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Rockin' rehab: Novel rocking chair for children with spinal cord injury to enable trunk muscle activation and detect muscle activation patterns.

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ROCKIN' REHAB: NOVEL ROCKING CHAIR FOR CHILDREN WITH SPINAL CORD INJURY TO ENABLE TRUNK MUSCLE ACTIVATION AND DETECT MUSCLE ACTIVATION PATTERNS

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B.S. Mechanical Engineering, 1993

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ABSTRACT

ROCKIN' REHAB: NOVEL ROCKING CHAIR FOR CHILDREN WITH SPINAL CORD INJURY TO ENABLE TRUNK MUSCLE ACTIVATION AND DETECT MUSCLE ACTIVATION PATTERNS

Johnathan J George

April 15 2024

Introduction: Activity-based locomotor training improves trunk control in children with spinal cord injury (SCI), and there is need for additional activities to allow these children to activate trunk muscles. The purpose of this research was to design, fabricate, and evaluate a rocking chair for children with SCI, and to investigate the activation of muscles during use. Sensorization of the chair to confirm muscle activation is also explored.

Methods: Quality Function Deployment (QFD) design methodologies identified and ranked needs and features for the rocking chair. A design was developed and evaluated via finite element analysis. The chair was fabricated and tested for stability and mechanical integrity. Eleven children with SCI and ten typically developing (TD) children aged 2-12 years rocked while surface electromyography was captured. Analyses were performed to compare muscle activity during rocking to baseline and to characterize temporal muscle activation patterns during rocking. Regression analysis and neural networks were used to predict muscle activation during rocking based on data from sensorization of the rocking chair.

Results: QFD analysis confirmed the design to have satisfied safety, therapeutic, practical, and aesthetic criteria. Static loading of the prototype chair to 136 kg, and dynamic loading 59 kg confirmed physical integrity, and static and dynamic tip testing showed a tipping factor of safety of 3.6. Analysis of muscle activation during rocking showed a significant increase ($p < 0.05$) during rocking in both SCI and TD groups confirming a primary hypothesis. Cluster analysis found SCI subgroups (one similar and one dissimilar) compared to TD. Neural networks performed better at predicting muscle activation based on senor data, than regression analysis, with statistically significant correlations ($p<0.05$) between predictions and targets for all children.

Conclusions: The prototype rocking chair provides a safe tool for further investigation of rocking to promote trunk muscle activation in children with SCI. Rocking activates the neuromuscular system and has potential for extending activity-based practices beyond the clinic and has great potential for commercialization. The use of common sensors along with machine learning techniques is a promising, non-invasive, non-obtrusive technique to extract useful information about muscle activation during chair use.

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CHAPTER 1
INTRODUCTION

As in adults, spinal cord injuries (SCI) for pediatric patients are often catastrophic, leading to dramatic changes in quality of life, overall health, and life expectancy, not to mention the emotional and financial burdens carried by the families of these patients. However, as younger SCI patients grow, additional medical complications arise that are unique to this population due to musculoskeletal immaturity, i.e. the patients are still growing. Conditions such as such as scoliosis and pneumonia can be generally attributed to poor *trunk control*, a term used to describe the ability for a patient to sit upright against the pull of gravity. Paradigm-shifting therapies such as locomotor therapy (LT) have recently been developed as a mechanism to engage these patients in an activity that enhances the quality of life for both adults and children living with SCI. Therapies that improve trunk control, for pediatric SCI patients, is a critical therapy target. As this dissertation will explore, LT has been shown to be a reliable method of improving trunk control in a clinical setting. Extending the ability to make gains beyond the clinic through the development of technology appropriate in the home environment is the primary focus of this dissertation research project. In particular, this dissertation outlines the development, evaluation, and analysis of a sensorized rocking chair designed specifically for children with spinal cord injuries.

1.1 Project Goals

The goals of this multifaceted research project included: 1) the development of a multi-sensor equipped prototype rocking chair for use by pediatric participants age 1-12 years with neurologic deficits that impair upright trunk control, 2) the characterization of trunk muscle activation when children with SCI rock, 3) comparison of muscle activation in TD children to muscle activation seen in children with impaired trunk control, 4) characterization the output of sensors integrated in the rocking chair when children with different levels of trunk control rock, and 5) the analysis of data produced by the rocking chair sensors to find correlations between muscle group usage patterns, and to produce an evaluation mechanism that clinicians can use to evaluate patient progress.

1.2 Project Specific Aims

To create a safe and engaging rocking chair for the pediatric patient population that incorporates mechanisms to investigate and assess trunk activity levels in a manner that is helpful to clinicians, this study has been broken down into four specific aims.

Aim 1: *Design and fabricate an instrumented rocking chair for children with impaired trunk control due to spinal cord injury and verify that it meets safety and operational criteria.*

This aim focuses on fabricating a rocking chair to provide therapists with a safe, enjoyable method to enable trunk movement in children with impaired trunk control for integration into activity-based therapy, or for use in increasing activity levels in the home. Additionally, it will enable research to discover patterns of muscle activation during

rocking and can be evaluated for its ability to provide data which can be used in assessment of trunk control in this population.

Aim 2: *Characterize muscle activation in typically developing children and in those with impaired trunk control while rocking in a rocking chair and describe differences between muscle activation in the two groups.*

This aim focuses on investigation of muscle activation during rocking in children with SCI to determine if rocking activates muscles of interest, and to characterize muscle activation patterns. This will help to investigate the hypothesis that rocking activates trunk muscles, and to provide information about muscle activation timing in typically developing children and children with SCI.

Aim 3: *Characterize the relationship between rocking chair dynamics and Segmental Assessment of Trunk Control (SATCo) score when children with different trunk control capabilities rock.*

This aim focuses on defining how the output of sensors changes when children with different levels of trunk control perform the rocking activity, and identifying the muscles in different domains (legs, arms, trunk) used during the activity. These will offer insight into the mechanisms of how a child initiates and maintains the rocking activity and will provide information which can be used to investigate other methods of assessing trunk control.

Aim 4: *Develop an algorithm to assess trunk control using data produced by sensors on the instrumented rocking chair and evaluate its clinical utility.*

This aim focuses on developing methods to utilize data collected from rocking chair sensors to provide therapists with useful information about the child's trunk control. Regression analysis will used to find correlations between sensor data and trunk control, and to produce a model for predicting SATCo score. If, however, after checking correlations, there are not any independent variables which are well correlated with SATCo other methods of data processing may be explored.

Successful completion of these aims sets the stage for future research to investigate the clinical use of the chair both as a diagnostic tool (perhaps initially as a confirmation of the existing SATCO assessment technique in the clinic), a tracking tool (to monitor patient gains made through LT applied in the clinic), and possibly as a means of applying activity-based therapy in the home environment.

CHAPTER 2
BACKGROUND

2.1 Demographics of Spinal Cord Injury

The National Spinal Cord Injury (SCI) Statistical Center, estimates that there are currently 299,000 people living with SCI in the United States, with about 18,000 new cases of SCI occurring annually [1, 2]. Of these, approximately 4-5% of are children at the time of injury [3]. The most prevalent cause of pediatric SCI is motor vehicle accidents (32%), followed by falls (18%) [4].

The economic impact of SCI can be devastating. SCI persons injured since 1970 spent an average of 171 days in a hospital over the first 2 years post injury [5]. In 2001, Sekhorn et al reported that initial hospital expenses averaged $95,203, and $2958 per year after initial recovery and rehabilitation. Other medical services and equipment averaged $4,908 per year, and personal assistance costs and costs of institutional care averaged $6,269 per year. In addition, loss of productivity and income are major factors for consideration especially in the case of young people and children [6].

2.2 Spinal Cord Physiology

The spinal cord is the primary information pathway that receives sensory information from the body and relays it to the brain. It also carries messages from the brain to other body systems [7]. In addition to transmitting information, the spinal cord actively processes information and generates motor outputs. Millions of nerve cells collected into neuronal networks, referred to as the central pattern generator, are situated

in the spinal cord and coordinate complex movement patterns such as rhythmic breathing and walking [8].

The spinal cord is linked to the muscles via spinal nerves which exit the spine at different levels and nerve function is determined by the level as shown in Figure 1. The cervical spinal nerves (C1 to C8) control the back of the head, the neck and shoulders, the arms and hands, and the diaphragm; the thoracic spinal nerves (T1 to T12) control the chest muscles, some muscles of the back, and many organ systems, including parts of the abdomen; the lumbar spinal nerves (L1 to L5) control the lower parts of the abdomen and

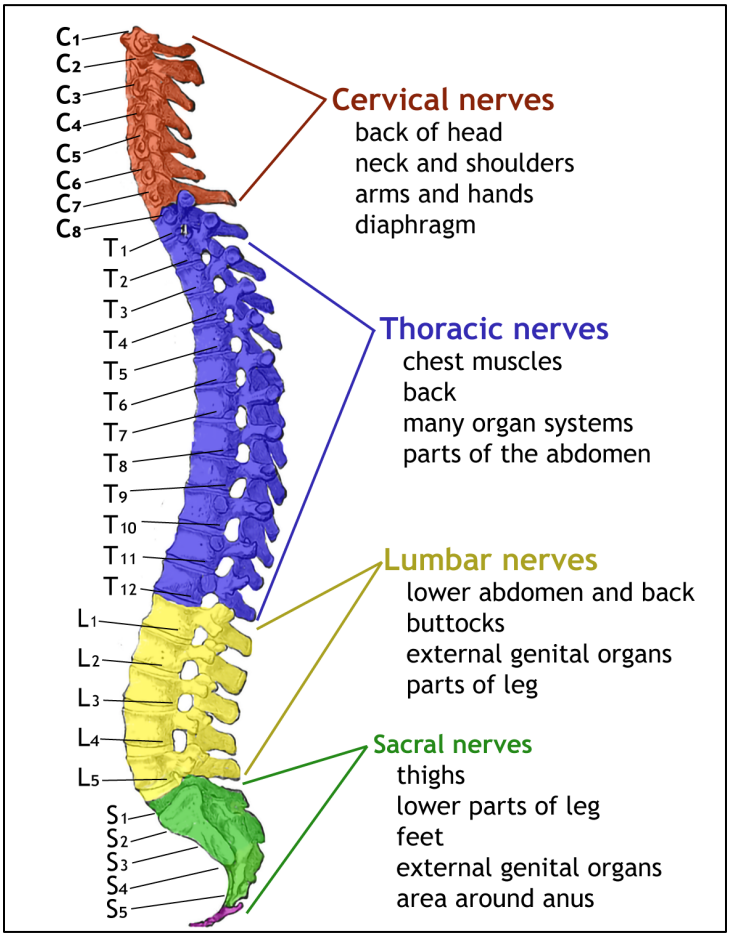


Figure 1: Spinal nerve origins and functions
Adapted from Henry Gray, Anatomy: descriptive and surgical (1858)

the back, the buttocks, some parts of the external genital organs, and parts of the leg; finally, the sacral spinal nerves (S1 to S5) control the thighs and lower parts of the legs, the feet, most of the external genital organs, and the area around the anus [7].

2.3 Spinal Cord Injury

The most common and severe cause of spinal cord injury (SCI) is trauma. Traumatic injuries (falls, etc.) often fracture vertebral bodies which can lead to compression of the spinal cord, and associated permanent impairments including motor, sensory and autonomic dysfunction. Other causes of SCI include inflammatory conditions, infections, vascular issues, and neoplastic or degenerative changes [9]. The nature and severity of dysfunction depends largely on the level of the spine at which the injury occurs, and the degree to which the spinal cord is damaged [9, 10].

Failure to recover post injury leads to neurological disability and is the result of axonal and other cellular damage, followed by regenerative failure and loss of neuroplasticity, the ability of the nervous system to alter activity in response to stimuli by reworking structure, functionality, and/or connections, in the region of the injury [9]. Recovery of function after injury depends upon the severity of neurological injury, with cell and axon survival leading to proportionately improved recovery, and also the neurological level of injury, with higher anatomical injuries leading to greater loss of function [7, 10]. It has typically been believed that most neurological recovery in patients with SCI occurs within the first 6 months after injury, but it has been established that improvements can continue to occur years later [10].

2.4 Impacts of Spinal Cord Injury

The long-term effects of SCI are far reaching and affect almost every body system, including respiration, head/trunk control, bladder control, speech, cardiovascular function, and the musculoskeletal system [11]. Table 1 includes an abbreviated list of conditions either caused by or aggravated by SCI and the prevalence in a cohort of patients whose initial injury occurred during childhood [12].

Table 1: Common complications associated with SCI

Complications	Number with complication	Number of Respondents	Percent of Respondents
Urinary tract infections	160	215	74%
Severe UTI	41	214	19%
Urinary stones	54	215	25%
Bladder incontinence	52	212	25%
Orchitis/ epididymitis	15	147	10%
Autonomic dysreflexia	85	157	54%
Hyperhidrosis	31	210	15%
Bowel incontinence	135	215	63%
Latex allergy	18	208	9%
Pressure ulcers	94	216	44%
Thromboembolism	41	216	19%
Respiratory complications	71	213	33%
Chronic medical conditions	42	214	20%
Other hospitalizations	59	215	27%

Adapted from Vogel et al 2002

2.5 Functional Impairments

In a survey of 681 adults with spinal cord injuries, 7 functions were ranked with respect to which would most dramatically improve the respondent's life if it was regained. The functions included arm/hand function, upper body/trunk strength, bladder/bowel function, sexual function, elimination of chronic pain, normal sensation, and walking movement. Results showed that those with paraplegia ranked sexual

function and bladder/bowel function as the first and second highest priority, and those with tetraplegia ranked arm/hand function and sexual function as the first and second highest priorities. Regaining trunk stability was rated the third highest of the seven functions most desired by both groups to improve their quality of life [13].

2.6 Spinal Cord Injury Rehabilitation

Physical rehabilitation, which is the primary intervention post-SCI for both adults and children, has traditionally focused on management and compensation as the primary solutions to combat impaired trunk control [14, 15]. Compensation in this context refers to the use of assistive technology devices often specifically designed for SCI patients, and management refers to medical interventions to treat medical conditions associated with SCI.

Traditional approaches have involved the use of support mechanisms such as thoracolumbosacral orthoses [16, 17], supportive and adaptive seating systems, cushions, and chest straps [14, 18]. Additionally, practical techniques such as hooking an arm over a wheelchair handle or positioning arms to create a stable base of support can help to compensate for lack of trunk control [14]. These compensation-based strategies can help the patient to engage in functional activities, but do not focus on neuromuscular function. Moreover, by restricting movement they may contribute to deconditioning and reduction in muscle mass, eventually leading to further impairment as neural circuits in the spinal cord become inactive with disuse [19, 20].

Task specific, activity-based training methods have been investigated in adults with thoracic SCI, to improve intrinsic trunk control by actively engaging the neuromuscular system through sensorimotor input. Methods that have been studied

include kayak ergometer training [21], exercises that move the upper body outside the base of support [22], and balance exercises performed on a rocker board which required subjects to engage their trunk muscles to maintain balance and stability [23]. These studies have demonstrated improvement in various functional measures of balance and trunk control, and provide evidence that it is possible to improve intrinsic trunk control in adults with SCI.

Recently, however, a new paradigm has emerged which promises the possibility of restoration of at least some intrinsic neuromuscular control. In the context of a healthy spinal cord, an input signal, which can be interpreted as *the intent to perform a physical action*, is provided by the brain, and arrives in the central pattern generator of the spinal cord via descending neural pathways. In the context of a compromised spinal cord, where the descending pathways have been interrupted (corrupted, damaged, completely severed), it has been shown that sensory input ascending to the spinal cord can instead (or in place of the descending signal) stimulate motor responses, and that the spinal cord can actually be retrained to respond by generating appropriate motor responses [24].

2.7 Pediatric Spinal Cord Injury

2.7.1 Trunk Control

Children with SCI experience many of the same consequences as those seen in adults, but in addition to the impact of the initial injury, there are also debilitating secondary consequences including altered growth and development as they mature [25]. In children as in adults, the long-term effects of SCI are far reaching and affect almost every body system, including respiration, head/trunk control, bladder and bowel control, speech, cardiovascular function, and the musculoskeletal system [11, 26, 27].

Skeletal immaturity and continuous musculoskeletal growth in the context of impaired trunk control can also place children with SCI at substantial risk for developing chronic conditions such as pneumonia, and scoliosis, a likelihood that increases the younger the age of injury [3, 13, 17, 27, 28]. In a retrospective study by Dearolf et al, of 130 children with spinal cord injuries sustained before the typical adolescent growth spurt (defined as age <12 years for girls and <14 years for boys), 97% developed scoliosis of greater than 10 degrees. By way of comparison, only 48% of those injured after the growth spurt developed scoliosis [17].

Surgical intervention to correct scoliosis (Figure 2) in particular, is a highly invasive procedure that increased in cost from approximately $72,000 in 2001 to $155,000 in 2011, with the cost of spinal implant mechanisms suggested as the primary reason for the annual 11.3% increase [29]. Further, surgery to correct for scoliosis is often

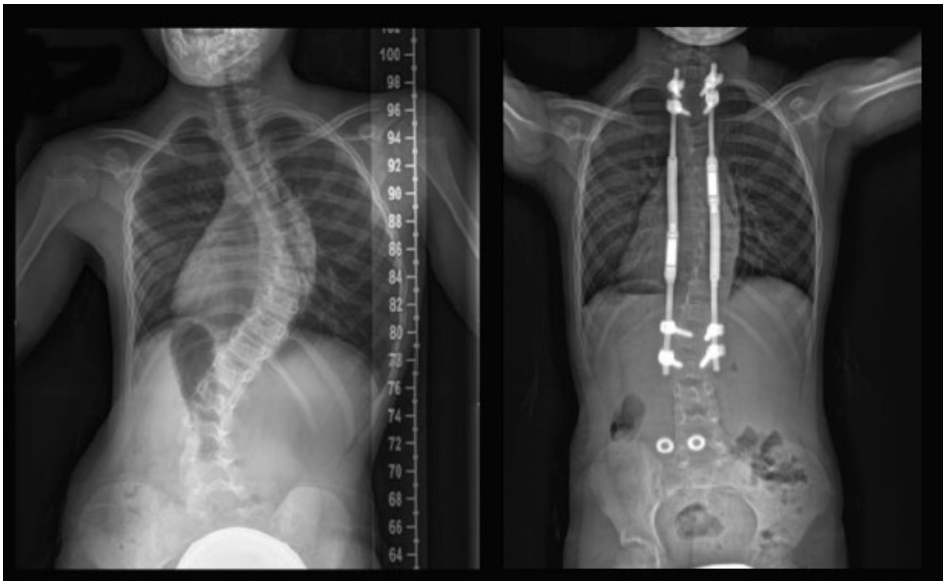


Figure 2: Representative image of scoliosis, pre (left) and post-surgery (right).
Source: pediatricscoliosissurgery.com/case-studies/meghan-pediatric-scoliosis-case/

repeated as a child ages, can result in further restriction of movement, and often interferes with development of lung capacity in younger children [30].

2.7.2 Compromised Respiratory Function

Impairment of respiratory muscles in pediatric SCI can lead to respiratory insufficiency [17, 28, 31, 32], and impairment of trunk muscles leads to the development of neuromuscular scoliosis in most children who sustain SCI prior to skeletal maturity. This can decrease the mechanical efficiency of the chest wall, further reducing lung capacity and function [3, 28, 32]. Furthermore, due to years of immobility and lack of weight bearing, pathophysiological changes in the musculoskeletal system progress, and respiratory function is further compromised [27, 31, 32]. Respiratory insufficiency can ultimately lead to complications such as infection, pneumonia (Figure 3) and even death [32].

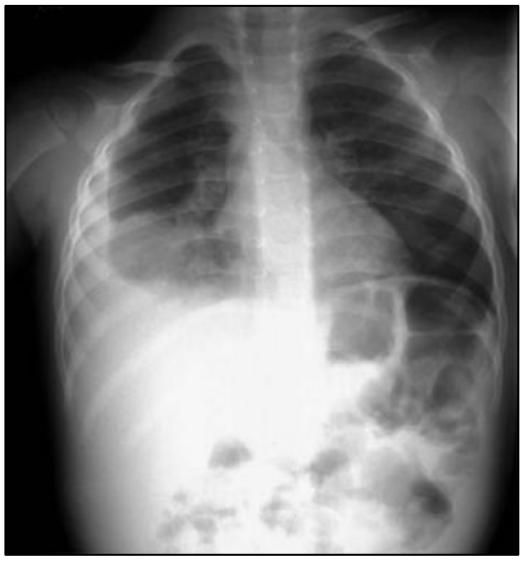


Figure 3: Image of bacterial pneumonia (right lobe of the lung)
Source: emedicine.medscape.com/article/967822-overview

2.7.3 Trunk Control Assessment

The Segmental Assessment of Trunk Control (SATCo) scoring tool was specifically developed for use in pediatric populations to evaluate the trunk incrementally across seven levels from shoulder support to no support and for three types of control (static, active and reactive) [33, 34]. With each incremental level of external support, trunk control above the location of support is evaluated across the control types and if the child is deemed competent, the assessment continues until the child is unable to maintain an appropriate sitting posture. A SATCo score of '0' indicates no head control, whereas a perfect score of '20' indicates that a child can sit without any support and control their head and trunk during static, active, and dynamic tests of control. Figure 4 shows a SATCO assessment form designed for clinical use [35].

2.8 Rehabilitation

Various assistive technologies and therapeutic interventions have been used to address impaired trunk control for children with SCI. During rehab sessions, patients learn specific methods to compensate for their impairment. For instance, to balance and sit upright by using counter-balance maneuvers with the arms and head above their passive trunk and to establish an adequately wide base of support (i.e. posterior pelvic tilt base). In some cases, the torso may be propped to a weight-bearing position using extended arms. practical techniques such as hooking an arm over a wheelchair handle or positioning arms to create a stable base of support can help to compensate for lack of trunk control [10]. These compensation-based strategies can help the patient to engage in functional activities, but do not focus on neuromuscular function.

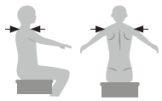
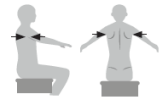
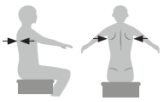
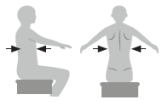
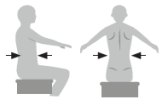
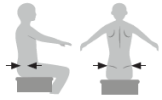
Client Name:	Level of Manual Support	Functional Level	Static	Active	Reactive
Ref# :	Pelvic / thigh strap used except as indicated	Arms and hands in air except as indicated	Maintain vertical neutral position of head and trunk above manual support level		
Tester Name:			Minimum of 5 seconds	While turning head with arms lifted	Maintain / quickly regain following brisk nudge
Date:					
	Shoulder girdle testers hand position may vary from horizontal	**Head control** Arms may be supported throughout			**NOT tested for head control**
	Axillae	**Upper Thoracic Control**			
	Inferior scapula	**Mid Thoracic Control**			
	Over lower ribs	**Lower Thoracic Control**			
	Below ribs	**Upper Lumbar Control**			
	Pelvis	**Lower Lumbar Control**			
	No support given and pelvic/thigh straps removed	**Full Trunk Control**			

Figure 4: SATCo testing procedure.

Rehabilitation interventions for children with SCI may also utilize devices such as standers, wheelchairs with supportive and adaptive seating systems, cushions, and chest straps [14, 18], and braces such as thoraco-lumbo-sacral orthoses (Figure 5) [16, 17]. While these devices provide support, many of them can also restrict trunk, leg, and body movement. Medications to manage spasticity, such as botox injections and baclofen can also add to paralysis, and further prevent movement [36]. By restricting movement some strategies may contribute to deconditioning and reduction in muscle mass, eventually

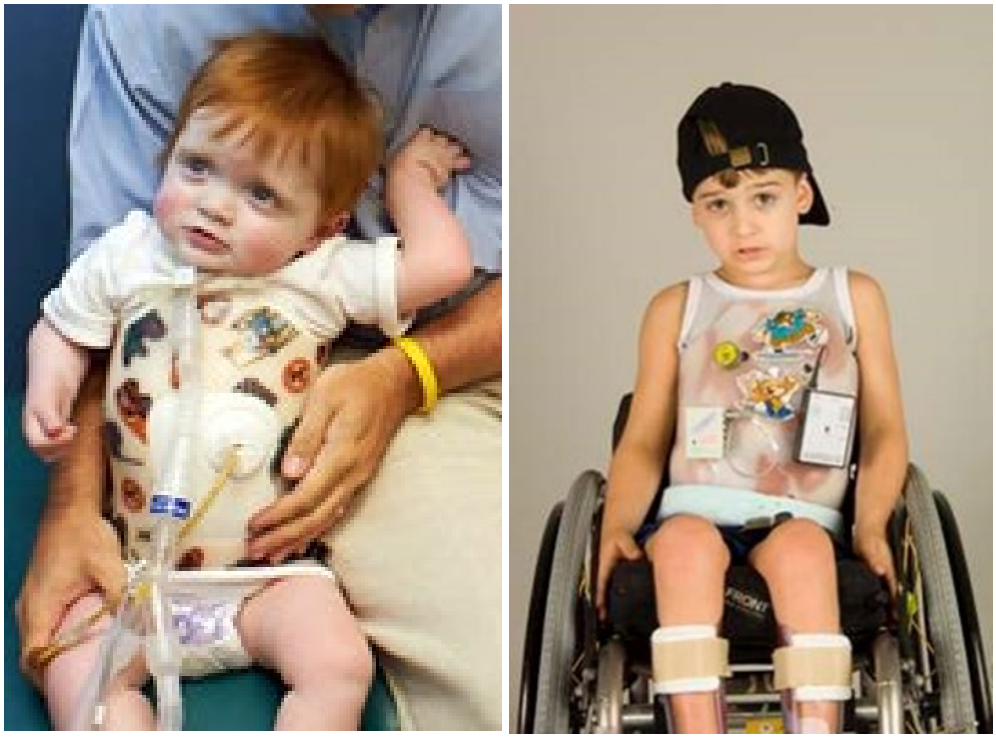


Figure 5: Thoraco-lumbo-sacral orthoses

leading to further impairment as neural circuits in the spinal cord become inactive with disuse [19, 20, 33].

From historical evidence and general clinical observation, pediatric rehabilitation professionals do not expect or even suggest that therapeutic interventions promote or restore trunk control in children post-SCI [33], and after 12 to 18 months post injury, additional recovery is generally not expected, and parents are often given little to no hope for recovery [36].

2.8.1 ABT for Children with SCI

Based on spinal cord neuroplasticity, a new field of therapy for SCI has emerged, which is referred to as Activity-Based Therapy (ABT). Currently, in the pediatric

recovery-based program at the University of Louisville, the primary therapeutic intervention for pediatric SCI subjects is activity-based locomotor training (AB-LT) conducted 1.5 hours per day, five days per week with a targeted goal of 60 sessions over roughly three months of therapy. Therapy sessions consist of a minimum of 55 minutes on a walking treadmill equipped with active body weight support (BWS), where the patient is assisted by four trained physical therapists, where the treadmill and body weight support are integrated into the unit (Figure 6), providing therapeutic intervention for SCI patients. The intervention delivered through use of the treadmill activity provides task-specific sensory input that reinforces upright, appropriate alignment of the trunk,

Figure 6: Pediatric locomotor training system.
Courtesy of Frazier Rehab and PowerNeuro Recovery.

pelvis and legs, weight bearing through legs, age-appropriate walking speeds, arm swing and inter/intra-limb coordination of kinematics for both standing and stepping [36].

AB-LT therapy is followed immediately by 30 minutes of assessment by the therapists and clinicians as well as off-treadmill activities that further emphasize and reinforce the gains attained/observed from repeated application of the specialized training. These extended activities promote active trunk extension or rotation by placing balls or toys overhead or to the child's side for them to reach for and grasp. Postures that minimize use of compensation are also encouraged by having children shoot baskets or carefully remove pieces of a puzzle tower while maintaining a stable trunk. Encouraging children to use postures such as arms in contact with the body or arms extended behind the body can also help to minimize compensation [37, 38].

2.8.2 Trunk Control Improvements with ABT

In children with SCI, research has shown that activity-based locomotor training (AB-LT), which provides sensorimotor input to activate the neuromuscular system, leads to improvements in intrinsic trunk control as measured by SATCo score. Significant changes in SATCo scores ($p < 0.0001$) were determined for all participants from initial to post-60th session evaluation [33, 34]. This improvement is observed regardless of the chronicity or severity of the initial impairment, with similar improvements seen in cervical, and in high and low thoracic injury [33]. These findings align with case studies that support the notion of sensorimotor input playing a crucial role in enhancing trunk control in children with SCI [39-41].

2.9 Rocking Chair to Activate Trunk Muscles in Pediatric SCI

Studies demonstrate that improving intrinsic trunk control in subjects with SCI is possible [21-23, 33, 39-41]. There is need, however, for methods to reinforce and maintain these gains in trunk control through community integration activities that allow patients to continue to extend their capacity via the retrained nervous system in the home and community [21].

One activity that researchers have explored is the act of rocking in a rocking chair, which enables a user to generate movement with minimal or no caregiver assistance. In one case study, a pediatric rocking chair was adapted for a 3-year-old with a cervical spinal cord injury to allow for weight bearing through the feet with upright posture and engaged muscle activation in both the arms and the trunk [19]. The periodicity of motion created by rocking and the requirement of an upright posture to initiate and maintain the rocking motion equally promote an accessible, self-initiated, and engaging activity for children of all ages, including those patients who have limited capacity to move and interact with their environment. Rocking would seem then to complement and reach beyond clinically delivered, activity-based therapies such as locomotor training. Clinically derived improvements in trunk control could be safely practiced by providing a home-based, age-appropriate, and accessible activity that encourages repetitive activation of the muscles associated with trunk control. Additionally, enjoyment of an activity is an important motivator for children which results in increased time/practice engaged in the activity, and in turn accelerates improvement and lasting use. To study the benefits of rocking, however, it is necessary to design a rocking chair that meets the particular needs of this population.

2.10 Rocking Chair Therapy Review

Rocking chairs have been investigated for their effectiveness in several domains, including postoperative recovery, enhancing physical function in the elderly, workplace ergonomics, and emotional regulation in substance-use disorder. Investigation of the effects of postoperative rocking revealed improvement in several measures of recovery including postoperative ileus duration and [42, 43] and time to first flatus [44].

Research on the use of rocking by elderly people showed improvements in physical performance as measured by the Berg Balance Scale, maximum knee extension strength, and maximum walking speed [45]. Other work has shown activation of the rectus abdominis during rocking, and improved rectus abdominis strength in elderly men as measured by number of sit-ups completed after six weeks of rocking chair use [46]. Pierce et al. observed a rise in blood pressure among hypotensive older adults during rocking, which suggests that rocking may improve cerebral perfusion in older adults with hypotension and thus help to slow Alzheimer's disease (AD) progression or improve function of AD patients [47].

Udo et al. examined the effects of rocking on pain and discomfort during seated work in an office environment, and found a significant decrease in pain in the neck, shoulders, back and lower back, but an increase in hip pain [48]. Cross et al performed a study involving veterans with substance use disorder and concluded that vestibular stimulation through rocking chairs might help self-regulate mood and cravings, potentially reducing relapse risk [49].

There were no studies found in the current literature that applied or investigated the use of rocking chairs in the context of pediatric SCI.

2.11 Instrumented Rocking Chair to Monitor Muscle Activation

In addition to providing a way to allow children with SCI to activate trunk muscles in the home, a rocking chair specifically designed for children with impaired trunk control and instrumented with sensors, would provide researchers and clinicians with an opportunity to collect data about the characteristics of the rocking activity, and such a device may be able to provide information about muscle activation and progress in trunk control. A quantifiable method of collecting data which could be utilized on an ongoing basis to assess and track changes in muscle activity would be highly beneficial to clinicians. Additionally, if data could be collected to allow the tracking of activities and trunk control in the home, clinicians would have a better picture of patient activity levels beyond the clinic, as well as an added dimension to the assessment of progress.

2.12 Existing Technology to Activate and Assess Trunk Muscles in Pediatric SCI

A thorough search of both relevant literature and commercial equipment offerings does not reveal the availability of rocking chair-based therapy tools for pediatric SCI patients. Additionally, there are no instrumented devices that have been designed to capture biometric data for purposes of assessing muscle activation in this patient population. These gaps in the technology provide a clear opportunity to develop a system to potentially provide a solution for both consumer and clinical use to extend the benefits of ABT beyond the clinic, while providing researchers and clinicians insight into muscle activation enabled by LT.

There are, however, products on the market that look to promote the use of trunk muscles by individuals with SCI. One example is the TherAdapt Wheelchair Platform

Rocker (TherAdapt Products Inc, Ludington, Michigan, USA), shown in Figure 7 (left), which is an add-on base to a standard wheelchair that allows a patient to increase their activity level through rocking [50]. Traditional rocking chairs are also available, however, as noted previously, these must be modified for use by children with SCI and, even after modification, significant safety concerns and practical limitations exist.

Other therapy devices designed to provide trunk exercise are available commercially. One example is the Meerkat stander (Etac AB, Torrance, California, USA) shown in Figure 7 (right). This device is a standing frame which supports an upright standing position for children needing varying levels of support. The central column can be positioned in front of or behind the child and support can be adjusted to meet

Figure 7: TherAdapt Wheelchair Platform Rocker (left), and Meerkat stander (right)
Sources: www.theradapt.com/store/ShowProduct.aspx?ID=118;
www.etac.com/en-us/us/products/pediatrics/standing/r82-meerkat/

individual needs. To encourage movement, the base can be set up with wheels or an optional rocker base which provides a mechanism to develop posture control [51].

None of the devices reviewed incorporate sensors to provide information to assess use of the device or track improvements in trunk control.

2.13 Dissertation Organization

Chapter 1 has introduced the project and provided an outline of the specific aims being pursued.

Chapter 2 has provided an overview of the issues involved with pediatric SCI, trunk control, and ABT necessary to an understanding of the motivations and techniques used in this project.

Chapter 3 will cover the methods used to achieve Aim 1 and the outcomes obtained. The objectives that have been pursued to achieve this aim are:

- Objective 1: Design of a rocking chair for children with SCI using a Quality Function Deployment (QFD) process.
- Objective 2: Fabricate the rocking chair.
- Objective 3: Experimentally verify safety and operation of rocking chair.

Chapter 4 will focus on the methods used to achieve Aim 2, and describes the activities undertaken to achieve the following objectives:

- Objective 1: Characterize muscle activation while rocking for typically developing children and children with impaired trunk control.
- Objective 2: Describe the differences between muscle activation for typically developing children and those with impaired trunk control.

Chapter 5 will focus on the methods used to achieve Aims 3 and 4, and describes the activities undertaken and results obtain in the completion of the following objectives:

Objective 1: Characterize the changes in 1) applied forces on footrest, seat and armrests, and 2) kinematics such as frequency, amplitude, and accelerations, when children with different trunk control capabilities rock.

Objective 2: Produce a model to predict patient's trunk control capabilities.

CHAPTER 3
ROCKING CHAIR DEVELOPMENT

3.1 Introduction

The methodology chosen for the design of the rocking chair for children with SCI is the quality function deployment (QFD) design process, a quality system that was originally developed in Japan in the 1960s and has now been adopted by major corporations worldwide. It is used to translate the needs of the end user (often referred to as “needs of the customer”) into specific design characteristics and to implement these characteristics in the design of the finished product [52]. The QFD process begins by identifying the needs that the design should meet. This is accomplished by gathering information from stakeholders about the specific needs and priorities for the product. This information is then used to develop specific design features and requirements, which are prioritized using tools like the House of Quality (HOQ) matrix to link them to the importance of each of the needs identified earlier. Multiple alternative design concepts that address the prioritized design requirements are developed and evaluated for how well each alternative fulfils the identified needs. A detailed design is then developed based on the selected concepts and drawings are created, materials are specified, and the manufacturing processes are determined. Based on this design, a prototype is fabricated and tested. Test procedures are designed to evaluate how well the prototype meets the needs originally identified. This helps to validate the design, identify any potential issues, and gather feedback for further improvements. The design may then be iterated until any

identified issues have been addressed. This design method can also be extended into the manufacturing and distribution of the product to ensure that the manufactured product continues to meet the standards set by the prototype build, and that it actually meets the needs of the end users [53].

The aim of this study is to apply these engineering design methodologies to the design, fabrication, and evaluation of a rocking chair that will meet the needs of children with SCI and will allow for further study of the effects of rocking in this population.

3.2 Materials and Methods

3.2.1 Design Process

The initial phase of the QFD methodology involved identifying the fundamental needs that the rocking chair should address. To accomplish this, a focus group discussion was conducted with five therapists experienced in working with children in the target demographic. Prior to the discussion, important topics to cover were identified, and a list of questions designed to elicit information about needs the chair should meet was produced. During the session, open-ended discussions were encouraged to allow participants to identify needs without biasing them towards any predetermined conclusions. As discussion progressed, the list of topics and questions was referenced to ensure that all important issues had been addressed, and any pertinent questions were asked. Conversation moved from general needs to more specific ones, and finally to the suggestion of specific features to meet the identified needs. The needs identified during the meeting were captured through notes taken on a pen board, and through audio recordings which were reviewed later to ensure that no needs had been missed. The identified needs were then compiled into an online form which the therapists filled out to

rate the importance of each need on a scale of 1 to 10. This ranked list of needs was used to develop potential features and design requirements for the rocking chair.

When considering the design and setup of the rocking chair, it was also important to take the anthropometric characteristics of the intended users into consideration. Anthropometric data was collected from 22 children in the target population and was used to define design targets that would ensure that the rocking chair would fit the intended population of users.

The primary anthropometric measures considered in defining rocking chair design targets were popliteal height (PH), buttock to popliteal length (BPL), and weight. PH is the measurement from the bottom of the foot to the back of the thigh just above the knee while sitting [54], and the range of PH in intended users is closely related to the range of adjustments that can be made to the footrest height. BPL measures the length from behind the buttocks to the back of the lower leg, just below the knee while sitting [54], and helps to determines the required seat depth. Seat depth is measured from the front edge of the seat to the backrest, and too deep of a seat can interfere with free movement of the legs during rocking, and so is specified in terms of the maximum allowed depth.

These needs, features and design requirements were incorporated into a “House of Quality” (HOQ) matrix which provides a structured approach for correlating customer needs with specific design features. Based on the results of the HOQ matrix, a design was created incorporating the features deemed important for addressing the needs of children with SCI, and solid models, accurately representing real-world geometries for all individual rocking chair parts, were generated using SolidWorks (v2020, Dassault

Systèmes SolidWorks Corporation, Waltham, MA). An assembly using these parts was created to study chair dynamics and to perform stress/loading analysis.

3.2.2 Simulation Using the Finite Element Method

To assess the design, several simulation techniques were employed to validate its performance. Motion studies that incorporate real-world physics were developed in the virtual computer model to evaluate the rocking motion and stability of the chair. To evaluate the structural integrity of the design, finite element analysis (FEA) was also performed (SolidWorks Simulation V2020). For wood-based furniture products, Eckelman recommends that the ultimate strength of wood members be reduced by 2/3 to account for manufacturing variations such as defects and humidity [55]. The mechanical properties of Baltic Birch plywood are anisotropic and therefore depend on the orientation with respect to surface grain. For safety, the lowest reported values (perpendicular to the face grain) of 3.58×10^7 N/m^2 for tensile strength, and 2.48×10^7 N/m^2 for compressive strength were used [56]. In the FEA analysis, these values were reduced to 1/3 of the rated strength, or 1.19×10^7 N/m^2 for tensile strength and 8.27×10^6 N/m^2 for compressive strength. The factor of safety (FOS), which is a ratio between ultimate stress of the material and the maximum working stress expected to be seen during normal use, was used to evaluate the design at each iteration. An FOS of 1.5 is typically used when evaluating reliable materials in conditions that are not severe (i.e. high temperatures, wet conditions, etc.) [57].

To simulate a worst-case scenario (an individual much larger than the intended user of the chair) the model was loaded with 136 kg (300lb) applied to the seat of the chair, and factor of safety and deflection plots were generated.

3.3 Fabrication

Parts for the rocking chair were cut from Baltic birch plywood on a Computer Numerical Control (CNC) router (ShopBot Tools, Inc. Durham, NC), with tool paths generated based on the validated solid model. Other miscellaneous parts and hardware (nuts, bolts, etc.) were purchased from commercial sources, and the chair was assembled, wood parts were sealed with lacquer, and painted with ocean scenes.

3.4 Rocking Chair Mechanical Testing

3.4.1 Tipping

The base of the chair was blocked to allow the chair to tip instead of sliding on the floor when a force was applied. The chair seat was then loaded with plate weights (59 kg [130 lbs.], the maximum expected weight of patients in the target population), and a horizontal force was applied at the top of the seat back. To apply and quantify this load, a rope was tied to the top of the backrest of the chair, and a luggage scale (American Tourister Travel luggage scale, 38 kg capacity - Model# AT97-635-027-61) was attached. The scale was then pulled horizontally in the desired direction until the chair reached the point at which it would continue to tip over ("tipping point") if not restrained. The maximum force exerted, and the lift height of the lifted side at the tipping point were recorded, and the angle at which the tipping point was reached was calculated. This was repeated for five repetitions each in forward, backward and side loading configurations.

3.4.2 Maximum Load Testing

The ability of the chair to support greater than the maximum expected load was also evaluated. For this test, 136 kg (300 lbs) of weights (representing 2.3 times the

maximum expected load) was placed on the seat of the chair and the chair was rocked gently. The chair was then examined for any evidence of damage or weakness such as cracking or bending of wood elements or fastener pull-out or deformation.

3.4.3 Strength and Stability Testing

Chair strength and stability in the expected range of dynamic loading were tested with loads of 11 kg (25 lbs), 35 kg (78 lbs), and 59 kg (130 lbs). For these tests, weights were placed on the seat of the chair and the chair was rocked manually to reach the maximum possible travel amplitude (the safety stops included in the build effectively limited maximum travel). During rocking, observations were made to identify signs of weakness or instability; if tipping was observed, the height that the feet lifted off the floor was recorded, and the angle of tilt was calculated. After loaded rocking, the load was removed, and the chair was thoroughly inspected for any signs of damage or weakness as mentioned previously.

3.5 Results

3.5.1 QFD Results

The QFD design process identified needs which fell into four categories. The highest rated category identified by the therapists was safety, followed by therapeutic needs, practical and aesthetic aspects, and a need for data to characterize and track the child's rocking. Table 2 and 3 show the categorized needs along with the importance rating each need was assigned and design features proposed to meet that need.

Table 2: Customer requirements and features determined from focus group with physical therapist (Safety and Therapeutic Need). Ratings on a scale of 1 to 10 and are averaged for each category of needs.

Customer Needs	Rating	Proposed Design Features and Testing
Safety		
Stability/strength	10.0	Baltic birch plywood construction; comprehensive strength/safety testing
Secure child in the chair	10.0	Belt/Harness to secure child in seat
Resist tipping	9.8	Glider Style rocker with stable base; safety stop to limit range of motion
Protect skin	10.0	Padding on seat, seat back, and armrests
Ability to lock rocker	8.0	Mechanism to prevent rocking during transfers etc.
Therapeutic Needs		
Enable independent movement	10.0	Means to position strap for adequate support while allowing as much trunk motion as possible
Provide support	9.8	Full back, armrests, and straps to secure and support child
Engage leg muscles	9.8	Footrest attached to base to allow children to push with legs
Engage arm muscles	8.3	Armrests for child to push/pull on
Engage Trunk muscles	9.5	Removeable footrest; footrest attached to seat rather than to base
Increase vestibular stimulation	4.0	Adjustable mode of rocking
Increase sensory stimulation	6.3	Adjustable mode of rocking; Rocking inherently induces sensory responses from multiple sense modalities (skin, muscle stretch sensors, vestibular etc.)

Several features were chosen to meet the need for safety. These include the implementation of safety stops to restrict the chair's range of motion, padding to prevent chafing and skin breakdown, the utilization of straps to securely hold the child in the seat, the mitigation of potential pinch points, and a wide, stable base to prevent tipping.

Table 3: Customer requirements and features determined from focus group with physical therapists (Practical Aspects/Aesthetic Appeal and Data for Assessment). Ratings on a scale of 1 to 10 and are averaged for each category of needs.

Customer Needs	Rating	Proposed Design Features and Testing
Practical Aspects/Aesthetic Appeal		
Sized for target population (age 1-12; up to 59kg)	8.8	Demographics of target population consulted when sizing chair features (seat width, depth, footrest location and adjustment range)
Adjust to fit child	9.8	Adjustable footrest; interchangeable seats; adjustable seat position (larger seat)
Fit into home aesthetics	8.3	Seats made from commercially available child-sized chairs
Attractive to child	8.5	Painted with attractive ocean scenes
Ease of Transport	8.3	Built in wheels; handles for pushing/carrying; mechanism to prevent rocking
Useable in multiple contexts	6.5	Detachable work surface; mechanism to prevent rocking for use in other contexts
Fun for the child	9.3	Adjustable modes of rocking to determine which is most enjoyable/most effective; ocean scenes painted on rocker to stimulate child's imagination
Ease of use	9.3	Make similar to traditional rocking chair. Straps to hold feet on footrest
Data for Assessment		
Capture Rocking Characteristics	6.3	Sensors to measure forces applied to chair surfaces
Muscle Activation Assessment	7.8	Data analysis algorithms to find correlations with muscle activation
Trunk control Assessment	7.5	Data analysis algorithms to find correlations with trunk control
User-friendly display of data	7.5	Wi-Fi link to sensor data/LabVIEW data capture software

Features selected to address therapeutic needs include a full chair back, armrests, and moveable straps to secure and support the child's pelvis and trunk while also allowing for as much independent movement as possible. Other features selected to facilitate muscle activation by the child include a footrest to allow the use of leg muscles in rocking and, a feature allowing for adjustment of the rocking motion to explore the effects this has on patterns of muscle activation and sensory response.

Practical and aesthetic needs were largely concerned with making the chair easy and enjoyable to use. To meet the need for the chair to fit the target population (age 1-12; up to 59kg), the footrest was made adjustable, and two commercial rocking chair seats of

different sizes were modified to attach interchangeably to the base of the chair, and to adjust forward and back. The need to appeal to children in the target population was met partly by the inherent appeal of rocking, but also by painting the base of the chair with attractive ocean scenes to stimulate the children's imagination.

To meet the need to track the child's use of the rocking chair, a position sensor, which tracks the motion of the seat during rocking was added to the rocking chair to make it possible to record the amplitude and duration of rocking. Force sensors were also added to the footrest, seat, and armrests to detect the forces applied to the rocking chair during rocking.

3.5.2 Final Prototype Design

The final prototype design incorporating the selected features was based on a glider style rocker, which uses linkages to suspend the seat of the chair from a base which remains stable on the floor. Figure 8 shows the solid model of the design which was used for motion studies and finite element analysis. Motion study results from early designs identified a tendency for the seat of the rocker to not return to center after rocking. This was corrected by adjusting the length and position of the linkages, until further motion study results showed it to consistently return to center.

Figure 8: Rendered solid model of rocking chair design

As shown in Figure 9, results from the finite element analysis of the final design indicate that the minimum FOS, which occurs in the front linkage arms, is greater than 5 indicating that the chair is able to support at least five times the applied load of 136 kg before failure. The maximum reported deflection is 0.024 mm.

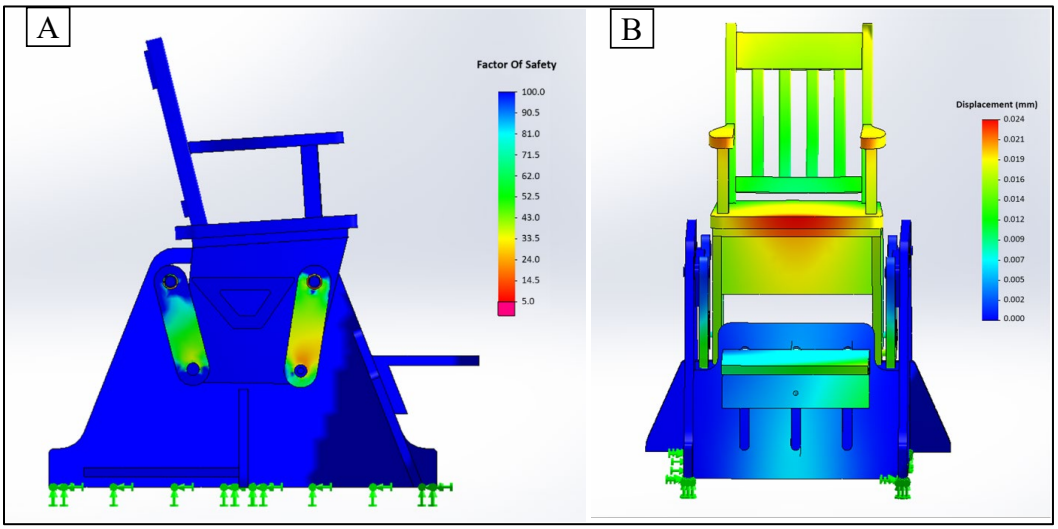


Figure 9: Finite Element Analysis results; A - Factor of Safety plot showing that minimum FOS is >5; B – Deflection plot showing that maximum deflection is less than .024 mm

3.5.3 Anthropometric Design Factors

Several design factors were directly related to the anthropometric characteristics of the intended user population. The target specifications for each of these, and the actual dimensions used in the final design are included in Table 4 along with design notes about how the specifications were identified.

Table 4: Anthropometrics Driven Design Specifications

Design Targets vs. Actual Dimensions		Design notes
Small seat max depth	Design Target: 19 cm	• Based on anthropometric data, to accommodate smallest children without need for padding behind back. • Smaller seat should not be deeper than this.
	Actual: 14 cm	• Exact seat dimensions depend on the size of commercially available children's chairs that are compatible with chair base design.
Large seat depth	Design Target: 36 cm	• Target depth for large seat based upon buttock-popliteal length data from the target population.
	Actual: 38 cm	• Exact seat dimensions depend on the size of commercially available children's chairs that are compatible with chair base design.
Footrest to seat range	Design Target: 23 – 40 cm	• Based on anthropometric data (popliteal height) from target population.
	Actual: 22 – 34 cm	• Larger range would require greater overall chair height, which conflicts with need for chair stability.

3.5.4 Prototype Chair

Figure 10 shows selected rocking chair features, and stages in the build process as well as the completed chair.

Selected materials for the chair build were as follows: Wooden parts were cut from Baltic birch plywood and assembled using 10 x 3½ inch wood screws (Hillman Deck*Plus) for all wood-to-wood connections. The seat portion of the chair was suspended on four equal linkage arms (239mm x 64mm) with ½" ball bearings (R8ZZ Shielded Bearings 1/2 x 1-1/8 x 5/16 Inch Ball Bearings) that were press fit into appropriately sized cut-outs and captured with washers attached with wood screws as shown in Figure 3D. The linkage arms were then attached to the base and chair with ½"-13 bolts and hex nuts. A position sensor constructed of a rotary potentiometer (TT

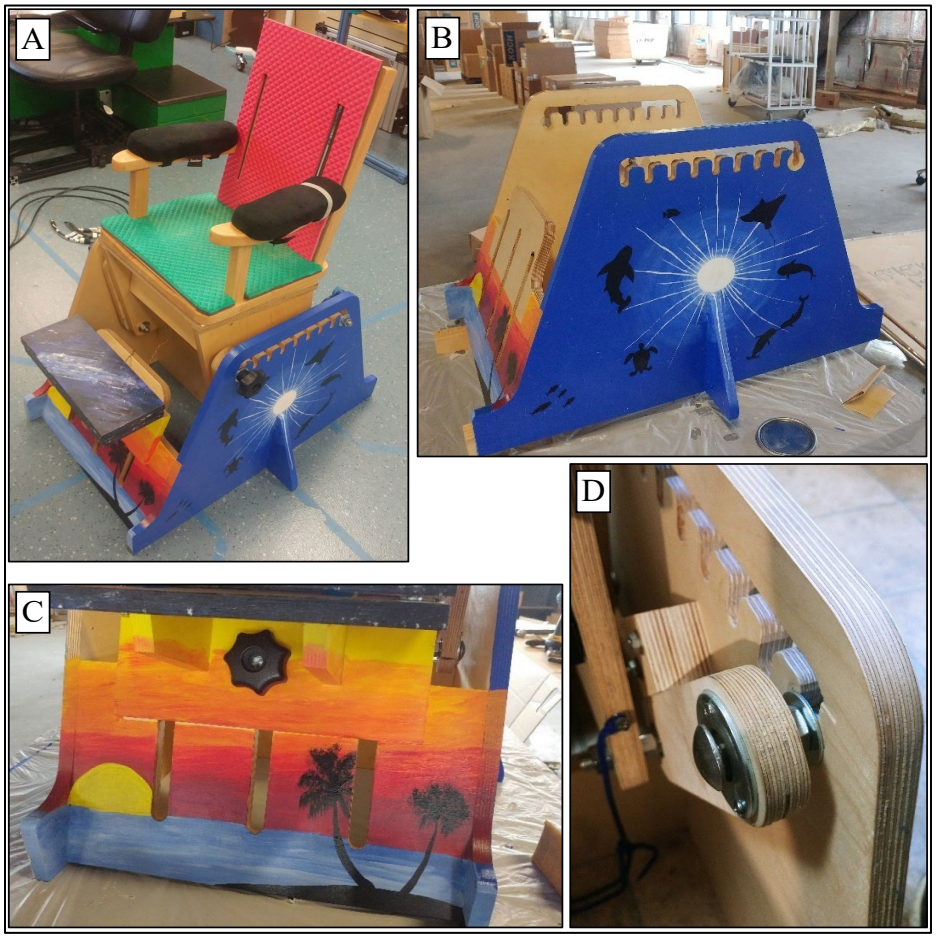


Figure 10: Rocking chair design details; Completed rocking chair (A); Painted base of rocking chair(B); Detail of footrest adjustment locking mechanism (C); Detail of bearing captured with washer in linkage arm, and revised safety stop (D).

Electronics, P160KNP) was installed on the base of the chair and coupled to one of the chair's linkage arms via spur gears. Two commercially available typical rocking chair seats of different sizes (e.g., ECR4Kids Classic North American Oak Wood Rocking Chair) were purchased and threaded studs (M6 x 50 mm) were added to the bottom of the seat to enable attachment to the rocking chair base. Three vertical slots were cut in the front of the chair base, with a ½"-13 bolt located in the middle slot to secure the footrest in position. A plastic knob with threaded insert (Morton Glass Fiber Polyamide Multiple Lobe Knob, Fluted Rim, Threaded Hole, ½"-13 Thread Size) was used to tighten the bolt

and secure the footrest in place. Wooden rails attach to the back of the footrest ramp in the adjacent outside slots and serve to keep the footrest aligned correctly. Total cost for all materials used and fabrication of parts on the ShopBot CNC router was kept under US$ 400.

3.6 Safety Testing Results

3.6.1 Tipping Results

Tipping study results show that a minimum of 6.4 kg of force in the horizontal direction at the top of the seat back is required for the chair to reach the tipping point. This minimum force occurs at the lowest loading of 11 kg, and higher loads required greater forces to tip. Overall, less force was required to tip the chair forward than to tip it back or to the side. The force required to reach the tipping point at each load level for each axis, as well as the lift height of the lifted side at the tipping point are shown in Table 5.

Table 5: Chair tipping test results.
Chair loaded with 11, 35, or 59 kg (n=5 trials)

	Mean tipping force (kg)			**Mean lift height at tipping point (cm)**		
Tilt Direction	11 kg	35 kg	59 kg	11 kg	35 kg	59 kg
Forward	7.1	11.1	15.0	41.3	31.5	29.8
Back	9.1	14.7	17.4	42.5	33.6	28.8
Sideways	7.7	12.6	18.0	34.3	27.3	26.5

3.6.2 Maximum Load Results

While loaded, the chair was observed for stability, deflection of weight bearing members, and structural integrity. No sign of weakness or instability was observed during

testing. After removing all weights from the chair seat, the assembly was inspected, and no structural damage was observed.

3.6.3 Chair Strength and Stability Results (Dynamic Loading)

During dynamic testing, the original safety stop design was found to allow the chair to bypass the rear stop and capsize at the 59kg (130 lbs) loading level. Based on this result, the safety stop was redesigned, and the test was repeated with the new safety stop, which performed well in all tests. No other signs of structural damage or weakness were observed. At maximum rocking amplitudes, the chair tipped slightly on impact with the safety stop at the maximum limit of travel. Comparing the angle of tilt during dynamic rocking to the tipping point angle during tipping tests, the maximum angle of tilt during dynamic testing was less than 1/3 of the tipping point angle that would be required to cause the chair to overturn. This adds confidence that the chair will remain stable during normal rocking. The full array of tilt angles observed during dynamic testing and their relation to the tipping point are included in Table 5.

Table 6: Chair tilt angle during dynamic loading.

Load	**Tilt Direction**	**Mean dynamic tilt[*] (degrees)**	**Maximum dynamic tilt (degrees)**	**Mean tipping point[†] (degrees)**	**Tipping point safety factor[ŧ]**
11 kg	Forward	5.3	6.4	33.4	5.3
	Backward	2.1	2.8	34.6	12.2
35 kg	Forward	5.5	6.9	24.8	3.6
	Backward	4.6	5.0	26.6	5.3
59 kg	Forward	5.5	6.7	29.8	4.4
	Backward	3.3	3.7	22.6	6.1

[*]n=10; [†]n=5; [ŧ] Tipping point safety factor represents the ratio of tipping angle to maximum dynamic tilt angle at a given load level.

3.7 Discussion

This project aimed to apply engineering design methodologies to develop a rocking chair specifically for children with spinal cord injury (SCI) to promote trunk control. Throughout the process, the needs identified in the QFD design process were used to guide design choices, and to evaluate the final design.

Safety was the highest rated need category and was one of the primary reasons for designing a custom rocking chair rather than simply adapting a commercially available rocker. The choice of a glider type rocker, rather than a more traditional rocking chair, was made primarily to provide a stable base which would resist tip-over. As shown in Figure 11, it is possible to limit the possible range of motion of this type of chair so that the center of gravity cannot move outside of the footprint of the base. This makes the chair naturally resistant to tipping.

Further evidence that the chair will resist tipping was provided by the results of physical testing which showed that at maximum amplitude of rocking under various loads, the chair does not come close to the tipping point. As seen in Table 5, the minimum tipping point factor of safety, defined as the ratio of the tipping point angle to the maximum dynamic tilt angle, is 3.6. This indicates that the chair would have to tip at an angle more than three times greater than what is actually seen in dynamic testing before tipping over. Other physical testing showed that the chair was capable of supporting the desired loads with an ample factor of safety.

The glider type rocker also has advantages with respect to meeting therapeutic needs. Independent movement, sensory stimulation, and muscle activation in arms, legs

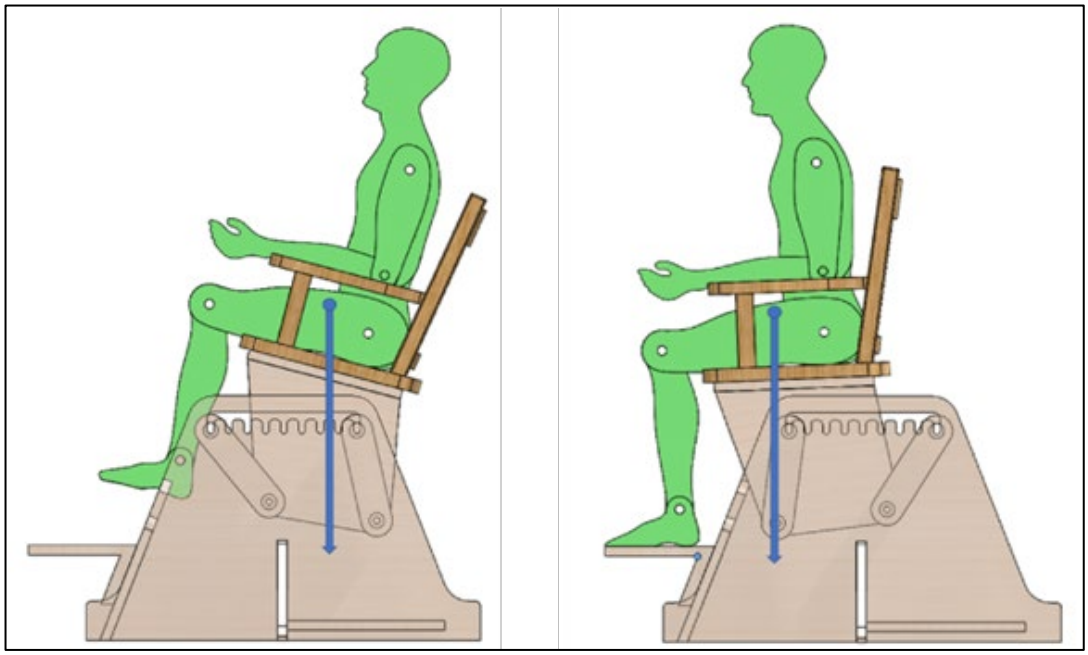


Figure 11: Rocking chair center of mass At maximum forward and back rocking, center of mass (blue arrow) stays within footprint of rocking chair and no overturning moment is created.

and trunk are all identified needs. The large, stable base of the glider type rocker provides a place to mount a footrest. Patients who have some leg control will be able to use the footrest to move the chair, providing a way to activate leg muscles. For patients without leg control, foot placement on the footrest will allow legs to flex as the chair rocks, stimulating sensory input to the spinal cord from the legs and feet.

Several of the features contributed towards meeting multiple needs. For instance, in addition to helping meet therapeutic needs, the footrest was also made adjustable to help meet the need for the chair fit children in the target population. Similarly, straps that could be adjusted higher and lower on the child's trunk helped to meet needs for safety, while also allowing as much independent trunk movement as possible.

The prototype rocking chair is intended for use in further studies in children with SCI to characterize muscle activation during rocking. As such, some features intended primarily for convenience in home use were not implemented in the current build but will likely be implemented in future version of the chair. These include features such as a mechanism to prevent the chair from rocking during transfers, wheels and handles to aid in transport, and a detachable work surface for use during other activities.

3.8 Limitations

There are several limitations to this work. Lack of human testing in the target population limits the ability to validate that the design meets the defined needs when used by children with SCI. Also, until human testing has been completed it will be unclear what clinical relevance rocking has for these children.

3.9 Future Work

Plans for future work include studies with children with SCI to validate that the chair meets the identified needs when used by the target population. One need in particular which could not be evaluated without having children rock in the rocking chair was the need for an activity that is enjoyable for children with SCI. This need was emphasized by therapists as one of the most important for children in this age group since enjoyment of an activity leads to motivation to engage in that activity, additional time spent in the activity, and better results from the activity. Additionally, efforts will be made to characterize muscle activation patterns in arms, legs and trunk during rocking to determine if rocking is an effective means of stimulating activation in muscles involved with trunk control.

3.10 Conclusion

This prototype rocking chair provides an opportunity to safely study rocking as a means of improving trunk control in children with spinal cord injuries. Further testing and refinement of the design, as well as the incorporation of embedded sensors to provide feedback on how the chair is used all hold potential for extending its usefulness. Ultimately, rocking may evolve into a valuable tool for therapists seeking a safe, accessible means for children with SCI and impaired trunk muscles to safely rock and activate their trunk muscles.

CHAPTER 4
MUSCLE ACTIVATION DURING ROCKING

4.1 Introduction

Spinal cord injury (SCI) is a debilitating condition that significantly impacts quality of life. Children with SCI in particular face numerous physical, emotional, and psychological challenges that often impede their overall development and well-being [25]. SCI is known to cause long term complications including negative effects on respiration, bladder and bowel control, cardiovascular function and head/trunk control [11]. Moreover, SCI in children is more likely to result in secondary conditions, such as scoliosis, respiratory complications, hip dysplasia, and pressure ulcers [11, 28], and the incidence of these conditions is greater for children injured at younger ages [3, 17, 27, 28].

4.1.1 Activity Based Therapy

With the existing state of the art science currently unable to fully resolve or ameliorate the various types and severities of paralysis associated with SCI, traditional rehabilitation approaches focus on compensation for paralysis via assistive devices, behavioral strategies, and adaptations to the environment to achieve mobility and function, and to facilitate activities of daily living [58]. However, researchers have recently demonstrated that activity-based therapy (ABT) is an effective intervention for at least partial restoration of intrinsic trunk control, as measured by SATCo score, in children with SCI [33]. The purpose of ABT is to activate the neuromuscular system

below the level of injury, and to promote the restoration of neuromuscular capacity. ABT interventions include locomotor training (facilitated walking on a treadmill) with partial body weight support (systems that modulate the offset of patient weight during the gait cycle), which aims to mimic typical standing/walking patterns, reinforce appropriate alignment of the trunk, pelvis, and lower extremities providing locomotor-specific sensorimotor input to the neural axis [19, 39]. In addition to training on the treadmill, off-treadmill interventions utilize the activated neuromuscular system targeting task-specific motor activities to integrate use of the progressively activated trunk in typical activities such as reaching, standing, and sit-to-stand [33]. ABT also focuses on home and community integration by giving children opportunities to utilize their new capacity and practice in a variety of everyday and functional activities [36].

Community integration considerations create opportunities to develop additional reinforcing activities that increase practice with new neuromuscular capacities and can be performed in the home and community. From that perspective, rocking in a rocking chair was explored in a case report by Argetsinger et al [40]. This study describes the trial of a pediatric rocking chair adapted for use by a child with SCI as an activity intended to support gains in trunk postural control outside of the clinic. Rocking in this chair created a self-initiated activity that promoted an upright posture and engaged trunk and arm muscles with little to no assistance by caregivers. Validating the effectiveness of this approach in applying the gains acquired through locomotor training is a critical next step to inform clinical decision-making.

4.1.2 Study Rationale

To better understand the effectiveness of rocking in the context of pediatric SCI, this study aims to answer the following research questions: 1) Does rocking in a rocking chair activate trunk muscles in children with SCI and in typically developing (TD) children? 2) What are typical temporal muscle activation patterns during a rocking cycle in children with SCI, and how do these patterns differ from those seen in TD children? 3) Is there a correlation between intrinsic trunk control, as measured by SATCo, and trunk muscle activation during rocking?

In addition to these specific technical questions, it is important to investigate practical factors that impact the rocking experience of the user. These factors include the child's enjoyment of rocking, and the safety and functionality of the rocking chair prototype.

4.2 Materials and Methods

A thorough examination of the concept, design methodology, fabrication, and safety testing of the rocking chair have been described previously [59]. Briefly, to develop new technology for accomplishing the goals of this study, a custom rocking chair specifically designed for children with spinal cord injuries was fabricated. Based on a glider style rocking chair to ensure stability and safety, the base of the chair was assembled from parts fabricated using Baltic birch plywood, a well-known furniture material which provided both durability and cost benefits and promoted ease of chair assembly. Seats from commercially available pediatric-scale rocking chairs of two different sizes were adapted to attach interchangeably to the custom base to accommodate children of varying sizes. An adjustable height footrest was also included in the design of the rocking chair

base to accommodate taller children.

To quantify the amplitude of rocking and to enable tracking of the temporal location of muscle activation in the rocking cycle, a custom chair angle/tilt sensor was incorporated into the design. This included a shafted potentiometer configured so that the rotational position of the shaft was adjusted by the angular movement of one of the chair suspension arm bearings during the rocking motion. This sensor generated a dynamic voltage which, when converted to angle of rotation, accurately reported the position of the seat as it was dynamically rotated from its neutral position by the user.

4.2.1 Participant Recruitment

The current study was performed under an Institutional Review Board (IRB) approved protocol for parental/caregiver informed consent and assent for children older than 7 years (University of Louisville IRB #17.0725). Two cohorts were enrolled: children with SCI and TD children, based on specific eligibility criteria. Children with SCI, age 1-12 years and currently participating in locomotor training, recently discharged (< 1 month) or, if discharged between 1 and 24 months prior, were eligible with a medical screening to determine health status and/or safety concerns. For TD children, age 1-12 years with no history of SCI or presence of neurological disorder, musculoskeletal disease, cardiovascular, pulmonary, or respiratory condition that would affect typical function, and the ability to follow age-appropriate instructions were eligible. For both cohorts, children with a physical condition or recent illness, identified via medical screen, that would prevent participation in rocking were excluded.

4.2.2 Participant Characteristics

A total of 11 children with SCI and 10 TD children were enrolled over a 22-month period. Age and height at time of testing, and sex were recorded for all participants in both groups. American Spinal Injury Association (ASIA) Impairment Scale (AIS) [60] was recorded for participants in the SCI group whose age and etiology allowed it to be determined. Injury level, time since injury, etiology, and SATCo scores were also recorded for participants in the SCI group. SATCo score is an indication of a child's capacity to sit upright in both static and dynamic conditions with a facilitated neutral pelvis position and varying biomechanical levels of trunk support, and represents the patient's inherent, uncompensated level of trunk control [33]. Scores range from 0 to 20, with higher values indicating better trunk control. SATCo was the primary measure of trunk control impairment and a primary descriptor of the population with SCI participating in this study.

4.2.3 Anthropometrics and Rocking Chair Fit

When considering the design and setup of the rocking chair, it was important to take the anthropometric characteristics of the users into consideration. The following anatomical features were considered to be important anthropometric measurements that might affect rocking chair fit.

Popliteal Height (PH) is the measurement from bottom of foot to underside of thigh while sitting. This helps to determine footrest height relative to the top of the seat. For a stationary chair, the seat to floor distance could match the PH, but for a rocking chair this leads to the feet lifting off the footrest as the chair rocks back. Consequently,

the footrest should be set up so that, the knees are slightly elevated off the seat when the chair is centered in the neutral position, and the feet do not lift when the chair rocks back.

Buttock-popliteal length (PBL) is the measurement from behind the buttock to the back of the lower leg just below the knee while sitting. This determines the depth of the seat measured from the front edge of the seat to the backrest of the chair (or to padding placed behind the user's back). The seat depth should be less than the BPL to allow for movement of legs during rocking. If the seat is too deep, padding can be added behind the child, but too much padding may disrupt the balance of the chair by moving the user's center of gravity forward.

User weight can interact with seat adjustments that move the center of balance forward or back due to size factors, such as when a smaller child has padding placed behind their back, or a larger child has the seat moved back. This is primarily a problem for larger, heavier children since a smaller child's weight is usually not enough to change the balance significantly.

Trunk width does not affect chair motion but should be checked to ensure that the child can sit comfortably with no squeezing or chafing from the sides of the chair.

4.2.4 Rocking Chair Setup and Fit Adjustment

Table 7 is a table of identified parameters that were considered when seating a child in the chair, including methods of adjustment for optimal fit and balance. When setting up the chair, it may be impossible to meet all the fit criteria simultaneously. For instance, if the seat balance is too far back, and the footrest has already been adjusted all the way down, it may not be possible to move the child forward to correct the balance without moving them too close to the footrest.

Table 7: Chair Setup and Fitting Parameters

Fitting parameter	Definition and adjustment
Seated balance	When sitting still in the rocking chair, the seat should not tilt more than 10 degrees in either direction from the neutral position. This can be compensated for by adding padding behind the child to move them forward, or by sliding the seat back or forward, or by switching to the larger/smaller seat.
Footrest placement	When the child rocks back in the rocking chair, the feet should not lift off footrest. This means that in the neutral position, there will be a gap between the front edge of the top of the seat and bottom of the child's leg just above the knee. The size of the gap will vary depending on the chair setup and child size, so the most reliable way to check this is to watch the child rock and adjust the footrest position until the bottoms of the legs (behind the knee) just touch the top of the seat when the chair reaches its farthest-back position, and the feet do not lift off the footrest.
Seat depth	When the child rocks all the way forward, the backs of the calves should not bump the front of the seat. If they do, switch to the smaller seat, or add padding behind the user to decrease the effective seat depth.
Seat width	When seating the child, the width of the chair should be checked to ensure that it is not too tight. If the sides of the seat squeeze or rub against the child significantly, the larger seat should be used if possible. Other width adjustments are not possible with the current design
Child weight	The chair has been tested and is safe for up to 130 lbs. Children heavier than this should not use the chair.

4.2.5 Chair Functionality Assessment

To validate the basic operation of the chair, a TD child first evaluated the chair by sitting in the seat to test its balance, followed by rocking to assess both comfort and function. Once basic chair operation was verified, children with SCI were allowed to rock in the chair. Children were asked to rock in several different ways to evaluate which muscles they were capable of using to rock the chair: 1) Free rocking, allowing participants to rock in any manner of their choosing; 2) arms-off-armrests, to promote use of trunk muscles; 3) leg-only rocking, restricting trunk motion to assess the contribution of leg muscles to rocking; 4) footrest removed, so that only upper body muscles contribute to rocking. Results from these modes of rocking were noted and compiled to better understand muscle use strategies.

During rocking sessions, children were observed closely while technicians engaged with them in conversation to understand their experience. Enjoyment of rocking, difficulties with making the chair rock, methods of initiating and maintaining rocking, and any potential safety or practical issues were observed and noted. Additionally, parents, children, engineers, and therapists engaged in debriefing conversations after each rocking session to obtain reactions and feedback, and to suggest possible improvements to the chair and protocols. Videos of rocking sessions were also reviewed to ensure that all data pertaining to chair use had been captured.

4.2.6 Surface Electromyography (sEMG) Data Acquisition

sEMG signals from muscles in the arms, legs, and trunk of both TD and SCI groups were recorded using wireless electrodes (Cometa Pico EMG, , pre-amplified, bipolar , 29 mm electrode spacing, 2000 Hz sampling rate, Cometa SRL, Milan, IT) as shown in Table 6.

Table 8: Muscles targeted for EMG readings

Trunk Muscles	Arm	Leg
Cervical paraspinal (PSC)	Biceps brachii (BB)	Rectus femoris (RF)
Thoracic paraspinal (PST)	Long head of triceps (TB)	Medial hamstring (MH)
Lumbar paraspinal (PSL)	Pectoralis (PEC)	Tibialis anterior (TA)
Rectus abdominis (RA)		Medial gastrocnemius (MG)
Oblique (OB)		

Appropriate locations on the skin above the muscle of interest were prepared by cleaning with alcohol swabs, then electrodes were placed over each muscle while the child was seated on a stationary table (see appendix D for full electrode placement protocol). Subjects were then asked to sit in (TD) or were placed in (SCI) the chair

(example in Figure 12), a safety strap was placed around the waist, and additional straps placed higher on the trunk if necessary for support.

Each child was instructed to sit quietly for one minute while sEMG was recorded to establish baseline muscle activation. All children were then instructed to rock in the chair using whatever methods were most natural to them. Once the child was accustomed to rocking and was observed to be rocking in a regular rhythm, sEMG was recorded for one minute. This process was repeated for the other three modes of rocking. Appendix D includes an outline of the full data collection protocol.

sEMG data was acquired at 2000 Hz and imported into MATLAB. sEMG data offset was removed by subtracting the mean value of all data points from each data point,

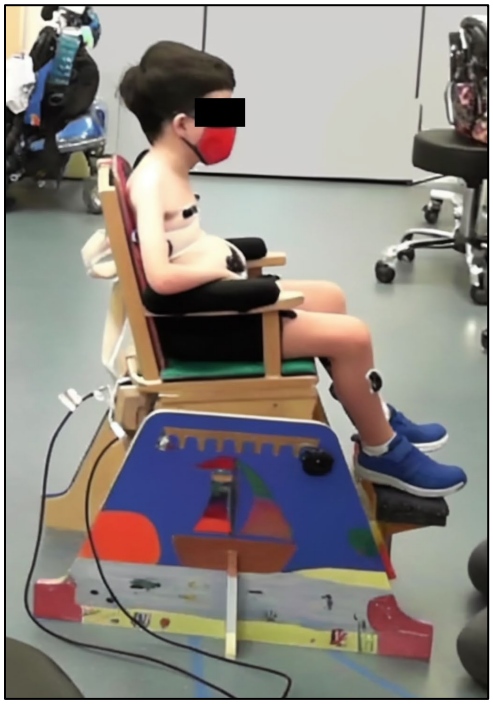


Figure 12: A participant with SCI using the custom rocking chair prototype.Note: strap around chest for support, and footrest raised to support feet.

and a 300-point moving window root mean square (RMS) was calculated for all datasets using custom MATLAB scripts (Appendix A).

4.2.7 Rocking Cycle

For this study, a single rocking cycle was defined as the position of the chair as it swings from the extreme front position to the extreme rear position and back to the front. Thus, the beginning and end of the cycle is defined as the point at which the chair reverses direction at the front of the cycle. As shown in Figure 13, the cycle was broken into two phases: Phase 1 is backward (BW) motion, starting with the chair all the way forward, and lasting while the chair swings backward to the farthest back point in the

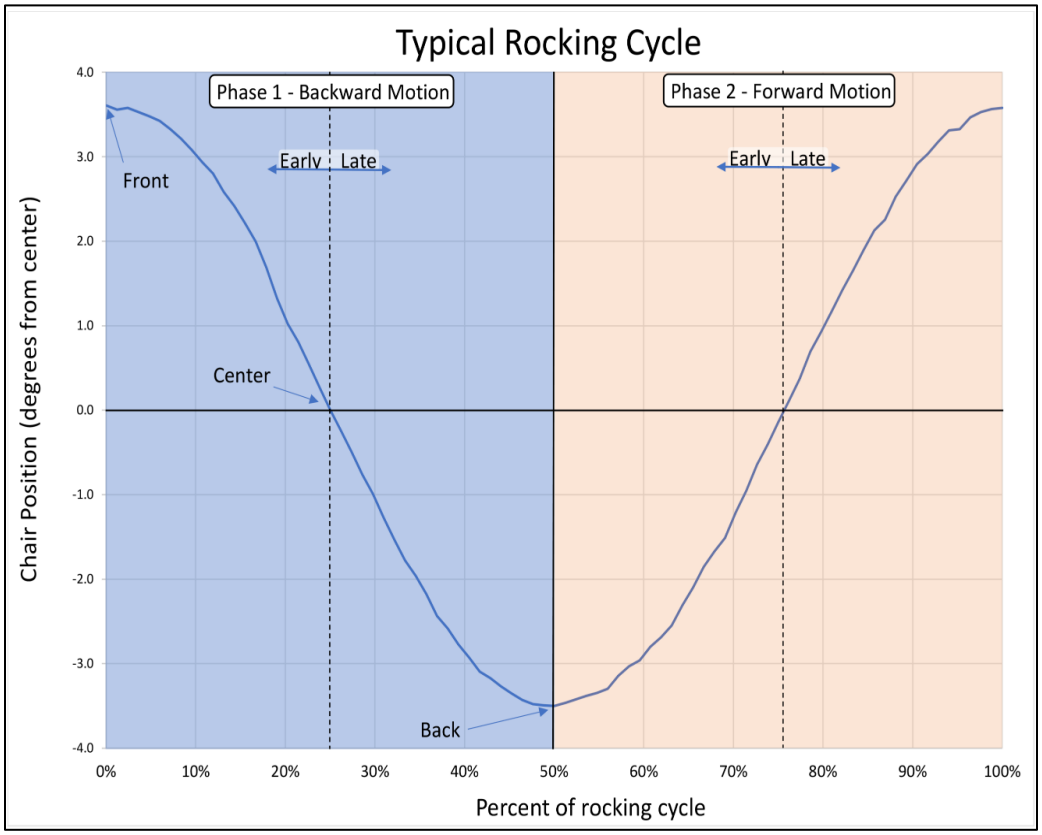


Figure 13: Sample position sensor data from one rocking cycle, to highlight cyclical phase of rocking Center vertical line marks change in direction; left quadrant is backward motion; right quadrant is forward motion.

cycle. Phase 2 is forward (FW) motion, starting with the chair at the farthest back point, and lasting until the end of the cycle with the chair again at the farthest forward point. Each of these phases was divided into early (EBW, EFW) and late (LBW, LFW) stages. Accordingly, the chair rocking direction reverses from forward to backward at the end point of the cycle, and reverses from backward to forward at the midpoint of the cycle.

4.2.8 Artifact Removal in sEMG Data

As is common with sEMG data, many of the trunk muscle data sets were contaminated with cardiac artifacts. To remove this interference, two methods were used. For data used to calculate increase in muscle activation while rocking, it was possible to use the data between heartbeats to calculate the magnitude of the sEMG signal. To delete the contaminated data, a custom MATLAB script (Appendix A) was used to identify the interfering signals and delete them from the dataset. Before running this script, each dataset was manually inspected to determine an appropriate threshold for detecting heartbeats. Typically, the cardiac signal was strongest in the left pectoral sEMG, so this signal was used initially to locate the heartbeats, and the start and end points of each heartbeat were identified. The erroneous data was then deleted from all data streams and the remaining data was concatenated.

To determine the temporal patterns of muscle activation during the rocking cycle, it was necessary to use a method of cardiac contamination removal that preserved the time-dependent nature of the data. Similar to the previous method, this involved identification of the start and end of each heartbeat. Since there was both significant variation in the strength of the cardiac signal across full session recordings and variation between subjects regarding which muscle activation data was contaminated, the data

from each trunk muscle was manually inspected. Muscle activity recordings with contamination were flagged for correction, and the contaminated data was deleted. A custom MATLAB script (Appendix A) was written to detect the rocking cycles, and missing data that had been deleted due to cardiac contamination was replaced by the averaged data from the same point in the rocking cycles with intact data for that part of the cycle.

In addition to the cardiac contamination, there were also two other, less prevalent, sources of data contamination. First, to capture data from the desired muscles, some sEMG sensor bodies were required to be positioned in locations that brought them into contact with the seat during rocking, potentially introducing artifacts into the recorded data in the event of a collision. Second, extraneous movements on the part of the child, such as a hand gesture, could introduce a signal unrelated to the rocking cycle into the data. These were identified and removed manually by inspecting the EMG data and cross-referencing with the corresponding video recording of the data collection session.

4.2.9 Muscle Activation Amplitude Calculation

For each participant, the mean sEMG (RMS) amplitude during rocking was calculated for each muscle. Baseline amplitude was also calculated by taking the three second period with the lowest mean sEMG (RMS) amplitude during quiet sitting for each muscle. Normalized activation amplitude for each muscle was calculated by subtracting the baseline amplitude from the mean amplitude during rocking of the corresponding muscle. Normalized activations were then plotted in a heatmap.

4.2.10 Prototype Cycle Creation

To determine the timing of muscle activation within the rocking cycle, an average or "prototype" rocking cycle was created for each muscle. To do this, a custom MATLAB script (Appendix A) was used to break the EMG data from each subject into rocking cycles using the data from the position sensor mounted on the rocking chair. These activation cycles for each muscle were averaged for each subject, and the resulting average cycles were normalized to a scale of 0 to 1 using the formula:

$$\frac{P_n - Cycle_{min}}{Cycle_{max} - Cycle_{min}} \qquad \text{Eq. 1}$$

where P_n is the nth data point, $Cycle_{max}$ is the maximum value for the given muscle, and $Cycle_{min}$ is the minimum value for the given muscle. The normalized cycles for each muscle were then averaged for the SCI group and the TD group, to produce typical activation cycles, and the resulting curves were again normalized to a scale of 0 to 1.

The normalized cycles for each muscle were plotted with SCI and TD data on the same graph to facilitate comparison.

4.2.11 Statistics

To address the first research question, "does rocking in a rocking chair activate trunk muscles in children with SCI and in TD children?" the mean sEMG (RMS) amplitude during rocking was calculated for each muscle activity recorded. Baseline amplitude was also calculated by taking the three second period with the lowest mean sEMG (RMS) amplitude during quiet sitting for each muscle. One-sided signed-rank tests were then used to test the hypothesis that for both SCI and TD groups, sEMG amplitude (RMS) for each muscle during rocking would be greater than baseline sEMG amplitude

(RMS) for the same muscle during quiet sitting. P-values were corrected for multiple hypothesis testing using the Holm-Sidak method [61].

To address the second research question, ”What are typical temporal muscle activation patterns during a rocking cycle in children with SCI, and how do these patterns differ from those seen in TD children?” cluster analysis was used to investigate how the timing of muscle activation in the SCI group compared to those observed in the TD group, and to determine if different rocking styles contributed to different muscle activation patterns in trunk muscles. To achieve this, the rocking cycle was subdivided into four segments, as described previously, and shown in Figure 13. EBW (first 25% of the cycle), LBW (26-50%), EFW (51-75%), and LFW (76-100%). A custom MATLAB script (Appendix A) was used to calculate the mean normalized muscle activation within these segments for each subject and each trunk muscle. This data was aggregated and used to perform cluster analysis. Cluster analysis was performed in MATLAB, using the ‘linkage’ function with the ‘average’ distance method to find clusters of subjects who used similar temporal muscle activation patterns while rocking. After clusters were identified, distance between each SCI subject and the TD cluster was calculated using the formula:

$$D = \sqrt{(TD_{25} - SCI_{25})^2 + (TD_{50} - SCI_{50})^2 + (TD_{75} - SCI_{75})^2 + (TD_{100} - SCI_{100})^2} \quad \text{Eq. 2}$$

where D equals distance, and TD_x and SCI_x represent the mean activation for the given muscle over the respective segment of the rocking cycle. These distances were then used to determine which SCI clusters were more similar to the TD cluster, and the mean activations were plotted for the TD subjects and each SCI cluster [62].

Two-sided t-tests were used to test for differences in activation in each segment between the TD group and each of the SCI clusters, and significant differences were noted on plots.

To examine the third research question, “Is there a correlation between intrinsic trunk control, as measured by SATCo, and trunk muscle activation during rocking?” Spearman correlation analysis was performed to assess the correlation between SATCo scores and trunk muscle activation amplitude. For purposes of this analysis the two children with acute flaccid myelitis (AFM) were excluded as their impairment presentations are atypical, not uniform across spinal cord levels, and often reflect greater to lesser impairment in a cephalad-caudal direction. In contrast, other participants demonstrate higher SATCo scores with greater control and activation of lower thoraco-lumbar muscles. Results were compiled in a table and significant correlations were noted.

All confidence levels were set at 95% ($p < 0.05$). Prism 10 (GraphPad Software, San Diego, CA, USA) was used for the analysis.

4.3 Results

4.3.1 Participant Characteristics

Characteristics of participants including age, height, SATCO score, and injury related details are shown in Table 9.

The SCI group included 7 males and 4 females between 3 and 11 years of age (mean = 7.1, SD = 2.7), and heights ranging from 77 to 42 cm (mean = 120, SD = 22). SATCo scores ranged from 0 to 19 (out of 20) (mean = 13.1, SD = 5.8). Two children presented with cervical SCI, 6 with thoracic SCI, and 1 with lumbar SCI. Time since injury ranged from 1.5 to 6.5 years (mean = 4.1, SD = 1.7).

The TD group included 6 males and 4 females with ages ranging from 5 to 11 years (mean = 7.2, SD = 2.4), and heights from 111 to 143 cm (mean = 128, SD = 14).

Table 9: Participant characteristics

Participant ID	Group	Age (yrs)	Sex	Height (cm)	SATCo Score	AIS	Injury level	Time since injury (yrs)	MOI	Etiology
P216	SCI	7	M	131	0	*	-	1.5	NT	Acute Flaccid Myelitis
P188	SCI	4	F	94	8	*	T2-T5	4	NT	Myelomalacia
P23	SCI	7	M	140	11	B	C4-C7	4.5	NT	Transverse Myelitis
P34	SCI	8	M	128	11	A	T2-T8	6.5	NT	Spinal Astrocytoma
P32	SCI	9	F	129	12	A	T2-T3	6	T	Motor Vehicle Accident
P187	SCI	3	M	77	12	*	T11	2.5	NT	Spinal Cord Ischemia
P204	SCI	9	M	130	15	A	L4	2	T	Motor Vehicle Accident
P217	SCI	3	M	91	18	*	C1-C3	3	NT	Perinatal
P15	SCI	9	F	127	19	A	T12	5.5	NT	Epidural Abscess
P21	SCI	11	F	142	19	A	T10	5	NT	Spinal Stroke
P215	SCI	9	M	139	19	*	-	4	NT	Acute Flaccid Myelitis
SCI Mean (SD)		7.1 (2.7)		120 (22)	13.1 (5.8)			4.1 (1.7)		
SCI Median (IQR)		7.8 (5.5,9.0)		129 (110,135)	12.0 (11.0,18.5)			4.1 (2.8,5.2)		
SCI Range		3-11		77-142	0-19			2-7		
P218	TD	9	M	143	-		-	-		-
P38	TD	8	F	129	-		-	-		-
P219	TD	5	F	-	-		-	-		-
P220	TD	5	M	115	-		-	-		-
P221	TD	8	M	134	-		-	-		-
P222	TD	5	F	111	-		-	-		-
P223	TD	11	M	149	-		-	-		-
P224	TD	9	M	141	-		-	-		-
P225	TD	5	M	119	-		-	-		-
P226	TD	5	F	113	-		-	-		-
TD Mean (SD)		7.2 (2.4)		128 (14)						
TD Median (IQR)		6.5 (5.2,9.0)		129 (115,141)						
TD Range		5-12		111-150						

*AIS not valid under 5 years of age [63]; SCI = Spinal cord injury; TD = Typically Developing; SATCo = Segmental Assessment of Trunk Control; AIS = ASIA Impairment Scale score; MOI = Mechanism of injury; T = traumatic; NT = Non-traumatic

4.3.2 Safety, Functionality, and Enjoyment

Data gathered during the observation of rocking sessions are summarized in Table 10.

Fit: Three of the children in the SCI group had minor issues with fit that were addressed satisfactorily by adding padding to the footrest or behind their back. Two other children had fit issues that couldn't be fully corrected. One was too big for the chair and

the balance was off towards the rear (participant P21 in Table 10 for details of chair adjustments). The other was too small for the chair even with padding on both the footrest and back of the seat (participant P187 in Table 10). Both these children were still able to rock, but their rocking mechanics (how they rock, and their overall experience rocking the chair) may have been affected by the balance and fit of the chair.

Safety: No adverse safety events or injuries were experienced during trials with children in the rocking chair. It was however, observed that a cross brace under the seat could create a potential pinch-point for smaller children.

Functionality: Regardless of previous experience with rocking or degree of impairment, all children in both groups were successful at making the chair rock. The two youngest children (both three years old) had some difficulty timing their efforts but were able to make the chair rock. After some practice, their timing improved, but the amplitude of rocking remained well below the chair's full range of motion.

All children in both the SCI and TD groups were able to fit in the rocking chair. The interchangeable seats and adjustable footrest accommodated most children without alteration, but for those with shorter legs, it was necessary to insert padding between the child and the seat back and, in one case, to place foam blocks on the footrest to enable their feet to reach comfortably. This adjustment allowed them to engage in rocking but made it more challenging to position them correctly.

Debriefing discussions following rocking sessions provided suggestions for functional improvements to the rocking chair. These suggestions included a larger footrest with straps and a non-slip surface to keep feet in place, and a mechanism to prevent rocking during transfers or other activities.

Enjoyment: During conversation several of the children specifically said they enjoyed rocking in the rocking chair, and two of the children, who had to return for a second session due to problems with data collection, both expressed their eagerness to return. Another indication of enjoyment was that many of the children rocked spontaneously while not specifically engaged in a rocking task, and in some cases, it was difficult to convince them to sit still.

Table 10: Participant experience while rocking

Participant ID	Description	Nervousness	Discomfort	Trunk Movement	Leg Use	Seat Size	Footrest Height (cm)	Added back padding (cm)	Added seat padding (cm)
P15	Initially nervous, but confident by end of session	Y	N	None	Y	S	15	0	0
P21	Very focused on completing rocking tasks; said she might use the chair at home if she had one, and her mom used to rock her when she was sick	N	N	Counter	Y	L	0	5	2
P23	Pretended to be in rocking boat; asked many questions; spontaneous rocking between trials, but a little tired by end	N	N	Sync	N	S	15	0	0
P32	Focused on tasks; Helped with EMG placement	N	N	Sync	N	S	0	0	0
P34	Commented rocking was fun; spontaneously rocked between trials	N	N	Sync	N	L	7	0	0
P215	Enjoyed pushing with legs. Said seat was too narrow	N	Y	None	Y	S	0	0	0
P187	Difficulty timing efforts, but made chair rock, and improved over course of session	N	N	Counter	N	S	24*	8	0
P188	Vigorous rocking, but tired by end of session	N	N	Sync	Y	S	15	7.5	0
P216	Returned for 2nd session, and parent mentioned they had purchased a rocking chair for home use	N	N	None	Y	L	0	4	0
P217	Played with toys during rocking	N	N	Counter	N	S	15	10	0
P204	Returned for 2nd session due to data collection error, and parent commented "he couldn't wait to come back here and do this"; child said he would rock at home if he had a rocking chair this cool	N	Y	Sync	N	L	0	0	0

*Included 9 cm block on top of footrest; Y= Yes, N= No, Sync = Movement synchronized with rocking so weight shifts forward during forward chair movement; Counter = Trunk movement counter to rocking so weight shifts back as chair moves forward; S = Smaller seat; L = Larger seat

There were no major, negative reactions to the rocking chair. One of the children did initially express some apprehension that the chair would tip over but was reassured when the safety stops which limit chair tilt were demonstrated, and quickly gained confidence as they rocked. Two of the children rocked vigorously at first but expressed that they were feeling tired toward the end of the rocking session.

4.3.3 Observed Trunk Motion During Rocking

The majority of children in the SCI group moved their trunk and/or head in time with the rocking cycle. Of these, five leaned their head and upper trunk, shifting their weight forward while the seat moved forward, and shifting their weight back while the chair moved back. In contrast, three children instead moved their trunk in a counterbalance rocking strategy, leaning forward from the waist as the seat of the chair moved back. This effectively kept the center of mass of the seat/child in approximately the same place but moved the seat back and forth. Finally, three children maintained a mostly stationary trunk.

4.3.4 Increase in Muscle Activation During Rocking

Mean RMS muscle activation during rocking was significantly higher than during quiet sitting ($p < 0.05$) for all twelve muscles tested in both SCI and TD groups, see Table 9 and Table 10 respectively.

Table 11: Increase in muscle activation while rocking for children with SCI

Muscle	n	Baseline: Median[IQR]	Rocking: Median[IQR]	Median Increase (CI*)	p-value†
Cervical PS‡	8	6.40[4.39, 13.2]	14.1[11.0, 35.0]	7.14(3.92 to 27.0)*	0.006
Thoracic PS	11	5.60[3.59, 9.08]	18.3[12.8, 37.7]	12.8(1.46 to 32.8)	0.006
Lumbar PS	11	3.78[3.40, 5.60]	9.49[5.43, 21.5]	6.13(0.56 to 21.1)	0.006
Pectoral	11	5.15[3.37, 10.7]	10.8[7.79, 19.8]	4.49(1.14 to 19.6)	0.006
Biceps	11	4.01[3.24, 5.66]	16.0[7.30, 30.1]	13.0(3.46 to 79.1)	0.006
Triceps	11	3.37[3.23, 6.20]	18.0[10.5, 34.3]	14.2(6.50 to 31.2)	0.006
Rectus Abdominis	11	3.58[2.92, 3.82]	6.76[3.57, 14.3]	3.56(0.45 to 15.4)	0.006
Oblique	11	4.01[3.28, 4.64]	10.0[4.79, 13.3]	3.82(1.00 to 10.6)	0.006
Rectus Femoris	11	3.13[2.81, 3.26]	3.84[3.42, 13.4]	0.71(0.42 to 25.1)	0.006
Hamstring	11	3.21[2.85, 3.31]	4.45[3.78, 13.5]	1.29(0.50 to 21.9)	0.006
Tibialis	11	3.17[2.75, 4.19]	3.54[3.14, 18.0]	0.44(0.37 to 8.18)	0.006
Gastrocnemius	11	2.98[2.70, 3.88]	3.69[3.22, 9.68]	0.86(0.36 to 10.1)	0.006

All muscles tested showed a significant ($p < .05$) increase in muscle activity (as measured by mean of EMG_{RMS}) while rocking vs. baseline during quiet sitting in rocking chair immediately prior to rocking; †p-values corrected for multiple hypotheses using the Holm-Sidak method; ‡Due to discomfort, 3 children did not use cervical paraspinal EMG sensors; *the confidence level was set to 95%; however, due to the nature of the non-parametric signed rank test and algorithms used by the Prism 10 software used, 98.8% and 97.9% CI were output for SCI and TD groups respectively for all muscles except for cervical paraspinals where 99.2% CI were output for both groups; PS = Paraspinal; CI = confidence interval; IQR = Interquartile range;

Table 12: Increase in muscle activation while rocking for TD children.

Muscle	n	Baseline: Median[IQR]	Rocking: Median[IQR]	Median Increase (CI)	p-value†
Cervical PS‡	8	6.86[5.37, 9.77]	17.0[11.3, 22.8]	8.09(4.80, 18.4)*	0.012
Thoracic PS	10	5.28[4.87, 6.40]	13.1[9.62, 21.5]	8.13(2.76, 20.4)	0.012
Lumbar PS	10	3.35[3.12, 3.90]	8.39[6.04, 13.6]	5.20(1.04, 10.1)	0.012
Pectoral	10	3.97[3.47, 5.33]	5.86[4.54, 11.7]	2.04(0.58, 9.15)	0.0137
Biceps	10	3.37[2.89, 4.19]	5.42[3.90, 7.96]	1.17(0.34, 5.22)	0.0136
Triceps	10	3.64[3.24, 4.81]	7.59[4.16, 8.81]	3.17(0.45, 5.79)	0.012
Rectus Abdominis	10	3.19[2.94, 3.50]	5.19[4.31, 7.43]	2.01(0.52, 5.84)	0.012
Oblique	10	4.13[3.33, 4.25]	6.76[5.13, 9.91]	2.80(0.99, 6.57)	0.012
Rectus Femoris	10	3.07[2.98, 3.62]	4.99[3.85, 6.83]	1.68(0.55, 6.67)	0.012
Hamstring	10	3.41[3.00, 3.87]	11.9[9.69, 18.9]	8.90(3.05, 19.3)	0.012
Tibialis	10	3.33[2.90, 4.96]	18.9[15.1, 29.0]	15.8(7.44, 25.8)	0.012
Gastrocnemius	10	2.81[2.52, 3.35]	5.75[4.38, 11.8]	2.79(1.46, 19.7)	0.012

All muscles tested showed a significant ($p < .05$) increase in muscle activity (as measured by mean of EMG in μV_{RMS}) while rocking vs. baseline during quiet sitting in rocking chair immediately prior to rocking; ; †p-values corrected for multiple hypotheses using the Holm-Sidak method; ‡Due to discomfort, 2 children did not use cervical paraspinal EMG sensors; *the confidence level was set to 95%; however, due to the nature of the non-parametric signed rank test and algorithms used by the Prism 10 software used, 98.8% and 97.9% CI were output for SCI and TD groups respectively for all muscles except for cervical paraspinals where 99.2% CI were output for both groups; PS = Paraspinal; CI = confidence interval; IQR = Interquartile range

Muscle activation is measured by the increase from baseline of EMG amplitude (μV_{RMS}). Due to discomfort, cervical paraspinal sensors were not used on several participants in each group leading to a smaller n for this muscle, and a different confidence interval. Median increase and confidence interval are shown for all.

4.3.5 Temporal Muscle Activation Patterns

Typical temporal muscle activation patterns during the rocking cycle for both SCI and TD groups are shown in Figure 14.

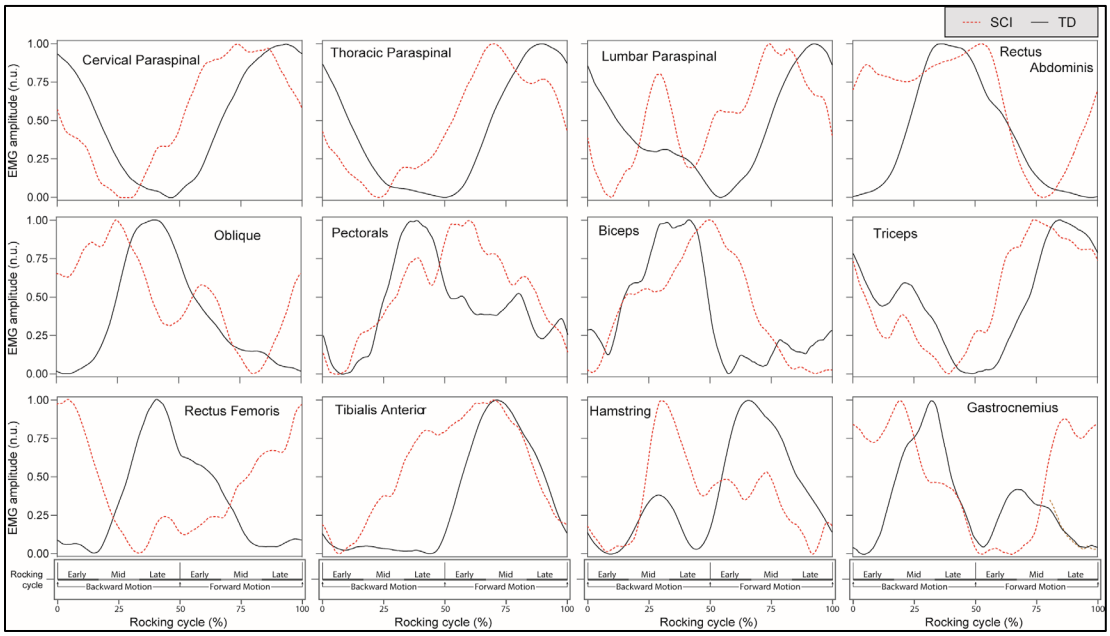


Figure 14: Averaged muscle activation during rocking in children.; x-axis is one full rocking cycle; y-axis is normalized to the amplitude of EMG_{RMS} in the rocking cycle; n.u. = normalized units

General trends indicate that many of the muscles exhibit similar activation patterns between the groups but are often out of phase with each other. For instance, cervical and thoracic paraspinals show very similar activation curves, but in the SCI group, the peak activation occurs earlier in the rocking cycle. Other muscles have maximum activations that occur close to the same point in the rocking cycle but exhibit different shaped curves. For example, both the SCI and TD groups show maximum activation of the rectus abdominis at the same point in the rocking cycle, but the SCI group has a much broader activation peak than the TD group. Table 13 describes the observed locations of peak muscle activation and the effects of muscle activation with respect to the rocking cycle in SCI and TD groups.

Table 13: Observed actions of muscles during rocking in children with SCI.

	Max Activation Location (% of cycle)			
Muscle	**SCI**	**TD**	**Curve comparison**	**Muscle Action**
Cervical Paraspinal	73% (Mid FW)	93% (Late FW)	Similar shape; SCI peak occurs earlier in cycle	Stabilizes trunk, resists forward motion, and shifts weight back to assist in rocking
Thoracic Paraspinal	70% (Mid FW)	89% (Late FW)	Similar shape; SCI peak occurs earlier in cycle	Stabilizes trunk, resists forward motion, and shifts weight back to assist in rocking
Lumbar Paraspinal	74% (Mid FW)	93% (Late FW)	SCI peak occurs earlier in cycle with secondary peak in BW phase	Stabilizes trunk, resists forward motion, and shifts weight back to assist in rocking
Pectoral	60% (Late FW)	38% (Late BW)	SCI peak occurs later in cycle	Pull on arm rests as chair reverses direction at back of cycle
Biceps	50% (Late BW)	42% (Late BW)	Very similar curves with single peak occurring close to direction reversal at back of cycle	Stabilizes and shifts weight forward at the end of back swing
Triceps	74% (Mid FW)	85% (Mid FW)	Max activation close to the same point, but TD has secondary peak in late BW phase, and SCI does not.	Stabilizes and shifts weight backward at the end of front swing
Rectus Abdominis	53% (Mid BW)	36% (Mid BW)	Max activation at similar location, but SCI has broader peak	Stabilizes trunk and shifts weight forward in preparation for reversal of direction
Oblique	25% (Mid BW)	40% (Mid FW)	Max activation occurs during backward motion, but SCI peak occurs earlier in cycle	Stabilizes trunk and shifts weight forward in preparation for reversal of direction
Rectus Femoris	5% (Early BW)	41% (Late BW)	SCI peak occurs as chair reverses direction at front of cycle; TD peak occurs just before back of cycle	Flexes hip
Hamstring	30% (Late BW)	66% (Early FW)	TD and SCI both have secondary peaks that occur close to each other's primary peaks	Straightens hip as chair moves back
Tibialis Anterior	70% (Mid FW)	71% (Mid FW)	SCI and TD peaks both occur mid FW motion, but SCI peak is broader	Lifts front of foot to avoid impeding forward motion
Gastroc	19% (Mid BW)	32% (Mid BW)	SCI peak that spans from before to after direction reversal at front of cycle. TD slightly later.	Push on footrest during backward motion

FW = Forward motion phase of rocking cycle; BW = Backward motion phase of rocking cycle; Early = first third of motion in FW or BW direction; Mid = middle third of motion in FW or BW direction; Late = last third of motion in FW or BW direction

Cluster analysis based on the timing of muscle activation divided the SCI group into two clusters of seven and four subjects as shown in the dendrogram in Figure 15. The average calculated distance from the seven and four-subject clusters to the TD group was 0.78 and 1.16 respectively. Thus, the seven-subject cluster was labeled the "TD-similar cluster", and the four-subject cluster was labeled the "TD-dissimilar cluster".

Plots of the clustering data for the trunk muscles are shown in Figure 16. This figure illustrates that, for most trunk muscles, the temporal activation patterns in the TD-similar cluster are closely comparable to those of the TD group, whereas the patterns of the TD-dissimilar group are not.

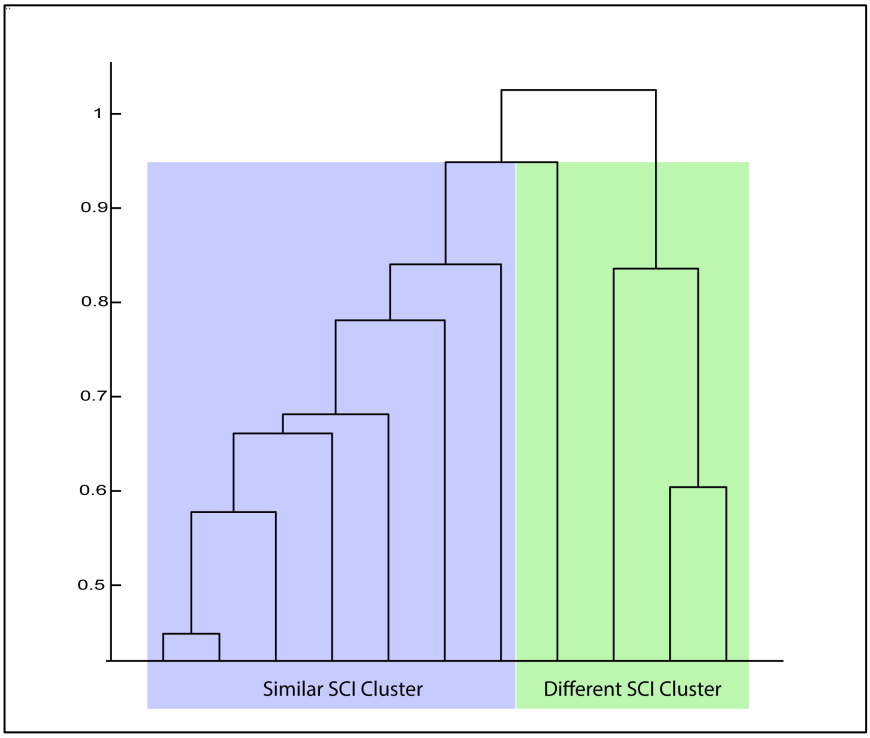


Figure 15: Dendrogram showing clusters based on average normalized EMG amplitude in each rocking cycle quartile for trunk muscles.

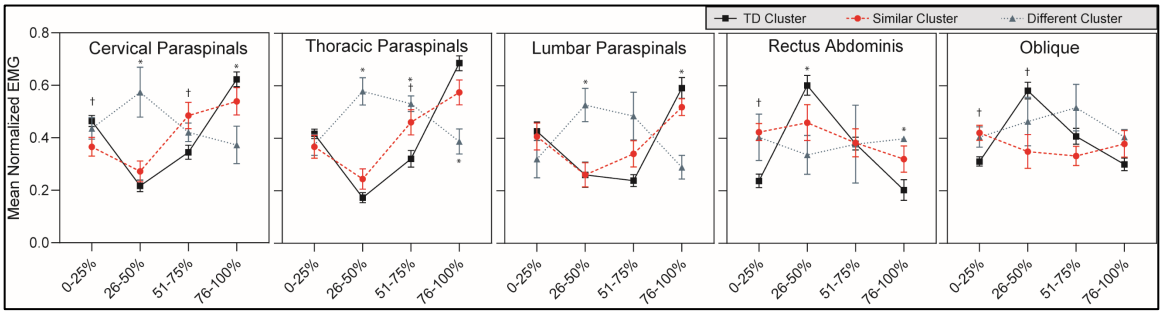


Figure 16: Average normalized EMG amplitude in trunk muscles during each quarter of the rocking cycle for the TD cluster and two SCI clusters; *significant difference between different cluster and TD cluster; †significant difference between similar cluster and TD cluster

4.3.6 Muscle Activation Amplitude

Figure 17 shows a heatmap of muscle activation in each muscle as measured by mean EMG amplitude (μV_{RMS}) during rocking. Each row represents one child, and each

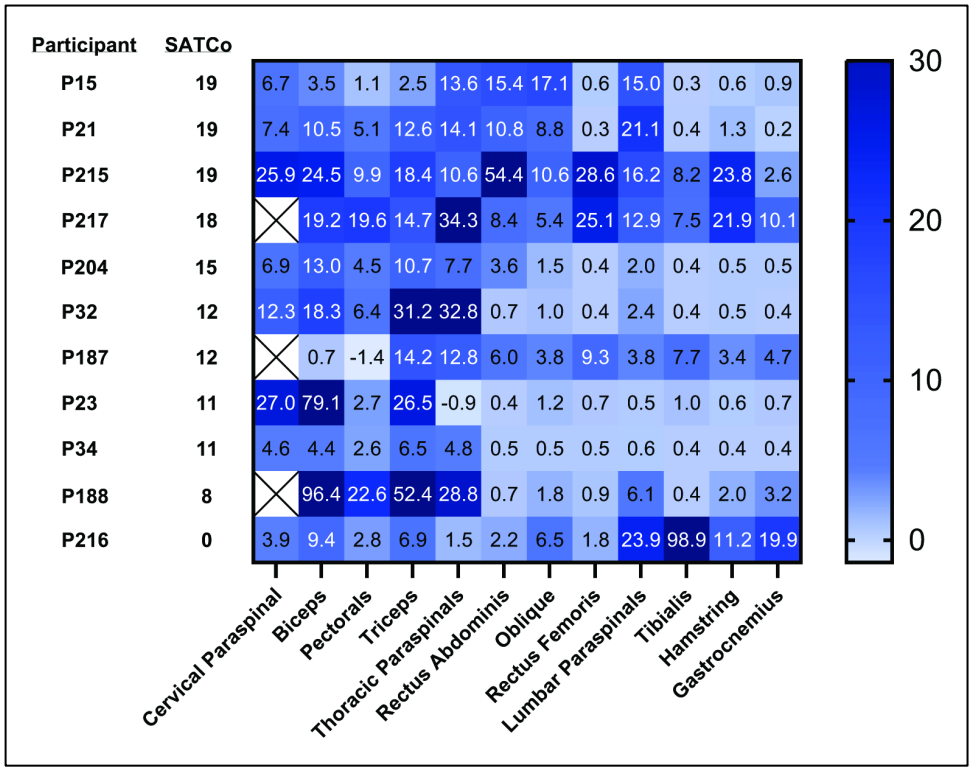


Figure 17: Muscle activation (μVRMS) heatmaps for SCI group. ; Higher numbers and darker colors represent higher activation; Muscles are on x axis, sorted by spinal cord level of nerve roots. Y axis shows SATCo score, representing trunk control. SATCo = Segmental Assessment of Trunk Control

column represents one muscle. Muscles are sorted from left to right in a cephalocaudal direction. For children with SCI, the rows are sorted by SATCo score.

Results of Spearman correlation analysis of SATCo vs. muscle activation amplitude for the SCI group are presented in Table 14. No significant correlation is observed for cervical or thoracic paraspinals, but a significant positive correlation is observed for rectus abdominis ($r = 0.89$, $p = 0.003$), oblique ($r = 0.73$, $p = 0.03$), and lumbar paraspinals ($r = 0.68$, $p = 0.05$), indicating that participants with higher SATCo scores show higher activation in muscles lower on the trunk than those with lower SATCo scores.

Table 14: Activation amplitude during rocking vs. SATCo score

Participant	SATCo	Cervical Paraspinal (μV_{RMS})	Thoracic Paraspinals (μV_{RMS})	Rectus Abdominis (μV_{RMS})	Oblique (μV_{RMS})	Lumbar Paraspinals (μV_{RMS})
Mean TD	20	9.5	10.1	2.8	3.5	6.9
P15	19	6.7	13.6	15.4	17.1	15.0
P21	19	7.4	14.1	10.8	8.8	21.1
P217	18	NA†	34.3	8.4	5.4	12.9
P204	15	6.9	7.7	3.6	1.5	2.0
P32	12	12.3	32.8	0.7	1.0	2.4
P187	12	NA†	12.8	6.0	3.8	3.8
P23	11	27	-0.9	0.4	1.2	0.5
P34	11	4.6	4.8	0.5	0.5	0.6
P188	8	NA†	28.8	0.7	1.8	6.1
Spearman's r		-0.18	0.30	0.89	0.73	0.68
P (two-tailed)		0.74	0.42	0.003*	0.03*	0.05*

*Significant difference ($p<.05$); †Cervical EMG sensors not used due to participant discomfort; SATCo = Segmental assessment of trunk control, RMS = root mean square

4.4 Discussion

Of primary importance, the results confirmed our first hypothesis that trunk muscle activation would increase above baseline during rocking. In fact, all muscles tested in both TD and SCI groups showed significantly higher levels of activation during rocking than at baseline. These results suggest that, in addition to activating trunk muscles and being helpful for children with poor trunk control, rocking may also be a useful activity for activation of leg muscles in children with SCI. Some children who can activate leg muscles may still not be ambulatory due to weakness, poor balance, or inability to manipulate an assistive device. Rocking may be an accessible form of enjoyable, voluntary movement to use available trunk and leg muscles.

Our second hypothesis of differences between trunk muscle activation during rocking by children with SCI and TD children was in part confirmed by cluster analysis of temporal activation of muscles during the rocking cycle. This revealed two muscle activation patterns, a pattern similar to TD and a pattern dissimilar to TD, providing insights into the motor strategies employed by children with SCI during rocking. One notable finding was the higher variability in muscle activation patterns in the SCI group, and the presence of synchronous and counterbalance rocking strategies employed by the children with SCI. These different rocking strategies are at least partially reflected in the cluster analysis. For instance, three of the four subjects in the “TD-dissimilar” cluster used the counterbalance strategy to rock, while none of those in the “TD-similar” cluster used this strategy.

There is also a possible relationship between optimal fit in the rocking chair and rocking styles. Both of the children with poor fit that could not be completely corrected

via padding or other adjustments were in the "TD-dissimilar" cluster, and all the children in the dissimilar cluster (P216, P21, P187, and P217) needed extra padding on the footrest, behind the back, or both due to issues with fit. In contrast, the "TD-similar" cluster only contained one child who needed additional padding (P188 with 7.5 cm of padding behind her back). Since the smallest and largest children were the most likely to need extra measures to achieve good fit, it is also possible that both the issues with fit and the differences in temporal muscle activation patterns were due to their size. Further research will be needed to clarify the question of proper fit relating to meaningful muscle activation.

A significant association was observed between trunk control, as measured by SATCo score, and activation of muscles lower on the trunk. This matches expectations, since higher SATCo scores reflect greater control and activation of trunk muscles in lower thoraco-lumbar areas. It should be noted that the two subjects with AFM were excluded from this analysis, since there is not a clear, level-dependent pattern of impairment with this etiology.

Primary motivations for investigating the use of a rocking chair in this population include accessibility and enjoyment. Importantly, there were no injuries during testing, and the identified safety concern has been addressed by repositioning a cross brace so that it no longer presents a potential to be a pinch point. It was found that all children included in the study were able to make the chair rock, regardless of previous experience or impairment. Feedback from children and parents during rocking also demonstrated that the children enjoyed rocking in the chair and were motivated to use their muscles to make it rock. These factors demonstrate that rocking gives children with SCI an enjoyable

opportunity to move independently, which may be rare outside use of a wheelchair for mobility and thus particularly motivating for them.

4.4.1 Limitations

The results highlighted in this study should be interpreted considering identified limitations. As noted previously, there were several sources of noise in the EMG data used for this analysis. While all of these were addressed, it is important to acknowledge that this does introduce some additional uncertainty regarding the accuracy of some of the source data.

Additionally, the SATCo scores of the participants, which indicate their inherent trunk control, ranged from 0 to 19. However, the distribution skewed towards higher SATCo scores. Ideally, a more balanced distribution of SATCo scores would have been preferred to ensure a broader representation of participants across the entire spectrum of trunk control abilities.

While all children were able to rock, fit in the rocking chair may have had an effect on muscle activation patterns, especially in cases where the balance of the rocking chair was significantly shifted away from its normal neutral position, and this may have effected the muscle activation patterns in some children, and influenced some results.

4.4.2 Future Work

In future research, enrolling children with a greater range of SATCo scores may better quantify the relationship between trunk control and muscle activation patterns during rocking and allow for exploration of additional strategies to activate the desired muscles for rocking. For example, redesigning the footrest to attach to the seat of the

chair instead of the base could target the use of trunk muscles, as it would prevent use of leg muscles initiating rocking by pushing the footrest. Additionally, asking children to take their arms off the armrests could encourage the use of trunk muscles for weight shifting stabilization during the forward and backward phases the rocking cycle.

Future work should also that the participants fit with the rocking chair may affect the resulting muscle activation patterns. In addition to defining what constitutes acceptable fit, parameters to fully characterize fit, such as chair balance point, footrest height, and seat position should be defined and recorded. This data could then be included in any analyses performed to learn how it affects rocking.

Investigating the long-term use of rocking chairs in the home would be valuable to understand the different rocking strategies employed by children with SCI and the progression of neuromuscular activation and capacity. Chairs could also be equipped with sensors to monitor rocking performance, including parameters such as time spent and amplitude of rocking. Sensors could also be installed to detect forces applied to the rocking chair and provide valuable information about the muscles being utilized by the child during rocking. Other possible uses of sensor data would be to adjust the difficulty of rocking to provide extra resistance or help depending on the needs of the child, or to provide feedback in the form of a game to encourage the use of target muscles.

4.5 Conclusions

Rocking in this prototype glider rocking chair activates the neuromuscular system and is an accessible activity for children with varying degrees of trunk impairment due to SCI. Additionally, the study provides the first examination of the timing and amplitude of muscle activation during rocking, and the differences between the TD and SCI groups.

These results, together with the observation that the rocking chair prototype is safe and enjoyable for use by children in this population, highlight the potential of rocking chair-based interventions as an effective approach for trunk muscle activation and a promising component of extending ABT in children with SCI beyond the clinic to the home and community.

CHAPTER 5
MUSCLE ACTIVITY PREDICTION FROM EMBEDDED SENSORS

5.1 Introduction

In children with SCI, lack of trunk control due to neuromuscular paralysis/paresis has been shown to increase the risk of secondary conditions such as scoliosis and compromised lung function [3, 13, 17, 27, 28]. Recent research has shown that activity-based therapy (ABT) is effective at improving trunk control in this population [33]. In order to address the need for children to continue to activate trunk muscles in the home, a rocking chair designed for children with SCI, and been designed, built and tested as described in chapter 3 [59].

To validate that rocking in this rocking chair activates muscles, TD children and children with SCI rocked in the chair while muscle activity was measured using EMG. As described in Chapter 4, comparisons were drawn between muscle activation patterns in the two cohorts, and it was established that muscle activity during rocking is significantly higher than at baseline for muscles in arms, legs, and trunk.

The current chapter will build on this previous work by incorporating various sensor technologies into the chair to provide feedback to therapists about user activity while rocking in the rocking chair. For example, sensors in the chair would enable therapists to track basic use factors such as rocking duration and amplitude. Appropriately located force sensors would be used to monitor specific activity of the limbs and trunk and therefore may eliminate the need to use EMG which, while an

accepted standard for measuring muscle activity, is expensive and requires training. Information about the which muscles are employed by the child to make the chair rock, as well as insight into the ways muscle use patterns change over time would provide useful information for therapists interesting in longitudinal tracking of improvements provided by muscle activation activities. By adding multiple sensors in strategic locations to measure forces applied to the rocking chair and body movements initiated by the child, a variety of rocking activity data can be collected.

Initially, specific aim 4 focused on using sensor data to develop methods to predict SATCo score using multivariate linear regression analysis. As the project progressed, this was found to be problematic since each child only provided a single data point with respect to SATCo score and not all SATCo scores were represented in the dataset. Additionally, correlations between sensor data and trunk muscle activation were too complex for standard linear regression techniques to be effective. To address these difficulties, machine learning techniques were implemented, and the focus was shifted from predicting SATCo score, to predicting muscle activation during rocking.

5.1.1 Study Rationale

In this chapter, data recorded from sensors embedded in the prototype rocking chair will be used to quantify chair and participant motion, as well as forces applied by users to train machine learning models in an attempt to infer subject muscle activations during rocking. Machine learning techniques used in this research will include both established regression learning and neural network model techniques.

5.1.2 Machine Learning Application to Chair Sensors

Biomechanical modeling using inverse dynamics calculated from 3-dimensional motion capture and force-plate data has been used to assess loads on internal anatomical structures including joints and muscles [64]. In the context of rocking in the home, however, biomechanical modeling cannot easily be used to quantify muscle activation forces. This challenge stems from multiple factors, including the requirement for costly motion capture systems, which are not available in the home or even in most clinical settings, and the need for accurate measurements of multiple reaction forces on the rocking chair. Additionally, factors such as the need for custom biomechanical modeling for each child, and complicated setup procedures for each rocking session complicates this approach.

For similar situations where motion capture and/or force plate data cannot be obtained, machine learning methods have been used to aid in biomechanical analyses [64]. Examples include estimation of ground reaction forces based on body-worn accelerometer data [65, 66] and estimation of voluntary elbow torque based on EMG and kinematic data [67]. In addition to analysis of biomechanical problems, machine learning techniques have been used to draw inferences based on data from sensors embedded in equipment used by patients. An example of this is the use of Logistic Regression and Feed Forward Neural Networks to categorize the orientation of patients in bed based on data from load cells positioned under the legs of the bed. This system could help to reduce the incidence of pressure sores by alerting caregivers when a patient's position has not changed after a prescribed period of time [68].

5.1.3 Regression Learning

Regression learning is a supervised learning technique that is used to find the correlation between independent input variables and a dependent output variable. In this work, ensemble learning, which utilizes multiple regression models to learn relationships between a set of features and a response, will be used. These models are then combined to produce a stronger learner with improved generalization performance. The base learner that was selected for this work is the decision tree, and boosting was chosen as the approach to constructing the composite learner. Boosting is an incremental learning process for constructing the composite learner, in which new learners compensate the error from previous learners. [69]

5.1.4 Neural Networks

Briefly, a neural network is a common machine learning model built from layers of interconnected artificial neurons. A typical neural network consists of an input layer, an output layer, and one or more hidden layers. Neurons in each layer are interconnected nodes with neurons in neighboring layers, and weights are assigned to these connections [70]. Training of a neural network involves adjusting these weights to minimize the error between the predictions and the actual targets. Learning algorithms, such as backpropagation, where errors are propagated back through the network from the output layer to reduce overall error, are used to adjust weights. Regularization techniques can also be applied to prevent overfitting, which causes the model to perform well on training data, but poorly on new data. Regularization can help maintain smaller weights and produces models that are better at generalizing to new data [71].

Using these techniques, models will be trained to infer muscle activation in 12 individual muscles in the user's arms, legs, and trunk. Finally, the performance of the model will be compared against individual sets of activity data to evaluate efficiency of predicting activation of specific muscles during rocking by SCI patients evaluated under IRB approval.

5.2 Materials and Methods

5.2.1 Participants

Participants for this analysis were the same as detailed in sections 4.2.1, 4.2.2, and 4.3.1, and were enrolled under University of Louisville IRB #17.0725. Two cohorts were enrolled: children with SCI and TD children. EMG data collected from these participants (as detailed in section 3.2.4) was also used in this analysis.

5.2.2 Rocking Chair Instrumentation

As detailed in Chapter 3, the prototype rocking chair was designed to include embedded sensors which could capture forces applied to different parts of the rocking chair, and movement of the seat and the subject's trunk during rocking. Sensors used, sensor locations, and data captured are shown in Table 13.

Single zone force sensitive resistors were installed on the arm rests (Walfront SF15-150 Force Sensitive Resistor, sensitivity range 0.1 – 100N), and in the seat of the chair (Interlink Electronics FSR® Model 406, sensitivity range 0.1 – 10N) to track forces applied during rocking. In order to increase the sensitivity of the FSRs, actuators were designed, and 3D printed to concentrate the applied force. For instance, the actuator for the arm rest FSR (Figure 18) sat between the armrest cushion and the FSR and helped to ensure that force applied to any part of the cushion would trigger a similar response from

the FSR. Similarly, the seat FSRs were mounted on a flexible 3D printed mat and 3D printed actuator positioned over them to enhance their sensitivity to forces applied to the seat padding overlaying them.

Table 15: Sensors used to collect data for training machine learning models

Sensor Name	Sensor Type	Measurement Taken
Footrest	Four half-bridge load cells configured as eight active element Wheatstone bridge	Force applied by feet to top of footrest
Right arm rest	FSR under pad on right armrest	Force applied to top of pad
Left arm rest	FSR under pad on armrest	Force applied to top of pad
Trunk Strap	Optical Time of Flight sensor	Elongation of strap around trunk as tension is applied.
Position	Rotary potentiometer driven by motion of linkage arms	Seat position in rocking cycle
Seat	Four FSRs in square array	Force applied to each seat FSR
CoP	Calculated from seat FSRs	Forward/back movement of pressure applied to the seat. Average of front FSRs minus the average of back FSRs.
Accelerometer	Accelerometer	Acceleration parallel to swing of the rocking chair

FSR = Force Sensing Resistor; CoP = Center of Pressure

The footrest was constructed of two sheets of Baltic Birch plywood, with four recesses cut in the lower piece and load cells (SMAKN® Half Bridge Body Load Cell Electronic Scale Weighing Sensor 50Kg) set into them. The top sheet of plywood was then placed on top of these load cells and attached with screws which passed through holes drilled in the lower sheet of plywood, which allowed the upper sheet to move vertically, but constrained horizontal motion. This allowed any load placed on the footrest to actuate the load cells. Load cells were connected in an eight active element Wheatstone bridge configuration, and changes in voltage were read to measure the applied loads.

Figure 18: Armrest FSR with 3D Printed actuator

As previously detailed in section 3.5.3, a position sensor was constructed of a rotary potentiometer (TT Electronics, P160KNP) installed on the base of the chair and coupled to one of the chair's rocker arms via spur gears. This setup can track the position of the chair throughout its entire range of motion. The potentiometer is configured as a voltage divider (5V input, 10k ohm fixed resistance, 10k ohm variable resistance), and the voltage read from the center pin corresponds to the position of the chair.

To track trunk motion, a novel sensor was utilized. This sensor has been described in detail in Lin et al [72], but briefly, consists of stretchable fibers with a urethane core and a silicone cladding sandwiched between two pieces of elastic fabric with the ends routed, via a 3d printed mounting block, to a 5 x 5 mm mirror oriented to couple the fiber ends to the ports of a miniature time-of-flight (TOF) sensor for light detection and ranging (LIDAR) (Pololu VL53L0X ToF sensor, Pololu Robotics and Electronics). This

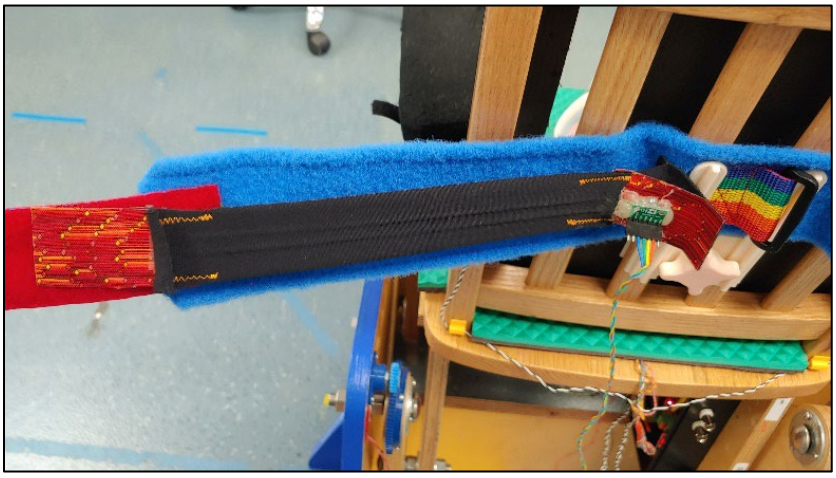


Figure 19: Optical stretch sensor on belt mounted on rocking chair

arrangement allows the TOF chip to detect elongation of the optical fiber as the fabric is stretched. This sensor was attached to a belt (AliMed® Pediatric Walker Belt) using hook-and-loop fasteners at each end, so that the elastic portion of the fabric would elongate when tension was applied to the belt. This belt was attached to the seat back of the chair as shown in Figure 19 and fastened around the trunk of the subject during rocking so that trunk movement would stretch the optical fiber, producing a signal from the TOF chip which was recorded. It should be noted that, as this sensor became available after data had been collected from the first seven children with SCI. Data from the strap is available for the last four children with SCI who were tested, and for all TD children.

All sensors were connected to a custom PCB, which was designed to plug into IO ports A and B on an NI myRIO 1900-(National Instruments, Austin, Texas) as shown in Figure 20. Schematics are included in Appendix C. A load cell amplifier (SparkFun Qwiic Scale NAU7802, Sparkfun Electronics, Niwot CO) was mounted on the PCB to acquire data from the load cells in the footrest. I^2C data from the load cell amplifier and

the TOF sensor were acquired by an Arduino Nano (Arduino.cc) mounted on the custom PCB and relayed to the myRIO-1900 where all data was saved to file.

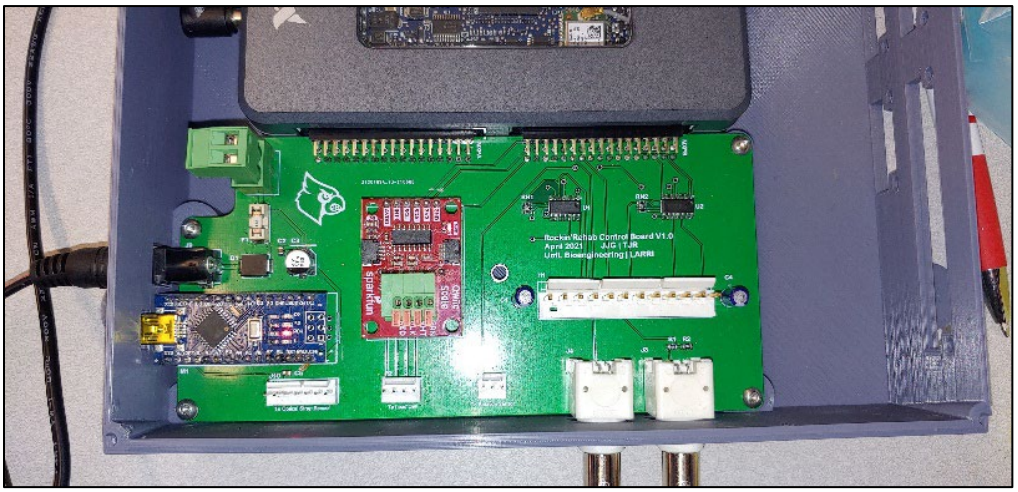


Figure 20: Custom PCB for data collection

5.2.3 Data Collection

sEMG data collected as previously detailed in section 3.2.4 was used to provide the target data for training and testing the machine learning models. Data from sensors embedded in the rocking chair was acquired at 40 Hz, and a pulse signal was recorded at the beginning and end of each data capture session to facilitate synchronization between the 2000 Hz sEMG data and the sensor data.

5.2.4 Regression Model Development

5.2.4.1 Data Processing and Feature Extraction

Four FSRs in the seat of the chair positioned in a square array were used to generate an approximation of the center of pressure applied to the seat. This was calculated by taking the average of the front FSRs minus the average of the back FSRs. This gives a measure of fore-aft changes in pressure as the child rocks and can be used to

detect weight shifts due to trunk movement. This data was treated as a separate sensor, and features were extracted from it as well as from the individual seat sensors.

To synchronize the sEMG data with the sensor data, it was necessary to increase the data rate of the sensor data to match the 2000 Hz rate of the sEMG data. This was done with a custom MATLAB script (Appendix A) which identified the beginning and end of each data collection in both data files using the synchronization pulse, and the sensor data was interpolated to match the length of the sEMG data.

5.2.4.2 Artifact Removal and Rocking Cycle Creation

As detailed in section 3.2 artifacts were removed from sEMG data, and data was broken into individual rocking cycles. Each rocking cycle was standardized to 1000 data points in length, and sensor data was normalized by to the peak-to-peak amplitude of the corresponding cycle using equation 1, similar to the method used previously in prototype EMG cycle creation, and described in Elamary et al. [73, 74].

Features were extracted for each rocking cycle for use as inputs in training of the regression model. The features listed in Table 14 were calculated based on data from each sensor using a custom MATLAB script (Appendix A). Features were calculated as follows. Points 1-10: The 1000 data points for the given cycle were coarse-grained down to 10 points (P1 – P10) by stepping through the data 100 points at a time and taking the average of those points. Thus, the first point (P1) represents the average of the first 100 points in the cycle, and P2 represents the average of points 101-200 and so forth. Area under the curve was calculated numerically simply by summing the value of all 1000 data points for the given cycle. Maximum and minimum values were simply the largest and

smallest data point in the given cycle. Average was calculated by taking the mean of all data points in the cycle. Peak-to-peak amplitude was the difference between the maximum and minimum values in the given cycle. Maximum and minimum locations were simply the index (from 1 to 1000) of the maximum and minimum data points in the cycle. RMS was calculated by taking the square root the mean of the squares of all data points in the cycle. Maximum Sum and maximum sum location were calculated by finding the value of the largest sum of 300 contiguous points, and the index of its center point. Frequency points 1-10 (F1 – F10) were calculated by taking the power spectrum between 0 and 6 Hz, split into 10 bins, with the value of each bin representing one feature. Centroid of the power spectrum with respect to frequency was calculated by dividing the sum of the ten frequency points by the number of points (10).

Table 16: Features extracted from sensor data to use when training machine learning models

Feature	**Description**
Points 1-10	y-value of data points in given cycle, course-grained to 10 points, giving 10 features per sensor
AUC	Area under the curve for the given cycle
Max_Value	Maximum y-value in given cycle
Min_Value	Minimum y-value in given cycle
Average	Mean y-value of all data points in the given cycle
P2P_Amplitude	Peak to Peak Amplitude: Max cycle y-value – Min cycle y-value
MaxLoc	Location on the x-axis of the maximum value in the given cycle
MinLoc	Location on the x-axis of the minimum value in the given cycle
RMS	Root mean square value of all data points in the cycle
MaxSum	Value of largest sum of 300 contiguous points
MaxLoc	Center of max 30% of data (largest sum of 300 points)
Frequency 1-10	Power spectrum between 0 and 6 Hz split into 10 bins, giving 10 features per sensor
Centroid	Location of centroid of power spectrum with respect to frequency

5.2.5 Regression Models

Due to challenges encountered when normalizing the EMG readings in SCI patients, where no maximum exertion is possible, selecting the normalization method that best corresponds with the amount of force exerted by the muscles was difficult. Several normalization techniques were trialed, including normalization by subtracting the baseline EMG reading before rocking started, using the peak-to-peak amplitude of the EMG readings during rocking, and normalizing by dividing each reading by the maximum reading recorded during rocking. Ultimately, training targets were based on EMG readings which were normalized by subtracting the baseline reading from each data point.

For training, data was segmented into a training data set and test datasets. First, data from each participant was segmented in half, and the first half of the data from all participants was assembled into a training dataset. The second half of the data for each participant was used to test the trained regression model.

Two regression models were developed. The first was developed using multiple linear regression in Prism 10 (GraphPad Software, San Diego, CA, USA). First, predictors were standardized by scaling to have a mean of zero, and a standard deviation of 1. Variance inflation factors (VIF) were calculated and were used along with a correlation matrix to manually remove predictors with a high degree of multicollinearity. Once all predictors had a VIF < 10, p-values of the remaining predictors were used to manually eliminate predictors which contributed little to the model. Multiple linear regression was then performed, and β values were produced for each predictor. This

procedure was repeated for each muscle. A custom MATLAB script was then used to test the models using testing data from each child.

Another regression model was also created, using the MATLAB regression learner. To evaluate for the optimal training method, sample datasets were trained all available methods including linear regression, regression trees, support vector machines, Gaussian process regression, kernel approximation regression, and ensembles of trees. Models were initially screened by comparing mean squared error (MSE) for sample datasets. A custom MATLAB script (Appendix A) was used to train the model using the ensembles of trees method, with the boosted trees option.

5.2.6 Neural Network Model Development

A nonlinear input-output time-delay neural network was created and trained in MATLAB, using sensor data as the predictors and EMG data as the targets. As with the data for the regression model, to standardize the length of a rocking cycle across subjects and cycles, and to ensure that time delayed inputs would always be representative of the same point in the rocking cycle relative to the target, data were interpolated to 1000 data points per rocking cycle. To optimize the network's parameters, several models were trained, altering input delays and the number of layers.

EMG and sensor data from each subject was split into training, testing, and validation datasets, with training data comprising the first 60% of the data, and testing and validation data comprising the 20% immediately following the training data, and the final 20% respectively. Since muscle activation, which provided the target data for training the neural network in the form of EMG data, was driving the sensor output, the sensor data was offset from the EMG data, so that the inputs used to predict a specific

target value were taken from the rocking cycle immediately following the target as well as the rocking cycle previous to the target time point.

The network was trained using Bayesian Regularization backpropagation, a network training function that uses Levenberg-Marquardt optimization to update weight and bias values. By minimizing a combination of squared errors and weights, it penalizes large weights and produces a network that generalizes well [74, 75].

The network was set to 8 hidden layers, 11 inputs based on the 11 sensor values, and 12 outputs for muscle activation targets as shown in Figure 21. Input delays were

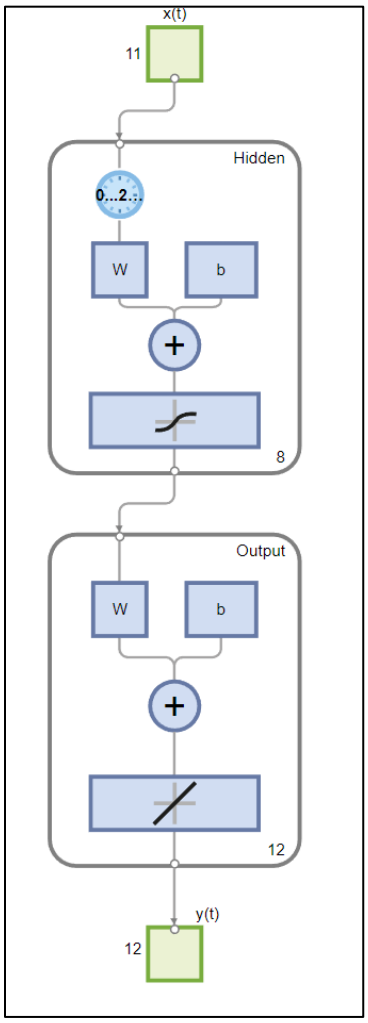


Figure 21: Neural Network diagram with 11 inputs, 8 hidden layers, and 12 outputs

between 0 and 2000 with a step-size of 100, giving an array of 21 values for each input (1 at the same time point as the target, 10 from the previous cycle, and 10 from the subsequent cycle). Maximum number of training epochs was set to 100, with a stop condition of 10 consecutive validation failures. Separate models were trained for each child, and trained models were tested using the prepared testing datasets.

5.2.7 Model Evaluation

The multiple linear regression model, ensemble regression model, and the NN model performance were tested using the test dataset previously created. Several measures of model performance were calculated based on the predictions produced by the entire test dataset. These include R^2, Mean Absolute Percentage Error (MAPE), Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and Sum of Squares (SS) [76], which were calculated for each model and compiled into a table for comparison.

To investigate the utility of the models in predicting muscle activation patterns in individual children during rocking, the test data for each child in the SCI group was used to predict muscle activation with each model. Correlation of the means of predictions with targets for each muscle was calculated to evaluate how well the activation patterns identified by the predictions matched the observed muscle activation. Many of the datasets failed normality tests, so Spearman correlation analysis was selected, and results were compiled into a table.

5.2.8 Evaluation of Sensor Data Correlations

Features were evaluated for correlation with muscle activity using the Minimum Redundancy Maximum Relevance (MRMR) algorithm in the MATLAB regression learner. For each muscle, the feature that was rated highest was tabulated and results were compiled into a table showing the sensors that were most correlated with trunk, arm, or leg muscle activity.

5.3 Results

5.3.1 Model Comparison

Table 17: Comparison of error for muscle activity prediction models

	R Squared			MAPE			MSE		
	Multiple Linear Regression	Decision Tree Regression	Neural Network	Multiple Linear Regression	Decision Tree Regression	Neural Network	Multiple Linear Regression	Decision Tree Regression	Neural Network
Cervical PS	0.000	0.226	0.402	229%	127%	59%	179.7	70.2	352.3
Thoracic PS	0.115	0.506	0.466	724%	309%	56%	583.4	79.3	169.5
Lumbar PS	0.006	0.411	0.441	738%	265%	72%	454.6	66.6	112.3
Pectorals	0.085	0.336	0.500	1996%	1459%	45%	502.8	64.2	106.2
Biceps	0.109	0.464	0.460	2641%	1394%	113%	1973.6	672.2	910.6
Triceps	0.246	0.434	0.444	751%	772%	87%	515.6	135.1	336.8
Rectus Abdominis	0.140	0.440	0.758	1359%	446%	58%	1218.6	84.1	67.1
Oblique	0.008	0.162	0.591	506%	206%	42%	115.8	38.4	28.9
Rectus Femoris	0.008	0.299	0.472	3335%	558%	61%	963.1	107.7	163.9
Hamstring	0.033	0.429	0.578	4082%	441%	56%	2908.2	73.0	96.5
Tibialis Anterior	0.007	0.261	0.584	7811%	1428%	66%	2200.5	234.8	242.8
Gastrocnemius	0.004	0.572	0.420	13809%	964%	81%	4176.1	90.4	189.4

R^2 = R Squared; MAPE = Mean Absolute Percent Error; MSE = Mean Squared Error; PS = Paraspinals

Table 15 compares several measures of error in each of the models. R^2 describes the proportion of the variance in observed activation in the given muscle that is described by each of the models. R^2 values for successful regressions typically range between 0 and 1, with higher values indicating a more successful regression. MAPE quantifies error in terms of percentages, making it suitable for comparing models with target data that has

been scaled differently, or when models have been tested on different data, as in the case of the neural network and the regression models. Mean squared error tends to be more sensitive to outliers than other measures of error and is the metric that is used by MATLAB to evaluate model performance during training [76].

R^2 and MAPE were the primary metrics used to compare models, due to their ability to compare models with outputs that are scaled differently from each other. By both these measures, the neural network outperformed both regression models, with the decision tree regression receiving a higher R^2 value than the neural network for only three muscles (thoracic paraspinal, biceps, and gastrocnemius) and multiple linear regression scoring worst in both measures for all muscles except the triceps, where it scored very slightly (751% vs 775%) better than decision tree regression.

5.3.2 Muscle Activation Pattern Prediction

Spearman correlation analysis of muscle activation predictions is shown in Table 16. Multiple Linear Regression predictions were significantly correlated ($p < .05$) with targets for four of the eleven children with SCI, while Decision Tree Regression predictions were significantly correlated with targets for five children. Neural Network predictions were significantly correlated with targets for all children.

Table 18: Spearman Correlation Analysis of Predictions for SCI Group

Participant ID	Multiple Linear Regression	Decision Tree Regression	Neural Network
P15	-0.161 CI (-0.683, 0.470) p = 0.619	0.371 CI (-0.276, 0.786) p = 0.237	**0.937 CI (0.778, 0.983) p = <0.0001***
P21	0.112 CI (-0.508, 0.656) p = 0.733	**0.727 CI (0.245, 0.921) p = 0.01***	**0.958 CI (0.848, 0.989) p = <0.0001***
P23	**0.587 CI (0.001, 0.873) p = 0.049***	0.35 CI (-0.298, 0.777) p = 0.266	**0.979 CI (0.947, 0.996) p = <0.0001***
P32	**0.636 CI (-0.020, 0.868) p = 0.03***	0.573 CI (-0.020 to 0.868) p = 0.055	**0.993 CI (0.973, 0.998) p = <0.0001***
P34	0.294 CI (-0.622, 0.549) p = 0.354	-0.056 CI (-0.622, 0.549) p = 0.869	**0.965 CI (0.872, 0.991) p = <0.0001***
P215	-0.133 CI (0.61, 0.968) p = 0.683	**0.881 CI (0.61, 0.968) p = 0.0003***	**0.895 CI (0.65, 0.972) p = <0.0001***
P187	0.045 CI (-0.583, 0.640) p = 0.903	0.445 CI (-0.230, 0.831) p = 0.173	**0.748 CI (0.153, 0.919) p = 0.007***
P188	**0.882 CI (0.585, 0.970) p = 0.0007***	**0.673 CI (0.102, 0.910) p = 0.028***	**0.993 CI (0.963, 0.998) p = <0.0001***
P216	0.273 CI (-0.374, 0.741) p = 0.391	0.517 CI (-0.099, 0.847) p = 0.089	**0.986 CI (0.947, 0.996) p = <0.0001***
P204	0.294 CI (-0.354, 0.751) p = 0.355	**0.636 CI (0.079, 0.890) p = 0.03***	**0.979 CI (0.973, 0.998) p = 0.001***
P217	**0.764 CI (0.284 to 0.938) p = 0.0086***	**0.682 CI (0.119, 0.913) p = 0.025***	**0.832 CI (0.324, 0.943) p = <0.0001***

Spearman r (95% Confidence interval) p-value of correlation between the mean muscle activation predictions and targets for each child in the SCI group; *Significant (P < .05) correlation between predictions and targets

Figure 22 compares predictions from each of the three models for one of the participants with SCI (P188). For this example, which showed significant correlation for all models, one can see that, although the distribution of predictions for a given muscle is often different than that of the targets, the general muscle activation pattern is similar. Thus, a therapist looking at these predictions would be able to get an idea of which muscles were primarily being activated during rocking, even if the exact magnitude of activation was uncertain.

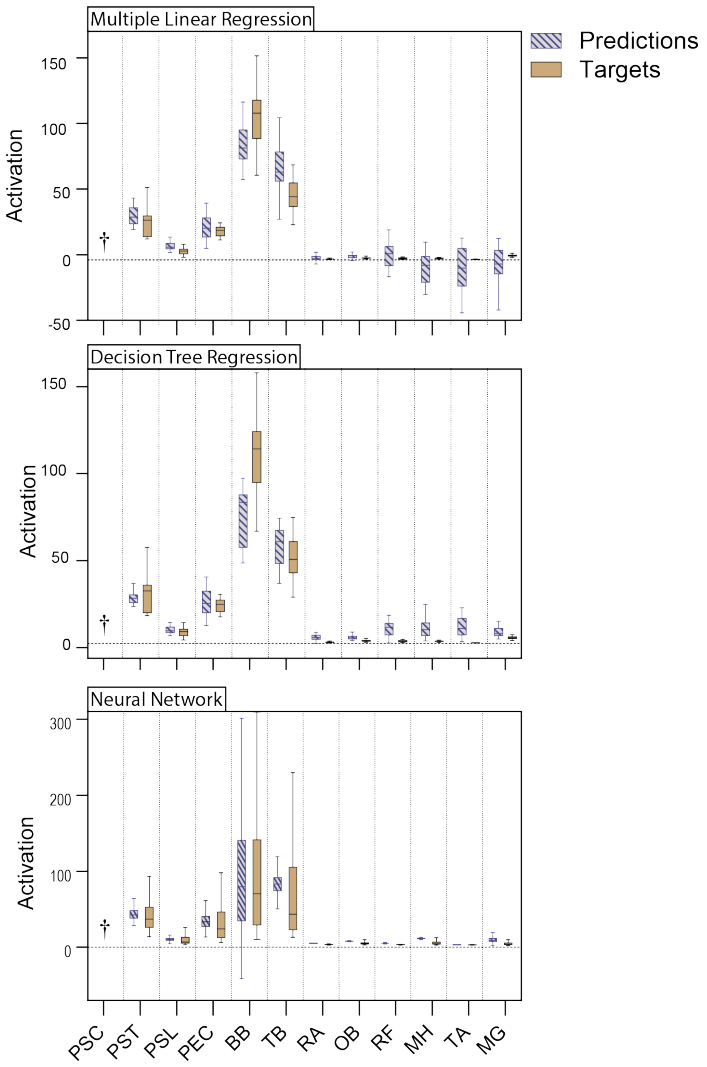


Figure 22: Example of muscle activation pattern predictions vs. target muscle activations for one participant with SCI (P188). Note that y scale for Neural Network predictions is different than for regression models due to differences in calculating targets. Activation is expressed in μV_{RMS}.

5.3.3 Sensor Correlation with Muscle Activity

MRMR analysis results are shown in Table 17. MRMR analysis revealed that the strap data produced more highly relevant features (29) than any other sensor. However, if all seat sensors are considered together, it surpasses the strap-based features with 39

highly relevant features. Strap features were highly relevant only for trunk and arm muscles, with no highly relevant features related to leg muscle activity. Other sensors showed a similar pattern of being more relevant to muscles they interacted more closely with. The footrest produced features that were more relevant to leg muscles (6 for legs, 3 for trunk, 0 for arms). Seat sensors produced highly relevant features for muscles in all domains with relatively balanced correlation to both upper and lower body muscles (19 for legs, 21 for upper body).

Table 19: Minimum Redundancy Maximum Relevance Analysis of correlation between features derived from each sensor and muscle activity in trunk, arms, and legs

Sensor	Trunk Extensors	Trunk Flexors	Arms	Legs Extensors	Legs Flexors	Total
Strap	15	7	7	0	0	29
Left Arm	0	1	5	2	1	9
Right Arm	2	2	2	1	0	7
Seat 0	1	1	1	1	1	5
Seat 1	0	0	2	1	1	4
Seat 2	2	1	2	2	2	9
Seat 3	3	2	2	3	4	14
CoP	0	3	0	3	1	7
Footrest	2	1	0	3	3	9
Accelerometer	3	2	4	4	6	19
Position	2	0	4	0	1	7

Count of how many features based on each sensor were the most correlated with different muscle groups; CoP = Center of Pressure

5.4 Discussion

5.4.1 Model Utility

There are two main metrics for evaluating whether the developed models are useful to therapists. First, while exact determination of muscle activation at a given point in time is not necessary, knowledge of the average activation of a given muscle relative to other muscles during a rocking session would be useful in helping therapists determine muscle use patterns, and to track changes in muscle use patterns over time. Correlation

analysis shows that the neural network performed better than either regression analysis, with predictions significantly correlated to targets for all children.

Although correlation does not guarantee that the magnitude of each prediction is close to the magnitude of the targets, Spearman correlation does show that the rank of the corresponding predictions and targets are similar, and statistically significant correlation shows that when ranked from most to least active, the order of predictions is similar to (if not precisely the same as) the targets.

Second, models should at minimum detect whether a specific muscle is "turned on" during rocking or whether it is inactive. With respect to this metric, the neural network model performed well, accurately predicting very low activation (arbitrarily set to $< 5\ \mu V_{RMS}$ for purposes of this analysis) in 34 out of 41 cases, and only incorrectly predicting low activation in two cases. The regression models, on the other hand, tended to overestimate leg muscle activity for most children, while also underestimating activity in those with significant leg muscle activation.

5.4.2 Sensor Relevance

In addition to the predictions produced by the models, the MRMR analysis provided valuable information about the contribution of each sensor to predictions. Importantly, sensor data was found to be most relevant to activity in muscles that they interacted more closely with. For instance, force sensors in the footrest produced data that was relevant to leg muscle activation, while sensors near the trunk (strap, armrest) produced data more correlated with trunk muscle activation. This helps to reinforce the conclusion that the sensor data contains information about muscle activation, and that the

machine learning models are using this to create their predictions, rather than simply overfitting based on unrelated data. Knowledge of how sensors contribute to the models for each muscle can also guide future sensor placement and feature selection decisions.

5.4.3 Limitations

The predictions made by these models are based on test data gathered in the same session as the training data so, while the data used for testing had not been specifically seen by the model during training, it was relatively similar in terms sensor data and EMG target data. Thus, it is likely that at least some of the results are based on the model learning to recognize the sensor data unique to a particular child and making predictions consistent with muscle activation typical for that child. Until data can be collected across several sessions in which there are differences in muscle activation patterns and in sensor data collected it will be difficult to tell how well the model is able to detect changes in muscle activation across time and across rocking sessions. Similarly, we cannot at this point quantify how well this model would generalize to other subjects who had not had the model trained on their data.

5.4.4 Future Work

There is need to collect additional data to assess the generalizability of the current models across subjects and over time. These expanded datasets can be used to test the accuracy of current models when applied to new data, and to facilitate their extending their predictive capacity to a broader range of situations.

Current models produce data that is potentially useful to therapists, but a more in-depth analysis to determine the level of accuracy and reliability required for predictive models to be of practical use is needed. This will entail a systematic investigation to ascertain the specific thresholds and criteria necessary to render predictions clinically meaningful.

Future investigations should also expand on the work done on correlations of different sensors with muscle activation to explore alternative types and locations for sensor placement, such as the back of the seat, to enhance the accuracy and precision of predictions.

To translate these findings for clinical use, it will be necessary to continue to work with therapists to define the best measures to machine learning algorithms toward, and to develop tools to provide the collected data to therapists in ways that are, convenient, timely and useful.

5.5 Conclusion

This study demonstrates the potential of instrumented rocking chairs for predicting muscle activation in pediatric SCI patients. Current models demonstrate that machine learning techniques can be used to extract information about muscle activation from force and motion sensors embedded in a rocking chair. While questions remain about how well these results can scale across time and subjects, further research is warranted to refine and validate these models for a broader population of pediatric SCI patients. By exploring these avenues, future research can advance the efficacy and applicability of predictive models in clinical settings.

CHAPTER 6
CONCLUSIONS AND FUTURE DIRECTIONS

6.1 Research Objectives

Affectionately known as Rockin'Rehab, this project was structured to accomplish four major objectives focused on the needs of children with spinal cord injury through the development of a simple yet novel mechanism to activate trunk muscles.

The first project aim was to design and build a rocking chair that could be used by children with SCI. The hope was that rocking would prove to be an accessible activity that these children could do on their own regardless of their level of impairment, and that in conjunction with other components of an ABT program, would augment the gains in trunk control made through participation in locomotor training. Of primary importance was to design and fabricate a rocking chair that would accomplish these goals in a safe, enjoyable way.

The second project aim was to investigate how rocking in the rocking chair affected muscle activation in children with SCI as compared to TD children. The primary research question was whether muscles of interest (primarily trunk muscles, but also muscles in arms and legs) would be activated during rocking. Another goal was to describe both temporal muscle activation patterns and which muscles typically would be used to drive rocking.

The third and fourth aims of the project were both centered around the use of various sensors to instrument (sensorize) the rocking chair, which could be used to gather

data about the rocking experience that would be of use to therapists in the ABT program. This would involve design and implementation of the sensor placement and data collection systems, and the development of algorithms to detect muscle activity based on the collected data.

6.2 Key Findings and Implications

The most important outcome of this study was the discovery that trunk muscles, as well as muscles in the arms and legs, are activated by rocking. This significant finding helped to achieve the second aim, which confirmed that rocking is a promising activity for use in conjunction with a program of ABT.

The successful build of the rocking chair, and validation that it provides a safe, enjoyable, and accessible activity for children with SCI was also an important outcome of this research. The use of the QFD design method helped to ensure that the needs of both the therapists and users were met and provides a solid reference point as further developments and improvements to the rocking chair are implemented. The rocking chair prototype was also found to be accessible and enjoyable to children with varying levels of impairment, which helps to add confidence that children will use it.

The analysis of data collected by commercially available sensors embedded at strategic locations in the chair to detect muscle activity was a novel idea and was the most exploratory of the major objectives of this research. Although more work remains to be done to fully develop these techniques for clinical use, the current results are promising, and this technique may be applicable to other rehabilitation contexts.

6.3 Challenges and Limitations

Some limitations related to the design of the rocking chair were discovered during rocking sessions with participants. Most of these were related to the ability of the rocking chair to adjust and accommodate children of different sizes. While the chair enabled children over a wide range of size to rock, some of the adjustments necessary to make this possible disrupted other factors such as balance. This may in turn have influenced muscle use patterns during rocking. Rethinking the methods of adjusting the chair in ways that mitigate these interactions may be possible. For instance, instead of moving the child in the seat to fit the distance to the footrest to the user's leg length, the footrest could be made to move backward and forward as well as up and down. Similarly, physically adjusting the depth of the seat instead of changing its effective depth by padding the backrest could address problems with fit, without changing the balance of the seat.

Additionally, while fit was considered in setting up the rocking chair for the user, it was not carefully characterized to investigate for its effects on muscle activation patterns and its potential role as a confounding factor in the analyses performed. Data that was collected about fit suggests that some factors (particularly balance) may have had an effect on temporal muscle activation patterns, but without more precise data and a larger sample size it is difficult to verify and quantify these effects.

Sensors used for sensing forces applied to the rocking chair were chosen for their form factor which integrated easily into the rocking chair without interfering with its operation. Some sensors, particularly the FSRs used in the seat and armrests, can suffer from issues with hysteresis and drift. To some extent these issues are mitigated by the use

of standardization techniques used in machine learning and regression, where the data is scaled to a mean of zero and an SD of 1. The time-dependent nature of hysteresis and drift may, however, introduce noise into the data that isn't completely removed by standardization techniques, and complicate the attempts to glean meaningful information about muscle activation from it.

Another challenge to training the machine learning models to predict muscle activation was that all training data came from one relatively short rocking session, with no major changes in rocking style or muscle use patterns over the course of the session. This made it difficult to confirm that the models that were developed would generalize to subjects whose data was not in the training dataset, or even to data taken from the same subjects at subsequent rocking sessions. Until more data can be collected and models can be refined, their reliability and utility will remain in question.

Finally, the temporal muscle activation patterns found for children with SCI are, in some cases, likely to be an average of several different activation patterns rather than a true representation of typical pattern for children with SCI. This may be due to children with SCI possessing a wide variety of muscle activation patterns due to the need to compensate for individually unique impairments. It is likely that instead of attempting to define one typical pattern from children with SCI, the emphasis should be on defining the patterns that are typical for TD children, and to study the ways that different impairments alter muscle activation patterns to differ from what is typically seen.

6.4 Future Directions

Over the course of the project, several observations and suggestions for improvements and additional features for the rocking chair were identified. Suggested

changes include items such as a larger footrest with straps to secure the feet, two or more rocking chair models of different sizes, wheels to make transport of the chair easier, an interlock to prevent chair rocking during transport, and other practical suggestions. These adaptations should be examined to determine the need they are intended to meet, and evaluated with for how well they meet the identified need in the same QFD manner from the original chair build. Any features that fill an identified need should be implemented in future versions of the rocking chair, or an alternative feature should be developed to meet that need. Adult SCI patients may also benefit from the natural activity of rocking, and additionally design parameters should be considered when developing for this population.

One goal of this project has been to move toward making rocking chairs available for use in children's homes, a hint towards the potential for commercialization of the chair design. But this is also a reasonable proposition since it would allow patients to further the gains from clinical LT in the home. To continue progress towards this goal, the chair design should be refined to optimize for production of multiple units. In addition, many of the suggested features discussed above are oriented towards making the chair more useable at home, so they should be considered with any future redesigns. Finally, any new designs will require further testing to ensure safety when used in the home. A study to determine the minimum number of sensors that would still allow tracking of chair use would also be appropriate.

To extend our knowledge of how use of rocking chairs in ABT contributes to the progression of improved neuromuscular activation, studies involving long-term use of rocking chairs in the home could be pursued. This kind of longitudinal research could

provide insight into whether rocking contributes to improvement in or retention of intrinsic trunk control.

As mentioned previously, datasets representing more subjects, and representing repeated data collections at different points in time would contribute to improved training of machine learning models. Future research in this area could focus on creating models that will generalize better, and on defining the reliability of models. In addition to training with larger datasets, it would be helpful to work with therapists and other clinicians to define the optimal balance between reliability of predictions, and specificity of the predictions made.

Finally, other uses for the sensor data collected from the rocking chair could be investigated. One example that is already in development is the incorporation of advanced control mechanisms to use sensor input to assess the intent of the child. For example, when a child needs additional help to maintain rocking, or alternatively needs additional resistance so the rocking activity will continue to challenge them, mechanical actuators working in concert with the sensor data could assist/resist rocking as appropriate. Gamification of the rocking experience could also be explored using sensor data to align the detection of activation of certain muscles and a reward system tied to progress in the game.

6.5 Concluding Summary

In summary, this work has produced several valuable results. First, it has resulted in a rocking chair that was designed and validated as a safe way for children with impairments due to SCI to move independently, and to activate muscles. This has the potential for use an integral component of a course of ABT therapy for children with SCI.

This study is also the first to investigate muscle activation patterns during rocking, and to verify that rocking in a rocking chair can activate muscles throughout the body for children with varying levels of impairment due to SCI. This sets the stage for use of rocking chairs in the context of pediatric SCI, provides a base on which to build further research into this topic and lays the groundwork for the development of new techniques for quantifying muscle activation using common sensors combined with powerful machine learning techniques. These tools should continue to be developed and implemented in ways that will benefit children with SCI and, along with other therapies, help them to improve their trunk control and their quality of life. Further research into the benefits of rocking in this population should also continue to better define how these tools can be used effectively, and to discover new applications where their benefit can be realized.

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APPENDIX A
MATLAB SCRIPTS

MATLAB script used for training and testing final Neural Network model

TimeDelayNNTrain_Test_Individual.m

```
%Script for training and testing a neural network using Bayesian
%Regularization backpropagation. Inputs are sensor data in a 22x12 cell
%array. Targets are EMG data in 22x13 cell array


%Set up NN properties
trainFcn = 'trainbr';  % Bayesian Regularization backpropagation.
inputDelays = 0:100:2000;
hiddenLayerSize = 8;

% Set the training options to use a GPU
options = trainingOptions('sgdm', 'ExecutionEnvironment', 'parallel');

%Assign NN properties to new network
net = timedelaynet(inputDelays,hiddenLayerSize,trainFcn);

%initialize variables
Sensors = [];
EMG = [];

%Compile sensor data and EMG data for training
for subject = 2:22

    %Create new network for next subject
    net = timedelaynet(inputDelays,hiddenLayerSize,trainFcn);

    %reinitialize variables
    Sensors = [];
    EMG = [];

    %Compile sensor data for this subject
    for sensor = 2:12
        sensorTable = A2_combinedSensorCycleCell{subject,sensor};

        for n = 1:width(sensorTable)
            sensorData((n-1)*1000+1:n*1000,sensor-1) = sensorTable(1:1000,n);
%#ok<*SAGROW>
```

```
    end
end

%Compile EMG data for this subject
for muscle = 2:13
    emgTable = A2_combinedEMGCycleCell{subject,muscle};
    for n = 1:width(emgTable)
        emgData(((n-1)*1000)+1:n*1000,muscle-1) = emgTable(1:1000,n);
    end
end

%convert sensor and EMG data into arrays for manipulation and
%preparation for conversion to training data
Sensors = table2array(sensorData);
EMG = table2array(emgData);

clearvars sensorArray emgArray emgData sensorData featureArray featureData

%offset sensor and EMG data by 1000 points so that delays include
% sensor data from cycle before and cycle after target
Sensors = flip(Sensors,1);
Sensors = Sensors(1001:height(Sensors),:);
EMG = flip(EMG,1);
EMG = EMG(1:height(EMG)-1000,:);

%Convert data to standard neural network cell array form
X = tonndata(Sensors,false,false);
T = tonndata(EMG,false,false);

% Prepare the Data for Training and Simulation
[x,xi,ai,t] = preparets(net,X,T);

% Setup Division of Data for Training, Validation, Testing
net.divideFcn= 'divideind';
trainLength = size(X,2);
trainInd = 1:trainLength*.6;
testInd = (trainLength*.6)+1:(trainLength*.8-1);
valInd = trainLength*.8:trainLength;
net.divideParam.trainInd = trainInd;
net.divideParam.valInd = valInd;
net.divideParam.testInd = testInd;


% Train the Network
%*************************************************************
net.trainParam.showWindow = true;
net.trainParam.epochs = 100;
net.trainParam.max_fail = 30;

[net,tr] = train(net,x,t,xi,ai,'useParallel','yes');

%Save trained network and training data in cell array
NNTrainer_TimeDelNetsRepeat{subject, 1} = net;
NNTrainer_TimeDelNetsRepeat{subject, 2} = tr;
```

```
    %test the Network
    y = net(x,xi,ai);

    %prepare test results to be saved
    e = gsubtract(t,y);
    targets = cell2mat(t)';
    predictions = cell2mat(y)';
    performance(subject,1) = perform(net,t,y);
    testStats(1,1) = mean(targets, "all");
    testStats(1,2) = std(targets(:,1));
    testStats(1,3) = height(targets);
    testStats(2,1) = mean(predictions, "all");
    testStats(2,2) = std(predictions(:,1));
    testStats(2,3) = height(predictions);
    testResults{1,1} = {cell2mat(x)', cell2mat(t)', cell2mat(y)'};

    %save test results in cell arrays
    NNTester_testResultsRepeat{subject,:} = testResults{1,1};
    TestStatsCellRepeat{subject,1} = testStats;

end
%clear variables
clearvars t T tr trainFcn X xi ai e hiddenLayerSize inputDelays n subject
testSubject
clearvars Sensors targets predictions testResults testStats x y yp tp sensor
clearvars sensorArray emgArray performance net muscle options emgTest
trainingFraction
clearvars endIndex EMG emgTable featureTable sensorTable testCell featureArray
clearvars featureData sensorData emgData sensorTest testInd valInd trainInd
```

MATLAB script to calculate moving window RMS for EMG data

```
MovWinRMS.m
%Script to calculate moving window RMS

RMSWin = 300; %length of RMS window
RMSWorking = RAYW; % working copy of table to calculate RMS for
RMSWorking = table2array(RMSWorking); %convert table to array for mathematical
operations

%Find mean values of EMG data and subtract to remove offset
RMSMeans = zeros(1,38);
for n = 4:27
    RMSMeans(n) = mean(RMSWorking(:,n));
end

RMSNorm = RMSWorking - RMSMeans;

%compute the moving window RMS of the normalized array
L = length(RMSWorking) - RMSWin/2;
RMSArray = zeros(length(RMSWorking),38);
for n = 4:27
    for m = 151:L
          RMSArray(m,n) = rms(RMSNorm(m-(RMSWin/2):m+(RMSWin/2),n));

    end
end

for n = [1 2 3 28 29 30 31 32 33 34 35 36 37 38]
    RMSArray(:,n) = RMSWorking(:,n);
end

%Var_names = Combined.Properties.VariableNames;

Var_names =
{'times','MANUALPULSE','RCSyncPulse','LPSC','LPST10','LPSL5','LPEC','LBB','LTB
','LRA','LOB','LRF','LMH','LTA','LMG','RPSC','RPST10','RPSL5','RPEC','RBB','RT
B','RRA','ROB','RRF','RMH','RTA','RMG','Strap','FootRest','LeftArm','RightArm'
,'Seat0','Seat1','Seat2','Seat3','Accel','Position','ManPulse'};

RAYW_RMS =
array2table(RMSArray((1+(RMSWin/2):L),:),'VariableNames',Var_names);

clear RMSWin;
clear RMSWorking;
clear RMSMeans;
clear RMSNorm;
clear L;
clear RMSArray;
clearvars n m Var_names;
```

MATLAB script to train ensemble leaner

```
% EnsembleTrainerAllMusclesEachChild.m
% Uncomment this block if training and test tables are not already set up
% startIndex = 1;
% %set up training and test tables. Training table is single table containing
% % first half of data from each participant.
% % Test tables are individual tables with second half of data from each
% % participant. Stored in testCell cell array.
% for j=2:22
%     data = table2array(featuresTablesCycleAmp{j,2});
%
%     endIndex = fix(height(data)/2);
%
%     trainingArray(startIndex:startIndex+endIndex-1,:) = data(1:endIndex,:);
%
%     testArray = data(endIndex+1:height(data),:);
%     startIndex = startIndex + endIndex;
%
%      mmediat = array2table(testArray,"VariableNames",VarNames);
%
%     testCellCycleAmp{j,2} =  mmediat;
%     testCellCycleAmp{j,1} = featuresTables{j,1};
%
%     clearvars  mmediat data testArray
%  end
%
%  trainingTableCycleAmp =
array2table(trainingArray,"VariableNames",VarNames);
%
%  clearvars trainingArray startIndex endIndex

%train a model for each muscle
for i=1:12
    %train the model on trainingTable, with column i+324 specified as
    %response
    [trainedModel, validationRMSE] =
trainRegressionModelV2_FtestParameterSelection(A2_trainingTableNormFreqFixMiss
ingDeleted,i+342,342);

    A4_allModels{1,i+1} = Muscles{i};
    A4_allModels{2,i+1} = trainedModel;
    A4_allModels{3,i+1} = validationRMSE;

    clearvars trainedModel

end
%make predictions using trained models, and set up cell array with
%predictions and targets
for j = 2:22
    for i = 1:12
         mmediat = A2_testCellNormFreqFix{j,2};
        testModel = A4_allModels{2,i+1};
        A4_testPredictionNormByMax(:,i) = testModel.predictFcn( mmediat);
```

```
    end
    A4_testPredictionNormByMax=
array2table(A4_testPredictionNormByMax,"VariableNames",Muscles);
    A4_testResultsNormByMax{j,2} = A4_testPredictionNormByMax;
    A4_testResultsNormByMax{j,1} = D2_featuresTablesNormByMax{j,1};
    A4_testResultsNormByMax{j,3} =  mmediat(:,343:354);

    clearvars D3_testPredictionNormByMax
end
A4_testResultsNormByMax{1,1} = {'Child ID'};
A4_testResultsNormByMax{1,2} = {'Predictions'};
A4_testResultsNormByMax{1,3} = {'Targets'};


clearvars i j validationRMSE  mmediat testModel
```

Training function called by ensemble trainer script

```
function [trainedModel, validationRMSE, includedPredictorNames] =
trainRegressionModelV2_FtestParameterSelection(trainingData,m,numFeatures)
% [trainedModel, validationRMSE] = trainRegressionModel(trainingData)
% Returns a trained regression model and its RMSE. This code recreates the
% model trained in Regression Learner app. Use the generated code to
% automate training the same model with new data, or to learn how to
% programmatically train models.
%
%  Input:
%      trainingData: A table containing the same predictor and response
%       columns as those imported into the app.
%
%
%  Output:
%      trainedModel: A struct containing the trained regression model. The
%       struct contains various fields with information about the trained
%       model.
%
%      trainedModel.predictFcn: A function to make predictions on new data.
%
%      validationRMSE: A double representing the validation RMSE. In the
%       app, the Models pane displays the validation RMSE for each model.
%
% Use the code to train the model with new data. To retrain your model,
% call the function from the command line with your original data or new
% data as the input argument trainingData.
%
% For example, to retrain a regression model trained with the original data
% set T, enter:
%   [trainedModel, validationRMSE] = trainRegressionModel(T)
%
% To make predictions with the returned 'trainedModel' on new data T2, use
%   yfit = trainedModel.predictFcn(T2)
%
% T2 must be a table containing at least the same predictor columns as used
% during training. For details, enter:
%   trainedModel.HowToPredict

% Auto-generated by MATLAB on 11-Jul-2023 17:36:32


% Extract predictors and response
% This code processes the data into the right shape for training the
% model.
inputTable = trainingData;
predictorNames = {'Strap1', 'Strap2', 'Strap3', 'Strap4', 'Strap5', 'Strap6',
'Strap7', 'Strap8', 'Strap9', 'Strap10', 'StrapIntegral', 'StrapMax',
'StrapMin', 'StrapAvg', 'StrapRange', 'StrapMaxID', 'StrapMinID', 'StrapRMS',
'StrapCentr', 'StrapMaxSum', 'StrapMaxLoc', 'StrapFreq1', 'StrapFreq2',
'StrapFreq3', 'StrapFreq4', 'StrapFreq5', 'StrapFreq6', 'StrapFreq7',
'StrapFreq8', 'StrapFreq9', 'StrapFreq10', 'FR1', 'FR2', 'FR3', 'FR4', 'FR5',
'FR6', 'FR7', 'FR8', 'FR9', 'FR10', 'FRIntegral', 'FRMax', 'FRMin', 'FRAvg',
```

```
'FRRange', 'FRMaxID', 'FRMinID', 'FRRMS', 'FRCentr', 'FRMaxSum', 'FRMaxLoc',
'FRFreq1', 'FRFreq2', 'FRFreq3', 'FRFreq4', 'FRFreq5', 'FRFreq6', 'FRFreq7',
'FRFreq8', 'FRFreq9', 'FRFreq10', 'LA1', 'LA2', 'LA3', 'LA4', 'LA5', 'LA6',
'LA7', 'LA8', 'LA9', 'LA10', 'LAIntegral', 'LAMax', 'LAMin', 'LAAvg',
'LARange', 'LAMaxID', 'LAMinID', 'LARMS', 'LACentr', 'LAMaxSum', 'LAMaxLoc',
'LAFreq1', 'LAFreq2', 'LAFreq3', 'LAFreq4', 'LAFreq5', 'LAFreq6', 'LAFreq7',
'LAFreq8', 'LAFreq9', 'LAFreq10', 'RA1', 'RA2', 'RA3', 'RA4', 'RA5', 'RA6',
'RA7', 'RA8', 'RA9', 'RA10', 'RAIntegral', 'RAMax', 'RAMin', 'RAAvg',
'RARange', 'RAMaxID', 'RAMinID', 'RARMS', 'RACentr', 'RAMaxSum', 'RAMaxLoc',
'RAFreq1', 'RAFreq2', 'RAFreq3', 'RAFreq4', 'RAFreq5', 'RAFreq6', 'RAFreq7',
'RAFreq8', 'RAFreq9', 'RAFreq10', 'S0_1', 'S0_2', 'S0_3', 'S0_4', 'S0_5',
'S0_6', 'S0_7', 'S0_8', 'S0_9', 'S0_10', 'S0Integral', 'S0Max', 'S0Min',
'S0Avg', 'S0Range', 'S0MaxID', 'S0MinID', 'S0RMS', 'S0Centr', 'S0MaxSum',
'S0MaxLoc', 'S0Freq1', 'S0Freq2', 'S0Freq3', 'S0Freq4', 'S0Freq5', 'S0Freq6',
'S0Freq7', 'S0Freq8', 'S0Freq9', 'S0Freq10', 'S1_1', 'S1_2', 'S1_3', 'S1_4',
'S1_5', 'S1_6', 'S1_7', 'S1_8', 'S1_9', 'S1_10', 'S1Integral', 'S1Max',
'S1Min', 'S1Avg', 'S1Range', 'S1MaxID', 'S1MinID', 'S1RMS', 'S1Centr',
'S1MaxSum', 'S1MaxLoc', 'S1Freq1', 'S1Freq2', 'S1Freq3', 'S1Freq4', 'S1Freq5',
'S1Freq6', 'S1Freq7', 'S1Freq8', 'S1Freq9', 'S1Freq10', 'S2_1', 'S2_2',
'S2_3', 'S2_4', 'S2_5', 'S2_6', 'S2_7', 'S2_8', 'S2_9', 'S2_10', 'S2Integral',
'S2Max', 'S2Min', 'S2Avg', 'S2Range', 'S2MaxID', 'S2MinID', 'S2RMS',
'S2Centr', 'S2MaxSum', 'S2MaxLoc', 'S2Freq1', 'S2Freq2', 'S2Freq3', 'S2Freq4',
'S2Freq5', 'S2Freq6', 'S2Freq7', 'S2Freq8', 'S2Freq9', 'S2Freq10', 'S3_1',
'S3_2', 'S3_3', 'S3_4', 'S3_5', 'S3_6', 'S3_7', 'S3_8', 'S3_9', 'S3_10',
'S3Integral', 'S3Max', 'S3Min', 'S3Avg', 'S3Range', 'S3MaxID', 'S3MinID',
'S3RMS', 'S3Centr', 'S3MaxSum', 'S3MaxLoc', 'S3Freq1', 'S3Freq2', 'S3Freq3',
'S3Freq4', 'S3Freq5', 'S3Freq6', 'S3Freq7', 'S3Freq8', 'S3Freq9', 'S3Freq10',
'Accel1', 'Accel2', 'Accel3', 'Accel4', 'Accel5', 'Accel6', 'Accel7',
'Accel8', 'Accel9', 'Accel10', 'AccelIntegral', 'AccelMax', 'AccelMin',
'AccelAvg', 'AccelRange', 'AccelMaxID', 'AccelMinID', 'AccelRMS',
'AccelCentr', 'AccelMaxSum', 'AccelMaxLoc', 'AccelFreq1', 'AccelFreq2',
'AccelFreq3', 'AccelFreq4', 'AccelFreq5', 'AccelFreq6', 'AccelFreq7',
'AccelFreq8', 'AccelFreq9', 'AccelFreq10', 'Pos1', 'Pos2', 'Pos3', 'Pos4',
'Pos5', 'Pos6', 'Pos7', 'Pos8', 'Pos9', 'Pos10', 'PosIntegral', 'PosMax',
'PosMin', 'PosAvg', 'PosRange', 'PosMaxID', 'PosMinID', 'PosRMS', 'PosCentr',
'PosMaxSum', 'PosMaxLoc', 'PosFreq1', 'PosFreq2', 'PosFreq3', 'PosFreq4',
'PosFreq5', 'PosFreq6', 'PosFreq7', 'PosFreq8', 'PosFreq9', 'PosFreq10',
'CoP1', 'CoP2', 'CoP3', 'CoP4', 'CoP5', 'CoP6', 'CoP7', 'CoP8', 'CoP9',
'CoP10', 'CoPIntegral', 'CoPMax', 'CoPMin', 'CoPAvg', 'CoPRange', 'CoPMaxID',
'CoPMinID', 'CoPRMS', 'CoPCentr', 'CoPMaxSum', 'CoPMaxLoc', 'CoPFreq1',
'CoPFreq2', 'CoPFreq3', 'CoPFreq4', 'CoPFreq5', 'CoPFreq6', 'CoPFreq7',
'CoPFreq8', 'CoPFreq9', 'CoPFreq10', 'SCI'};
predictors = inputTable(:, predictorNames);
response = inputTable(:,m);
isCategoricalPredictor = [false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
```

```
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
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false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, true];

% Feature Ranking and Selection
% Replace Inf/-Inf values with NaN to prepare data for normalization
predictors = standardizeMissing(predictors, {Inf, -Inf});
% Normalize data for feature ranking
predictorMatrix= normalize(predictors, “DataVariable”,
~isCategoricalPredictor);

% Rank features using Ftest algorithm
featureIndex = fsrftest(…
    predictorMatrix, …
    response);
numFeaturesToKeep = numFeatures;
includedPredictorNames =
predictors.Properties.VariableNames(featureIndex(1:numFeaturesToKeep));
predictors = predictors(:,includedPredictorNames);
isCategoricalPredictor =
isCategoricalPredictor(featureIndex(1:numFeaturesToKeep));



% Train a regression model
% This code specifies all the model options and trains the model.
Template = templateTree(…
    ‘MinLeafSize’, 4, …
    ‘NumVariablesToSample’, 11);
regressionEnsemble = fitrensemble(…
    predictors, …
    response, …
    ‘Method’, ‘LSBoost’, …
    ‘NumLearningCycles’, 46, …
    ‘Learners’, template, …
    ‘LearnRate’, 0.1744570431275861);
```

```
% Create the result struct with predict function
predictorExtractionFcn = @(t) t(:, predictorNames);
ensemblePredictFcn = @(x) predict(regressionEnsemble, x);
trainedModel.predictFcn = @(x) ensemblePredictFcn(predictorExtractionFcn(x));

% Add additional fields to the result struct
trainedModel.RequiredVariables = {'Accel1', 'Accel10', 'Accel2', 'Accel3',
'Accel4', 'Accel5', 'Accel6', 'Accel7', 'Accel8', 'Accel9', 'AccelAvg',
'AccelCentr', 'AccelFreq1', 'AccelFreq10', 'AccelFreq2', 'AccelFreq3',
'AccelFreq4', 'AccelFreq5', 'AccelFreq6', 'AccelFreq7', 'AccelFreq8',
'AccelFreq9', 'AccelIntegral', 'AccelMax', 'AccelMaxID', 'AccelMaxLoc',
'AccelMaxSum', 'AccelMin', 'AccelMinID', 'AccelRMS', 'AccelRange', 'CoP1',
'CoP10', 'CoP2', 'CoP3', 'CoP4', 'CoP5', 'CoP6', 'CoP7', 'CoP8', 'CoP9',
'CoPAvg', 'CoPCentr', 'CoPFreq1', 'CoPFreq10', 'CoPFreq2', 'CoPFreq3',
'CoPFreq4', 'CoPFreq5', 'CoPFreq6', 'CoPFreq7', 'CoPFreq8', 'CoPFreq9',
'CoPIntegral', 'CoPMax', 'CoPMaxID', 'CoPMaxLoc', 'CoPMaxSum', 'CoPMin',
'CoPMinID', 'CoPRMS', 'CoPRange', 'FR1', 'FR10', 'FR2', 'FR3', 'FR4', 'FR5',
'FR6', 'FR7', 'FR8', 'FR9', 'FRAvg', 'FRCentr', 'FRFreq1', 'FRFreq10',
'FRFreq2', 'FRFreq3', 'FRFreq4', 'FRFreq5', 'FRFreq6', 'FRFreq7', 'FRFreq8',
'FRFreq9', 'FRIntegral', 'FRMax', 'FRMaxID', 'FRMaxLoc', 'FRMaxSum', 'FRMin',
'FRMinID', 'FRRMS', 'FRRange', 'LA1', 'LA10', 'LA2', 'LA3', 'LA4', 'LA5',
'LA6', 'LA7', 'LA8', 'LA9', 'LAAvg', 'LACentr', 'LAFreq1', 'LAFreq10',
'LAFreq2', 'LAFreq3', 'LAFreq4', 'LAFreq5', 'LAFreq6', 'LAFreq7', 'LAFreq8',
'LAFreq9', 'LAIntegral', 'LAMax', 'LAMaxID', 'LAMaxLoc', 'LAMaxSum', 'LAMin',
'LAMinID', 'LARMS', 'LARange', 'Pos1', 'Pos10', 'Pos2', 'Pos3', 'Pos4',
'Pos5', 'Pos6', 'Pos7', 'Pos8', 'Pos9', 'PosAvg', 'PosCentr', 'PosFreq1',
'PosFreq10', 'PosFreq2', 'PosFreq3', 'PosFreq4', 'PosFreq5', 'PosFreq6',
'PosFreq7', 'PosFreq8', 'PosFreq9', 'PosIntegral', 'PosMax', 'PosMaxID',
'PosMaxLoc', 'PosMaxSum', 'PosMin', 'PosMinID', 'PosRMS', 'PosRange', 'RA1',
'RA10', 'RA2', 'RA3', 'RA4', 'RA5', 'RA6', 'RA7', 'RA8', 'RA9', 'RAAvg',
'RACentr', 'RAFreq1', 'RAFreq10', 'RAFreq2', 'RAFreq3', 'RAFreq4', 'RAFreq5',
'RAFreq6', 'RAFreq7', 'RAFreq8', 'RAFreq9', 'RAIntegral', 'RAMax', 'RAMaxID',
'RAMaxLoc', 'RAMaxSum', 'RAMin', 'RAMinID', 'RARMS', 'RARange', 'S0Avg',
'S0Centr', 'S0Freq1', 'S0Freq10', 'S0Freq2', 'S0Freq3', 'S0Freq4', 'S0Freq5',
'S0Freq6', 'S0Freq7', 'S0Freq8', 'S0Freq9', 'S0Integral', 'S0Max', 'S0MaxID',
'S0MaxLoc', 'S0MaxSum', 'S0Min', 'S0MinID', 'S0RMS', 'S0Range', 'S0_1',
'S0_10', 'S0_2', 'S0_3', 'S0_4', 'S0_5', 'S0_6', 'S0_7', 'S0_8', 'S0_9',
'S1Avg', 'S1Centr', 'S1Freq1', 'S1Freq10', 'S1Freq2', 'S1Freq3', 'S1Freq4',
'S1Freq5', 'S1Freq6', 'S1Freq7', 'S1Freq8', 'S1Freq9', 'S1Integral', 'S1Max',
'S1MaxID', 'S1MaxLoc', 'S1MaxSum', 'S1Min', 'S1MinID', 'S1RMS', 'S1Range',
'S1_1', 'S1_10', 'S1_2', 'S1_3', 'S1_4', 'S1_5', 'S1_6', 'S1_7', 'S1_8',
'S1_9', 'S2Avg', 'S2Centr', 'S2Freq1', 'S2Freq10', 'S2Freq2', 'S2Freq3',
'S2Freq4', 'S2Freq5', 'S2Freq6', 'S2Freq7', 'S2Freq8', 'S2Freq9',
'S2Integral', 'S2Max', 'S2MaxID', 'S2MaxLoc', 'S2MaxSum', 'S2Min', 'S2MinID',
'S2RMS', 'S2Range', 'S2_1', 'S2_10', 'S2_2', 'S2_3', 'S2_4', 'S2_5', 'S2_6',
'S2_7', 'S2_8', 'S2_9', 'S3Avg', 'S3Centr', 'S3Freq1', 'S3Freq10', 'S3Freq2',
'S3Freq3', 'S3Freq4', 'S3Freq5', 'S3Freq6', 'S3Freq7', 'S3Freq8', 'S3Freq9',
'S3Integral', 'S3Max', 'S3MaxID', 'S3MaxLoc', 'S3MaxSum', 'S3Min', 'S3MinID',
'S3RMS', 'S3Range', 'S3_1', 'S3_10', 'S3_2', 'S3_3', 'S3_4', 'S3_5', 'S3_6',
'S3_7', 'S3_8', 'S3_9', 'SCI', 'Strap1', 'Strap10', 'Strap2', 'Strap3',
'Strap4', 'Strap5', 'Strap6', 'Strap7', 'Strap8', 'Strap9', 'StrapAvg',
'StrapCentr', 'StrapFreq1', 'StrapFreq10', 'StrapFreq2', 'StrapFreq3',
'StrapFreq4', 'StrapFreq5', 'StrapFreq6', 'StrapFreq7', 'StrapFreq8',
'StrapFreq9', 'StrapIntegral', 'StrapMax', 'StrapMaxID', 'StrapMaxLoc',
'StrapMaxSum', 'StrapMin', 'StrapMinID', 'StrapRMS', 'StrapRange'};
```

```
trainedModel.RegressionEnsemble = regressionEnsemble;
trainedModel.About = 'This struct is a trained model exported from Regression
Learner R2023a.';
trainedModel.HowToPredict =  mmedi('To make predictions on a new table, T,
use: \n  yfit = c.predictFcn(T) \nreplacing ''c'' with the name of the
variable that is this struct, e.g. ''trainedModel''. \n \nThe table, T, must
contain the variables returned by: \n  c.RequiredVariables \nVariable formats
(e.g. matrix/vector, datatype) must match the original training data.
\nAdditional variables are ignored. \n \nFor more information, see <a
href="matlab:helpview(fullfile(docroot, ''stats'', ''stats.map''),
''appregression_exportmodeltoworkspace'')">How to predict using an exported
model</a>.');

% Extract predictors and response
% This code processes the data into the right shape for training the
% model.
inputTable = trainingData;
predictorNames = {'Strap1', 'Strap2', 'Strap3', 'Strap4', 'Strap5', 'Strap6',
'Strap7', 'Strap8', 'Strap9', 'Strap10', 'StrapIntegral', 'StrapMax',
'StrapMin', 'StrapAvg', 'StrapRange', 'StrapMaxID', 'StrapMinID', 'StrapRMS',
'StrapCentr', 'StrapMaxSum', 'StrapMaxLoc', 'StrapFreq1', 'StrapFreq2',
'StrapFreq3', 'StrapFreq4', 'StrapFreq5', 'StrapFreq6', 'StrapFreq7',
'StrapFreq8', 'StrapFreq9', 'StrapFreq10', 'FR1', 'FR2', 'FR3', 'FR4', 'FR5',
'FR6', 'FR7', 'FR8', 'FR9', 'FR10', 'FRIntegral', 'FRMax', 'FRMin', 'FRAvg',
'FRRange', 'FRMaxID', 'FRMinID', 'FRRMS', 'FRCentr', 'FRMaxSum', 'FRMaxLoc',
'FRFreq1', 'FRFreq2', 'FRFreq3', 'FRFreq4', 'FRFreq5', 'FRFreq6', 'FRFreq7',
'FRFreq8', 'FRFreq9', 'FRFreq10', 'LA1', 'LA2', 'LA3', 'LA4', 'LA5', 'LA6',
'LA7', 'LA8', 'LA9', 'LA10', 'LAIntegral', 'LAMax', 'LAMin', 'LAAvg',
'LARange', 'LAMaxID', 'LAMinID', 'LARMS', 'LACentr', 'LAMaxSum', 'LAMaxLoc',
'LAFreq1', 'LAFreq2', 'LAFreq3', 'LAFreq4', 'LAFreq5', 'LAFreq6', 'LAFreq7',
'LAFreq8', 'LAFreq9', 'LAFreq10', 'RA1', 'RA2', 'RA3', 'RA4', 'RA5', 'RA6',
'RA7', 'RA8', 'RA9', 'RA10', 'RAIntegral', 'RAMax', 'RAMin', 'RAAvg',
'RARange', 'RAMaxID', 'RAMinID', 'RARMS', 'RACentr', 'RAMaxSum', 'RAMaxLoc',
'RAFreq1', 'RAFreq2', 'RAFreq3', 'RAFreq4', 'RAFreq5', 'RAFreq6', 'RAFreq7',
'RAFreq8', 'RAFreq9', 'RAFreq10', 'S0_1', 'S0_2', 'S0_3', 'S0_4', 'S0_5',
'S0_6', 'S0_7', 'S0_8', 'S0_9', 'S0_10', 'S0Integral', 'S0Max', 'S0Min',
'S0Avg', 'S0Range', 'S0MaxID', 'S0MinID', 'S0RMS', 'S0Centr', 'S0MaxSum',
'S0MaxLoc', 'S0Freq1', 'S0Freq2', 'S0Freq3', 'S0Freq4', 'S0Freq5', 'S0Freq6',
'S0Freq7', 'S0Freq8', 'S0Freq9', 'S0Freq10', 'S1_1', 'S1_2', 'S1_3', 'S1_4',
'S1_5', 'S1_6', 'S1_7', 'S1_8', 'S1_9', 'S1_10', 'S1Integral', 'S1Max',
'S1Min', 'S1Avg', 'S1Range', 'S1MaxID', 'S1MinID', 'S1RMS', 'S1Centr',
'S1MaxSum', 'S1MaxLoc', 'S1Freq1', 'S1Freq2', 'S1Freq3', 'S1Freq4', 'S1Freq5',
'S1Freq6', 'S1Freq7', 'S1Freq8', 'S1Freq9', 'S1Freq10', 'S2_1', 'S2_2',
'S2_3', 'S2_4', 'S2_5', 'S2_6', 'S2_7', 'S2_8', 'S2_9', 'S2_10', 'S2Integral',
'S2Max', 'S2Min', 'S2Avg', 'S2Range', 'S2MaxID', 'S2MinID', 'S2RMS',
'S2Centr', 'S2MaxSum', 'S2MaxLoc', 'S2Freq1', 'S2Freq2', 'S2Freq3', 'S2Freq4',
'S2Freq5', 'S2Freq6', 'S2Freq7', 'S2Freq8', 'S2Freq9', 'S2Freq10', 'S3_1',
'S3_2', 'S3_3', 'S3_4', 'S3_5', 'S3_6', 'S3_7', 'S3_8', 'S3_9', 'S3_10',
'S3Integral', 'S3Max', 'S3Min', 'S3Avg', 'S3Range', 'S3MaxID', 'S3MinID',
'S3RMS', 'S3Centr', 'S3MaxSum', 'S3MaxLoc', 'S3Freq1', 'S3Freq2', 'S3Freq3',
'S3Freq4', 'S3Freq5', 'S3Freq6', 'S3Freq7', 'S3Freq8', 'S3Freq9', 'S3Freq10',
'Accel1', 'Accel2', 'Accel3', 'Accel4', 'Accel5', 'Accel6', 'Accel7',
'Accel8', 'Accel9', 'Accel10', 'AccelIntegral', 'AccelMax', 'AccelMin',
'AccelAvg', 'AccelRange', 'AccelMaxID', 'AccelMinID', 'AccelRMS',
'AccelCentr', 'AccelMaxSum', 'AccelMaxLoc', 'AccelFreq1', 'AccelFreq2',
```

```
‘AccelFreq3’, ‘AccelFreq4’, ‘AccelFreq5’, ‘AccelFreq6’, ‘AccelFreq7’,
‘AccelFreq8’, ‘AccelFreq9’, ‘AccelFreq10’, ‘Pos1’, ‘Pos2’, ‘Pos3’, ‘Pos4’,
‘Pos5’, ‘Pos6’, ‘Pos7’, ‘Pos8’, ‘Pos9’, ‘Pos10’, ‘PosIntegral’, ‘PosMax’,
‘PosMin’, ‘PosAvg’, ‘PosRange’, ‘PosMaxID’, ‘PosMinID’, ‘PosRMS’, ‘PosCentr’,
‘PosMaxSum’, ‘PosMaxLoc’, ‘PosFreq1’, ‘PosFreq2’, ‘PosFreq3’, ‘PosFreq4’,
‘PosFreq5’, ‘PosFreq6’, ‘PosFreq7’, ‘PosFreq8’, ‘PosFreq9’, ‘PosFreq10’,
‘CoP1’, ‘CoP2’, ‘CoP3’, ‘CoP4’, ‘CoP5’, ‘CoP6’, ‘CoP7’, ‘CoP8’, ‘CoP9’,
‘CoP10’, ‘CoPIntegral’, ‘CoPMax’, ‘CoPMin’, ‘CoPAvg’, ‘CoPRange’, ‘CoPMaxID’,
‘CoPMinID’, ‘CoPRMS’, ‘CoPCentr’, ‘CoPMaxSum’, ‘CoPMaxLoc’, ‘CoPFreq1’,
‘CoPFreq2’, ‘CoPFreq3’, ‘CoPFreq4’, ‘CoPFreq5’, ‘CoPFreq6’, ‘CoPFreq7’,
‘CoPFreq8’, ‘CoPFreq9’, ‘CoPFreq10’, ‘SCI’};
predictors = inputTable(:, predictorNames);
response = inputTable(:,m);
isCategoricalPredictor = [false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
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false, false, false, false, false, false, false, false, false, false, false,
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false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false, false, false, false, false, false, false,
false, false, false, false, false];

% Perform cross-validation
partitionedModel = crossval(trainedModel.RegressionEnsemble, ‘Kfold’, 5);

% Compute validation predictions
validationPredictions = kfoldPredict(partitionedModel);

% Compute validation RMSE
validationRMSE = sqrt(kfoldLoss(partitionedModel, ‘LossFun’, ‘mse’));
```

MATLAB script to find and delete cardiac artifacts in EMG data

```
%CardiacArtifactDelete.m
%Script to find and delete cardiac artifacts

Working = table2array(RAYW_RMS);
Working3 = table2array(QS_RMS);
RAYW_ORIG = Working(:,10);
QS_ORIG = Working3(:,7);

m=1;
Threshold = 10;
PlaceHold = 1;
Beat = zeros(2,50);
InsideBeat = false;

%Find heart beat locations and store locations in Beat() array
for n = 1:length(Working)
    if Working(n, 10) >= Threshold && InsideBeat == false
        InsideBeat = true;
        Beat(1,m) = n;
    elseif Working(n,10) < Threshold && InsideBeat == true
        InsideBeat = false;
        Beat(2,m) = n;
        m=m+1;
    end
end


%set all data with cardiac contamination to 0 (150 data point before and
%after locations in Beat)
for m = 1:width(Beat)
    if Beat(1,m)-150 <= 0
    %do nothing if < 150 data points before first beat
    else
        if m == 1
            startIndex = 1;
        else
            startIndex = Beat(2,m-1)+200;
        end
        endIndex = Beat(1,m)-200;
        Working2(PlaceHold:PlaceHold + endIndex-startIndex,:) =
Working(startIndex:endIndex,:);
        PlaceHold = PlaceHold + endIndex-startIndex;
    end
end
RAYW_DEL = Working2(:,7);
RAYW_RMS_Cardiac_Delete = array2table(Working2,"VariableNames",Var_names);

clearvars m  Beat endIndex InsideBeat startIndex Threshold PlaceHold Working;

%************Delete cardiac contaminated data from quiet sitting table
```

```
Threshold = 40;
m=1;
PlaceHold = 1;
Beat = zeros(2,50);
InsideBeat = false;

%Find heart beat locations and store locations in Beat() array
for n = 1:length(Working3)
    if Working3(n, 7) >= Threshold && InsideBeat == false
        InsideBeat = true;
        Beat(1,m) = n;
    elseif Working3(n,7) < Threshold && InsideBeat == true
        InsideBeat = false;
        Beat(2,m) = n;
        m=m+1;
    end
end


%set all data with cardiac contamination to 0 (150 data point before and
%after locations in Beat)
for m = 1:width(Beat)
    if Beat(1,m)-150 <= 0
    %do nothing if < 150 data points before first beat
    else
        if m == 1
            startIndex = 1;
        else
            startIndex = Beat(2,m-1)+200;
        end
        endIndex = Beat(1,m)-200;
        Working4(PlaceHold:PlaceHold + endIndex-startIndex,:) =
Working3(startIndex:endIndex,:);
        PlaceHold = PlaceHold + endIndex-startIndex;
    end
end

QS_DEL = Working4(:,7);

QS_RMS_Cardiac_Delete = array2table(Working4,"VariableNames",Var_names);

clearvars RAYW_DEL RAYW_ORIG QS_DEL QS_ORIG m Beat endIndex InsideBeat
startIndex Threshold PlaceHold Working3 Working2 Working4;
```

MATLAB Script to substitute cardiac artifacts for good data

```
%run this script after running CardiacDelete.m to remove cardiac
%artifacts. Must inspect data first and set muscle to equal columns
%containing cardiac artifacts
Note(3,1) = "RAYW_RMS_Cardiac_Interp contains data which has had the cardiac
contaminated data deleted, and the missing data replaced by interpolation
based on average activation over all cycles.";

list = {'4','5','6','7','10','11','16','17','18','19','22','23'};
[indx,tf] = listdlg('ListString',list,'PromptString','Columns with Cardiac
Artifact');
muscleIndex1 = [4 5 6 7 10 11 16 17 18 19 22 23];
count = 1;
for n=indx
    muscleIndex2(1,count)=muscleIndex1(n);
    count = count+1;
end

for muscle = muscleIndex2
    count = 0;
    m=1;
    InsideBeat = false;

    %set all data with cardiac contamination to 0 (150 data point before and
    %after locations in Beat)
    for m = 1:width(Beat)
        if Beat(1,m)-150 <= 0
            startIndex = 1;
        else
            startIndex = Beat(1,m)-150;
        end
        Working(startIndex:Beat(2,m)+150,muscle) = 0;
    end

    %Interpolates data for each rocking cycle to make all cycles the same
length
    %Peak Array is a table with each row being the EMG response for one
rocking
    %cycle. After interpolation, zeroed sections are replaced with a separate
linear
    %interpolation.
    For n = 1:width(Pos)-1
        x=maxArray(n)+1;
        v=Working(Pos(2,n):Pos(2,n+1),muscle); %Values to interpolate
        xq=1☹x-1)/M:x;

        for m = 1:length(v)
            k=m;
            if v(m,1) == 0
                z = m;
                while v(z,1) == 0 && z < length(v)
                    z=z+1;
```

```
            end

            if m < 6
                k=2;
                tempEnd = v(z+2,1);
                tempStart = mean(v(z+2:z+12,1));
            elseif z > length(v) - 6
                tempStart = v(m-2,1);
                tempEnd = mean(v(m-12:m-2,1));
                z=length(v)-1;
            else
                tempStart = v(m-2,1);
                tempEnd = v(z+2,1);
            end
            tempStep = (tempEnd-tempStart)/(z-k+2);

            v(k-1:z+1,1)=tempStart:tempStep:tempEnd;

        end
    end

    tempArray(:,1) = transpose(interp1(1:x,v,xq));
    cycleArray(1:M,n) = tempArray(1:M,1);
    clear tempArray;
end

cycleSum = 0;
count = 0;
count2 = 0;
count3 = 1;


%Calculates the average of all rocking cycles to make a prototype cycle -
%avgCycle
for m = 1:length(cycleArray)
    for n = 1:width(cycleArray)
        if cycleArray(m,n) > 0
            cycleSum = cycleSum+cycleArray(m,n);
            count = count + 1;
        end
    end
    avgCycle(m,muscle) = cycleSum/count;
    cycleSum = 0;
    count = 0;
    count2 = 0;
end

count = 1;
beatEnd = 1;
beatStart = 1;
%Calculates the scale factor to multiply the prototype beat by before
%replacing cardiac contaminated data
for n=1:width(Beat)
    InsideBeat = false;
```

```
        y = true; %gets set to false when beatStart and beatEnd have both been
set
        for x = beatEnd:length(Working)
            if Working(x, muscle) == 0 && InsideBeat == false && y == true
                InsideBeat = true;
                beatStart = x - 1;
                if beatStart < 1
                    beatStart = 1;
                end
            elseif Working(x,muscle) > 0 && InsideBeat == true && y == true
                beatEnd = x;
                y = false;
            elseif beatEnd < beatStart && x == length(Working)
                beatEnd = x;
                Working(x,7) = Working(beatStart-1,7);
            end

        end

        for m=1:width(Pos)-1
            %Calculate the percent of the way through the current rocking
            %cycle that the current heart beat starts
            if beatStart < Pos(2,1)
                BeatPercent = (M - (Pos(2,1)-beatStart))/M;
            elseif Pos(2,m) <= beatStart && Pos(2,m+1) > beatStart
                BeatPercent = (beatStart+1-Pos(2,m))/(Pos(2,m+1) - Pos(2,m));
            end
        end


        SubStart = fix(length(avgCycle)*BeatPercent);
        if SubStart < 1
            SubStart = 1;
        end
        SubEnd = SubStart+beatEnd-beatStart;
        if SubEnd > length(avgCycle)
            beatArray(1,1:length(avgCycle)-SubStart+1) =
transpose(avgCycle(SubStart:length(avgCycle),muscle));
            beatArray(1,length(avgCycle)-SubStart+2:1+SubEnd-SubStart) =
transpose(avgCycle(1:SubEnd - length(avgCycle),muscle));
            SubEnd = 1+SubEnd-SubStart;
        else
            beatArray = transpose(avgCycle(SubStart:SubEnd,muscle));
        end
        if Beat(1,n)-151 <= 0
            startIndex = 1;
            Working(startIndex,muscle) = mean(Working(:,muscle));
        else
            startIndex = beatStart;
        end
        if beatEnd >= length(Working)
            endIndex = length(Working);
        else
            endIndex = beatEnd;
        end
```

```
        ScaleStart = Working(startIndex,muscle)/beatArray(1,1);
        ScaleEnd = Working(endIndex,muscle)/beatArray(1,width(beatArray));
        ScaleStep = (ScaleEnd-ScaleStart)/(beatEnd-beatStart);
        ScaleFact = ScaleStart:ScaleStep:ScaleEnd;
        beatArray = beatArray.*ScaleFact(1,1:width(beatArray));

        Working(beatStart:beatEnd,muscle) = transpose(beatArray);
        clear beatArray;
    end
    clearvars n m x v beatArray BeatPercent blanksArray count count2 count3
cycleArray cycleSum endIndex InsideBeat;
    clearvars ScaleEnd ScaleFact ScaleStart ScaleStep startIndex SubEnd
SubStart Threshold xq y beatEnd beatStart z;
    clearvars tempEnd tempStart tempStep k;
end
clearvars Pos muscle Beat M maxArray avgCycle muscleIndex1 muscleIndex2 indx
list tf;
RAYW_RMS_Cardiac_Interp = array2table(Working,"VariableNames",Var_names);
```

MATLAB script to do cluster analysis

```
%#ok<*SAGROW>

%Uncomment this section to do cluster analysis
X = A2_featuresTablesNormFreqFix{2,2};
for subject = 3:21
    X = horzcat(X, A2_featuresTablesNormFreqFix{subject,2});
end
    X = X(:,1:341);
    %T = clusterdata(X,3,"Linkage");
    T = clusterdata(X,'Linkage','average','Maxclust',4);
    %figure(3)
    %scatter3(X(:,1),X(:,2),X(:,3),100,T,'filled');
    %titleMuscle = string(Muscles{1,muscle});
    %distanceFunction = @customDistance;
    tree = linkage(X,'average');
    figure(1)
    ax = gca; % Get the current axes
    ax.FontName = 'Arial'; % Change font for tick labels on both x and y axes
    %ax.FontSize = 10; % Change font size for tick labels
    %title(titleMuscle, 'FontName', 'Arial', 'FontSize', 16);

    dendrogram(tree)
    figureFile = 'FullDendrogramTrunkSCI.EPS';
    exportgraphics(figure(1), figureFile)
   % ClusterAnalysis_FulltreeCell{2,2} = T;
    %ClusterAnalysis_FulltreeCell{3,2} = tree;

% %Uncomment this section to calculate distances from each SCI subject to TD
% %group
% % Calculate distances between each SCI subject and TD subjects
%
% allPoints = A2_percentileCell{2,2};
% for muscle = [3, 4, 8, 9]%3:13
%     allPoints = horzcat(allPoints, A2_percentileCell{2,muscle});
% end
% Tdpoints = allPoints(12:21,
```

```
clearvars X T tree muscle figureFile newPoint distances Tdpoints ax distance
clearvars m subject allPoints titleMuscle
```

MATLAB script to combine sensor data with EMG data

```
% ColName = table2array(Header);
% EMG.Properties.VariableNames = ColName(1,1:27);
% Chair.Properties.VariableNames = ColName(1,28:38);
ColName(1:27) = EMG.Properties.VariableNames;
ColName(28:38) = Chair.Properties.VariableNames;

Chair_Working = table2array(Chair); %insert Chair sensors table name

EMG_Working = table2array(EMG); %insert EMG table name


M = length(Chair_Working); %Sets constant variables
M2 = length(EMG_Working);
N = width(Chair_Working);
N2 = width(EMG_Working);
N3 = N + N2;
h = 0; %counter to place pulse data in correct row
k = 0; %counter to place pulse data in correct row
h2 = 0;
k2 = 0;
p = zeros(2,20); %array with row numbers of each pulse in sensor and EMG data


for m = 2:M %finds beginning of each manual pulse in sensor data
    if Chair_Working(m,11) > 0 %Finds beginning of each digital pulse in
sensor data
        if Chair_Working(m-1,11) == 0 %check to make sure this is the first
data point for this pulse
            k = k + 1;
            p(2,k) = m;
        end
    end
end
for m = 2:M2 %finds beginning of each pulse
    if EMG_Working(m,2) > 1.2  %Finds beginning of each analog pulse
        if EMG_Working(m-1,2) <= 1.2
            h = h + 1;
            p(1,h) = m;
        end
    end
end
if h == k  %check to make sure both files contain the same number of pulses
    disp("Equal number of pulses!");
else
    disp("Sensor data has ", k, " pulses, but EMG data has ", h, " pulses");
end

Working = zeros(M2,N3);

% R = ((p(1,h) - p(1,1))/(p(2,k) - p(2,1)));
```

```
x2 = p(2,1)+1:1:p(2,k); %lengths from first to last pulse in analog and
digital signals
x = p(1,1)+1:1:p(1,h);
Working(:,1) = EMG_Working(:,1);    %sets first column of Working to the times
from the ECG sensor
for n = 2:1:27
    for s = 1:h     %Interpolates EMG data between each set of pulses to be
same size as interpolated Chair sensor data between the same pulses
        if s == 1
%starts interpolation at first pulse
            m1 = p(1,1);
%sets start point
            m3 = p(1,s)-1:1:p(1,(s+1))-1;
%sets EMG range between pulses (pulse 1 to pulse2)
            m4 = p(2,s)-1:1:p(2,(s+1))-1;
%sets Chair sensor range between pulses (pulse 1 to pulse 2)
            y1 = length(m3);
%Length of EMG range from pulse 1 to pulse 2
            y2 = length(m4);
%length of chair sensor range from pulse 1 to pulse 2
            m5 = p(2,s):y2/y1:p(2,(s+1))-1;
%sets query point range for Chair sensors
            m7(s) = length(m3)-length(m5);
%finds difference in EMG and Chair sensors ranges
            m8 = p(1,s):1:(p(1,(s+1))-m7(s))-1;
%sets query point range for EMG data to be equal in size to chair sensor
interpolation
            Working(m1:(length(m8)-1)+m1,n) =
transpose(interp1(m3,EMG_Working(m3,n),m8,'linear'));

        elseif s >= 2 && s <= (h-1)
            m1 = (p(1,s));
%sets start point
            m3 = p(1,s):1:p(1,(s+1))-1;
            m4 = p(2,s):1:p(2,(s+1))-1;
            y1 = length(m3);
            y2 = length(m4);
            m5 = p(2,s):y2/y1:p(2,(s+1))-1;
            m7(s) = length(m3)-length(m5);
            m8 = p(1,s):1:(p(1,(s+1))-m7(s))-1;
            Working(m1:(length(m8)-1)+m1,n) =
transpose(interp1(m3,EMG_Working(m3,n),m8,'linear'));

        elseif s == h
            m1 = (p(1,s));
%sets start point
            Working(m1,n) = EMG_Working(p(1,s),n);

        end
    end
end
for n = 28:1:38
    for s = 1:h %Interpolates Chair sensor data between first and last pulse
        if s == 1
```

```
            m1 = p(1,1);
%sets start point
            m3 = p(1,s)-1:1:p(1,(s+1))-1;
            m4 = p(2,s)-1:1:p(2,(s+1))-1;
            y1 = length(m3);
            y2 = length(m4);
            m5 = p(2,s):y2/y1:p(2,(s+1))-1;
            Working(m1:(length(m5)-1)+m1,n) =
transpose(interp1(m4,Chair_Working(m4,n-27),m5,'linear'));

        elseif s >= 2 && s <= (h-1)
            m1 = (p(1,s));
%sets start point
            m3 = p(1,s):1:p(1,(s+1))-1;
            m4 = p(2,s):1:p(2,(s+1))-1;
            y1 = length(m3);
            y2 = length(m4);
            m5 = p(2,s):y2/y1:p(2,(s+1))-1;
            Working(m1:(length(m5)-1)+m1,n) =
transpose(interp1(m4,Chair_Working(m4,n-27),m5,'linear'));

        elseif s == h
            m1 = (p(1,s));
%sets start point
            Working(m1,n) = Chair_Working(p(2,s),n-27);

        end
    end
end

A910 = array2table(Working,"VariableNames",ColName);

p2 = zeros(4,h);
for m = 2:length(Working) %finds beginning of each pulse
    if Working(m,2) > 1.2  %Finds beginning of each analog pulse
        if Working(m-1,2) < 1.2
            h2 = h2 + 1;
            p2(1,h2) = m;
        end
    end
    if Working(m,38) > 0 %Finds beginning of each digital pulse
        if Working(m-1,38) == 0
            k2 = k2 + 1;
            p2(2,k2) = m;
            p2(4,k2) = Working(m,1); %saves pulse start times
        end
    end
end
for n = 1:h2 %calculates offset of digital and analog signals
   p2(3,n) = p2(1,n) - p2(2,n);
end

z = zeros(1,h2);
s = 0;
```

```
for m = 2:length(Working)   %finds value  mmediately following the last value
of each pulse
    if Working(m,2) == 0
        if Working((m-1),2) > 0
            s = s + 1;
            z(1,s) = m;
        end
    end
end

clear ans;  %clears calculated constant variables
clear m;
clear n;
clear s;
clear m1;
clear m3;
clear m4;
clear m5;
clear m7;
clear m8;
clear y1;
clear y2;
clear x;
clear x2;
clear h;
clear h2;
clear k;
clear k2;
clear M;
clear M2;
clear N;
clear N2;
clear N3;
clear Chair_Working;
clear EMG_Working;
clear p;
```

APPENDIX B
IRB DOCUMENTATION

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

INFORMED CONSENT AND RESEARCH AUTHORIZATION

Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

Individuals with Spinal Cord Injury or Other Neurological Deficit

Investigator(s) name, Degree, University Department, & address: Andrea Behrman, PhD, PT
Frazier Rehab Institute, Suite 1506
220 Abraham Flexner Way
Louisville, KY 40202

Site(s) where study is to be conducted: Frazier Rehabilitation Institute
U of L Department of Neurological Surgery

Phone number for subjects to call for questions: 502-569-7996

Introduction and Background Information

You/Your child (referred to as you in the rest of this document) are invited to take part in a research study because you have a neurological condition that has made it hard for you to move parts of your body, are currently or have previously been enrolled in our clinical or research Pediatric NeuroRecovery Program, are enrolled in the study IRB #15.0183, or are enrolled in our Human Locomotor Research Center Inquiry database (IRB #06.0647). The study is being conducted under the direction of Andrea L. Behrman, PhD, PT, Thomas Roussel, PhD, and Jennifer Thompson, MD at the University of Louisville. About 20 local participants with a neurological deficit will be invited to take part in this research and 15 children without a neurological deficit. A total of 35 local participants will be invited to take part in the entire research study.

Purpose

The purpose of this study is to test the function and design for a pediatric rocking chair that promotes movement (trunk, legs, or arms) and monitors how much and how the chair is used. This chair will be used for activity-based therapy in children 1-12 years old with spinal cord injury or other disorders that make moving difficult. We will examine how your child rocks in the chair and how much she or he rocks in the chair.

Procedures

Your participation in this study will be 1-2 visits that may last up to 1 hour. You may be asked to return for additional visits (up to 10 visits). You also may be asked to use the rocking chair in your home, thus, having the opportunity to rock in the chair as often as you like. We will collect information including age, gender and ethnicity. We will measure and record your height and weight. This information may be taken from your medical history if they are available. You or your parent will report on your readiness for participation.

This study will take place in the 'Discovery Cove', the pediatric Neurorecovery research lab at Frazier Rehab Institute and at your home. Therapists or technicians will work with you as well as the researchers while in Discovery Cove and instruct your parents in how to use the rocking chair.

To assist you, therapists and technicians will help you move from your wheelchair or from standing to sit in the rocking chair.

You will be secured safely with a seatbelt or other strapping by the therapists or technicians. Participants will sit on a cushion to minimize risk of skin abrasion or pressure sores.

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

You will be asked to rock in the rocking chair in several different ways; to your own liking, using only your arms, using only your trunk, and finally using only your legs.

We may place small sensors on your skin or the rocking chair to record information about how you rock during the session.

This information will be collected as written records. Data from the computer and the sessions may be video recorded.

The session will be conducted and supervised by the principal investigator or a physical therapist.

Potential Risks

This study may involve risks that are currently unforeseeable. The study may involve the following physical risks and/or discomforts:

1. Skin irritation due to adhesive tape, sensors, wires, and/or pads (likely)
2. Falling out of chair while rocking (rare)
    a. Fracture if you were to fall out of chair (rare)
    b. Skin abrasion if you were to fall out of chair (rare)
    c. Autonomic dysreflexia if unforeseen pressure during sitting (rare, for participants with SCI only)

- Sensors are placed on the skin with hypoallergenic tape or athletic wrap or velcro straps. Irritation may occur based on skin sensitivity of the participant. Hypoallergenic tape reduces the risk, as well as use of wraps.

- To reduce the risk of falling, you will be guarded by one or more licensed and experienced physical therapists getting in or out of the rocking chair. You will be secured safely with a seatbelt, butterfly harness and/or padding by therapists or technicians. Participants will sit on a cushion to minimize risk of skin abrasion or pressure sores. Falling may also place risk for skin abrasion.

- Individuals with SCI are at risk for fracture due to diminishing bone health and inactive weight-bearing. Incidence of fractures, with children, is reported to occur during transfers as opposed to weight-bearing activities. Over a seven year history of providing therapy to children, there has not been an incidence of fracture. The risk of fractures is rare.

- For participants with SCI with an injury T6 and above, there is an infrequent risk of autonomic dysreflexia (AD). Autonomic dysreflexia is a situation that occurs when the blood pressure may increase quickly and the participant can experience a severe, pounding headache and a lot of sweating. A history of AD episodes will be taken. Participants will be asked to empty their bladder prior to the session to avoid AD. We will ask if you have any history of AD.

Overall, the risks in this study for children with SCI are less than those in children undergoing physical and occupational therapies on a daily basis. Using a rocking chair is a typical activity for children. Those with neurological deficit, however, are at a greater risk for falling in any circumstance due to weakness of trunk, arm, and leg muscles.

In addition, you may suffer harms that we have not seen before. If you should have any of these difficulties during the assessments, we will stop. There are no reasonably foreseeable psychological risks, social risks, and/or legal risks. This study may involve risks that are currently unforeseeable.

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

Benefits
You may not directly benefit from participating in this study, however the information learned may be of benefit in the future to others with spinal cord injury.

Alternatives
Instead of taking part in this study, you could choose to not participate. This will have no influence on your access and availability to routine care and evaluations for your child.

Research Related Injury
If you are injured by being in this research study, the study doctor will arrange for you to get medical treatment. The sponsor, the study site, or your study doctor has not set aside money to pay for treatment of any injury. You and your insurance will be billed for the treatment of these injuries. Before you agree to take part in this research study you should find out whether your insurance will cover an injury in this kind of research. You should talk to the study doctor or staff about this. If you are injured, there is no money set aside for lost wages, discomfort, disability, etc. You do not give up your legal rights by signing this form. If you think you have a research related injury, please call Dr. Jennifer Thompson at 502-588-3440 or the Center for Pediatric NeuroRecovery at 502-569-7996.

Payment
There is no compensation for participating in this study.

Costs
Unless you are injured, there will be no costs to participate in this study. Sessions will not be charged to you.

HIPAA Research Authorization
The Health Insurance Portability and Accountability Act of 1996 (HIPAA) provides federal safeguards for your protected health information (PHI). Examples of PHI are your name, address, and birth date together with your health information. PHI may also include your medical history, results of health exams and lab tests, drugs taken and results of this research study. Your PHI may not be used or shared without your agreement, unless it meets one of the HIPAA exceptions.

State and federal privacy laws protect your health information. In most cases, health information that identifies you can be used or shared by the research team only if you give your permission by signing this form.

If you sign this form your health information will be used and shared to answer the research questions described above and to make sure that the research was done correctly. The time period when information can be used or shared ends when all activities related to this study are completed.

Your access to your health information will not be limited during this study.

You do not have to sign this form. If you do not sign this form you may not participate in the study and health information that identifies you will not be shared with the research team.

Site(s) where health information about you will be used or shared for this research:

In our research, the research team will look at and may share information about you and your health. Federal law requires that health care providers and researchers protect the privacy and security of health information that identifies you. We may ask for your health information from the following:

Affiliated Sites:
University of Louisville
Frazier Rehab Institute

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

Protected health information (PHI) that will be used or shared for research

- History and physical exams
- Videotapes of tests/training

Revocation of Research Authorization

You may cancel the permission you have given to use and share your protected health information at any time. This means you can tell us to stop using and sharing your protected health information. If you cancel your permission:

- We will stop collecting information about you.
- You may not withdraw information that we had before you told us to stop.
  - We may already have used it or shared it.
  - We may need it to complete the research.
- Staff may ask your permission to follow-up with you if there is a medical reason to do so.

To cancel your permission, you will be requested to complete a written "Revocation of Research Authorization" form located at the end of this document. You may also obtain a copy from your study doctor, designated personnel or from the Human Subjects Protections Program Office website (https://louisville.edu/research/humansubjects/templates/biomedical-forms).

Confidentiality

Total privacy cannot be guaranteed. We will protect your privacy to the extent permitted by law. If the results from this study are published, your name will not be made public. Once your information leaves our institution, we cannot promise that others will keep it private.

Your information may be shared with the following:

- Organizations that provide funding at any time for the conduct of the research.
- The University of Louisville Institutional Review Board, Human Subjects Protection Program Office, Privacy Office, others involved in research administration and compliance at the University, and others contracted by the University for ensuring human subjects safety or research compliance
- The local research team
- People who are responsible for research, compliance and HIPAA oversight at the institutions where the research is conducted
- Government agencies, such as:
- Office for Human Research Protections
- Office of Civil Rights
- Food and Drug Administration

Security

Your data will be kept private by assigning you a coded identification number. All paperwork that has your name or personal information will be kept in a password protected file or in a file cabinet in a room with limited or key-coded access.

Voluntary Participation

Taking part in this study is completely voluntary. You may choose not to take part at all. If you decide not to be in this study, you won't be penalized or lose any benefits for which you qualify. If you decide to be in this study, you may change your mind and stop taking part at any time. If you decide to stop taking part, you won't be

penalized or lose any benefits for which you qualify. You will be told about any new information learned during the study that could affect your decision to continue in the study.

Termination
Your study doctor or the study sponsor has the right to stop this study at any point. Your study doctor may remove you from this study with or without your okay.

Participation in Other Research Studies
You may take part in this study if you are currently in another research study. It is important to let your doctor know if you are in another research study.

Contact Persons
If you have any questions, concerns, or complaints about the research study, please contact Dr. Andrea Behrman at 502-569-7996.

Research Subject's Rights
If you have any questions about your rights as a research subject, you may call the Human Subjects Protection Program Office at (502) 852-5188. You may discuss any questions about your rights as a research subject, in private, with a member of the Institutional Review Board (IRB). You may also call this number if you have other questions about the research, and you cannot reach the study doctor, or want to talk to someone else. The IRB is an independent committee made up of people from the University community, staff of the institutions, as well as people from the community not connected with these institutions. The IRB has approved the participation of human subjects in this research study.

Concerns and Complaints
If you have concerns or complaints about the research or research staff and you do not wish to give your name, you may call the toll free number 1-877-852-1167. This is a 24 hour hot line answered by people who do not work at the University of Louisville.

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

Acknowledgment and Signatures

This informed consent document is not a contract. This document tells you what will happen during the study if you choose to take part. Your signature indicates that this study has been explained to you, that your questions have been answered, and that you agree to take part in the study. You are not giving up any legal rights to which you are entitled by signing this informed consent document. You will be given a copy of this consent form to keep for your records.

Subject Name (Please Print)	Signature of Subject	Date Signed
Printed Name of Legally Authorized Representative (if applicable)	Signature of Legally Authorized Representative	Date Signed

Authority of Legally Authorized Representative to act on behalf of Subject

*Authority to act on behalf of another includes, but is not limited to parent, guardian, or durable power of attorney for health care.

Printed Name of Person Explaining Consent Form	Signature of Person Explaining Consent Form (if other than the Investigator)	Date Signed
Printed Name of Investigator	Signature of Investigator	Date Signed

List of Investigators:	Phone Numbers:
Andrea L. Behrman, PhD, PT	502-569-7996
Thomas Roussel, PhD	502-852-1528
Jennifer Thompson, MD	502-588-3440

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

REVOCATION OF AUTHORIZATION FOR USE AND DISCLOSURE OF YOUR HEALTH INFORMATION FOR RESEARCH

PI Address: 220 Abraham Flexner Way - 15th Floor
Louisville, KY 40202
PI Phone: 502.569.7996

Return To:

OR

Institutional Review Board
300 E. Market, Suite 380
Louisville, KY 40202

Do not sign this letter unless you are withdrawing from this research. You will be sent confirmation that this notice was received.

To Whom It May Concern:

I would like to discontinue my participation in the research study noted above. I understand that health information already collected will continue to be used as discussed in the Authorization I signed when joining the study.

Your options are (***choose one***):

☐ **Withdraw from Study & Discontinue Authorization:**
Discontinue my authorization for the future use and disclosure of protected health information. In some instances, the research team may need to use your information even after you discontinue your authorization, for example, to notify you or government agencies of any health or safety concerns that were identified as part of your study participation.

☐ **Withdraw from Study, but Continue Authorization:**
Allow the research team to continue collecting information from me and my personal health information. This would be done only as needed to support the goals of the study and would not be used for purposes other than those already described in the research authorization.

_____ _____
Printed Name and Signature of Subject | Date Signed

_____ _____
Signature of Subject's Legal Representative (if subject is unable to sign) | Date Signed

_____ _____
Printed Name of Subject's Legal Representative | Birthdate of Subject

_____
Relationship of Legal Representative to Subject

_____ _____
Subject's Address | Subject's Phone Number

Optional:
I am ending my participation in this study because:

_____

_____

UofL Institutional Review Boards
IRB NUMBER: 17.0725
IRB APPROVAL DATE: 03/16/2022

SUBJECT ASSENT

Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

Individuals with Spinal Cord Injury or Other Neurological Deficit

I am invited to be in a research study being done by Dr. Andrea L. Behrman, PhD, PT and Thomas Roussel, PhD.

When a person is in a research study, they are called a "subject". Research studies are done when doctors want to find new ways to help patients get better. I am invited because I am currently or was previously enrolled in therapy or was a subject in a prior study. I am also taking part in this study because I am under 12 years old and healthy.

By being in this study, the researchers hope to understand how using a rocking chair may help children who have difficulty moving, move more easily.

By agreeing to be a part of this study, I may be asked sit and rock in a rocking chair – in any way I like, or if I can using just my arms, just my legs, or just my trunk muscles to make the chair move back and forth. I am being asked to participate for up to two visits that last about 1 hour each. Up to 35 children may participate in this project. I may be videotaped and how I move may be recorded with special sensors. The sensors may be placed on my arms, legs, or trunk with tape or athletic wrap.

I may be asked to return for additional visits (up to 10 visits, or every 2 weeks). I also may be asked to use the rocking chair in my home, using it as often as I like.

I can tell the therapist at any time that I do not want to do some of these things if I do not feel comfortable or safe doing them. If I am in the study, I will come to the therapy room on time. I will not benefit directly from participating in this study.

I understand that by being in this study, the researchers hope to better measure how children, who have had a spinal cord injury or other injuries that make it difficult to move, get better after receiving therapy.

My family will know that I'm in the study. If anyone else is given information about me, they will not know my name. A number or initials will be used instead of my name.

12/08/2021

UofL Institutional Review Boards
IRB NUMBER: 17.0725
IRB APPROVAL DATE: 03/16/2022

I have been told about this study and know why it is being done and what I have to do. My parent(s) have agreed to let me be in the study. If I have any questions I can ask Dr. Andrea L. Behrman, PhD, PT and she will answer my questions. If I do not want to be in this study or I want to quit after I am already in this study, I can tell the study doctor and she will discuss this with my parents.

If there are any questions now or at any time during the study, I can contact Dr. Andrea Behrman at 502-569-7996.

Printed Name of Subject	Signature of Subject	Date Signed

Printed Name of Investigator	Signature of Investigator	Date Signed

12/08/2021

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

INFORMED CONSENT AND RESEARCH AUTHORIZATION

Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control
Typically Developing Participants

Investigator(s) name, Degree, University Department, & address: Andrea Behrman, PhD, PT
Frazier Rehab Institute, Suite 1506
220 Abraham Flexner Way
Louisville, KY 40202

Site(s) where study is to be conducted: Frazier Rehabilitation Institute
U of L Department of Neurological Surgery

Phone number for subjects to call for questions: 502-569-7996

Introduction and Background Information

You/Your child (referred to as you in the rest of this document) are invited to take part in a research study because you are a typically developing child and have no history of a spinal cord injury (SCI), are enrolled in the IRB #15.0183 study, or are enrolled in our Human Locomotor Research Center Inquiry database (IRB #06.0647). The study is being conducted under the direction of Andrea L. Behrman, PhD, PT, Thomas Roussel, PhD, and Jennifer Thompson, MD at the University of Louisville**.** About 15 local participants with SCI and 20 typically developing participants will be invited to take part in this research. A total of 35 local participants will be invited to take part in the entire research study.

Purpose

The purpose of this study is to test the function and design for a pediatric rocking chair that promotes movement (trunk, legs, or arms) and monitors how much and how the chair is used. This chair will be used for activity-based therapy in children 1-12 years old with spinal cord injury or other disorders that make moving difficult. We will examine how your child rocks in the chair and how much she or he rocks in the chair.

Procedures

Your participation in this study may be to 1-2 visits that may last up to 1 hour each. You also may be asked to use the rocking chair in your home. We will collect information including age, gender and ethnicity. We will measure and record your height and weight. This information may be taken from your medical history if they are available. You or your parent will report on your readiness for participation.

This study will take place in the 'Discovery Cove', the pediatric Neurorecovery research lab at Frazier Rehab Institute and at your home. Therapists or technicians will work with you as well as the researchers while in Discovery Cove and instruct your parents in how to use the rocking chair.

You will be secured safely with a seatbelt, butterfly harness by the therapists or technicians.

You will be asked to rock in the rocking chair in several different ways; to your own liking, using only your arms, using only your trunk, and finally using only your legs.

We may place small sensors on your skin or the rocking chair to record information about how you rock during the session.

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control
This information will be collected as written records, data from the computer and the sessions may be video recorded.

The session will be conducted and supervised by the principal investigator or a physical therapist.

Potential Risks
This study may involve risks that are currently unforeseeable. The study may involve the following physical risks and/or discomforts:

1. Skin irritation due to adhesive tape, sensors, wires, and/or pads (likely)
2. Falling out of chair while rocking (rare)
    a. Fracture if you were to fall out of chair (rare)
    b. Skin abrasion if you were to fall out of chair (rare)
    c. Autonomic dysreflexia if unforeseen pressure during sitting (rare, for participants with SCI only)

- Sensors are placed on the skin with hypoallergenic tape or athletic wrap or velcro straps. Irritation may occur based on skin sensitivity of the participant. Hypoallergenic tape reduces the risk, as well as use of wraps.

- To reduce the risk of falling, you will be guarded by one or more licensed and experienced physical therapists getting in or out of the rocking chair. You will be secured safely with a seatbelt, butterfly harness and/or padding by therapists or technicians, as appropriate.

In addition, you may suffer harms that we have not seen before. If you should have any of these difficulties during the assessments, we will stop. There are no reasonably foreseeable psychological risks, social risks, and/or legal risks. This study may involve risks that are currently unforeseeable.

Sitting in a rocking chair is a typical, familiar everyday activity for children of all ages.

Benefits
You may not directly benefit from participating in this study, however the information learned may be of benefit in the future to others with spinal cord injury.

Alternatives
Instead of taking part in this study, you could choose to not participate. This will have no influence on your access and availability to routine care and evaluations for your child.

Research Related Injury
If you are injured by being in this research study, the study doctor will arrange for you to get medical treatment. The sponsor, the study site, or your study doctor has not set aside money to pay for treatment of any injury. You and your insurance will be billed for the treatment of these injuries. Before you agree to take part in this research study you should find out whether your insurance will cover an injury in this kind of research. You should talk to the study doctor or staff about this. If you are injured, there is no money set aside for lost wages, discomfort, disability, etc. You do not give up your legal rights by signing this form. If you think you have a research related injury, please call Dr. Jennifer Thompson at 502-588-3440 or the Center for Pediatric NeuroRecovery at 502-569-7996.

Payment
There is no compensation for participating in this study.

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

Costs
Unless you are injured, there will be no costs to participate in this study. Sessions will not be charged to you.

HIPAA Research Authorization
The Health Insurance Portability and Accountability Act of 1996 (HIPAA) provides federal safeguards for your protected health information (PHI). Examples of PHI are your name, address, and birth date together with your health information. PHI may also include your medical history, results of health exams and lab tests, drugs taken and results of this research study. Your PHI may not be used or shared without your agreement, unless it meets one of the HIPAA exceptions.

State and federal privacy laws protect your health information. In most cases, health information that identifies you can be used or shared by the research team only if you give your permission by signing this form.

If you sign this form your health information will be used and shared to answer the research questions described above and to make sure that the research was done correctly. The time period when information can be used or shared ends when all activities related to this study are completed.

Your access to your health information will not be limited during this study.

You do not have to sign this form. If you do not sign this form you may not participate in the study and health information that identifies you will not be shared with the research team.

Site(s) where health information about you will be used or shared for this research:
In our research, the research team will look at and may share information about you and your health. Federal law requires that health care providers and researchers protect the privacy and security of health information that identifies you. We may ask for your health information from the following:

Affiliated Sites:
University of Louisville
Frazier Rehab Institute

Protected health information (PHI) that will be used or shared for research
- History and physical exams
- Videotapes of tests/training

Revocation of Research Authorization
You may cancel the permission you have given to use and share your protected health information at any time. This means you can tell us to stop using and sharing your protected health information. If you cancel your permission:

- We will stop collecting information about you.
- You may not withdraw information that we had before you told us to stop.
    - We may already have used it or shared it.
    - We may need it to complete the research.
- Staff may ask your permission to follow-up with you if there is a medical reason to do so.

To cancel your permission, you will be requested to complete a written "Revocation of Research Authorization" form located at the end of this document. You may also obtain a copy from your study doctor, designated personnel or from the Human Subjects Protections Program Office website (https://louisville.edu/research/humansubjects/templates/biomedical-forms).

Confidentiality

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

Total privacy cannot be guaranteed. We will protect your privacy to the extent permitted by law. If the results from this study are published, your name will not be made public. Once your information leaves our institution, we cannot promise that others will keep it private.

Your information may be shared with the following:

- Organizations that provide funding at any time for the conduct of the research.
- The University of Louisville Institutional Review Board, Human Subjects Protection Program Office, Privacy Office, others involved in research administration and compliance at the University, and others contracted by the University for ensuring human subjects safety or research compliance
- The local research team
- People who are responsible for research, compliance and HIPAA oversight at the institutions where the research is conducted
- Government agencies, such as:
- Office for Human Research Protections
- Office of Civil Rights

Food and Drug Administration

Security

Your data will be kept private by assigning you a coded identification number. All paperwork that has your name or personal information will be kept in a password protected file or in a file cabinet in a room with limited or key-coded access.

Voluntary Participation

Taking part in this study is completely voluntary. You may choose not to take part at all. If you decide not to be in this study, you won't be penalized or lose any benefits for which you qualify. If you decide to be in this study, you may change your mind and stop taking part at any time. If you decide to stop taking part, you won't be penalized or lose any benefits for which you qualify. You will be told about any new information learned during the study that could affect your decision to continue in the study.

Termination

Your study doctor or the study sponsor has the right to stop this study at any point. Your study doctor may remove you from this study with or without your okay.

Participation in Other Research Studies

You may take part in this study if you are currently in another research study. It is important to let your doctor know if you are in another research study.

Contact Persons

If you have any questions, concerns, or complaints about the research study, please contact Dr. Andrea Behrman at 502-569-7996.

Research Subject's Rights

If you have any questions about your rights as a research subject, you may call the Human Subjects Protection Program Office at (502) 852-5188. You may discuss any questions about your rights as a research subject, in private, with a member of the Institutional Review Board (IRB). You may also call this number if you have other questions about the research, and you cannot reach the study doctor, or want to talk to someone else. The IRB is an independent committee made up of people from the University community, staff of the institutions, as well as people from the community not connected with these institutions. The IRB has approved the participation of human subjects in this research study.

Concerns and Complaints

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

If you have concerns or complaints about the research or research staff and you do not wish to give your name, you may call the toll free number 1-877-852-1167. This is a 24 hour hot line answered by people who do not work at the University of Louisville.

Acknowledgment and Signatures

This informed consent document is not a contract. This document tells you what will happen during the study if you choose to take part. Your signature indicates that this study has been explained to you, that your questions have been answered, and that you agree to take part in the study. You are not giving up any legal rights to which you are entitled by signing this informed consent document. You will be given a copy of this consent form to keep for your records.

Subject Name (Please Print)	Signature of Subject	Date Signed
Printed Name of Legally Authorized Representative (if applicable)	Signature of Legally Authorized Representative	Date Signed

Authority of Legally Authorized Representative to act on behalf of Subject

*Authority to act on behalf of another includes, but is not limited to parent, guardian, or durable power of attorney for health care.

Printed Name of Person Explaining Consent Form	Signature of Person Explaining Consent Form (if other than the Investigator)	Date Signed
Printed Name of Investigator	Signature of Investigator	Date Signed

List of Investigators:	Phone Numbers:
Andrea L. Behrman, PhD, PT	502-569-7996
Thomas Roussel, PhD	502-852-1528
Jennifer Thompson, MD	502-588-3440

STUDY TITLE: Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control

REVOCATION OF AUTHORIZATION FOR USE AND DISCLOSURE OF YOUR HEALTH INFORMATION FOR RESEARCH

PI Address: 220 Abraham Flexner Way - 15th Floor
Louisville, KY 40202
PI Phone: 502.569.7996

Return To:

OR

Institutional Review Board
MedCenter One, Suite 200
501 E. Broadway
Louisville, KY 40202

Do not sign this letter unless you are withdrawing from this research. You will be sent confirmation that this notice was received.

To Whom It May Concern:

I would like to discontinue my participation in the research study noted above. I understand that health information already collected will continue to be used as discussed in the Authorization I signed when joining the study.

Your options are (***choose one***):

☐ **Withdraw from Study & Discontinue Authorization:**
Discontinue my authorization for the future use and disclosure of protected health information. In some instances, the research team may need to use your information even after you discontinue your authorization, for example, to notify you or government agencies of any health or safety concerns that were identified as part of your study participation.

☐ **Withdraw from Study, but Continue Authorization:**
Allow the research team to continue collecting information from me and my personal health information. This would be done only as needed to support the goals of the study and would not be used for purposes other than those already described in the research authorization.

_____ _____
Printed Name and Signature of Subject | Date Signed

_____ _____
Signature of Subject's Legal Representative (if subject is unable to sign) | Date Signed

_____ _____
Printed Name of Subject's Legal Representative | Birthdate of Subject

_____
Relationship of Legal Representative to Subject

_____ _____
Subject's Address | Subject's Phone Number

Optional:
I am ending my participation in this study because:

_____

_____

UofL Institutional Review Boards
IRB NUMBER: 17.0725
IRB APPROVAL DATE: 07/20/2018

SUBJECT ASSENT

Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control
Typically Developing Participants

I am invited to be in a research study being done by Dr. Andrea L. Behrman, PhD, PT and Thomas Roussel, PhD.

When a person is in a research study, they are called a "subject". Research studies are done when doctors want to find new ways to help patients get better. I am invited because I do not have any injuries or conditions that make it difficult for me to easily sit, stand, or walk. In addition, I may have participated in research studies here before. I am also taking part in this study because I am a typically developing child under 12 years old, am between 30-60" tall and weigh between 25-130 lbs.

By being in this study, the researchers hope to understand how using a rocking chair may help children who have difficulty moving, move more easily.

By agreeing to be a part of this study, I may be asked sit and rock in a rocking chair – in any way I like, or using just my arms, just my legs, or just my trunk muscles to make the chair move back and forth. I am being asked to participate for up to two visits that last about 1 hour each.

Up to 35 children may participate in this project. I may be videotaped and how I move may be recorded with special sensors. The sensors may be placed on my arms, legs, or trunk with tape or athletic wrap.

I can tell the therapist at any time that I do not want to do some of these things if I do not feel comfortable or safe doing them. If I am in the study, I will come to the therapy room on time. I will not benefit directly from participating in this study.

My family will know that I'm in the study. If anyone else is given information about me, they will not know my name. A number or initials will be used instead of my name.

I have been told about this study and know why it is being done and what I have to do. My parent(s) have agreed to let me be in the study. If I have any questions I can ask Dr. Andrea L. Behrman, PhD, PT and she will answer my questions. If I do not want to be in this study or I want to quit after I am already in this study, I can tell the study doctor and she will discuss this with my parents.

If there are any questions now or at any time during the study, I can contact Dr. Andrea Behrman at 502-569-7996.

Printed Name of Subject	Signature of Subject	Date Signed

Printed Name of Investigator	Signature of Investigator	Date Signed

UF	HUMAN SUBJECTS PROTECTION PROGRAM	**RESEARCH ELIGIBILITY CHECKLIST** **Name:** **Date Consent Signed:**	IRB# and Title: **17.0725** Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control PI: Andrea L. Behrman, PhD, PT

Research Participant - Attestation

ELIGIBILITY CRITERIA
Use source documents to capture data, and then use this checklist to ensure each subject meets criteria for enrollment. This form must be signed by an Investigator.

Inclusion Criteria	Comments	Criterion Met? All Must be "Yes"	Supporting Source documents?
Age 1 - 12		Yes No	Yes No
Currently or previously enrolled in ABT, clinical or research based, OR typically-developing child without history of neurological deficit		Yes No	Yes No
In good health via parent report		Yes No	Yes No

Exclusion Criteria	Criteria Met and Documented?	Criterion Met? All Must be "No"	Supporting Source documents?
Physical condition or illness that prevents rocking in a chair safely via parent report		Yes No	Yes No

Attestation

I, _____ (printed name), do attest that the above information on this form is accurate.

_____ _____
Signature of Participant Date Signed

_____ _____ _____
Printed Name of Legally Authorized Representative Signature of LAR Date Signed

_____
Authority of LAR
*Authority to act on behalf of another includes, but is not limited to, parent, guardian, or durable power of attorney for health care

UF	HUMAN SUBJECTS PROTECTION PROGRAM	**RESEARCH ELIGIBILITY CHECKLIST** **Name:** **Date Consent Signed:**	IRB# and Title: **17.0725** Instrumented Rocking Chair to Promote/Monitor Recovery of Pediatric SCI Trunk Control PI: Andrea L. Behrman, PhD, PT

Research Participant - Attestation

Participant is: **Eligible**

Ineligible

_____

_____

Declined

_____

_____

Completed by: _____
Print Name **Signature**

Investigator: _____ _____ _____
Print Name **Signature** **Date of Eligibility**

Withdrawn **Completed**

_____

_____

Investigator: _____ _____
Print Name **Signature** **Date of Withdraw or Completion**

APPENDIX C
SENSORS, SCHEMATICS, CUSTOM PCB, AND BILL OF MATERIALS TABLE FOR ELECTRONICS

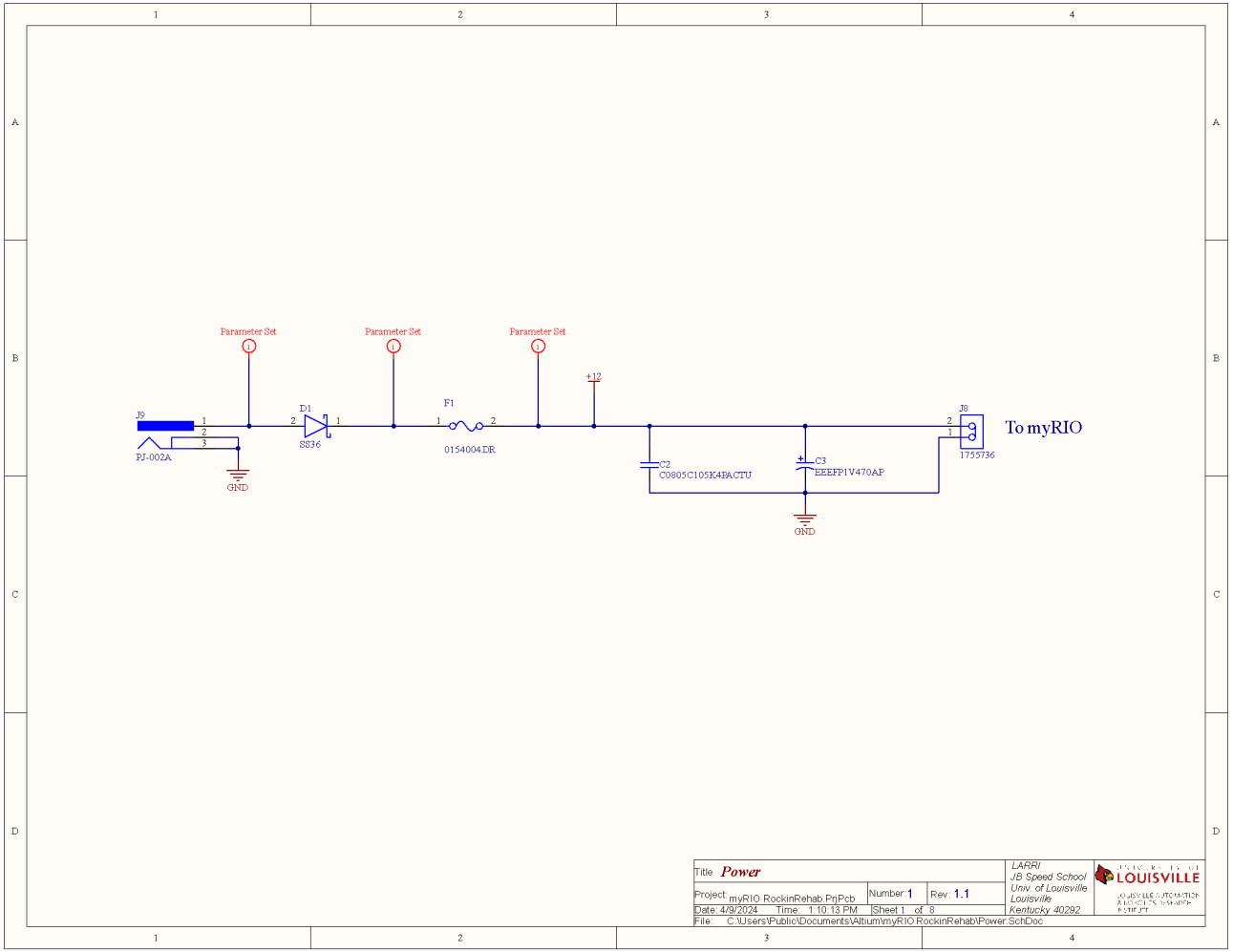

Figure 23: Electronics schematic: Power

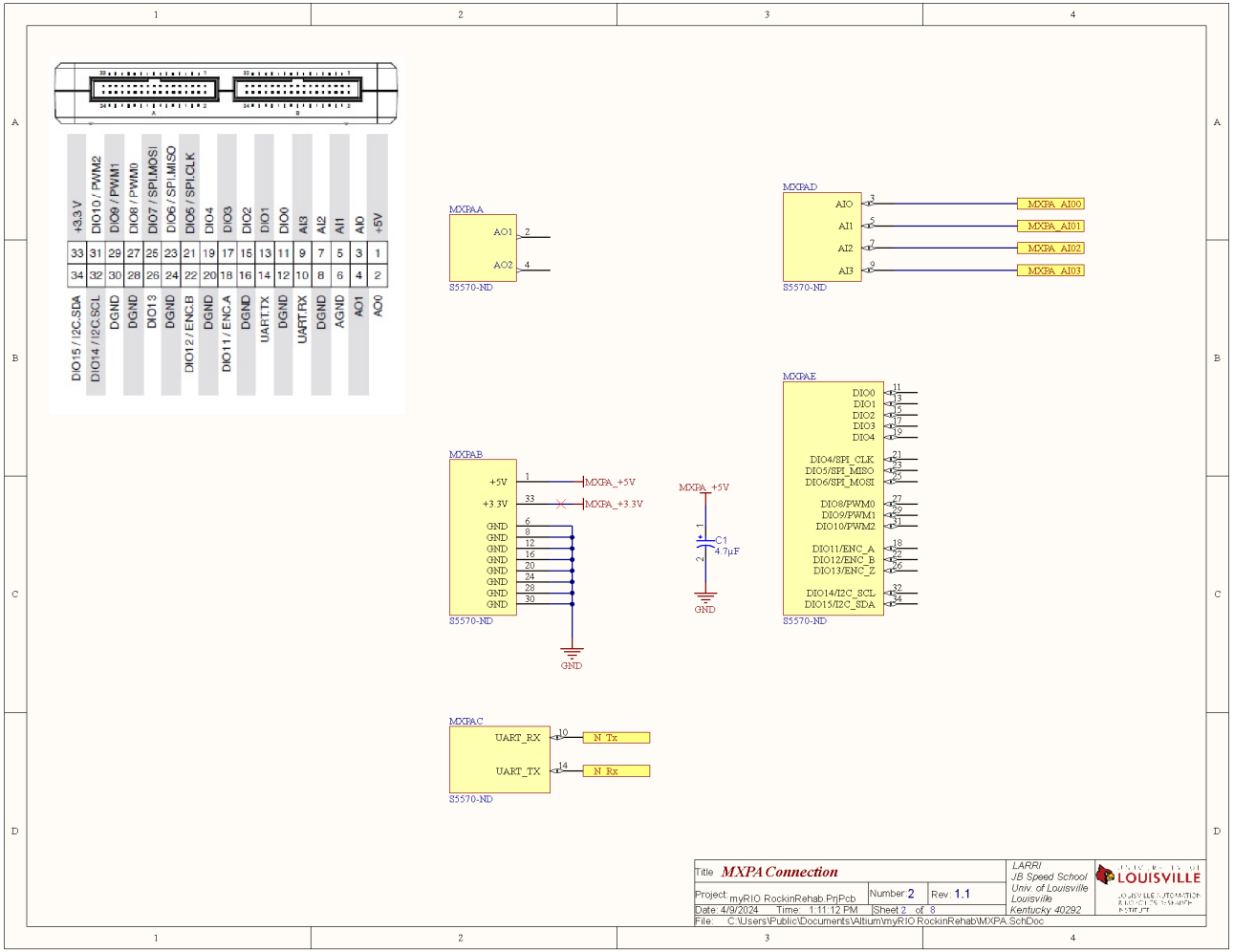

Figure 24: Electronics schematic: MXP A Connection

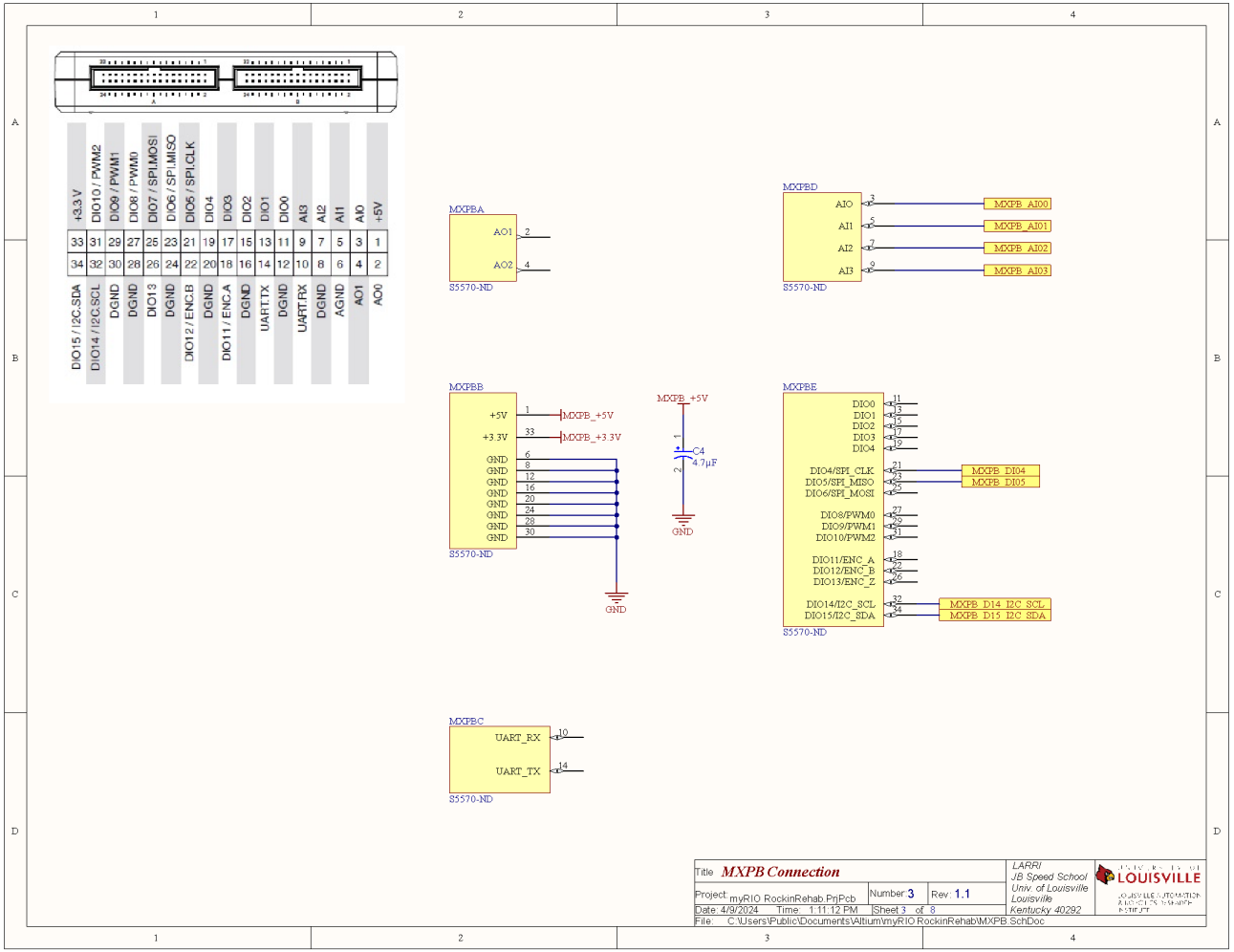

Figure 25: Electronics schematic: MXP B Connection

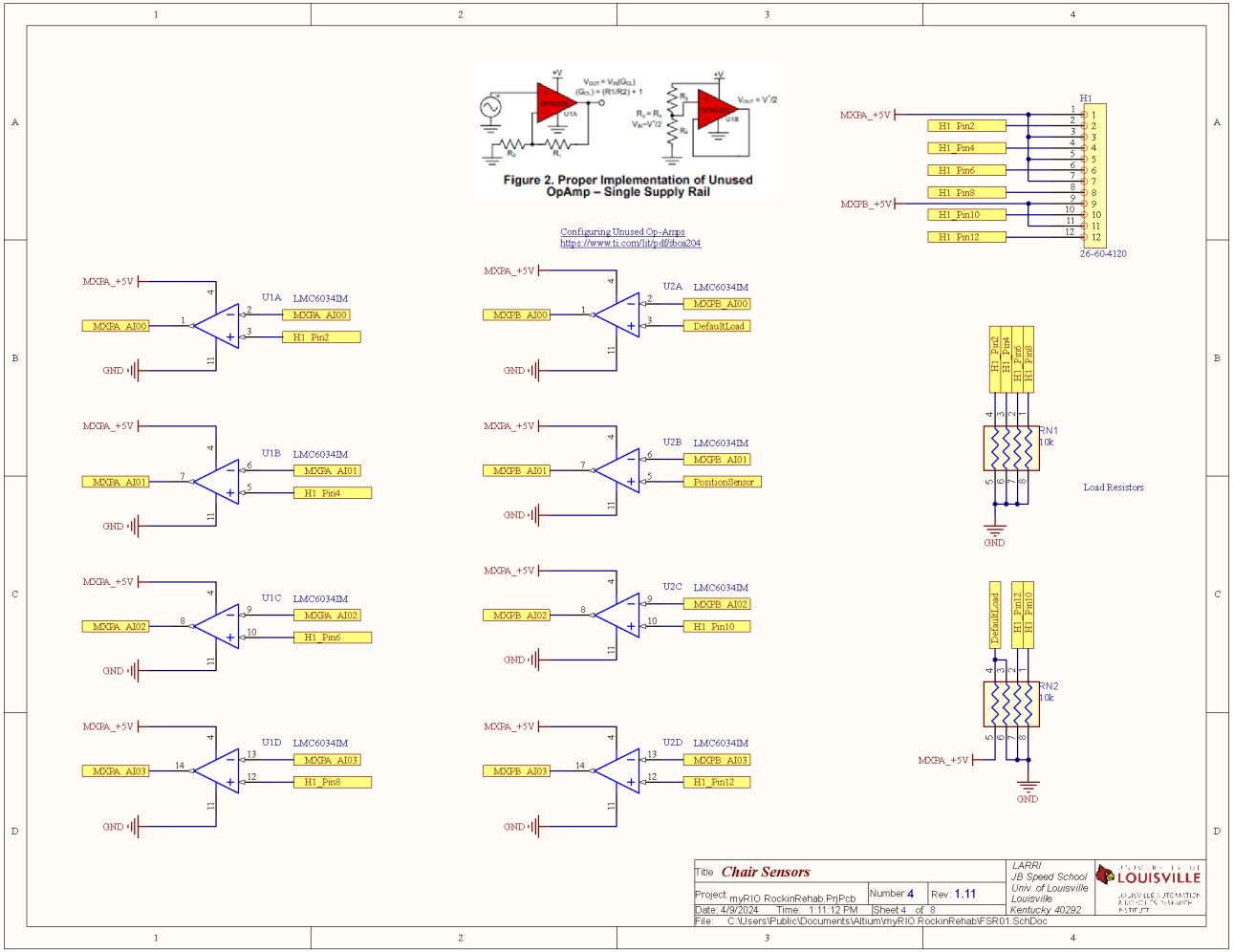

Figure 26: Electronics schematic: Sensors and Amplifiers

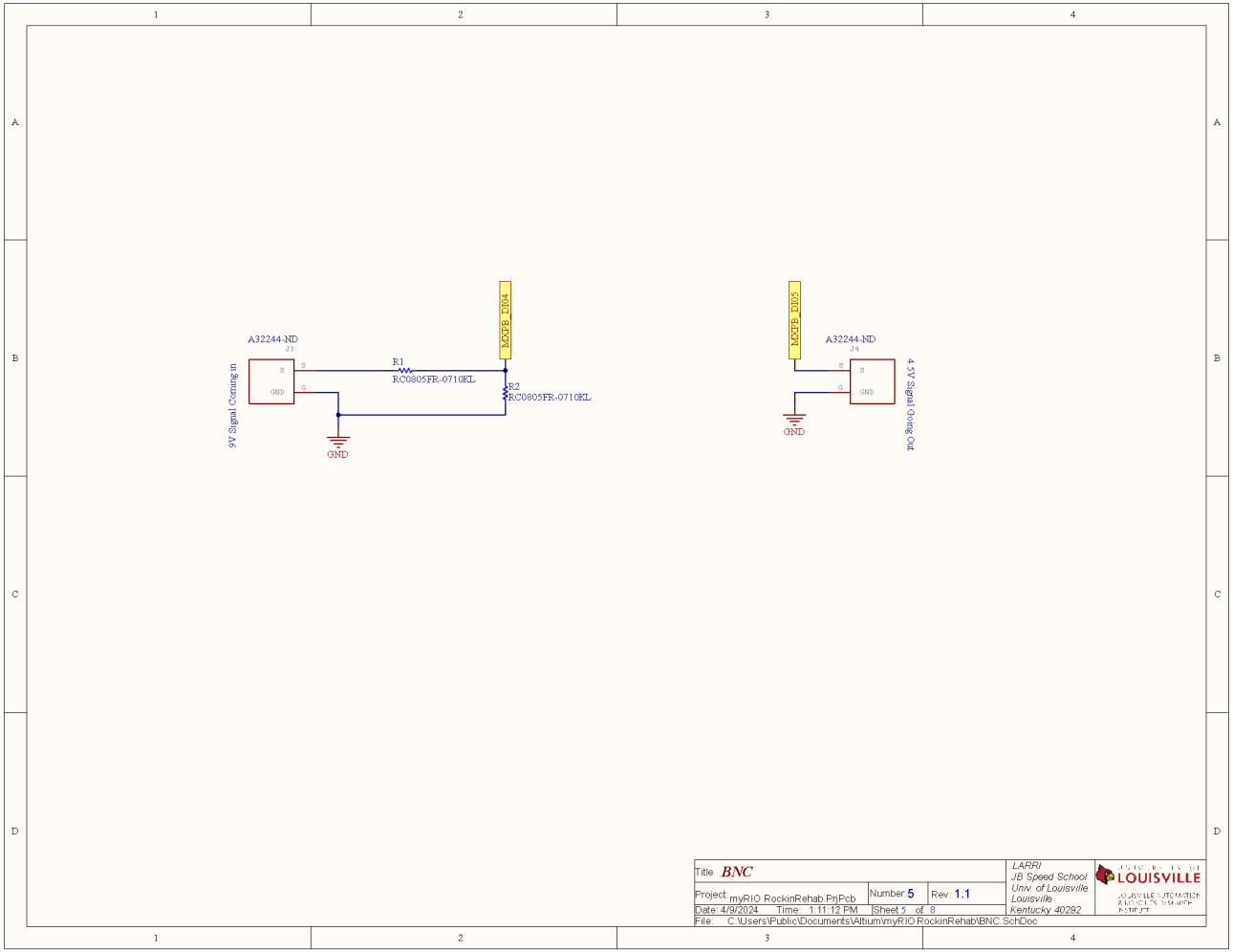

Figure 27: Electronics schematic: BNC Connectors

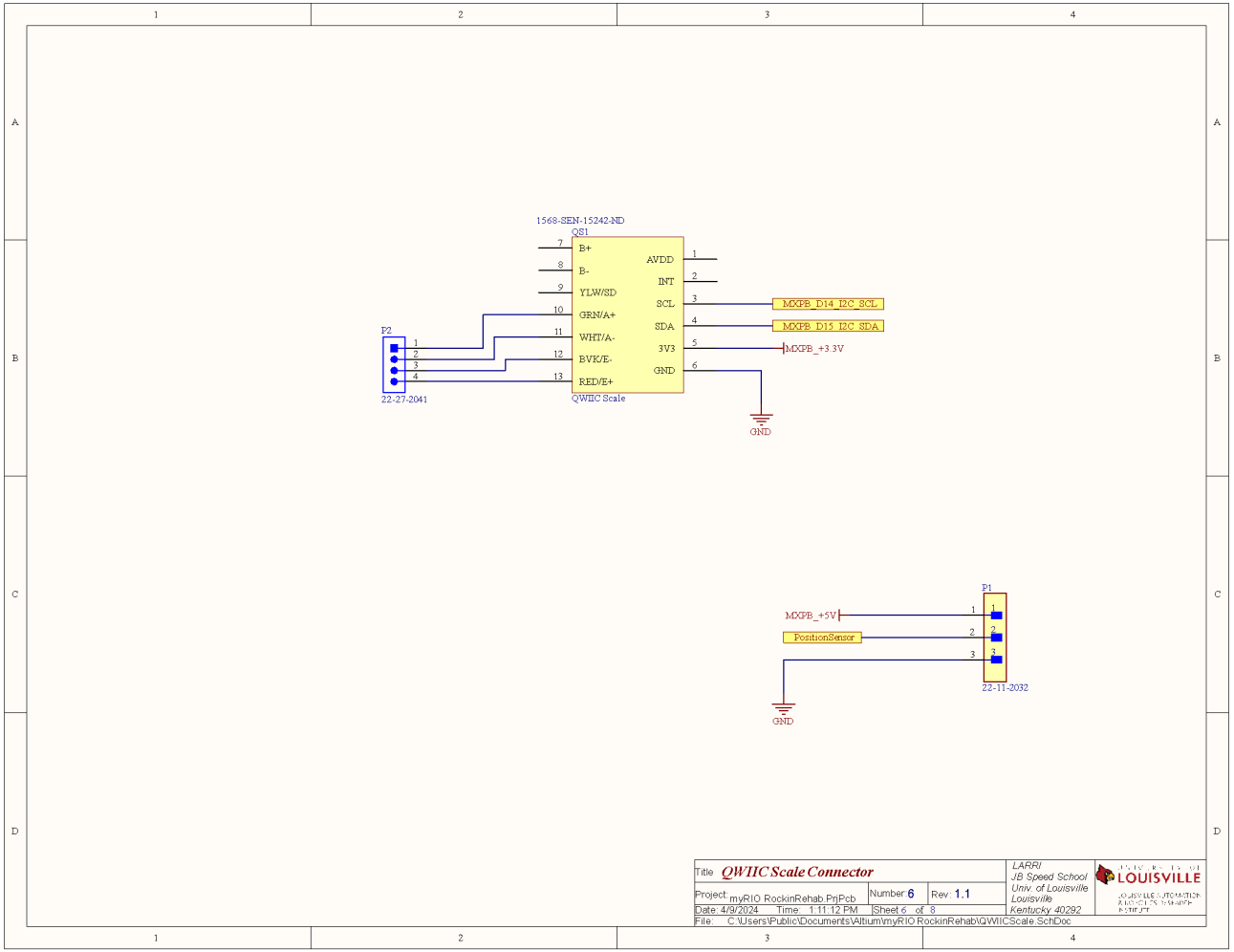

Figure 28: Electronics schematic: QWIIC Scale Header Connection

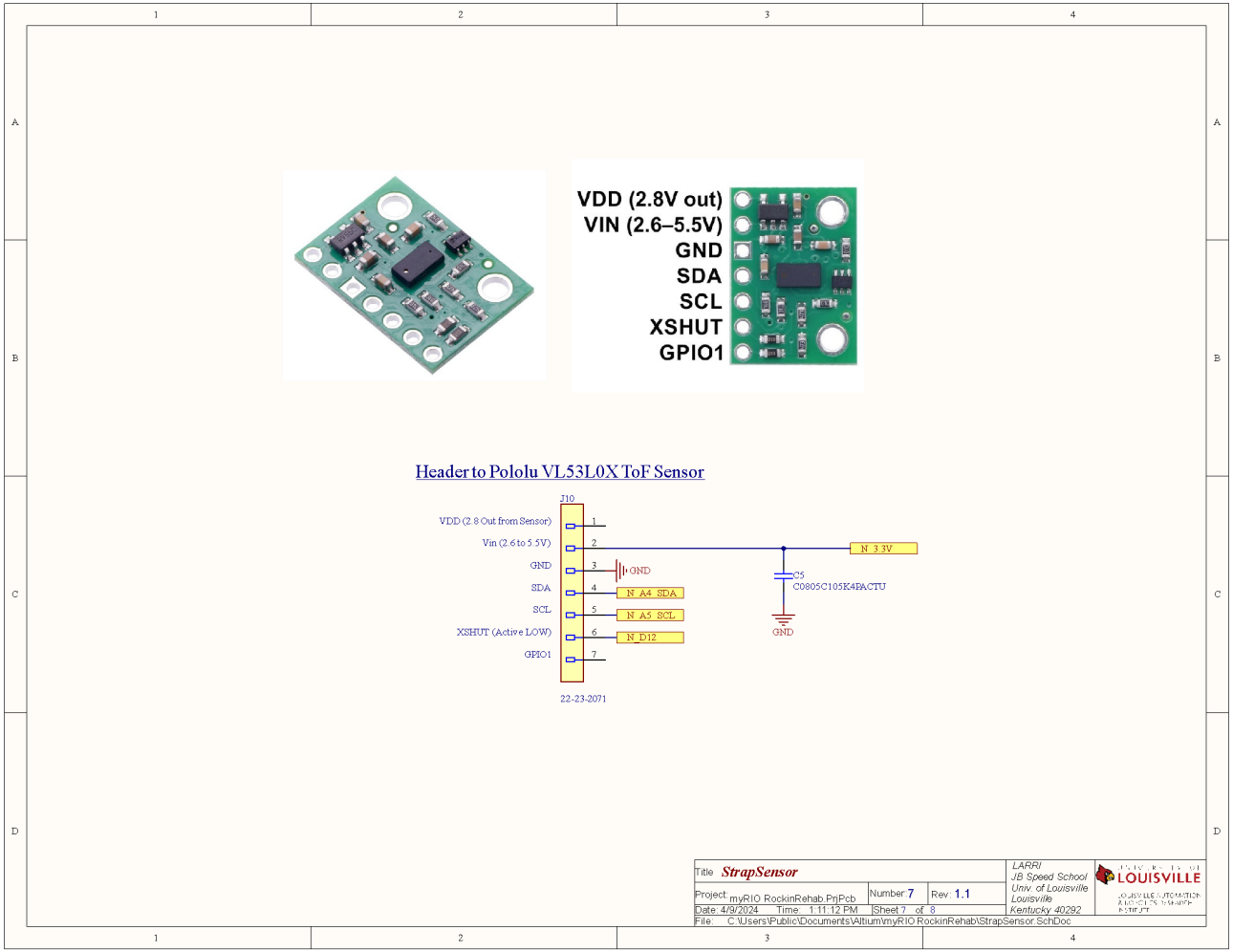

Figure 29: Electronics schematic: Pololu VL53L0X Time of Flight Sensor Header Connection

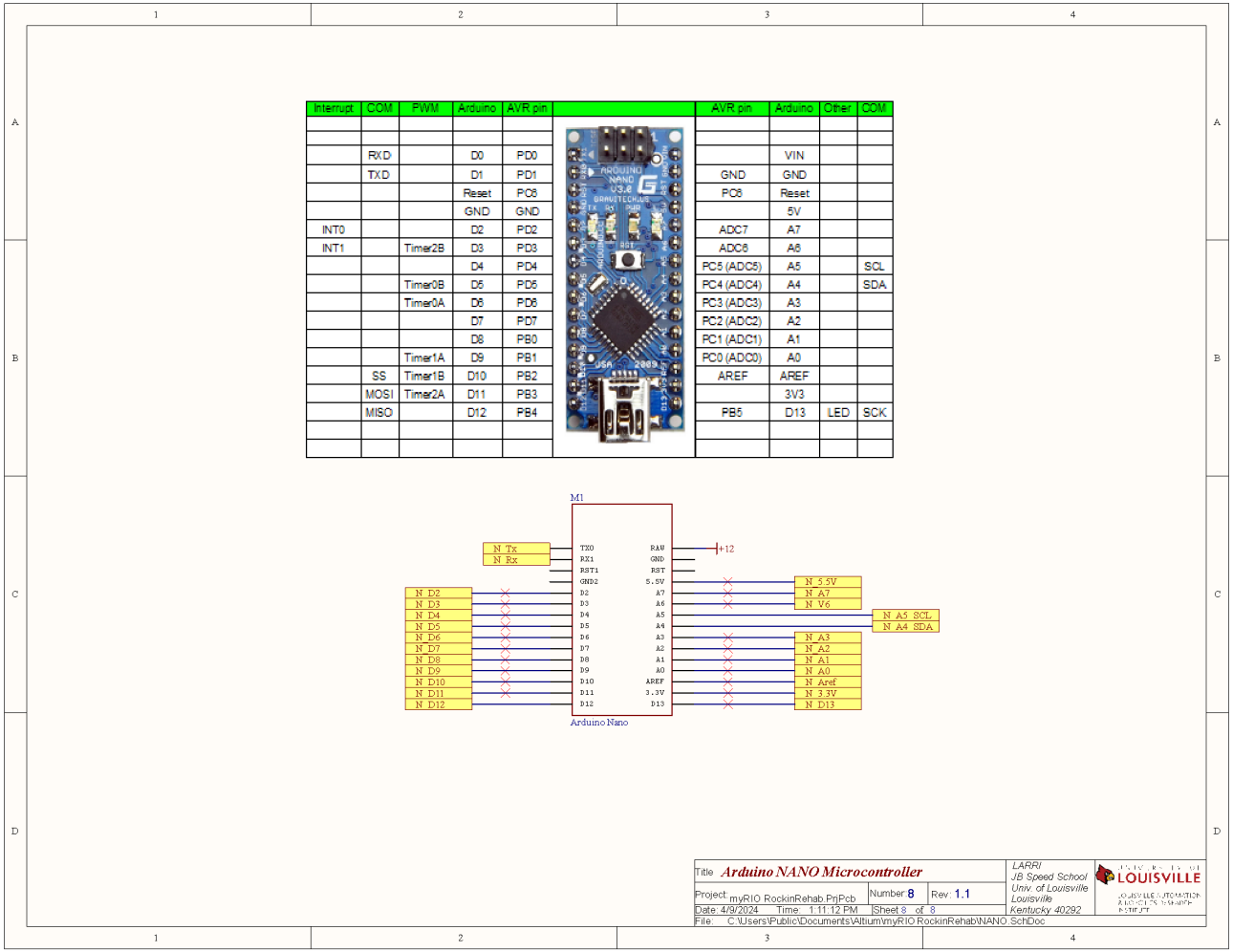

Figure 30: Electronics Schematic: Microcontroller

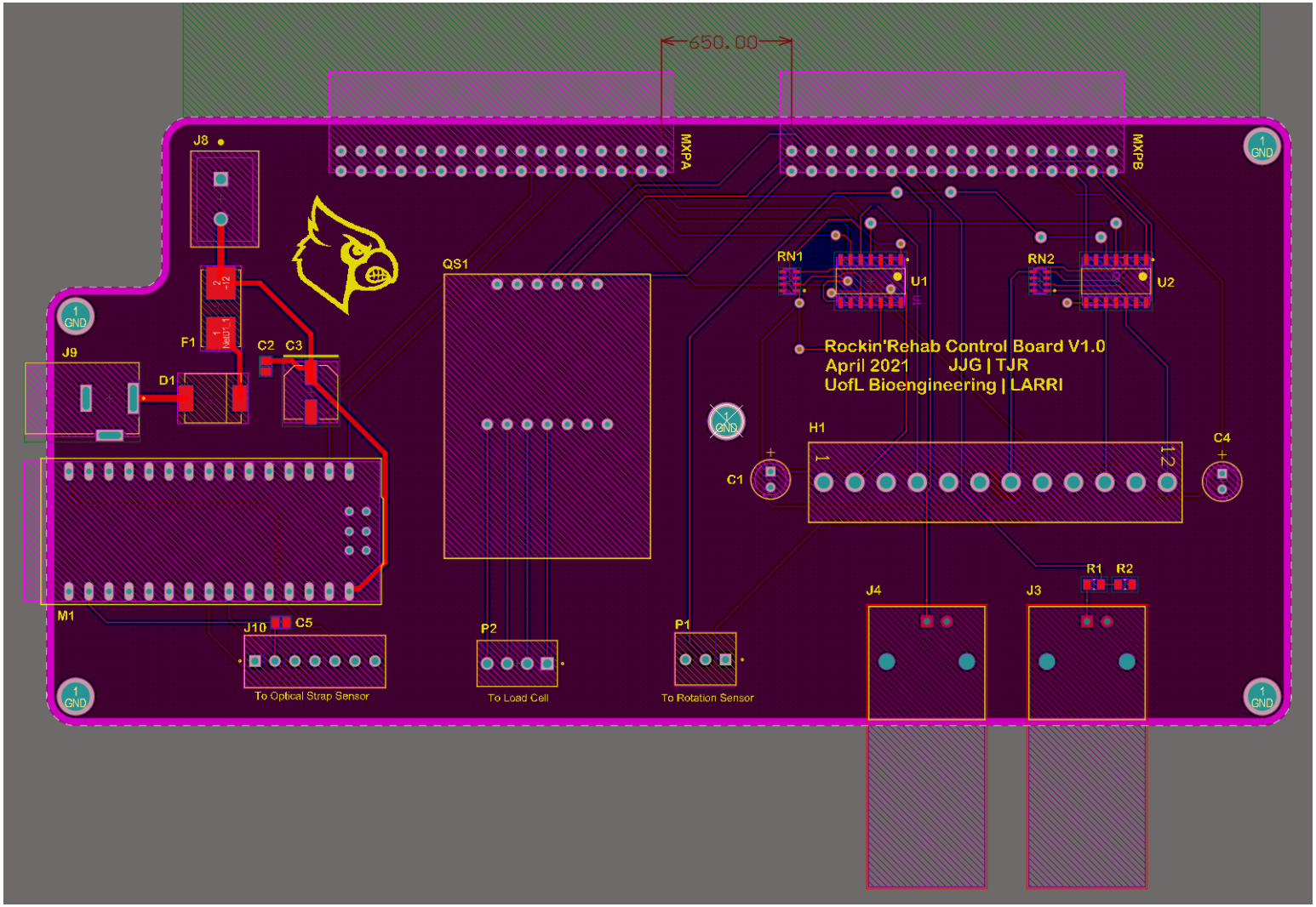

Figure 31: Custom PCB – Altium™ Transparent 2D View (Copper Pours Hidden)

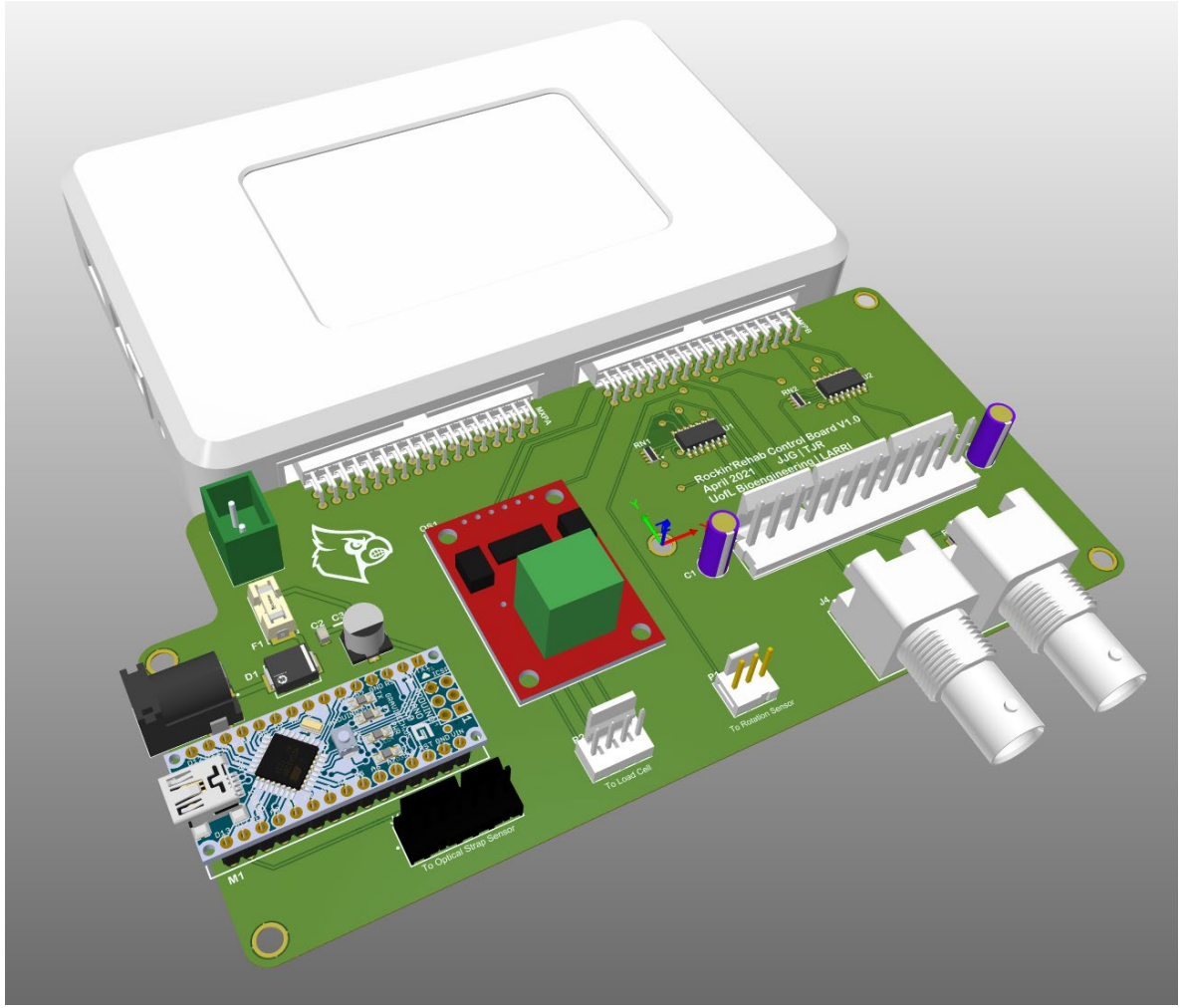

Figure 32: Custom PCB 3D Rendering (ISO View)

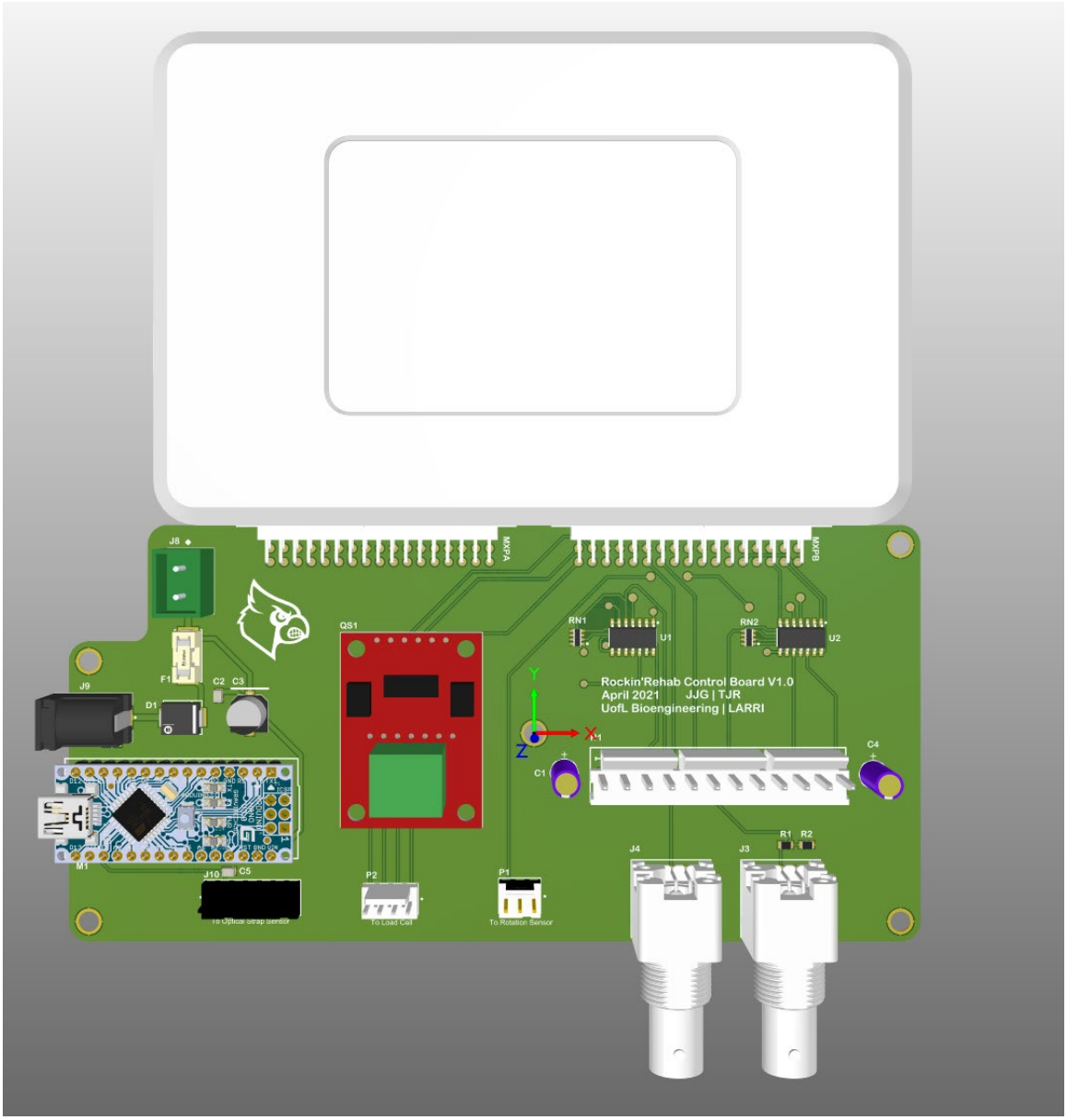

Figure 33: Custom PCB 3D Rendering (Top View)

Table 20: Custom PCB Bill of Materials

Designator	Part Name	Description	Designator	Quantity	Manufacturer 1	Manufacturer Part Number	Manufacturer Lifecycle	Supplier	Supplier Part Number	Unit Price	Subtotal
C1, C4	ECA1HM4R7	Aluminum Electrolytic Capacitor, 4.7 uF, +/- 20%, 50 V, -4	C1, C4	2	Panasonic	ECA-1HM4R7	Volume	Mouser	667-ECA-1HM4R7	0.21	0.42
C2, C5	C0805C105K4PACT	CAP ALUM 1UF 20% 35V SMD	C2, C5	2	KEMET	C0805C105K4RACTU	Volume	Mouser	80-C0805C105K4R	0.11	0.22
C3	EEEFP1V470AP	CAP ALUM 47UF 20% 35V SMD	C3	1	Panasonic	EEE-FP1V470AP	Volume	Mouser	667-EEE-FP1V470AP	0.43	0.43
D1	SS36	DIODE SCHOTTKY 60V 3A SMC	D1	1	Vishay Semiconductors	SS36-E3/57T	Unknown	Mouser	625-SS36-E3	0.56	0.56
F1	0154004.DR	FUSE BRD MNT 4A 125VAC/VDC 2SMD	F1	1	Littelfuse	0154004.DR	Volume	Mouser	576-0154004.DR	2.41	2.41
H1	26-60-4120	CONN HEADER VERT 12POS 3.96MM	H1	1	Molex	26-60-4120	Volume	Mouser	538-26-60-4120	0.85	0.85
J3, J4	Jack, PCB; 50 Ohms	BNC Connector Jack, Female Socket 50Ohm Panel Mount	J3, J4	2	TE Connectivity	5227161-1	Volume	Digikey	A32244-ND	4.32	8.64
J8	1755736	Male Header, Pitch 5.08 mm, 1 x 2 Postion, Height 12 mm	J8	1	Phoenix Contact	1755736	Volume	Mouser	651-1755736	0.58	0.58
J9	PJ-002A	Through Hole Right Angle DC Power Jack, 2.5 A, 2 mm Ce	J9	1	CUI Devices	PJ-002A	Volume	Mouser	490-PJ-002A	0.6	0.6
J10	22-23-2071	CONN HEADER 7POS .100 VERT TIN	J10	1	Molex	22-23-2071	Volume	Mouser	538-22-23-2071	0.43	0.43
M1	Arduino Nano	Evaluation Board, MCU 8-Bit, Arduino Nano, AVR, ATmeg	M1	1	Arduino	A000005	Unknown	Mouser	782-A000005	24.9	24.9
MXPA, MXPB	myRIO_MXP	34 Position Header Connector 0.100" (2.54mm) Through	MXPA, MXPB	2	Sullins	PPPC172LJBN-RC	Volume	Digikey	S5570-ND	2.44	4.88
P1	22-11-2032	CONN HEADER VERT 3POS 2.54MM	P1	1	Molex	22-11-2032	Volume	Mouser	538-22-11-2032	0.69	0.69
P2	22-27-2041	Male Header, Pitch 2.54 mm, 1 x 4 Position, Height 11.7 n	P2	1	Molex	22-27-2041	Volume	Mouser	538-22-27-2041	0.41	0.41
QS1	QWIIC Scale	QWIIC Scale load cell amplifier. Sparkfun NAU7802	QS1	1	SparkFun	15242	Unknown	Digikey	1568-SEN-15242-ND	16.5	16.5
R1, R2	RC0805FR-0710KL	Chip Resistor, 10 KOhm, +/- 1%, 0.125 W, -55 to 155 deg	R1, R2	2	Yageo	RC0805FR-0710KL	Volume	Mouser	603-RC0805FR-0710KL	0.017	0.17
RN1, RN2	CAY16-102J4LF	Chip Resistor Array, 1 KOhm, +/- 5%, 62.5 mW, -55 to 125	RN1, RN2	2	Bourns	CAY16-102J4LF	Volume	Mouser	652-CAY16-102J4LF	0.1	0.2
U1, U2	LMC6034IM	CMOS Quad Operational Amplifier, 14-pin Narrow SOIC	U1, U2	2	TI National Semiconductor	LMC6034IM/NOPB	Volume	Mouser	926-LMC6034IM/NOPB	2.04	4.08
										Total	66.97

Connector Pinouts

NI myRIO-1900 Expansion Port (MXP) connectors A and B carry identical sets of signals. The signals are distinguished in software by the connector name, as in `ConnectorA/DIO1` and `ConnectorB/DIO1`. Refer to the software documentation for information about configuring and using signals. The following figure and table show the signals on MXP connectors A and B. Note that some pins carry secondary functions as well as primary functions.

Figure 3. Primary/Secondary Signals on MXP Connectors A and B

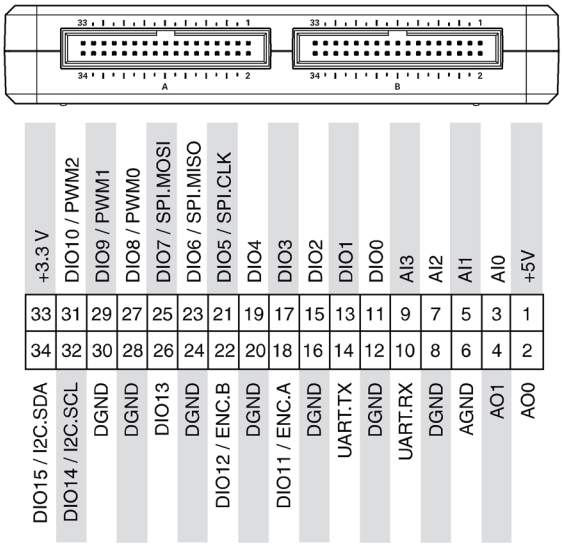

Figure 34: National Instruments myRIO-1900 MXP Connector Pinout

Table 21: Descriptions of Signals on MXP Connectors A and B

Signal Name	Reference	Direction	Description
+5V	DGND	Output	+5 V power output.
AI <0..3>	AGND	Input	0-5 V, referenced, single-ended analog input channels. Refer to the *Analog Input Channels* section for more information.
AO <0..1>	AGND	Output	0-5 V referenced, single-ended analog output. Refer to the *Analog Output Channels* section for more information.
AGND	N/A	N/A	Reference for analog input and output.
+3.3V	DGND	Output	+3.3 V power output.
DIO <0..15>	DGND	Input or Output	General-purpose digital lines with 3.3 V output, 3.3 V/5 V-compatible input. Refer to the *DIO Lines* section for more information.
UART.RX	DGND	Input	UART receive input. UART lines are electrically identical to DIO lines.
UART.TX	DGND	Output	UART transmit output. UART lines are electrically identical to DIO lines.
DGND	N/A	N/A	Reference for digital signals, +5 V, and +3.3 V.

Table 22: Pololu Time of Flight Sensor Pinout

PIN	Description
VDD	Regulated 2.8 V **output**. Up to around 100 mA is available to power external components. (If you want to bypass the internal regulator, you can instead use this pin as a 2.6 V to 3.5 V input with VIN disconnected.)
VIN	This is the main 2.8 V to 5.5 V power supply connection. The SCL and SDA level shifters pull the I²C lines high to this level.
GND	The ground (0 V) connection for your power supply. Your I²C control source must also share a common ground with this board.
SDA	Level-shifted I²C data line: HIGH is VIN, LOW is 0 V
SCL	Level-shifted I²C clock line: HIGH is VIN, LOW is 0 V
XSHUT	This pin is an active-low shutdown input; the board pulls it up to VDD to enable the sensor by default. Driving this pin low puts the sensor into hardware standby. *This input is not level-shifted.*
GPIO1	Programmable interrupt output (VDD logic level). *This output is not level-shifted.*

APPENDIX D
DATA COLLECTION PROTOCOLS

Table 23: EMG Sensor Placement Protocol

Cervical Paraspinals (PS-C)	Placed approx. 2-fingers width away from the lateral border of the spinal process at C5 orientated vertically following the line of the muscle fibers
Thoracic Paraspinals (PS-T10)	Placed approx. 2-fingers width away from the lateral border of the spinous process at T10 orientated vertically following the line of the muscle fibers
Lumbar Paraspinals (PS-L5)	Placed approx. 2-fingers width away from the lateral border of the spinous process at L5 orientated vertically following the line of the muscle fibers
Pectoralis Major (PEC)	Placed approx. 2-fingers width above the nipple line orientated horizontally along the line of the muscle fibers
Bicep Brachii (BB)	On the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit orientated in the direction of the line between the acromion and the fossa cubit following muscle fibers
Tricep Brachii (TB)	Placed at 50 % on the line between the posterior crista of the acromion and the olecranon at 2 finger widths medial to the line orientated in the direction of the line between the posterior crista of the acromion and the olecranon following the muscle fibers
Rectus Abdominus (RA)	Placed approx. 2-fingers width away from and just superior to the navel orientated vertically along the line of the muscle fibers
External Oblique (OB)	Placed superior to the iliac crest following the line of the muscle fibers
Rectus Femoris (RF)	Placed at 50% (on muscle belly) on the line from the anterior spina iliaca superior to the superior part of the patella orientated in the direction of the line from the anterior spina iliaca superior to the superior part of the patella following the line of the muscle fibers
Medial Hamstring (MH)	Placed at 50% on the line between the ischial tuberosity and popliteal fossa and just medial to midline following the muscle fibers
Tibialis Anterior (TA)	Placed top 1/3 on the line between the tip of the fibula and the tip pf the medial malleolus orientated in the direction of the line between the tip of the fibula and the tip of the medial malleolus following the muscle fibers
Medial Gastrocnemius (MG)	Placed on the middle of the medial muscle belly (most prominent bulge of the muscle) orientated following the muscle fibers

PEDS Rocking Chair 02.21.2022

EXAMINER: Encourage and demonstrate all activities wher
with task where the child will be successful. Cues provided
exactly wording can vary based on each child's compreh

Two pulses will be used for all activities if possible.

---

1. 60 second Relaxation

Activity: Quiet relaxation
Position: Child positioned in the chair with body relaxed fo
Arms begin resting in their lap for 30 seconds of collection t
armrests for 30 seconds.
Start: When subject is still with no movement-associated EM
operator to begin.
Cue: Encourage a calm, relaxed body

-Pulse for beginning and end of relaxation at 60 second m
-Pulse for beginning and end of relaxation at each 30 secc

Labview operator:
-Take notes of any movements (time and what moved) thc
relaxation

---

2. Familiarize With Chair/Learn to Rock

PEDS Rocking Chair 02.21.2022

3. Independent Rocking

Activity: Child will attempt to rock in the chair for 60 seco
Position: Child positioned in the chair, arms may be used h
accomplish the task. Start the child's arms on the armrests
Start: Wait for Labview operator to signal OK to begin 60 s
Give Labview operator signal to indicate a good rocking
Cue: "Use your body to rock the chair", "Rock your ship or

-Pulse for beginning and end of rocking attempts at the 6

---

4. Rocking with intention through feet

Activity: Child will attempt to rock in the chair for 60 seco
pushing through their feet
Position: Child positioned in the chair, arms on armrests
Start: Wait for Labview operator to signal OK to begin 60 s
Give Labview operator signal to indicate a good rocking
Cue: "Rock the chair by pushing down through your feet",
pushing through the waves",

-Pulse for beginning and end of rocking attempts at the 6

PEDS Rocking Chair 02.21.2022

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5. Rocking without Arms (Intention with trunk)

Activity: Child will attempt to rock in the chair for 60 seco
their arms
Position: Child positioned in the chair, arms placed on the
their chest, or hovering above their lap
Start: Wait for Labview operator to signal OK to begin 60 s
Give Labview operator signal to indicate a good rocking
Cue: "Without using your arms, use your body to rock the
without using your hands"

-Pulse for beginning and end of rocking attempts at the 6

---

6. Rocking with Footrest Removed (Intention wi

Activity: Child will attempt to rock in the chair for 60 seco
their trunk muscles (no arms or legs)
Position: Child positioned in the chair with footrest remove
their lap, crossed over their chest, or hovering above thei
Start: Wait for Labview operator to signal OK to begin 60 s
Give Labview operator signal to indicate a good rocking
Cue: "Without using your arms, use your body to rock the
without using your hands"

-Pulse for beginning and end of rocking attempts at the 6

CURRICULUM VITAE

Name: Johnathan George

Address: 4013 Delaware Drive
La Grange, KY 40031

Skills and Areas of Expertise

Pediatric Spinal Cord Injury Rehabilitation Equipment	Laboratory equipment installation maintenance and certification	GMP cell culture
Biomechanics and Rehabilitation	Electronic instrumentation design and implementation	BSC aseptic & sterile laboratory technique
EMG data collection, processing and analysis	Design for 3D printing and implementation	Cell counting, environmental monitoring, cryopreservation etc.
Data Processing and Machine Learning (MATLAB)	Solid Modeling (SolidWorks)	LabVIEW programming

Education

PhD in Interdisciplinary Studies: Specialization in Translational Bioengineering	J.B. Speed School of Engineering University of Louisville	Anticipated May 2024
Bachelor of Science in Mechanical Engineering	University of Tennessee at Chattanooga	December 1993

Experience

Bioinstrumentation Controls R & D Lab – Graduate Research Assistant January 2017 – Present
J. B. Speed School of Engineering; Dr. Thomas Roussel, Director

- Project lead in design and implementation of research and development of therapy device for use by children with spinal cord injuries
- Provide input to research projects, NIH grant writing (R15 and F31)
- Assist with laboratory equipment setup; provide expertise in 3D printing for laboratory and student projects
- Assist with teaching of classes and labs, creation of assignments, grading, and mentoring undergraduates in their co-op experience

Center for Advanced Cellular Therapies Internship Jan 2016 – March 2017
U of L School of Medicine, Dept. of Cardiology; Vincent LaRussa, PhD; Laboratory Director

- Trained as student team lead for GMP cell manufacturing
- Installation, validation, and maintenance of equipment for newly renovated GMP facility to include refrigerators, centrifuges, incubators, LN2 & CO2 system manifold switchers, cryo-freezer, and cryo-tanks.
- GMP manufacture bone marrow and cardiac tissue source materials to expand selected MSC therapeutic cells used for wound, tissue and organ regeneration clinical studies.
- Participated in performance of GMP CD4 CAR T validation studies including T Cell culture, lentiviral transduction, expansion, harvest, packaging, labeling, cryopreservation, and assays for killing effectiveness and transduction efficiency by flow cytometry.
- Performed assays and analysis for release testing to include fresh and post-thaw analysis of viability, cell enumeration and recovery using hemocytometer Trypan Blue, Nexcellom Cellometer AOPI, and Single Platform Trucount flow cytometry 7-AAD. Testing for endotoxin, and CFUs performed.
- Performed environmental monitoring to include surface and personnel touch plates and viable and nonviable air static and dynamic sampling.
- Participated in TEVA, SENECA, and CONCERT clinical trial cell preparation for administration.
- Maintenance and Smart-Vue alarm monitoring of cryo-storage tanks and incubators and gasses
- Trained in cryo-shipping and receipt of cellular materials, supply inventory and records, cell product inventory and records, facility cleaning and disinfection, GMP gowning, laboratory safety, and biohazard waste disposal.

Islet Cell Processing Laboratory Internship April 2017 – December 2017
U of L School of Medicine, Dept. of Surgery; Balamurugan Appakalai, Islet Director

- Assisted with technical writing including RO1 grants, journal articles and book chapters.

Publications

George, Johnathan J., A.L. Behrman, and T.J. Roussel, Development of a rocking chair for use by children with spinal cord injuries. *Disability and Rehabilitation: Assistive Technology*, 2024(Epub ahead of print).

Dhanasekaran, Maheswaran; **George, Johnathan J.**; Loganathan, Gopalakrishnan; Narayanan, Siddharth; Hughes, Michael G.; Williams, Stuart K.; Balamurugan, Appakalai N.; Pig Islet Xenotransplantation; *Current Opinion Organ Transplant*, 2017, Oct 22(5); 452-462

George, Johnathan J., A.L. Behrman, B. Ugiliweneza, G. Morgan and T. J. Roussel, Rocking in a Rocking Chair Activates Trunk Muscles in Children with Spinal Cord Injury and Impaired Trunk Control. *Journal of Pediatric Rehabilitation Medicine*, 2024(Submitted: In Peer Review)

George, Johnathan J., A.L. Behrman, and T.J. Roussel, Sensor-Based Detection of Muscle Activation During Rocking in Children with Spinal Cord Injuries. *Journal of Rehabilitation and Assistive Technologies Engineering*., 2024 (Submission Pending by April 30, 2024).

Conference Abstracts and Presentations

Integration of Soft Optical Sensor into Pediatric SCI Rocking Chair Safety Harness	BMES Annual Meeting 2022	SanAntonio, TX

Integration of Soft Optical Sensor into Pediatric Spinal cord injury Rocking Chair Safety Harness	NSF EPSCoR Super Collider 2022	Louisville, KY
Trial of Instrumented Rocking Chair for Children with SCI: Muscle Activation and Sensor Response	BMES Annual Meeting 2021	Virtual (Online)
Preliminary Trial of Instrumented Rocking Chair for Children with Spinal Cord Injury: Investigating Muscle Activation and Embedded Sensor Response	NSF EPSCoR Super Collider 2021	Virtual (online)
Smart Rocking Chair for Promotion and Assessment of Trunk Control in Children with Spinal Cord Injury	NSF EPSCoR Super Collider 2020	Lexington, KY
Rockin' Rehab - New Tools for Tracking and Assessment of Trunk Activity in Pediatric Spinal Cord Injury	BMES Annual Meeting 2019	Philadelphia, PA
Instrumented rocking chair to augment activity-based locomotor training to improve trunk control in children with spinal cord injury	Research!Louisville 2019	Louisville, KY
Instrumented Rocking Chair for Use in Activity-Based Therapy for Improvement of Trunk Control in Children with Spinal Cord Injury	Research!Louisville 2018	Louisville, KY
Force Sensitive Resistors in Measurements Laboratory Teaching Module	BMES Annual Meeting 2018	Atlanta, GA
Smart Rocking Chair for Promotion and Assessment of Trunk Control in Children with Spinal Cord Injury	Graduate Student Regional Research Conference	Louisville, KY

Awards

Best Graduate Student Peer-Reviewed Journal Paper, Interdisciplinary Studies with Specialization in Translation Bioengineering program Spring, 2024

Top 3 Presentation: Kentucky EPSCoR SuperCollider Conference & Research Showcase 2022

Top 3 Presentation: Kentucky EPSCoR SuperCollider Virtual Conference & Research Showcase 2021

Professional Societies:

BMES Biomedical Engineering Society 2018-Present

Other Activities

Business owner

Business focused on high-complexity microelectronic repairs of mobile devices. Specialized in advanced repair jobs from other mobile device repair shops throughout the US.

Research & Design Mechanical Engineer

Carlisle Tire and Wheel; Clinton, TN

- Responsible for entire design process from tread pattern and mold design to specification development, developing over 40 tires in first two years with the company. Assisted with prototype builds, analyzed completed prototypes, and made recommendations for optimization.
- Designed and coded design software which is still in use 16 years after initial release.
- Traveled to locations around the US to promote products and answer technical questions.

Produced and maintained databases of test data and standard specifications, including official tire data book for company-wide use.