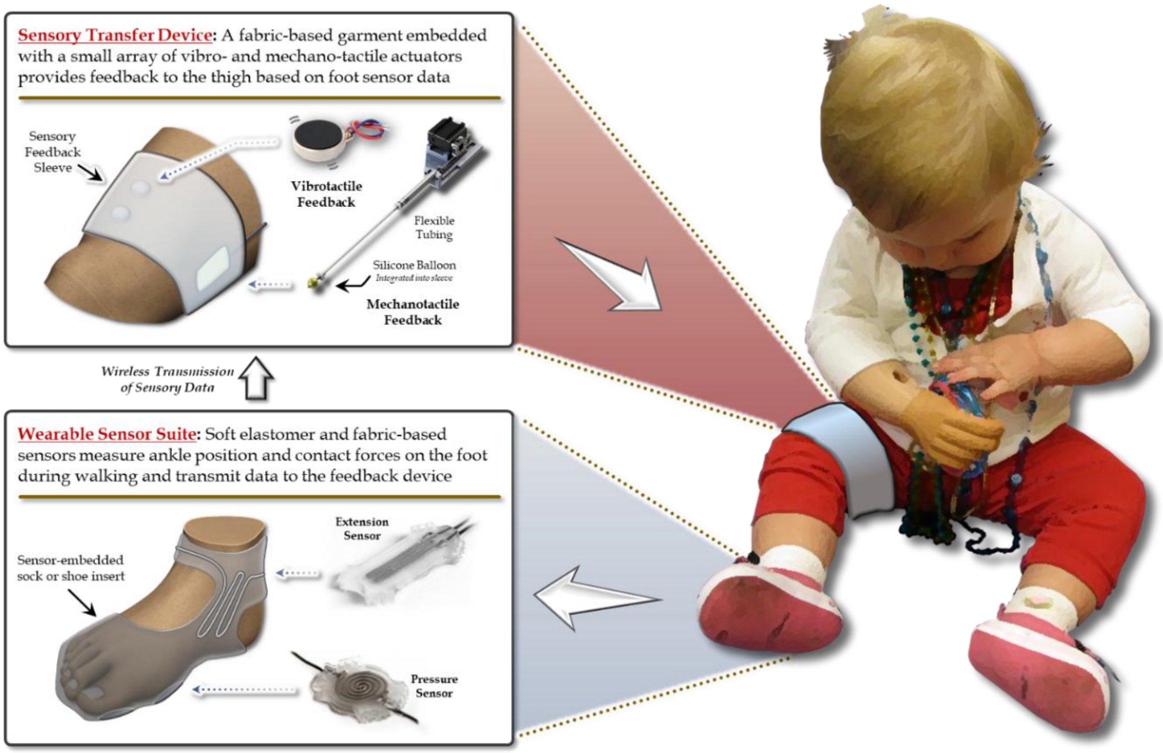

Figure. Concept of a wearable sensory transfer device for lower extremity peripheral neuropathy

Our **objective** in this research is to ***restore peripheral tactile and proprioceptive sensitive for pediatric patients with spinal cord injuries*** (**SCI**). We will develop a sensory transfer device for SCI-related impairments and evaluate its effect on a group of five human subjects. The results of this study will provide scientific and engineering bases upon which to extend the use of the wearable sensory transfer device to other conditions that cause sensory impairment in children.

Specific Aims: We will test our central hypothesis via the following Aims:

Aim 1: ***Develop a prototype wearable pediatric sensory transfer device for a specific sensory impairment condition (Engineering Design)*.** The prototype will display encoded sensory information via a combination of localized vibrations (vibrotactile stimulation) and small pressures (mechanotactile stimulation) applied to the skin. The initial prototype system will be designed as a soft band to be worn on the subject's arm or leg. The band will stimulate the underlying skin in proportion to physical events such as contact forces, temperatures, strains, or changes in the activity or state of a natural limb (e.g. joint motion), which are acquired by a suite of wearable wireless sensors (to be developed by Co-PI Yeo) placed on the human body.

Wireless sensor array development: Co-PI Yeo's group has matured technologies, proven by the prior works (Mishra 2020; Kwon 2020; Mahmoud 2019; Kim 2019), to develop various types of nanomembrane, wireless electronic sensors, including pressure, strain, temperature, and motions. Data will be wirelessly transmitted via Bluetooth over 10 meters. An additive nanomanufacturing based on aerosol jet printing will be used to fabricate both sensors and electronics. The key innovation of this technology is in the miniaturization of the entire sensor package by using stretchable nanomembranes as well as the soft material packaging to avoid rigid, bulky electronics.

Evaluation: The sensory device will first be evaluated in-lab using mechanical testers to verify that vibrotactile and mechanotactile feedback are accurately generated in proportion to sensor signals received from a remote wearable sensor suite. The device will then be tested on human subjects to determine the placements and output settings (i.e. signal frequency and magnitude) for the sensory feedback elements that allow subjects to perceive feedback without causing physical discomfort or cognitive burden.

Aim 2: ***Experimentally assess the efficacy of sensory transfer*** by conducting a preliminary study with five subjects having a sensory impairment. The sensory transfer tests will involve instrumenting either the sensor-impaired regions of a subject's body with tactile and joint motion sensors. Joint angles and contact force information from the sensors or the hand or foot (depending on the subject) will be displayed on a subject's skin using the sensory transfer device. The location of the display will be selected based on a sensitivity and perception data from Aim 1.

Evaluation: The study will measure, among several outcomes, the subjects' abilities to discern the contact forces and joint angles of the limbs, with and without vision, using the sensory transfer device. The impact of sensory transfer to manipulation capabilities or walking gait (depending on the subject) will be quantified using standardized clinical assessment methods. Cognitive loading (NASA TLX) and user experience surveys will be conducted and analyzed along with the quantitative experimental data.

Long-Term Impact: The results of this work have broad implications not only for pediatric patients with sensory impairment, but also for the following applications:

- Adults with sensory impairments due to diabetes-related peripheral neuropathy
- Providing sensory feedback for myoelectric adult prostheses
- Use of the wearable sensory transfer device to diagnose sensory impairments

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